SolarPACES Task II Activity:
Roadmap to Solar Fuels

Strategy for Industry Involvement and Market Penetration

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Activity duration: 01.10.2012 – 30.09.2015

Period covered by the report: 01.10.2012 – 30.09.2015

Date of preparation: 05.10.2015

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Revision: 1

Number of pages (incl. cover): 68

Content

List of Figures

List of Tables

List of Abbreviations

ARENA	Australian Renewable Energy Agency
ASTRI	Australian Solar Thermal Research Initiative
AUD	Australian Dollar
COP21	2015 Paris Climate Conference
CSF	Concentrating Solar Fuels
CSIR	Council for Scientific and Industrial Research, South Africa
CSIRO	Commonwealth Science and Industrial Research Organisation, Australia
CSP	Concentrating Solar Power
DG	Direction General of European Commission (EC)
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V., German Aerospace Center, Germany
DME	Dimethyl ether
DOE	Department of Energy, South Africa
DST	Department of Science and Technology, South Africa
Eskom	South Africa's power utility
EU	European Union
GTL	Gas to liquid
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
NWU	North-West University, South Africa
PetroSA	South Africa's national oil company
PSI	Paul Scherrer Institute, Switzerland
SASAA	South African Airways
SANEDI	South African National Energy Development Institute
SolarPACES	Solar Power and Chemical Energy Systems
US	United States of America
WIS	Weizmann Institute of Science, Israel
ZAR	South African Rand

1. Introduction

The roadmap to solar fuels project aims at enhancing industry involvement in solar fuels production and promoting market penetration of the most mature solar fuels technologies. For this purpose, two sun-rich countries – Australia and South Africa – have initially been chosen to organize workshops together with external SolarPACES experts, with the aim of presenting to targeted local industry and governments the state-of-the-art and discuss with them the market potential of the most advanced technologies for solar fuels production. Subsequent to the successful first phases, China recently joined as third country. This study is a role model for broadening the effort, offering finally the whole SolarPACES community to benefit from the country-specific roadmaps and the methodology developed.

The outcome shall be roadmaps that enable the participating countries to accelerate the implementation of solar fuel production as well as a methodology that makes this attempt transferable to other SolarPACES members (Figure 1), or to countries that are of special interest for the SolarPACES members but are not members by themselves yet. The project and the roadmaps for the participating countries shall be connected to existing roadmaps like the one of the European Industrial Initiative on solar energy - CSP[i] (Figure 2) and national roadmaps and political guidelines. An example is the roadmap of the Australian Renewable Energy Agency ARENA[ii]. There shall be a link between the existing Concentrating Solar Power (CSP) industry and the future Concentrating Solar Fuel (CSF) industry as it will most probably integrate stakeholders from the CSP side as well as from the oil and gas companies and the utilities. Therefore, the goal is to show where early market entries might be feasible, especially focused on unique conditions in the SolarPACES member countries.

Figure 1: SolarPACES members[iii] (currently 19 members): Algeria, Austria, Australia, Brazil, China, Egypt, European Commission (DG RESEARCH & INNOVATION and DG ENERGY), France, Germany, Israel, Italy, Mexico, Morocco, Republic of Korea, South Africa, Spain, Switzerland, United Arab Emirates, and United States of America.

Both example countries chosen for the first phase – Australia and South Africa – have a number of factors in common like excellent solar resources, combined with abundant natural resources like coal, natural gas, and metal ores. However, there are substantial differences in national or regional policy, in geographic location, or in market connection.

Phase 1 of the project describes how this disparity is affecting the view of the regional industry, while in Phase 2 the possibilities to improve the situation shall be investigated. In Phase 3, the transfer to other countries shall be prepared. China – as the example country in the third phase – has an outstanding potential, but its starting conditions are different in many aspects from those of Australia and South Africa.

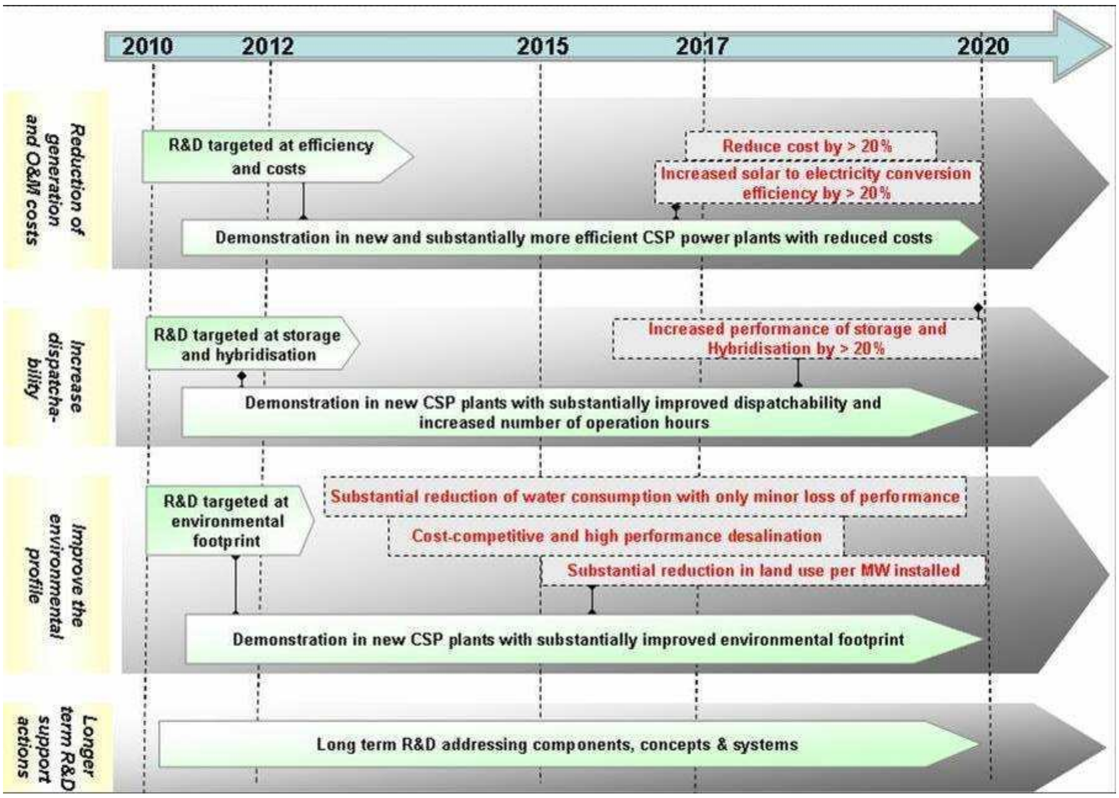

Figure 2: Roadmap of the European Industrial Initiative on solar energy – Concentrating Solar Power. The strategic objective is to demonstrate the competitiveness and readiness for mass deployment of advanced concentrating solar power (CSP) plants, through scaling-up of the most promising technologies to pre-commercial or commercial level.

2. State of the Art

2.1. Definition of a Solar Fuel

A **fuel** can be defined as any chemical compound that stores energy, which can be released by being oxidized (or reacted with oxygen) to provide heat. The term is sometimes extended to any source of primary energy, for example nuclear fuel. Fuels can also react with oxygen in a fuel cell for direct production of electricity.

A **solar fuel** is any chemical compound that can be reacted with oxygen to release energy, which has first been formed in part or in full by input of energy from solar radiation. There are a range of approaches for achieving this solar-to-chemical energy transformation. Arguably biomass, produced by photosynthesis, is the 'original' solar fuel. Engineered approaches include photolytic processes that mimic photosynthesis, adapted biological processes such as algae that preferentially produce lipids or hydrogen, and electrolysis of water using electricity produced from solar energy. However, this project is primarily concerned with technologies that use **concentrated solar radiation** to store solar energy in a chemical form as a fuel via high temperature **thermochemical** reactions.

Examples are conventional liquid hydrocarbons, alcohols and hydrogen, which can be oxidized by combustion to drive a heat cycle or to power an electric motor in a fuel cell.

Thus, solar fuels provide potential input energy to the same end-use applications as fossil fuels, i.e.:

- on-board combustion for transportation;
- electric power generation;
- on demand production of process heat.

Transportation may be the most attractive end-use application for a solar fuel when compared to a non-fuel renewable energy approach – mainly due to the value of the incumbent fossil fuel options. In moving toward a future energy mix that is increasingly supplied by intermittent renewable energy sources such as solar and wind, solar fuels offer:

- high density energy storage for time-scales extending to many months;
- cost-effective energy transport over long distances from point of capture to point of use;
- rapid and convenient recharging of energy for transportation.

2.2. Fuels in the Global Energy Mix

Figure 3 shows the breakdown of globally traded primary energy at present (2007) together with the IEA's prediction for 2030. By far the majority is provided by the three fossil fuels – coal, oil, and gas – and that dominance is projected to persist well into the future. At the present time, oil accounts for over 30% and gas a further 20% of the world's primary energy demand. In terms of the financial value invested in delivering that primary energy to the point of use, oil accounts for nearly 70% of cash flows, reflecting its higher value, and gas a further 17%.

Arguably, the world is at a point of change in its energy supply and use patterns, so forward projections that rely on extrapolation of historical trends could easily prove false. In fact, rapid changes in energy supply are currently being experienced and seem assured to continue.

In this global energy supply mix, a future solar fuel industry will compete with fossil oil and gas. Potentially, a solar fuel may directly compete for price; however, an underlying assumption is that it will also offer the benefits of lower greenhouse gas emissions and other sustainability benefits.

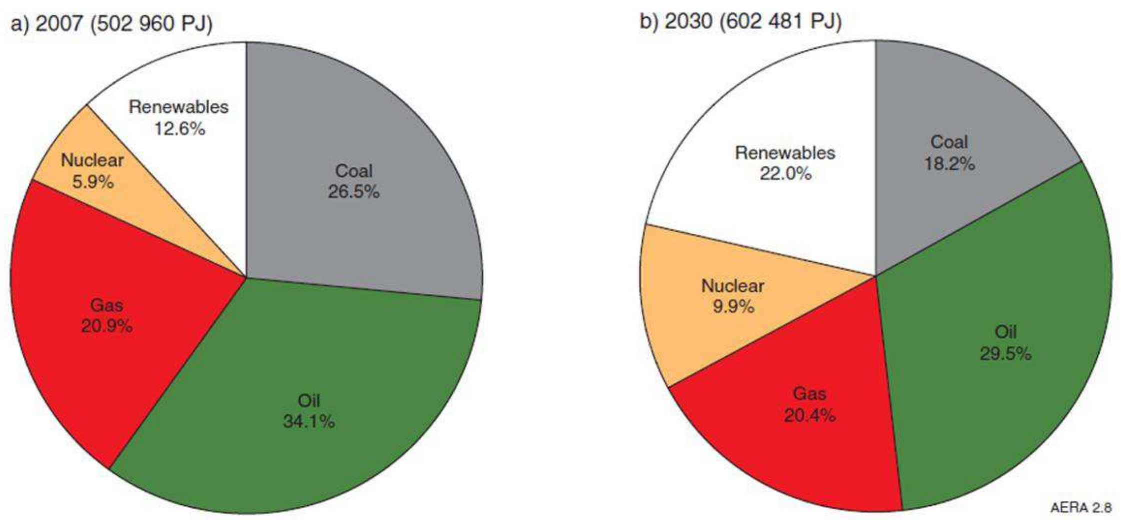

Figure 3: Outlook for world primary energy demand, based on IEA data, reproduced from ABARES (2010)[iv].

Historical changes in oil price and future trends are the subject of much analysis and speculation. Figure 4 illustrates the real and nominal crude oil price over the period 1946 to 2012. It shows a strong increasing trend from 2004 to 2008 with a sudden reversal coinciding with the global financial crisis, followed by a return to close to 2008 prices correlating with financial recovery. It also shows a price variance during the 1970's "oil crisis".

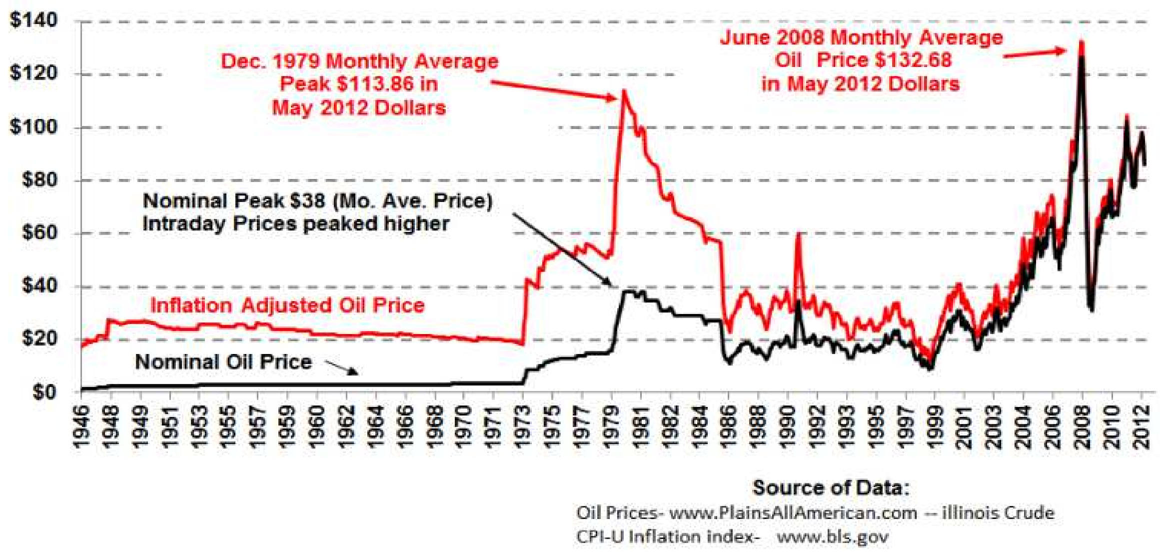

Figure 4: Real and nominal crude oil prices in May 2012 USD reproduced from www.InflationData.com.

There is much debate on the timing of "peak oil" i.e., the point in time where demand exceeds supply, and increased exploration and extraction efforts no longer keep pace with the depletion of a finite resource and the growing demand. There appears to be a consensus that at least for "conventional" oil this will occur sometime within the next decade (and in fact it may already have happened). If that turned out to be the case, then the historic price trend could be interpreted as underlying trend to ever-increasing prices, since demand continues to grow faster than supply. The IEA is projecting a slow but steady growth in real oil prices in the coming decades (IEA, 2012)[v]. Of course, sudden financial crises can diminish such a trend for their duration and also market manipulation – such as in the 1970s – can have a major impact.

2.3. Current and Future Fluid Fuels

In this context, fluid fuels most likely seem to keep an important role for quite some time or even indefinitely into the future. The choice of the dominant fluid fuel may well change over time, however. Possible fluid fuels include:

- **Hydrogen** (H_2) has been the subject of much promotion and expectation over many decades. It has the advantage of combusting to pure water. Its major disadvantage consists in the extreme difficulty to achieve a practical volumetric or mass-based energy density for storage or long distance transport. H_2 can be produced both from fossil fuels or splitting of water.
- **Methane** (CH_4) is the main constituent of natural gas. Liquefaction is costly but practical and now proven for international trade. Methane can be synthesized from other sources such as coal or biomass.
- **Methanol** (CH_3OH) is the simplest hydrocarbon liquid. It can be synthesized from base sources such as natural gas, coal or biomass. Methanol is more convenient for use and transport than methane. It is, however, carcinogenic and has a lower energy density than current oil based fuels.
- **DME** (dimethyl ether or CH_3OCH_3) requires a slightly elevated pressure to remain as a liquid (similar to LPG). It has no carcinogenic concerns. It can be used for transport relatively easily and is synthesized from methanol.
- **Ammonia** (NH_3) has been extensively studied to establish its practicality as a liquid fuel. It must be kept at slightly elevated pressure to remain as a liquid. A large spill can create a caustic and cryogenic hazard. Ammonia can be seen as a practical liquid vector for use of hydrogen since it is made from hydrogen combined with nitrogen from the air.
- **Synthesized "drop-in fuels"** that meet existing standards for diesel, gasoline and aviation fuels have the advantage that the existing infrastructure and market place can continue to be used seamlessly. In terms of inherent desirability, especially diesel has a lot of benefits. These fuels can be synthesized from coal, natural gas, biomass or any other source of hydrogen and carbon.

Of these various options, there is a dichotomy between those that contain carbon and those that do not. If the carbon in a fuel originates from biomass, then nature provides a closed cycle. If the carbon originates from a fossil fuel, then combustion will release CO_2 with greater or lesser intensity depending on the processes of producing and utilizing the fuel. If the CO_2 was captured at the point of combustion, in principle it could either be sequestered or returned for recycling.

2.3.1 Gasoline and Diesel – Composition

Gasoline or petrol is a liquid hydrocarbon fuel produced principally from petroleum, but can also be synthesized from other fossil fuels such as coal, natural gas, and oil shale. A typical gasoline consists mainly of hydrocarbons with between 4 and 12 carbon atoms per molecule (commonly referred to as C4-C12).

Diesel fuel in general is any liquid fuel that can be used in diesel engines. Like gasoline, it can be produced from any of the aforementioned fossil fuels, but is predominantly petroleum-derived. However, alternative diesel fuels – such as bio-diesel – are increasingly being developed and adopted. Petroleum diesel is produced by fractional distillation of crude oil at atmospheric pressure and temperature between 200 and 350°C, resulting in a mixture of hydrocarbons that contain between 8 and 21 carbon atoms per molecule (C8-C21).

2.4. Pure Solar Fuels vs. Solar Hybrid Fuels

Solar-fossil hybrid fuels combine solar energy with a carbonaceous fossil fuel such as natural gas or coal to provide a product, which contains both renewable and fossil energy. It is also possible to use other non-fossil carbonaceous feedstock – such as biomass and biogas – to make fully renewable fuels.

Solar technologies can also be used to produce renewable fuels such as hydrogen from thermochemical water-splitting cycles, or conventional fuels by splitting carbon dioxide and water, followed by synthesizing fuels from the intermediate products (carbon monoxide and hydrogen, i.e., syngas).

Figure 5 illustrates various pathways available for producing solar thermochemical fuels.

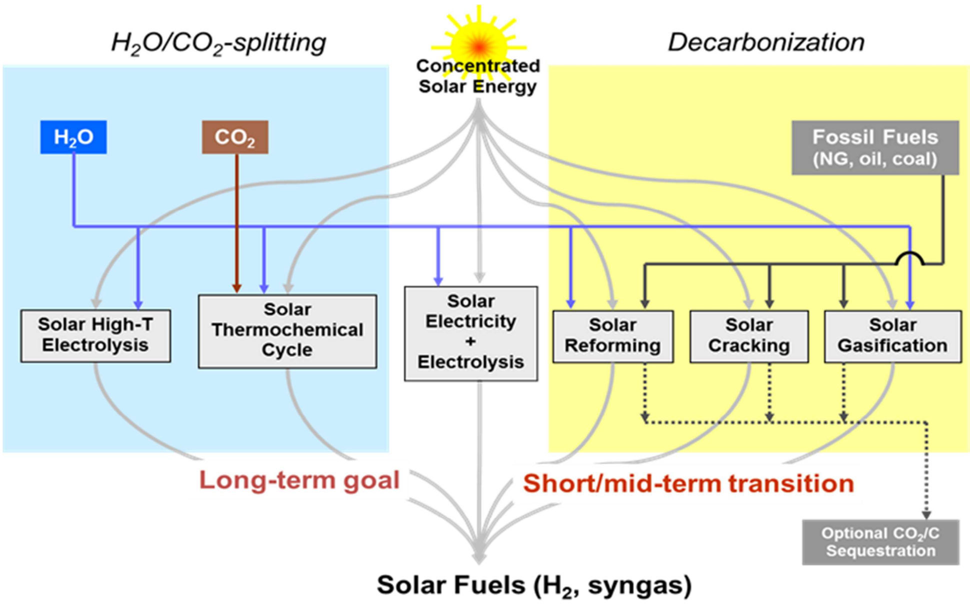

Figure 5: Overview of potential routes for thermochemical production of fuels using concentrated solar energy (courtesy of Aldo Steinfeld).

Short and midterm processes use conventional unprocessed fuels as a feedstock with energy upgrading of the fuels by embedding solar energy into the products at an amount equal to the enthalpy change of the endothermic reaction under investigation. Longer term options look at water and/or carbon dioxide splitting processes. A commonality is that all products of the fuels processes involve hydrogen and could enable subsequent synthesis of products that possess physical and chemical properties equivalent to today's commonly used hydrocarbon fuels like diesel and petrol.

2.5. Concentrating Solar Technologies

Most technologies referred to in this study need high temperatures that can only be provided efficiently by point-focusing solar concentrating devices like paraboloids or dishes, and especially solar towers. The temperature range typically starts from 750°C for reforming and might even go as high as 1800°C for some thermochemical redox processes for water or CO_2 splitting.

However there are lower-temperature industrial processes that enable industry the entrance into concentrating solar technologies, such as the generation of process steam, which might even be carried out in parabolic trough or linear Fresnel collectors, depending on the required temperature and pressure.

3. Methodology

The methodology developed in this study shall enable a discussion between research, industry, and policy to get the most promising options for solar thermochemical fuels. Screening of potential solar fuels processes and a techno-economic evaluation of CSF technologies will eventually lead to a country-specific "Roadmap to Solar Fuels".

Phase 1 (July 2012 – September 2013): The proposed Task II activity comprises the following steps:

- Identification of potentially interested industries – primarily from the oil, gas, and coal sectors – and responsible governmental representatives in two selected host countries (Australia and South Africa).
- Preparation of a "Road Show" (written documents and oral presentations) illustrating CO_2 mitigation and market potential of specific solar fuels (e.g., syngas; liquid fuels).
- Organization of workshops with interested high-level industrial and governmental representatives in the selected host countries.
- Presentation of the "Road Show" with a well-developed showcase (e.g., "solar reforming and gasification") by SolarPACES experts at the workshops in the host countries.
- Initiation of a "Roadmap to Solar Fuels" (strategy for industry involvement and market penetration) by local and external SolarPACES experts together with the identified industries and other interested bodies.
- Collection of requisitions and pre-conditions for implementing the roadmap that will serve as a feedback for further development works to supply the country-specific needs.

Phase 2 (October 2013 – September 2014): The proposed Task II activity comprises the following steps:

- Organization of two follow-up workshops and meetings with interested industries, government, and academia for the definition and preparation of a comprehensive roadmap concept and document in the two selected host countries (Australia and South Africa).
- Screening analysis to identify the most promising options for solar fuels and development of a country-specific "Roadmap to Solar Fuels" by the local and external SolarPACES experts, interested industries and governmental representatives. Links between interested industries and potential technology providers will be established.
- Collection of requisitions and pre-conditions for implementing the roadmap that will serve as a feedback for further development works to supply the country-specific needs.

Phase 3 (January 2015 – April 2016). The proposed Task II activity comprises the following steps:

- Identification of potentially interested industries – primarily from the oil, gas, and coal sectors – and responsible governmental representatives in the selected host country (China).
- Preparation of a "Road Show" (written documents and oral presentations) illustrating CO_2 mitigation and market potential of specific solar fuels (e.g., H_2; syngas; liquid fuels).
- Organization of workshops and meetings with interested industries, government, and academia for the definition and preparation of a comprehensive roadmap concept and document in the selected host country (China).
- Screening analysis to identify the most promising options for solar fuels and development of a country-specific "Roadmap to Solar Fuels" by the local and external SolarPACES experts, interested industries and governmental representatives. Links between interested industries and potential technology providers will be established.
- Collection of requisitions and pre-conditions for implementing the roadmap that will serve as

a feedback for further development works to supply the country-specific needs.

Phase 4 (expected for 2016-2017): Anticipating successful results of Phase 3, the roadmap concept will be proposed for the benefit of other countries (e.g., Brazil, Mexico, Morocco, etc.), involving different industries and various solar fuels or materials production technologies.

To achieve these goals, the evaluations of the examples Australia and South Africa need to be structured in a way that the main drivers for an industrial involvement into CSF can be defined precisely, and the specific outcome has to be organized in a checklist that can be used for other countries as well.

The checklist should be arranged according to the following main points:

- Natural resources:
    - Solar
    - Fossil energy resources
    - Minerals, Metals
    - Other
- Fuel demand
- Major industry
    - Fuels
    - Utilities
    - Other
- Political Framework
    - Industrial development
    - Renewable energy
    - CO_2 reduction
    - Pollution reduction
- Research & Development

FIRST PHASE

Project Initiation and Concept Preparation

(July 2012 – September 2013)

4. Phase 1: Project Initiation and Concept Preparation

Phase 1 (July 2012 – September 2013) has been concluded in accordance with the work plan with the following major achievements:

- Potentially interested industries and responsible governmental representatives have been identified in both host countries: Australia and South Africa.
- A "Road Show" (including written documents and oral presentations) has been prepared illustrating the CO_2 mitigation and market potential of specific solar fuels (e.g., hydrogen, syngas; liquid fuels such as methanol, diesel, and jet fuel).
- Workshops have been successfully organized by local SolarPACES experts with the participation of interested high-level industrial and governmental representatives. On February 14-15, 2013, a SolarPACES Workshop "Roadmap to Solar Fuels" was held in Potchefstroom, South Africa. Australia's first workshop on developing a Solar Fuels Road Map was held on 23 April 2013 at the Cypress Lakes Resort in the Hunter Valley, Australia.
- The "Road Show" has been presented by external SolarPACES experts at the workshops. All relevant documents have been made accessible to the participants.
- A country-specific "Roadmap to Solar Fuels" has been initiated by local and external SolarPACES experts together with the identified industries and other interested bodies.
- Requisitions and pre-conditions for implementing the roadmap have been collected and will serve as a feedback for further development works to supply the country-specific needs.

It was recognized that the development of a complete country-specific "Roadmap to Solar Fuels" would require additional meetings and further discussions with the local interested bodies. In fact, both countries were planning follow-up workshops in October 2013 (South Africa) and November 2013 (Australia). In order to secure continuation of the special Task II activity, a proposal for Phase 2 (October 2013 – September 2014) was prepared and approved at the ExCo meeting on September 22, 2013, in Las Vegas, USA.

It is anticipated that such missions, if successful, may later be extended to other countries (e.g. China, Brazil) involving different industries and various solar fuels or materials production technologies.

4.1. Feedback Report from South Africa (J. van Ravenswaay)

4.1.1 Overview

The SolarPACES Workshop "Roadmap to Solar Fuels" was held on 14 & 15 February 2013 at the Potchefstroom campus of the North-West University in Potchefstroom, South Africa. The objective of the workshop was to identify potential industrial and governmental players and to create awareness of the potential of solar as an energy source for production of syngas and/or liquid fuels by reforming and gasification of carbonaceous feedstock. SolarPACES experts presented first-hand information on CO_2 mitigation and market potential of solar fuels technologies. The workshop was well attended (43 people, including 5 persons from the SolarPACES expert panel) with 8 persons from various government departments, 15 persons from industry and 14 persons from research institutions and academia. The SolarPACES experts did an excellent job in preparing and presenting on solar fuels related projects, research, markets and opportunities to the diverse audience.

This report aims to provide an overview of the workshop with program (Table 1), persons attending (Table 2) as well as a summary of discussion and Q&A sessions, major outcomes and next steps.

Table 1: Final program for the First SolarPACES Workshop "Roadmap to Solar Fuels" in Potchefstroom, South Africa, on February 14-15, 2013

Session	Topic	Presenter	Time
DAY 1: Thursday 14 February 2013			
Coffee / Tea			
Welcome and Intro	**Welcome and introductions**	**Prof LJ Grobler** **J. van Ravenswaay**	**30'**
Session 1	**Introductory presentation, general overview, background:** - Introduction to SolarPACES - Introduction to solar energy (CSP, PV, CPV) - Technologies for concentrating solar thermal power plants (Trough, Fresnel, Tower, Dish): • Examples of commercial solar power plants • R&D for cost reduction • Thermal energy storage - Technologies for high temperature solar chemical processes: • Pathways to solar fuels (H_2, syngas, liquid hydrocarbons) • Benchmark (solar electricity + electrolysis); solar medium and high-temperature electrolysis • Solar thermochemical cycles (Examples: sulfur-based, ferrites, Zn/ZnO, ceria-base, etc.) • Solar reforming (SOLREF), cracking (SOLHYCARB), gasification (SYNPET, SOLSYN, Biomass, etc.) - Outlook: long-term potential of solar thermal electricity (STE, CSP) and solar thermochemical fuels (STF) - Collaboration with other international organizations (besides SolarPACES)	**A. Meier** **C. Sattler**	**90'**
Q&A Session			**20'**
Session 1	**Overview of activities in Australia**	**R. McNaughton**	**30'**
Q&A Session			**10'**
Lunch			
Session 2	**Solar fuels opportunities/topics in RSA:** - Solar resources in RSA - HySA Infrastructure overview	**T. Roos** **D. Bessarabov**	**30'**
Q&A Session			**5'**
Session 2	**Coal and gas conversion:** - General introduction: • Solar gasification (coal and biomass), reforming (steam and CO_2), and cracking (SOLHYCARB) - Solar gasification: • Solar gasification of petcoke (SYNPET) • Solar gasification of coal and C-waste (SOLSYN) - Solar reforming: • Solar methane reforming (SOLASYS, SOLREF)	**A. Meier** **M. Epstein** **C. Sattler**	**70'**
Q&A Session			**15'**
Coffee / Tea			
Session 3	**Chemicals & Materials:** - Mineral processing - Chemical production: • Solar production of lime and cement • Solar production of aluminum	**C. Sattler** **A. Meier**	**60'**
Q&A Session			**60'**
	Adjourn Day 1		

Session	Topic	Presenter	Time
DAY 2: Friday 15 February 2013			
Coffee / Tea			
Session 4	**Thermochemical processing & storage:** - Solar thermochemical fuels (H_2, syngas, hydrocarbon fuels) production: • Sulfur, Ferrites • Zn/ZnO, Ceria • Volatile metal oxides (implications on storage and gasification) - Thermal and thermochemical storage options: • Thermal storage • Thermochemical storage	**C. Sattler** **A. Meier** **M. Epstein**	**75'**
Q&A Session			**15'**
Session 4	**Integrated modeling and system analyses:** - Modeling of integrated systems - Systems analyses	**Christian Sattler**	**45'**
Q&A Session			**15'**
Coffee / Tea			
Session 5	**Q&A, Summary and Way Forward**	**All**	**90'**
Lunch			

Table 2: List of participants at the First South African SolarPACES Workshop "Roadmap to Solar Fuels"

#	Surname	First name	Affiliation	Category
1	Maja	Machoene Lilly	Department of Economic Development	Government
2	Mashimbye	Ms Lindiwe	Department of Energy	Government
3	Modiba	Elias	Department of Energy	Government
4	Sudarkasa	Michael	Africa Business Group	Government
5	Surridge-Talbot	Karen	SANEDI	Government
6	Thembakazi	Mali	SANEDI	Government
7	Zibi	Zukile	Technology Innovation	Government
8	Qase	Nomawethu	Department of Energy	Government
9	Bhugwandin	Kubeshnie	Eskom	Industry
10	Dreyer	Herbert	Eskom	Industry
11	Langley	Peter	Eskom	Industry
12	Meyburgh	Lean	Eskom	Industry
13	Mhlongo	Themba	Eskom	Industry
14	Pule	Keikantse	Eskom	Industry
15	Matzner	Dieter	Hatch	Industry
16	Swanepoel	Dr Kokkie	Hatch	Industry
17	Crous	Duncan	Escience	Industry
18	De Wet	Johan	Sasol	Industry
19	Pascoa	Mitch	Powertech	Industry
20	Pekelharing	Ruan	Yokogawa	Industry
21	Plaskitt	Mika	Exxaro	Industry
22	Pretorius	Cornel	Yokogawa	Industry
23	Prinsloo	Schalk	EPCM Global	Industry
24	Bessarabov	Dmitri	Hydrogen South Africa (HYSA)	Research
25	Longmi	Dr Henrietta	Hydrogen South Africa (HYSA)	Research
26	Hlabano-moyo	Bongibethu	Hydrogen South Africa (HYSA)	Research
27	Govender	Dr Sagren	CSIR	Research
28	Damm	Oliver	CSIR	Research
29	Mehlo	Mrs Themi	CSIR	Research
30	North	Brian	CSIR	Research
31	Klein	Peter	CSIR	Research
32	Roos	Thomas	CSIR	Research
33	Grobler	Prof LJ	North-West University	Research
34	Helberg	Albert	North-West University	Research
35	Van Niekerk	Prof Frikkie	North-West University	Research
36	Van Ravenswaay	Jan	North-West University	Research
37	Everon	Ray	North-West University	Research
38	Kauchali	Shehzaad	Wits University	Research
39	Epstein	Michael	WIS	SolarPACES
40	Hinkley	Jim	CSIRO	SolarPACES
41	McNaughton	Robbie	CSIRO	SolarPACES
42	Meier	Anton	PSI	SolarPACES
43	Sattler	Christian	DLR	SolarPACES

4.1.2 Points of Discussion and Q&A

Various lively discussions and debates were held over the two days. Mostly to answer/clarify questions from presentations and to identify opportunities for the South African industry. During the last session a summary was done and a way forward was defined.

In summary, the major points of discussion and views from industry and government:

1) *Eskom (South Africa's power utility)*: Eskom is interested in a number of opportunities such as storage and stability of the grid, but large scale storage is the most pressing need for Eskom. Solar smelting of aluminum and similar projects can reduce electricity demand, which is in Eskom's interest.

2) *Sasol (Large international petrochemical company who has developed CTL technology):* Sasol has no activity on solar fuels, they are skeptical but are willing to assist and need info to evaluate competitiveness.

3) *Hatch (International consulting engineering company and technology developer):*

   - South Africa needs a multi-purpose research facility of say 1 MW_{th}, even better in size similar to the DLR facility in Jülich, Germany (7,5 MW_{th}).
   - Many process technologies have been researched, but what is commercially feasible in SA is not clear. There is a need to do independent "business case" analysis of all the presented processes to see which one or two processes might be worth concentrating efforts on.
   - Any process technology that cannot be commercialized within the next 10 years is not worth pursuing, since support from government and other stakeholders will be lost. Hatch sees definite applications in mining and metals application (drying of slurries and maybe melting) as well as the reduction of metal oxides for large scale grid electricity energy storage batteries. These value propositions need to be investigated to understand the economic constraints within which these applications could be made commercially viable.
   - As far solar methane reforming is concerned, the opportunities in South Africa might be shale gas in the Karoo coupled with the solar resource in the Karoo. Also, some coal-bed methane gas has quite a high content of CO_2 (about 20%) and is unsuitable for piping and clean power generation. Dry reforming might then be worth looking into and then using the higher energy value syngas for power generation.
   - Within the South African government's National Development Plan (NDP), six focus areas have been identified, one of which is the green energy area and another is the minerals beneficiation area. The Solar Road Map must be connected with these government identified focus areas in the NDP, in order to get financial support.

4) *SANEDI (R&D implementing agency for Department of Energy):* The presence of a national CSP training, research and innovation center is key objective of SANEDI. SANEDI supports the development of CSIR's facility as they are furthest along in their design. Stellenbosch University also wants to build a facility. SANEDI's position is that if public funds are used it must be for a separate application so there is no duplication. There is also a solar road mapping process under way sponsored between DOE and DST. These roadmaps will cover power and thermal processes coupled to solar. The SolarPACES road mapping activity will integrate well with a portion of solar thermal road map.

5) *NWU (North-West University):* The science system in South Africa is fragmented. Although there's DST, all government departments have research activities. The Deputy President,

Kgalema Mothlante is overseeing the coordination of innovation activities between State Departments. The roadmap needs triple-helix collaboration between the private sector, public sector and higher education institutions. Developing nations have the advantage of using technology already developed in US and EU, to circumvent adverse effects on the environment. There is a need to work towards give and take. Don't redevelop the wheel – capitalize on previous and existing work in EU, US, Australia etc.

6) *Michael Epstein (Weizmann Institute of Science):* Supports South Africa having a small tower research facility. It is better to place this facility in an academic/research institution rather than with industry. The advantage of an academic institution is its multi-disciplinary nature, benefit from campus services and access to students. Also make the most of the coming CSP power stations in South Africa to show stakeholders that it works.

7) *CSIR (Council for Scientific and Industrial Research):* In order to secure funding, the solar fuels value proposition needs to be sold. Don't sell the technology, sell the opportunity. It is important when you do something to link it to government policy. If it is not in the policy, get it written into policy.

4.1.3 Major Outcomes

The following outcomes were observed:

1) Attendees were not aware of work being done worldwide on solar fuels.
2) There needs to be a concise one-pager that gives a clear value proposition to solicit funding for solar fuels R&D.
3) South Africa needs a solar concentrating research facility.
4) Need to leap frog South Africa using previous and existing solar fuels R&D in the SolarPACES community as base. Need to evaluate work done on solar fuels and determine applicability and feasibility in South Africa.

4.1.4 Follow-up Steps

The following activities have been scheduled as follow-up steps:

1) Organize follow-up meetings with key stakeholders in industry and government to collect requirements for solar fuels related activities as input to the road map.
    - *Remark:* Within the roadmap activity, there was more interaction with government and industry – also as part of the IEA process for developing a Solar Energy Technology Road Map (SETRM) for South Africa. A document has been drafted and is being reviewed. A follow-up workshop was planned in October 2013.
2) Develop a concise one-pager to be used as reference communication with regards to solar fuels – needs to give a clear value proposition to solicit funding for solar fuels R&D.
3) Integrate with other South African solar road mapping activities.
    - *Remark:* As part of the SETRM project, a panel of people was looking at the road map as well as for CSP and the interconnections.
4) Evaluate existing solar fuels R&D work and customize for South African applications to understand which opportunities are worth pursuing.

5) Develop SolarPACES Solar Fuels road map for South Africa – pending SolarPACES ExCo direction.
   - *Remark:* Phase 2 (see below) was expected to include a screening analysis to identify the most promising options for solar fuels and development of a detailed and complete "Roadmap to Solar Fuels" for South Africa.

4.2. Feedback Report from Australia (R. McNaughton and J. Hinkley)

4.2.1 Overview

Australia's first workshop on developing a Solar Fuels Road Map was held on 23 April 2013 at the Cypress Lakes Resort in the Hunter Valley, Australia. The objective of this workshop was to:

- Discuss the context and drivers for developing sustainable transport fuels
- Share information about applicable solar technologies
- Develop a preliminary vision of what the future may hold for solar fuels:
  - Opportunities and barriers – technical, financial etc.
  - Requirements for research, development and deployment
  - How this may unfold in the next few decades.

This workshop was jointly supported by the Australian Renewable Energy Agency (ARENA) under the Australian Solar Institute (ASI) funded project "Solar Hybrid Fuels"[1], and also the IEA SolarPACES outreach efforts through the special Task II (Solar Chemistry Research) activity "Roadmap to Solar Fuels"[2], enabling the participation of international experts from Germany, Israel and Switzerland. The SolarPACES experts presented on both solar fuels as well as alternative uses of solar thermal energy, including minerals processing, cement and chemical production (Table 3). All these processes in their current form produce a significant amount of GHG emissions – thus providing high-temperature process heat from solar energy can assist with Australia's commitment to reduce GHG emissions. Probably due to the remote location, the workshop was less attended than the previous one in South Africa (27 people, including 6 persons from the SolarPACES expert panel), with 2 persons from government departments, 8 persons from industry, and 11 persons from research institutions and academia (Table 4).

[1] This is a three year project to establish a road map for Australia towards sustainable and indigenous liquid transport fuels. The project will draw on the expertise of international experts and the results of many decades of research into the use of concentrated solar thermal technologies to generate fuels. The output of the project is a road map that will define the research, demonstration and development needs to develop a solar fuels industry in Australia.

[2] This workshop in conjunction with a similar activity in South Africa is funded by the SolarPACES executive and enables world leading experts in "Solar Fuels Science and Technology" to interact with Australian industry and government to develop a road map for deployment of these innovative technologies.

Table 3: Final program for the First SolarPACES Workshop "Roadmap to Solar Fuels" in Cypress Lakes Resort in the Hunter Valley, Australia, on April 23, 2013

Session	Topic	Presenter	Time
Tuesday 23 April 2013			
Coffee / Tea			
Welcome and Intro	**Welcome** - Introduction - Expectations / Interests	**R. McNaughton**	**20'**
Session 1	**Introductory presentations, general overview, background:** - Introduction to SolarPACES - Overview of solar thermal technologies and paths to solar sustainable fuels: • Technologies for solar thermal electricity (STE) • Technologies for high temperature solar thermochemical processes – Solar fuels and materials - Prospects for solar fuels	**A. Meier**	**40'**
	- Potential for solar fuels in Australia	**K. Lovegrove**	**25'**
Coffee / Tea			
Session 2	- Solar Fuels Development in Western Canada	**S. Trottier**	**20'**
	- Solar Hybrid Fuels Workshop: • Introduction to the ARENA/ASI project	**J. Hinkley**	**20'**
	Coal and Gas conversion: - General introduction: • Solar gasification (coal and biomass), reforming (steam and CO_2), and cracking (SOLHYCARB) - Solar gasification: • Solar gasification of petcoke (SYNPET) • Solar gasification of coal and C-waste (SOLSYN) - Solar reforming: • Solar methane reforming (SOLASYS, SOLREF)	**A. Meier** **M. Epstein** **C. Sattler**	**40'**
Q&A Session	**Solar Fuels Roadmap - Near term discussion**	**J. Hinkley**	**30'**
Lunch			
Session 3	**Future solar fuels:** - Solar thermochemical fuels production – Overview - Water/CO_2 splitting: • Volatile metals (e.g., Zn/ZnO cycle) • Non-volatile metals (e.g., ferrites, ceria) - Sulfur cycles - Hydrogen future	**A. Meier** **M. Epstein** **C. Sattler**	**40'**
	- Solar thermochemical water splitting cycles for H_2 production	**T. Kodama**	**30'**
Q&A Session	**Solar Fuels Roadmap - Long term discussion**	**J. Hinkley**	**15'**
Coffee / Tea			
Session 4	**Fuel displacement and energy storage:** - Mineral processing: • Solar production of lime and cement • Solar production of aluminum - Thermochemical energy storage	**A. Meier** **M. Epstein** **C. Sattler**	**45'**
	- Systems analysis and market study	**C. Sattler**	**15'**
Session 5	**Techno Economics:** - Modeling electricity and transport sectors simultaneously	**J. Hayward**	**30'**
Q&A Session	**Solar Fuels Roadmap – Modeling discussion**	**J. Hinkley**	**15'**
Q&A Session	**Summation and Discussion**	**J. Hinkley**	**30'**
	Close		

Table 4: List of participants at the First Australian SolarPACES Workshop "Roadmap to Solar Fuels"

#	Surname	First name	Affiliation	Category
1	Ashman	Peter	The University of Adelaide	Aust Research
2	Burke	Nick	CSIRO	Aust Research
3	Dolan	Michael	CSIRO	Aust Research
4	Hayward	Jennifer	CSIRO	Aust Research
5	Hinkley	Jim	CSIRO	Aust Research
6	McNaughton	Robbie	CSIRO	Aust Research
7	Pye	John	Australian National University	Aust Research
8	Stein	Wes	CSIRO	Aust Research
9	Sun	Yanping	CSIRO	Aust Research
10	Wilson	Greg	CSIRO	Aust Research
11	Davies	Matt	Sinclair Knight Merz	Consultant
12	Lovegrove	Keith	IT Power	Consultant
13	Epstein	Michael	Weizmann Institute of Science	Expert Panel
14	Kodama	Tatsuya	Niigata University	Expert Panel
15	Meier	Anton	Paul Scherrer Institute	Expert Panel
16	Sattler	Christian	German Aerospace Centre (DLR)	Expert Panel
17	Stechel	Ellen	Arizona State University	Expert Panel
18	Trottier	Stephanie	Alberta Innovates	Expert Panel
19	Easter	Don	Department of Industry, Innovation, Climate Change, Science, Research and Tertiary Education	Government
20	Fisher	Jo	Ausindustry	Government
21	Anderson	John	Uniquip Engineering	Industry
22	Parsons	Quinn	Uniquip Engineering	Industry
23	McMenimin	Michael	Caltex	Industry
24	Segal	Julian	Caltex	Industry
25	Smith	Neil	Energy Pipelines CRC	Industry
26	Vu	Cung	Office of Naval Research	Industry
27	Want	Andrew	AUSTELA	Industry

4.2.2 Points of Discussion and Q&A

The major points of discussion and views from the audience concerning solar fuels are summarized below:

1) There are a plethora of technological solutions to the problem of producing solar fuels. However, because of this breadth of solutions, it would be difficult for financiers to make any assessments as to the value of such technologies and to try and pick any particular technology, i.e. they cannot see the wood through the trees.

2) The technologies seem to be at the early stages of development and thus may be available beyond the year 2050.

3) The focus of the roadmap should not be on choosing the best technology, but rather looking at the needs of industry and identifying a niche opportunity, one that will be the first step towards making solar fuels economic. Supplying an alternative to diesel to the Pilbara may be one example. The ultimate goal will be trade in solar fuels.

4) The fuel to focus on is syngas. From syngas you can make the other fuels. Jet fuel is a good example as it is a high value product. Fuels can be produced remotely even, using a mini-scale GTL unit. This application could be used for demonstration purposes (~1 bbl/day; 200 kW solar) before scaling up. Building a demonstration unit is vital to prove the technology at scale. Note that 120 MW_e = 250 MW_{th} will produce 1000 bbl/day if the efficiency is 30% and the capacity factor is high.
5) The fuel will need to be blended as it won't contain aromatics. Aromatics are essential for a drop-in fuel, and synthetic fuels don't contain those aromatics. However, synthetic fuels burn more cleanly.
6) Certification of the fuel and validation of the product are important steps, and the solar fuels industry needs to get in early. Biofuels should not be seen as a rival, but solar and biofuels should work together towards a renewable fuel standard. At the moment, the Commercial Aviation Alternative Fuels Initiative (CAAFI) only has a biofuel standard.

4.2.3 Major Outcomes

There were many valuable comments raised in discussion; here are some of the key take-away thoughts:

1) We need to develop a simple value proposition – a cost target for technologies. The workshop presented a lot of information, and the message needs to be simpler.
2) Synthetic fuels cannot be a 100% replacement for conventional oil derived fuels. Blending will be required to meet fuel quality standards, particularly to provide the necessary aromatics.
3) Solar fuels could be a major export opportunity, as well as providing security of supply. Japan in particular is seeking to source low carbon fuels from overseas.
4) Don't dismiss hydrogen. Although the transition to a hydrogen economy seems remote for Australia, hydrogen is consumed in large quantities for fertilizer manufacture and refining.

4.2.4 Next Steps

The following activities are planned as next steps:

1) After the first workshop, CSIRO will be working with an extended international expert panel as well as with local companies and academics to develop a state-of-the-art document on solar fuels technologies (both hybrid and pure solar).
   - *Remark:* An initial version of this document will be released mid of September 2013. It includes a report on the outcomes of the first joint workshop on solar fuels.
2) A second workshop will be held to discuss these initial documents and how the roadmap project will develop.
   - *Remark:* The follow-up workshop is planned for November 2013. At this time, the state-of-the-art document will be complete and work will begin on defining the path for solar hybrid fuels. The Australian roadmap project "Solar Hybrid Fuels" runs till July 2015, with a July 2014 milestone for an industry based ranking of potential. The final goal is to develop a comprehensive roadmap which can be used to progress solar fuels activities across Australia.

- *Remark:* A preliminary version of the SolarPACES roadmap document will be prepared after the November 2013 industry workshop.

4.3. Conclusions & Outlook Phase 1

Phase 1 of the special Task II activity was concluded successfully, mainly thanks to the local organizers of the workshops held in South Africa and Australia. As can be seen from Table 5, the proposed time schedule was kept closely except for the preparation of the initial roadmap concept, which was delayed until December 2013.

Table 5: Milestones Phase 1

Date	Activity	Deliverable	Responsible
Jul / Aug 2012	Identification of industry; Preparation of "Road Show" concept	List of interested industries, etc.; Flyer "Solar Fuels"; ppt-Presentation "Road Show"	NC RSA & AUS; Task II OA
Sep 2012	Meeting Marrakech	Approval of "Road Show" concept	Task II OA
February 14-15, 2012	Workshop South Africa	Participants list; Minutes; Major outcomes; Next steps	NC RSA
April 23, 2013	Workshop Australia	Participants list; Minutes; Major outcomes; Next steps	NC AUS
Sep 2013	Preparation of report to ExCo	Report to ExCo	Task II OA
December 2013	Preparation of initial roadmap concept	Initial "Roadmap to Solar Fuels" document	NC RSA & AUS; Task II OA

4.3.1 Summary of Major Outcomes of Phase 1

Major outcomes of **Phase 1** (July 2012 – December 2013):

- In the host countries Australia and South Africa, potentially interested industries and responsible governmental representatives have been identified and invited by local SolarPACES experts to participate in workshops on solar fuels (hybrid and pure solar).
- A "Road Show" (including written documents and oral presentations) has been prepared and presented at the workshops by external SolarPACES experts.
- Feedback received from the workshop attendees and during follow-up discussions has been collected and will contribute to the development of the country-specific "Roadmap to Solar Fuels".
- Initial state-of-the-art documents on solar fuels are in the final stage of preparation and will be released soon.
- Since Phase 1 was just a preliminary trigger, follow-up activities for further development work are necessary in both countries (Phase 2).

As a follow-up specific Task II activity, **Phase 2** was promoted (October 2013 – September 2014):

- Follow-up workshops and meetings with industry, government, and academia for the preparation of the initial roadmap concept and the initial "Roadmap to Solar Fuels" document.
- Screening analysis to identify the most promising options for solar fuels.
- Development of a detailed and complete "Roadmap to Solar Fuels" by the local and external SolarPACES experts, interested industries, and responsible governmental representatives.

A proposal was submitted to the SolarPACES ExCo with the request to further help fostering specific solar fuel topics in South Africa and Australia by funding Phase 2 of the specific Task II activity "Roadmap to Solar Fuels".

4.4. Financial Report Phase 1

According to the conditions defined by the SolarPACES ExCo, a total amount of 25.000 EUR was requested for the special Task II activity "Roadmap to Solar Fuels". The budget contains the payment received / expected for the activities / expenses of the participating institutions, including working hours and travels of Task II OA, NCs, and SolarPACES experts (Table 6).

Table 6: Financial Report Phase 1

Responsible (Institution)	**Activity**	**Expenses**	**Payment received (€)**
Task II OA (PSI)	Coordination; "Road Show" preparation; Workshop participation	Proposal; Reporting; Travels to workshops in South Africa and Australia	5.000
SP expert (DLR)	"Road Show" preparation; Workshop participation	Travels to workshops in South Africa and Australia	5.000
SP expert (WIS)	"Road Show" preparation; Workshop participation	Travels to workshops in South Africa and Australia	4.563
NC AUS (CSIRO)	Preparatory work for workshop in AUS; Documentation; Reporting	Organization of workshop with interested industries, governmental representatives, and SolarPACES experts	5.000
NC RSA (CSIR)	Preparatory work for workshop in RSA; Documentation; Reporting	Organization of workshop with interested industries, governmental representatives, and SolarPACES experts	5.000
		Total	24.563

4.5. Coordinator Contact

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SECOND PHASE

Preparation of the Final Roadmap Concept

(October 2013 – September 2014)

5. Phase 2: Preparation of the Final Roadmap Concept

Phase 2 (October 2013 – September 2014) was progressing well according to the work plan. Completion of the roadmap document, however, required additional efforts and further discussions. Submission was delayed until the ExCo meeting in autumn 2015. The major events and achievements during Phase 2 are listed below:

- A critical review of Phase 1 and the preliminary planning of Phase 2 took place at the annual Task II Meeting held in Las Vegas (September 2013).
- In November 2013, a preparatory workshop was held in Newcastle, Australia (mainly attended by Australian researchers), to define the framework for the techno-economic evaluation of CSF technologies. The goal was to determine a cost of fuel for different technologies using a techno-economic model under development at CSIRO.
- On February 27, 2014, a workshop was held in Sydney, Australia (building on the workshop held in April 2013; Phase 1), to discuss the techno-economic model. Three technology case studies were presented: (1) solar reforming of natural gas, (2) solar gasification of coal and (3) solar water/carbon dioxide splitting.
- Following this workshop, a first draft of the "Roadmap to Solar Fuels" was prepared by local and external SolarPACES experts using input from participating industries and other interested bodies.
- On August 20-21, 2014, a "Hybrid Solar/Fossil Energy Conference" was organized in Johannesburg, South Africa, by the Fossil Fuel Foundation in collaboration with North-West University, CSIR and SolarPACES. Solar fuels and high temperature applications were presented by external SolarPACES experts, and the integration of fossil and solar for industry was discussed.
- Following this workshop, a second draft of the full "Roadmap to Solar Fuels" was prepared by local and external SolarPACES experts based on the latest suggestions and preliminary project proposals from the participants.
- After further discussions, the final roadmap document for Australia and South Africa was prepared in summer 2015, in parallel to the finalization of the Solar Hybrid Fuels Roadmap in Australia.

In summary, the progress made in both countries is very encouraging. Contacts with potentially interested industries and responsible governmental representatives have been established. Opportunities for joint projects involving industry, government agencies and international solar research centers have been identified and some of them will presumably be concretized in the near future. Continuation of this Task II activity is warranted.

Based on the experience from Australia and South Africa (documented in the reports to the ExCo and in the draft roadmap), a similar Solar Fuels Roadmap was then envisaged for China, possibly involving different industries and various solar fuels or materials production technologies. For that purpose, a proposal for Phase 3 (January 2015 – March 2016) was prepared and approved at the ExCo Meeting on September 21, 2014, in Beijing, China.

5.1. Feedback Report from Australia (R. McNaughton)

5.1.1 Overview

Australia is an energy-intensive economy that is based largely on fossil fuels. It also has large areas of high insolation which, in many cases, are co-located with significant resources of coal and methane-containing gases such as natural and coal seam gas, that at certain sites contain varying levels of CO_2. Therefore, in the Australian context, considerable scope exists for developing cost-effective solar thermo-chemical hybrid technologies involving solar-driven methane reforming and coal gasification which, depending on the end-use application, would involve using steam, a mixture of steam and CO_2, or CO_2 alone. Much work has been conducted in Australia and overseas on solarized methane reforming and, to a lesser extent, coal gasification.

Whilst these solar-fossil fuel hybrid technologies have a significant GHG intensity, they should be regarded as transitional for the near- to medium-term future and they will provide a valuable learning curve for the large-scale application of solar thermal concentrating technologies in Australia. In the longer term, however, there will be a need for truly renewable technologies for the production of solar fuels and chemicals and, in this context, the use of metal oxide/redox cycles for H_2O and CO_2 splitting is one promising route based on world-wide developments to date and the current scale of R&D effort being devoted to this option.

Solar hybrid fuels combine solar energy with a carbonaceous fuel, such as natural gas or coal, to form a product that embodies both renewable and fossil energy. This is done by using concentrated, high temperature solar energy to provide the heat to drive endothermic (heat absorbing) chemical reactions that convert the particular fossil fuel into intermediate and final products such as liquid transport fuels. In doing so, the amount of solar energy embodied in the final product is equal to the enthalpy change of the chemical reaction. Solar fuels can also be fully renewable by using solar energy to split water and carbon dioxide, to produce products such as hydrogen and synthetic liquid fuels.

Various technologies can be used to produce solar fuels, a review of which can be found in (Hinkley et al., 2013[3]). The review found that most of the technologies have only been developed to the pilot scale, and the most advanced only to a scale of 500 kW_{th}. There is also a lack of key data needed to evaluate the technologies, cost data in particular. However, it is known from experience with CSP that the solar field is a significant proportion of the overall investment cost, around 50%. This means that the conversion efficiency of solar thermal to chemical energy is critical for achieving a cost effective process.

To make up for this lack of data, the conversion efficiencies and costs of the various processes were extensively discussed via interactions with stakeholders and experts at the Second Australian Solar Fuels Workshop held on February 27th 2014 in Sydney, NSW. 35 participants from Industry, government and research were present. The aim of the workshop was to reflect the present status of the roadmap against the position of the shareholders to formulate the most important questions to be answered for a successful implementation of CSF technologies in Australia.

The Workshop was organized in a way that in the beginning the big picture was presented focused on economic necessities (Table 7). The role of Japan as the most important partner of Australia for energy export was presented and Japan's policy and industrial strategies was discussed.

[3] Hinkley et al., 2013, Solar Hybrid Fuels (3-A018), Stream 4: Road Map Technical Report, Milestone 3: Scoping Study, State of the Art and Outcomes of Workshop.

In the following technical part of the Workshop an overview was given on the roadmap development, which was detailed in three case studies on

- Reforming of natural gas
- Gasification of coal
- Splitting of H_2O and CO_2

After each technical presentation, the auditorium was asked to develop questions on the different technologies in small groups that were presented and discussed with all participants.

Based on these questions an extensive catalogue of tasks can be formulated.

Table 7: **Final program for the Second Australian Solar Fuels Workshop in Sydney, NSW, Australia**, on February 27, 2014

Session	Topic	Presenter	Time
	CSIRO Solar Fuels Workshop, Thursday 27 February 2014		
Session 1	**Introduction and economic** **Welcome and overview of workshop** - Welcome and overview of workshop - The challenges and pitfalls of deployment and scale up of new technologies - Products and markets: an economist's perspective - Japan – a potential market for solar fuels exports • State of the relationship Japan - Australia • Strategies • Scenarios	**J. Hinkley** **P. Hartley** **P. Graham** **K. Lovegrove**	**90'**
Q&A Session			**15'**
	Coffee / Tea		
Session 2	**Solar Fuels Study and selected case studies** - Solar to fuels TEA framework: component technologies and integration challenges - Case Study No 1: methane reforming	**J. Hinkley** **R. McNaughton**	**75'**
Q&A Session			**15'**
	Lunch		
Session 3	**Selected Case Studies** - Case Study No 2: coal gasification	**G. Nathan**	**45'**
Q&A Session			**15'**
	Coffee / Tea		
Session 4	**Selected Case Studies** - Case Study No 3: CO_2/H_2O splitting	**C. Sattler**	**45'**
Q&A Session			**15'**
Session 5	**Reflection** - Summary and facilitated discussion - Wrap up	**E. Stechel** **K. Lovegrove**	**45'**
	End		

5.1.2 Task Catalogue

The different topics of the workshop resulted in a number of questions and tasks that have to be answered for the next development and the implementation of CSFs in Australia. This catalogue is a role model to evaluate the position and define a roadmap for all countries to develop solar fuels. The general questions are clustered and are available as a questionnaire as Annex A of this document. The specific questions are focused on the Australian strategy of prioritizing hybrid solar fuel production.

General Questions

The general questions of the audience reflect the diverse state of knowledge on the technologies. It shows that it is still a key issue to inform society and stakeholders on the possibilities and the state of the art of CSP and CSF to have a better impact.

<u>Technology</u>

- What would put CSF on the radar?
    - Awareness of biofuels, electrification, PV, what is different?
- What are other ways to handle storage/intermittency?
- Uncertainty and risk: How to factor it into planning?
    - Design of plants needs to be adapted to size, locations and feedstock
- What other processes are there in addition to the case studies?
    - A comparison with competing technologies (renewables, fossil, nuclear) should be done. However nuclear power is not available yet in Australia although South Australia produces 31% of the world's uranium.
- How far can it be scaled up?
- Have we considered risk of volcanic ash?
    - In general the influence of possible serious incidents should be discussed. The state of the art needs to be explained and examples of risk preventions should be given.

<u>Policy</u>

- What would put CSF on the radar?
    - Other energy areas like biofuels, electrification, PV are very well known to policy makers. How can CSF be transported into their planning?
- Measures for Australia:
    - The Australian policy presently is very much oriented in harvesting the immense resources of the country. However, reasons have to be presented that underline especially the economic potential of integrating concentrated solar radiation into this strategy. Therefore, a sound analysis of the major customers – especially Japan, Korea, China, and India – has to be done to make a forecast on the development in these crucial markets.
    - What sort of support mechanism is needed?
- How to best leverage international opportunities?
    - Is there a possibility – bilateral and multilateral – for joint efforts as well on industrial, economic cooperation as on research, development, and deployment? Existing contacts, e.g. with Europe, can be used to strengthen research and development in joint programs. Reducing the financial risk and improving the participation in worldwide developments. The European HORIZON 2020 program has a particular part for such cooperation.

- Uncertainty and risk: How to factor it into planning?
    - A techno-economic risk assessment has to be provided to explain how the sizing of a CSF plant takes risks and uncertainties into account.
- Check carbon accounting:
    - Presently, there are no mechanisms in Australia, but as CSF will be mainly export goods the key markets have to be evaluated for that.
- Is there need for more international coordination?
    - This can be approached from different sides:
        - Is there already international coordination available that could be used by Australia?
        - What is the position of the government? How can additional coordination help Australia to strengthen its position?
        - What are the needs of the major stakeholders?
- Are community acceptance and decommissioning issues addressed sufficiently?
    - Who must be informed or educated?
    - Who could act as multipliers?

Economy

- What would put CSF on the radar?
    - How to get more industry involved?
    - The workshop showed again that industry will find applications for CFS technologies. Information is crucial and bilateral discussions that allow the possible interested companies to get business advantages.
- What are early/niche opportunities?
    - This question must be answered by industry, as early niches or opportunities rarely cover a tough market competition.
    - Or a support from policy must be defined that allows more stakeholders to take part in these early opportunities.
- How to best leverage international opportunities?
    - International opportunities must be visible to the stakeholders. Can SolarPACES support this, e.g. by setting-up a data base?
- Uncertainty and risk: How to factor it into planning?
    - A techno-economic risk assessment has to be provided to explain how the sizing of a CSF plant takes risks and uncertainties into account.
- How fast can it be scaled up?
    - How much money would be available for such an effort? A realistic evaluation might support the decision process in industry.
- Based on TCA, what would the CO_2 price have to be to make a plant economic?
- What is required to get break even CO_2 price down to X?
- Are the markets different for the different approaches?
    - There are different markets for different products more than for different approaches. However, industry knows the markets best. SolarPACES can support wherever additional information especially on the technologies are available.
- Is there value in coal to CH_4?
    - It depends on the margin, but it is more likely that there will be processes with a higher priority.
- How about chemical products?

    - Other than energy carriers, chemical products can have immense margins even if produced in smaller scale. How can solar processes make these margins even larger?
- Check carbon accounting!
    - A study needs to be carried out to describe the present situation in the major markets and give a perspective on possible future developments.
- Can common industrial processes be redesigned for batching?
    - In principle yes, but what actions are necessary to demonstrate this for industry?

Ecology

- Check carbon accounting:
    - The ecological benefit of the technology should be quantified.
- Can we compare CO_2 balance to other technologies?
    - A comparison should be carried out. It should include alternatives that are neither CSF nor pure fossil.

Methane Reforming

The reforming of natural gas is the CSF technology Australia concentrated its research effort on in the last decade at least. The rationale behind this is on one side the economic importance of natural gas for the Australian society and the rather straight forward technology of solar reforming based on established conventional technology and long term experience.

Substantial developments could be achieved up to the demonstration of a 600 kW_{th} solar reformer on the tower of the CSIRO center in Newcastle, NSW. Based on this status the next steps into industrial application have to be done and the following questions need to be answered to get a relevant industrial involvement:

Technology

- At which technology readiness level (TRL) is the state of the art?
    - A detailed answer on all parts of the process is necessary as e.g., receivers are already very advanced while catalysts still need some improvement.
- What is the best scale for a pilot plant in Australia?
    - This should be determined with the stakeholders that support the set-up of such a pilot plant.
- Would such a pilot plant evaluate all components together, or be attached to a larger plant on a slip-stream?
    - Small modular plants for stranded gas?
- Which site shall be selected?
    - Close to a natural gas well?
        - Pilbara, WA as location – facilities, skills. But cyclones?
        - Pilots to leverage existing infrastructure
        - Site for pilot: too remote = high cost
        - Some gas fields have high CO_2
    - Close to a research facility?
        - Pilots to leverage existing infrastructure
        - Existing CO_2 streams -> methane -> back to LNG plant
        - Newcastle Pilot!
- Size/storage/scalability
- High temperature materials

- FT: Products can be dialed up to some extent

Policy

- Will there be Government to Government support (AUS – JPN, AUS – NN)?
- Social license?

Economy

- On which technology readiness level (TRL) is the technology?
- Which are the key attributes to make business sense?
- Will Japan pay a premium?
- Need to work with small scale GTL
- Good on paper but risk?
- Where is compelling reason to invest 'real option theory'?
- Site for pilot: too remote = high cost
- Capital raising challenge
- Competition for gas feedstock
- Stranded gas opportunity
- Which product route has the biggest margin? Not lowest LCOF.
- CO_2 has negative cost if it is converted
- Need whole supply chain
- Drop in fuels highest value

Ecology

- Is it green enough?

Gasification of coal

Coal plays a dominant role in the Australian economy and opportunities for advanced coal technologies coupled with CO_2 sequestration are actively investigated in Australia and also in Japan, the biggest customer for coal. This motivates consideration of solar-driven processes to contribute to such advances.

Technology

- A lot of risks
- Arckaringa, SA = coal or unconventional hydrocarbons + sun for pilot
- Feedstock flexible is positive
- Timing follows solar reactor demo/pilot -> R&D center
- Leigh Creek Collie (WA) central Queensland for pilots/command
- Co-location of biomass
- Scale challenge

Policy

- A lot of risks

Economy

- A lot of risks
- Brown coal opportunity (cheap)

- Arckaringa = coal + sun for pilot
- Is baton process economic
- Trade balance, oil independence as positives
- Good economic analysis
- Does variability add cost (FT)
- Risk issue stops CTL today
- CTL is a business case challenge. SCTL costs more!
- Risk issue stops CTL today
- FT very expensive – co-locate in South Africa

Ecology

- Environmental foot print
- Consider CCS resource also for siting
- Carbon foot print issue?
  - How to make it smaller?
- A lot of risks

5.1.3 Key Messages

As shown above, there were many valuable comments raised in discussion through strong participation of industry and other stakeholders. The following are some of the key messages from the workshop:

1) The proposed model for evaluating the cost of fuel should be adequate for screening technologies – going beyond a production cost to a business case is really where investors and industry must make the case.
2) Project risk is a key concern – not just the technology, but also the prevailing policy climate and social issues (social license to operate). Coal to liquids was seen as particularly risky, and solar coal to liquids is more expensive when coal- to-liquid plants are already very large and capital intensive. Similarly, the question was raised as to whether solar methane reforming is green enough?
3) Need to identify early market niches, and leverage international expertise and even infrastructure: perhaps work with South Africa as the experts in GTL technologies.
4) Related to this, location is everything in terms of identifying the right match of resources and opportunities.
5) CO_2 avoidance or re-use could be a game changer, especially for natural gas resources with high levels of CO_2.
6) How far and how fast can these technologies be scaled up?
7) Carbon accounting and understanding CO_2 impacts is critical to selling concentrating solar fuels (CSF).

5.1.4 Follow-up Steps

The following activities have been scheduled as follow-up steps:

1) CSIRO continues to develop a solar fuels roadmap (both hybrid and pure solar) for Australia and identify a technology trajectory with targeted research, development and demonstration

requirements. The roadmap involves international experts in solar thermal fuels as well as local stakeholders including researchers, government and industry.

- *Remark:* The Australian roadmap project "Solar Hybrid Fuels" runs till November 2015. The final goal is to develop a comprehensive roadmap which can be used to progress solar fuels activities across Australia. A milestone report on an industry-based evaluation and ranking of solar fuels technologies was released in July 2014 (Hinkley et al., 2014[4]). It includes market opportunities for solar fuels, both domestic and international. Since Japan is likely to be the most obvious future export market for Australian solar fuels, a case study was performed on the idea of solar fuels trade with Japan.

2) At the SolarPACES Conference in Beijing, China, a plenary session was dedicated to the topic "Solar Fuels and Materials – From Research to the market Place", September 19, 2014.

- *Remark:* The plenary included talks on "SolarPACES initiative for a solar fuels roadmap", "European perspective on developing Solar Fuels into the market", "Solar fuels export vision from Australia to Asia", "Status and Opportunities for Solar Fuels in South Africa", and "Vision of solar fuels – An industry perspective".

5.2. Feedback Report from South Africa (J. van Ravenswaay)

5.2.1 Overview

On August 20-21, 2014, the Second South African Workshop took place in Johannesburg in the framework of the joint HYBRID SOLAR/FOSSIL ENERGY CONFERENCE of the Fossil Fuel Foundation South Africa and SolarPACES (Table 8), in collaboration with North-West University (NWU) and the Council for Scientific and Industrial Research (CSIR).

33 delegates from Industry, government and research were present (Table 9). The aim of the workshop was to reflect the present status of the roadmap against the position of the shareholders to formulate the most important questions to be answered for a successful implementation of CSF technologies in South Africa.

The **Objective of the Conference** was:

- To provide a forum in which new concepts in hybridization in energy production will be presented in Southern Africa.
- To increase the awareness of solar fuels.
- To determine the applicability and feasibility of specific solar fuels technologies in RSA.
- To emphasize the economic and political aspects of solar fuels that could be a major export opportunity, as well as providing security of supply.
- To expose the technical public and potential users to the co-utilization of two energy sources for mutual and economic benefit.
- To generate collaboration between two sectors of the energy industry, academia and government.

[4] Hinkley et al., 2014, Solar Hybrid Fuels (3---A018) Stream 4: Road Map Technical Report, Milestone 4: Evaluation and Ranking of Technologies.

Table 8: Final program for the Second South African Workshop in Johannesburg, South Africa, on August 20-21, 2014

HYBRID SOLAR/FOSSIL ENERGY CONFERENCE

Solar Fuels and High Temperature Solar Applications

- Integration of Fossil and Solar for Industry -

PROGRAMME*

Day 1, 20 August 2014

08:00 – 09:00	***Registration with Tea & Coffee***
09:00 – 09:30	**Welcome and Opening by Brian North**
Session 1 CHAIR: JAN VAN RAVENSWAAY	
09:30 – 10:00	**SANEDI ENERGY: FOSSIL FUELS AND SOLAR POTENTIAL** Tony Surridge, SANEDI
10:00 – 10:30	**CSP IN ESKOM** Vikesh Rajpaul, Eskom
10:30 – 11:00	***Tea & Coffee Break***
Session 2 CHAIR: THOMAS ROOS	
11:00 – 11:30	**SOLAR TECHNOLOGY SELECTION AND COST OF SOLAR FUEL IN HYBRID POWER PLANTS** Jose Barak, BrightSource Energy
11:30 – 13:00	**GENERAL OVERVIEW AND BACKGROUND OF HTSA** Tony Meier and Christian Sattler, SolarPACES
13:00 – 14:00	***Lunch***
Session 3 CHAIR: JAN VAN RAVENSWAAY	
14:00 – 14:30	**HYSA INFRASTRUCTURE CENTER OF COMPETENCE: A STRATEGIC COLLABORATION PLATFORM FOR SOLAR TO HYDROGEN PRODUCTION AND STORAGE** Dmitri Bessarabov, North-West University
14:00 – 15:00	**SOLAR COAL AND GAS CONVERSION** Tony Meier and Christian Sattler, SolarPACES
15:00 – 16:00	**SOLAR CHEMICALS & MATERIALS** Tony Meier and Christian Sattler, SolarPACES
16:00 – 16:30	***Tea & Coffee Break***
Session 4 CHAIR: THOMAS ROOS	
16:30 – 17:00	**SOUTH AFRICAN CARBON TAX IMPLICATIONS FOR BUSINESSES** Mansoor Parker, ENSafrica
17:00 – 17:30	Summary and Q&A
17:30	***Networking Drinks***

Day 2, 21 August 2014

08:30 – 09:00	***Arrival Tea & Coffee***
Session 5 CHAIR: THOMAS ROOS	
09:00 – 10:00	**THERMOCHEMICAL PROCESSING & STORAGE** Tony Meier and Christian Sattler, SolarPACES
10:00 – 10:45	**INTEGRATED MODELING AND SYSTEM ANALYSES** Tony Meier and Christian Sattler, SolarPACES
10:45 – 11:30	***Tea & Coffee Break***
Session 6 CHAIR: JAN VAN RAVENSWAAY	
11:30 – 12:00	**AN ELECTROCHEMICAL ROUTE TO LIQUID SOLAR FUEL FROM CARBON DIOXIDE** Shankara Radhakrishnan, University of Pretoria
12:00 – 12:30	**LIQUID SOLAR FUEL FROM CARBON DIOXIDE: MOTIVATION FOR A STRATEGIC EFFORT** Philip Crouse, University of Pretoria
12:30 – 13:00	**A GTL MARKET FOR CAPTURED CO2: SUNSHINE AND CO2 REDUCES NATURAL GAS CONSUMPTION IN FUEL PRODUCTION AND PRODUCES 50% CARBON-NEUTRAL FUEL** Thomas Roos, CSIR
13:00 – 13:30	Summary, Discussion and Q&A Close of Conference
13:30 – 14:30	***Lunch***

Table 9: List of participants at the Second South African SolarPACES Workshop "Roadmap to Solar Fuels"

Surname	Given Name	Job Title	Organization	E-mail
Allen	Kenneth	Postdoctoral Researcher	CRSES	kallen@sun.ac.za
Badenhorst	Heinrich	Senior Lecturer	University of Pretoria	carbon@up.ac.za
Badenhorst	Piet	Senior Account Manager	IDC	pietb@idc.co.za
Barak	Jose		Bright Source Energy	jbarak@brightsourceenergy.com
Bessarabov	Dmitri		North-West University	Dmitri.Bessarabov@nwu.ac.za
Bisaka	Kabwika	Head: New Technology-Pyrometallurgy Division	MINTEK	kabwikab@mintek.co.za
Bischof-Niemz	Tobias	Chief Engineer	CSIR	tbischofniemz@csir.co.za
Chauke	Lindiwe		Department of Environmental Affairs	OChauke@environment.gov.za
Cleary	Colleen	Sales & Marketing Executive	Promech Publishing CC	samecheng@promech.co.za
Crouse	Philip		University of Pretoria	Philip.Crouse@up.ac.za
Gericke	Gerhard	Snr Consultant	Eskom Holding SOC Limited	gerhard.gericke@eskom.co.za
Jorgensen	Paul	Environmental Scientist	SRK Consulting (SA)	PJorgensen@srk.co.za
Knottenbelt	Cyril	Manager Research Laboratory	PetroSA	cyril.knottenbelt@petrosa.co.za
Kruyswijk	Gerrit	Industry Champion	IDC	gerritk@idc.co.za
Lubbe	Salmon	Post Doctorate		salmon.lubbe@up.ac.za
Maja	Ngoanathari	Project Manager	CSIR	nmaja@csir.co.za
Meier	Anton		Paul Scherrer Institute (PSI)	Anton.Meier@psi.ch
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Rogers	Dave			decrogers@gmail.com
Roos	Thomas		CSIR	throos@csir.co.za
Rycroft	Mike	Features Editor	EE Publishers Pty Ltd	mike.rycroft@ee.co.za
Sattler	Christian		German Aerospace Center DLR	Christian.Sattler@dlr.de
Surridge	Tony	Senior Manager	SANEDI	tonys@sanedi.org.za
van der Merwe	Frikkie	Senior Lecturer	North-West University	1021361@nwu.ac.za
van der Walt	Albert	Senior Manager	Eskom Holding SOC Limited	vdwaltaj@eskom.co.za
van Niekerk	Frikkie	DVC: Research, Innovation and Technology	North-West University	Frik.vanniekerk@nwu.ac.za
van Ravenswaay	Jan		North-West University	jvr@raventechcorp.com
van Werkhaven	Johan	SDF	EHL Consulting Engineers	baugustyn@ehl.co.za

5.2.2 Outcome of the Workshop

Various lively discussions and debates were held over the two days, mostly to answer and clarify questions from presentations and to identify opportunities for the South African industry.

In summary the following points of discussion and views from industry and government:

View by SANEDI *(R&D Implementing Agency for Department of Energy)*

1) South Africa is demonstrating its commitment to a more sustainable future growth path by supporting renewable energy and energy efficiency measures, together with skills development and job creation through fostering a green economy. It is among the highest emitters of carbon dioxide in the world, currently ranked 12th in terms of top emitters (473 Mt/a in 2012)[vi] and ranked 29th per capita in 2011[vii], since more than 75% of its primary energy requirement is derived from fossil fuels.
2) The country responded to the urgent need to reduce fossil fuel dependency, diversify the energy mix and supply and reducing the country's carbon footprint with a supportive policy and legislative framework to exploit the excellent renewable energy resources, especially wind and solar. South Africa's renewable energy sector experienced explosive growth in the past few years with investment of more than $5.5 billion ZAR in 2012, up from $30 million ZAR in 2011 – representing an impressive increase of 20,500%. The rapid investment growth over the past two years made South Africa the ninth-leading destination for clean energy investment among the Group of 20 (G-20) of the world's developed and emerging economies. Solar technology combined with current fossil fuel usage opens the door to compatible technology hybridization allowing for a wide range of potential applications in the solar-fossil-fuel nexus.[viii]

View by ESKOM *(South Africa's power utility)*

1) There are a myriad of examples within the South African policy environment that support the utilization of renewable energy sources in the country as an integral means of reducing carbon footprint, diversifying the national economy, and reducing poverty. Eskom, as a state owned entity and a responsible corporate citizen, supports the drivers for low carbon growth and diversification of the energy mix, as documented in its six point plan for addressing climate change and its strategic imperative of reducing its environmental footprint and pursuing a low-carbon growth path. In order to support the achievement of these strategic objectives, Eskom established a Renewables Unit with a mandate to drive Eskom's renewables generation capacity by developing and operating proven technologies and becoming a center of excellence for renewables business initiatives.
2) Solar Thermal (CSP), is one of four programs / portfolios within the Renewable Unit, responsible for developing, constructing and operating new CSP generating capacity as well as solar augmentation for own consumption.
3) Augmenting existing fossil power plants with solar thermal energy provides a viable opportunity for energy diversification, as it involves incorporating free solar energy into the steam cycle of a conventional Rankine cycle power plant, to reduce the amount of coal used or to boost the plant output for a given coal supply. This reduces the absolute station emissions for a fixed load or the net emissions when solar energy is used to boost the energy output of the station.
4) In addition, solar energy provides opportunity to produce energy carriers such as liquid fuels,

syngas and hydrogen as well as in the production of chemical or material commodities such as metals, lime or cement. In this regard, Eskom Research has formed partnerships and sponsored various studies to investigate how solar energy can be used to reduce the country's environmental footprint while reducing the demand associated with energy intensive industries.

5) The discussion will focus on Eskom's work in CSP, specifically on solar augmentation, and will cover some of the partnerships entered into to explore opportunities of using solar energy to produce energy carriers.[ix]

View by BrightSource Energy –
Solar technology selection and cost of solar fuel in hybrid power plants

Introduction

The respective costs of coal and solar inputs to a hybrid power plant can be compared by calculating fuel costs at the steam generator for each fuel and technology option. In the case of central tower solar thermal technology, the technology option generally regarded as the lowest-cost approach for future standalone solar electricity projects turns out to be a considerably more expensive best option for hybrid projects.

Inputs to solar fuel cost

1) In the case of coal, the cost of the fuel itself is by far the most important input to any comparison with solar. The capital cost of a coal-fired power plant is heavily dominated by the cost of the boiler, power block and electrical infrastructure, which are all common to both conventional and solar inputs and therefore can be ignored when making the comparison. On the solar side, on the other hand, the cost of the 'solar fuel' heat input to the steam generator consists mostly of amortization of the capital cost of the solar energy collection system – which can include the heliostat field and, if applicable, intermediate systems for capturing and storing heat in a working fluid other than steam. Amortization is directly affected by the project site selection, as annual irradiance values can vary from site to site – selecting a good site is akin to locking in low solar fuel costs for the life of the project.

2) While there are O&M costs for maintaining the cleanliness of the mirrors, there are no variable costs for purchasing fuels.

3) Currently, two competing tower technologies vie for primacy in the solar electricity market: direct-steam generation receivers, and molten-salt receivers. Molten-salt receivers, although not yet proven commercially at utility scale, are considered to be the lower-cost approach for standalone solar operation because of built-in integration of thermal energy storage. A working fluid comprising a mixture of molten salts is heated by concentrated solar radiation and directed to a storage tank, and the heated fluid can later be used to generate steam in a salt-steam heat exchanger. Direct-steam receivers, where the tower-based steam generator uses concentrated sunlight as the sole heat input, are already in operation in three commercial tower plants of about 130 MW_e each in California.

4) In this study we will compare the cost of solar fuel inputs with coal in South Africa for both solar tower technology options and for a range of annual solar irradiance values.

5) The better-proven direct-steam option yields a solar fuel cost per MJ that is less than half of the corresponding cost for molten-salt technology. The difference is due to the capital costs of (a) the tower-based molten-salt receiver where the salts are heated from insolation, (b) the high-temperature tanks to accommodate storage of both the cold (290°C) and hot

(560°C) salts (and associated piping), and (c) the salts themselves[x].

***View by HySA** (Hydrogen South Africa)*

1) The Department of Science and Technology of South Africa developed the National Hydrogen and Fuel Cells Technologies (HFCT) Research, Development and Innovation Strategy. The National Strategy was branded Hydrogen South Africa (HySA).
2) The scope of the Hydrogen Infrastructure Competency Centre (HySA Infrastructure CoC[xi]) is to develop applications and solutions for small- and medium-scale hydrogen production and storage through innovative research and development.
3) The aim of this paper is to present an overview of the HySA Infrastructure CoC projects related to renewable hydrogen and fuel cell applications. The presentation will discuss how the HySA Infrastructure could assist South African and international stake holders in the area of renewable (e.g., solar) energy with providing a potential strategic platform for developing and testing various renewable energy solutions for fuel cell applications specific to African conditions[xii].

Discussion on an idea for a GTL market for captured CO_2: Sunshine and CO_2 reduces natural gas consumption in fuel production and produces 50% carbon-neutral fuel

Three South African state-owned companies face different challenges in the medium-term:

1) Eskom *(South Africa's power utility)* is South Africa's largest CO_2 emitter (at 220 million tons per year), so the introduction of the South African carbon tax will place pressure on electricity tariffs going forward.
2) PetroSA *(South Africa's national oil company)* converts natural gas into liquid fuel using the Fischer-Tropsch gas-to-liquids (GTL) process. Apart from carbon tax implications (PetroSA emits 2.2 million tons CO_2 per year, a more pressing issue is that the gas is becoming depleted in the gas-fields that PetroSA exploits, requiring the building of a capital intensive natural gas terminal.
3) SAA *(South African Airlines)* is under pressure to reduce its carbon footprint, driven largely by the carbon tax that the EU wishes to impose on commercial airliners[5]. The carbon tax is payable for the duration of the flight, not just the portion of the flight over European airspace. This unfairly penalizes airliners with hubs distant from the EU (SAA, QANTAS, etc.) compared to those with hubs close to the EU (Emirates, Etihad, Qatar airlines), which may lead to the former losing market share to the latter and becoming regional players instead of global players. The only current option for commercial aerospace to reduce their carbon footprint is to switch to carbon-neutral fuels, which currently means biofuels. South Africa used 2 367 million liters of jet fuel in 2012[xiii].

This presentation explores the possibility of:

1) using CO_2 captured from Eskom power stations (reducing net emissions),
2) to "dry" reform methane to syngas at PetroSA using concentrated solar heat (reducing methane consumption by half for the same amount of syngas produced) to produce liquid fuel,

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[5] Although the tax law was suspended in 2012 [xxxiii] the political will to make air traffic cleaner is still an important task and regulations will become stricter in the future. See chapter 8.

3) being 50% carbon-neutral (allowing SAA to greatly reduce new downstream emissions and therefore reduce carbon taxes liabilities).

5.3. Conclusions & Outlook Phase 2

Phase 2 was progressing well according to the work plan. Completion of the roadmap document, however, required additional efforts and further discussions. Submission was first expected before the ExCo meeting in spring 2015, but had to be postponed until the ExCo meeting in autumn 2015. The major events and achievements during Phase 2 are listed in Table 10 below.

Table 10: Milestones Phase 2

Date	Activity	Deliverable	Responsible
September 2013	Task II Meeting in Las Vegas	Critical review of Phase 1 and preliminary planning of Phase 2	Task II OA NCs RSA / AUS
November 2013	Workshop Newcastle, Australia; mainly for Australian researchers	Framework for techno-economic evaluation of CSF technology	NC AUS
February 2014	Workshop Sydney, Australia; Techno-economic assessment	Participants list; Meeting minutes; List of topics/challenges for "Roadmap to Solar Fuels"	NC AUS
March 2014	Preparation of initial roadmap document	First draft of "Roadmap to Solar Fuels"	C. Sattler (DLR)
August 2014	Hybrid Solar/Fossil Energy Conference, Johannesburg, South Africa; Industry representatives	Participants list; Conference program; industry contacts; ideas for joint projects	NC RSA Fossil Fuel Foundation
September 2014	Preparation of draft roadmap	Second draft of "Roadmap to Solar Fuels"	C. Sattler (DLR)
September 2014	Task II Meeting in Beijing	Critical review of Phase 2 and preliminary planning of Phase 3	Task II OA NCs RSA / AUS
September 2014	Plenary Session in Beijing	Presentations on "Solar fuels and materials – From research to the market place"	Task II OA C. Sattler (DLR) NCs RSA / AUS Industry (Mitsui)
March 2015	Preparation of complete roadmap	Final "Roadmap to Solar Fuels" document; Final report to ExCo	Task II OA NCs RSA / AUS

5.3.1 Summary of Major Outcomes of Phase 2

Major outcomes of **Phase 2** (October 2013 – September 2015)

- The follow-up workshops/conferences and meetings in the host countries Australia and South Africa were well attended. Further contacts with potentially interested industries and responsible governmental representatives have been established and intensified.

- Opportunities for joint projects involving industry, government agencies and international solar research centers have been identified and some flagship projects are expected to be concretized in the near future.

As a follow-up specific Task II activity, **Phase 3** was promoted (January 2015 – April 2016):

- Based on the experience from Australia and South Africa (documented in the reports to the ExCo), a similar Solar Fuels Roadmap is being envisaged for China, presumably involving different industries and various solar fuels or materials production technologies.
- It is anticipated that at least two workshops/conferences and several follow-up meetings with interested industry, government, and academia will be required to develop a solar fuels roadmap concept for China with the support of external SolarPACES experts.

A proposal was submitted to the SolarPACES ExCo with the request to further help fostering specific solar fuel topics in China by funding Phase 3 of the specific Task II activity “Roadmap to Solar Fuels”.

5.4. Financial Report Phase 2

According to the conditions defined by the SolarPACES ExCo, a total amount of 25.000 EUR was attributed to Phase 2 of the special Task II activity “Roadmap to Solar Fuels”. The financial report contains the payment for the activities and expenses of the participating institutions, including working hours and travels of Task II OA, NCs, and SolarPACES experts (Table 11).

Table 11: Financial Report Phase 2

Responsible (Institution)	Activity	Expenses	Payment (€)
Task II OA (PSI)	Coordination; Reporting; “Road Show” preparation; Participation at conference	Proposal; Reporting; Travel to conference in South Africa	6.000
SP expert (DLR)	“Road Show” preparation; Participation at workshop and conference; Reporting	Travels to workshop in Australia and conference in South Africa	6.000
NC AUS (CSIRO)	Preparatory work for workshop in AUS; Documentation; Reporting	Organization of workshop with interested industries, governmental representatives, and SolarPACES experts	6.000
NC RSA (CSIR)	Preparatory work for conference in RSA; Documentation; Reporting	Organization of conference with interested industries, governmental representatives, and SolarPACES experts	6.000
		Total	24.000

5.5. Coordinator Contact

Anton Meier (PSI); Phone: +41 56 310 27 88; E-mail: anton.meier@psi.ch

6. Phase 2: Final Roadmap Proposals

With this project, SolarPACES already raised the awareness of the solar fuels options not only in the participating countries Australia and South Africa, but also in related countries and markets in Asia (China, Japan, Korea), North America (Canada, USA), Latin America (Brazil, Chile), and Africa (Morocco). For all these countries, the transfer of the following proposals would be of very high value.

An important action – in addition to the solar fuels roadmaps – is the continuation and strengthening of the topic at the SolarPACES conferences. The positive response – especially from industry in the last two years – reflects the importance for the future. The plenary presentations at the conferences in Beijing in 2014 and the upcoming one in Cape Town in 2015 will demonstrate this.

The roadmaps for the participating countries will be different based on the different starting points of Australia and South Africa in this project. The final goals should be common and in line with actions taking place globally.

6.1. Roadmap Proposal for Australia

Australia has traditionally a very strong export oriented economy based on coal and natural gas. As the wealth of the country relies greatly on its resources, it is necessary not only to incorporate policy and industry into the development, but also show them the possibilities why and how they can use solar fuels to secure and possibly enlarge the strength of its energy based economy.

A key outcome of the project was the identification of both domestic and international markets for solar fuels. While the domestic market was well defined at the beginning of the project, a significant export market has been identified.

Energy continues to be a major export item for Australia, as can be seen in Table 12. Coal is currently the second source of Australia's export income behind iron ore. LNG is the fourth source of Australia's export income; however, this is expected to increase when the LNG facilities in Gladstone are brought online, beginning in 2014/2015. Once fully operational, it is expected that 25.3 million tons of LNG will be exported per year from Gladstone.

Table 12 Australian energy exports by fuel type for the 2012/2013 financial year [xiv]

	Quantity exported (PJ)	Share of energy export market (%)
Black coal	9485	61.2
Gas	1303	8.4
Oil and LPG	648	4.2
Refined products	125	0.8
Uranium	3944	25.4
Total	**15504**	**100**

Currently, the vast majority of Australia's LNG exports are sold to Japan, with China, South Korea and Taiwan making up the rest of the market. India is projected to be an important future market.

Similarly, the majority of Australia's coal is exported to Japan, followed by South Korea, China and Taiwan. However, recent announcements by the Chinese and Indian governments mean that black coal exports to these regions will slow or even stop (as has been announced by India) before 2020.

While Australia exports coal and LNG, it is a net importer of crude petroleum and refined petroleum products, which represents the second and fourth highest import expense respectively (after personal travel and passenger motor vehicles). The growth trend in oil imports is expected to continue. If coal exports slow, Australia needs to look for other major, alternative energy export opportunities to offset its dependency on imports.

Given the high demand for energy in our major Asian trading partners, there may be an opportunity to export solar fuels to those trading partners with strong renewable energy policies but limited DNI, e.g. Japan, China and South Korea. Also, the cost of shipping energy-dense fuels to these countries is relatively inexpensive; the cost of shipping LNG to Asia is less than 1 $/GJ.

When considering the potential for solar fuels energy exports from Australia, it becomes apparent that Japan may be the most obvious trading partner.

As illustrated in Figure 6a, Japan is very dependent on fossil fuels, virtually all of which is imported – it is the world's largest LNG importer, second largest coal importer and third largest oil importer. Overall approximately 90% of primary energy is imported. In Figure 6b, it can be seen that the Middle East is the major source of oil for the country. Within the coal and natural gas segments of this primary energy mix, supply by Australia is highly significant and represents a very major ongoing trading relationship for both countries. Figure 7 illustrates the state of trade in coal and indicates that Japan is Australia's biggest coal customer and in turn Australia is Japan's biggest coal supplier. In 2012-13, 118 million tons were traded at a value of AUD 15.4 bn equivalent to $4.7/GJ.

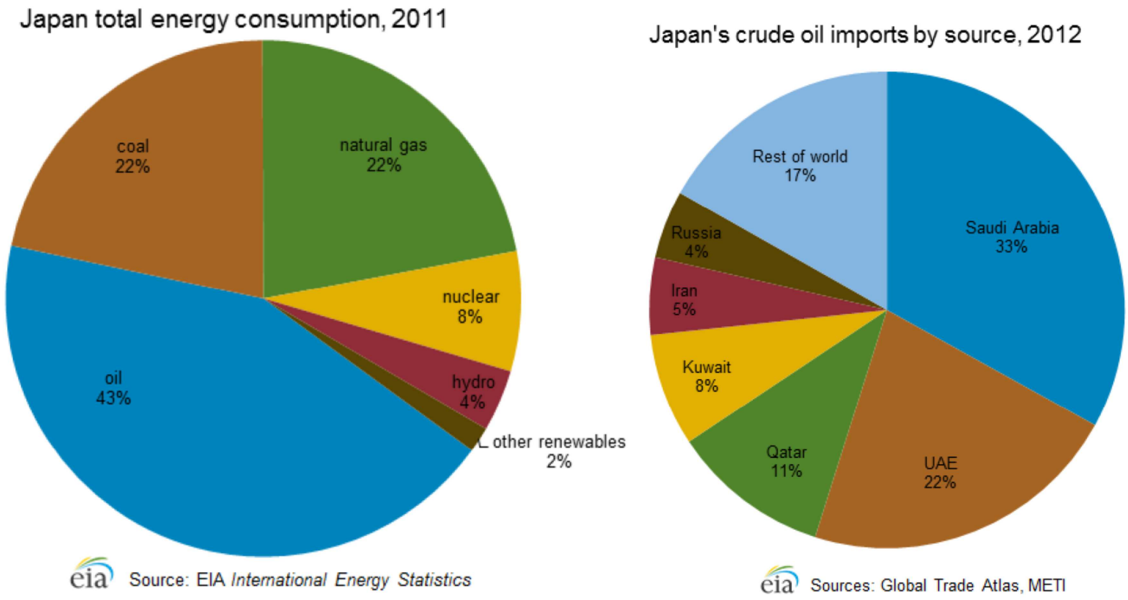

Figure 6: (a) Japanese Primary Energy Consumption and (b) sources for oil. [xv]

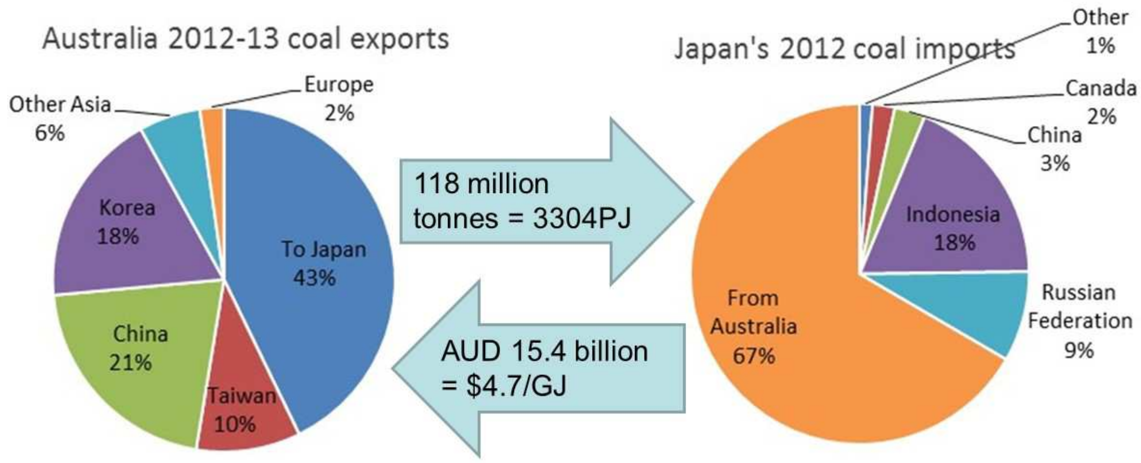

Figure 7: Balance of trade between Australia and Japan.

LNG exports are similarly strongly linked as shown in Figure 8. In this case, nearly three quarters of all Australian LNG is destined for Japan. For Japan, that represents the biggest single source but only by a small margin. It is estimated that the trade was worth $10.3 Billion in 2012/13 equivalent to $12/GJ or more.

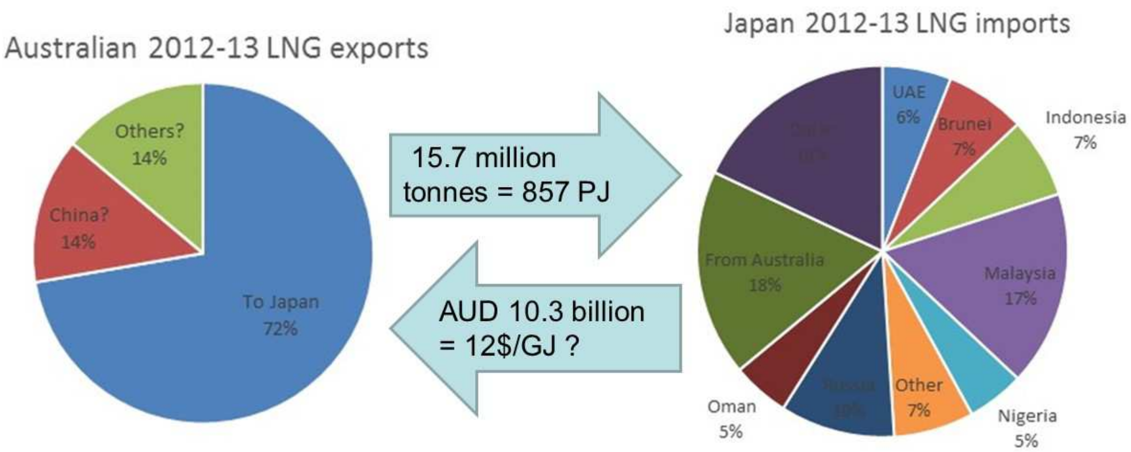

Figure 8: LNG trade between Australia and Japan.

Japanese investment has played a large part in developing Australia's coal, oil and gas projects, **Table 13** lists some major investments in the oil and gas sector.

Thus there are very strong existing energy sector economic linkages and also transport/shipping linkages between the two countries[xvi] together with a history of major co-investment in Australian-based energy projects. The relationship was recently discussed in a "High Level Group" meeting between Japan and Australia in Brisbane on 23 and 24 June 2014.

The concept of solar fuels export from Australia to Japan has been on the table for over a decade. One of the first to promote the idea was Professor Yutaka Tamaura of Tokyo Institute of Technology, one of the founders of solar fuels R&D in Japan. The Pilbara in WA, Darwin in the NT and Gladstone in Queensland are all current and future export ports for fossil fuels destined for Japan. All three are conveniently located to access world's best solar resources.

Table 13: Japanese investments in Australia

Project	Japanese equity
Ichthys LNG Project, Browse Basin, Western Australia	Inpex, 66% Japanese electric utilities: 2.74%.
Pluto LNG Project	Tokyo Gas 5% and Kansai Electric 5%
Timor Sea Joint Petroleum Development Area	Inpex, Tokyo Gas, and TEPCO, combined 20%
Prelude LNG	Inpex 17.5% acquired from Shell in 2012.
Darwin LNG	Inpex 11.3%, TEPCO 6%, and Tokyo Gas 3%
Wheatstone LNG	Japanese electric & gas utilities: 9.5%
Browse LNG	Mitsubishi and Mitsui 14.7% in LNG terminal. 16% in East Browse and 8% in West Browse.
Van Gogh and Ravensworth oil fields	Inpex: 47.5% of Van Gogh, 28.5% of Ravensworth
Timor Sea Joint Development Area	Inpex: 35% of Kitan oil field
NW Shelf Mutineer and Exeter fields	JX Nippon: 25%

Japan recently developed a strategic vision for energy supply and distribution[xvii]. This rests on three pillars: energy security, economic efficiency and environment. Energy security is seen as the biggest problem facing Japan. As stated above, it relies heavily on imported fossil fuels, which has only increased since the Fukushima nuclear accident in 2010. In particular, Japan's reliance on the Middle East for 83% of its oil is seen as the largest security problem. Japan sees diversification of energy supply (or "multi-layered" energy supply) as key to increasing energy security, which may mean returning to nuclear energy. However, it also provides an opportunity for alternatives to Middle Eastern oil for transport to enter the market. Another solution envisaged for increasing energy security (particularly in disaster situations) is to promote the use of distributed generation (such as fuel cells and photovoltaics), battery storage and smart grids. The use of methane hydrates, which are located in the oceans surrounding Japan, are seen as an opportunity for secure, domestic supply, even with the potentially high greenhouse gas emissions associated with this resource.

Improving economic efficiency is the second pillar of Japan's energy vision. Since the Fukushima disaster and the increasing reliance on LNG, Japan's trade deficit has increased to a record high of 11.5 trillion yen. In addition, because of the high cost of LNG, electricity prices in Japan are six times higher than in the US. The concern is that industry will relocate from Japan to regions with lower-cost energy, making Japan's economic situation worse. Therefore, energy efficiency and the use of cheaper forms of energy are being promoted. Removing energy sectoral barriers and increasing competition is also seen as an advantage. One of the cheaper forms of energy is coal, which Japan currently imports from Australia. Japan is promoting the development of efficient integrated gasification combined cycle (IGCC) coal technologies in its bid to continue domestic coal use. It is also examining projects in Australia using low-cost brown coal and converting it to a transport fuel to be used in Japan [xvi].

The third pillar is the environment. Japan remains committed to the imperative for reducing its Greenhouse Gas Emissions. It sees "cleaner" advanced coal technologies as a key route to this together with major initiatives in renewable energy. The main policy for the development of renewable energy in Japan is a feed-in tariff. Other assistive measures include battery storage and hydrogen as storage for smoothing wind and solar output and assistance with development proposals. Japan is also actively promoting the use of hydrogen.

The Japanese Ministry of Economy, Trade and Industry (METI), in collaboration with industry and other government bodies, produced a roadmap for the uptake of hydrogen in Japan[xviii]. Japan is interested in pursuing hydrogen for several reasons[xix]:

- A market for fuel cells – Japan currently holds the majority of fuel cell patents, thus a push for hydrogen use in fuel cells (fuel cell vehicles in particular) will result in greater use of Japanese technology globally and thus improve Japan's economy. By 2025 it is estimated that the fuel cell market will be worth five trillion yen, and Europe, the US and South Korea have hydrogen and fuel cell programs.
- Increase energy security – use of hydrogen results in diversification of energy resources as hydrogen can be produced from fossil fuels and renewable energy and thus may be produced locally, reducing reliance on imported oil in particular. In addition, the use of hydrogen in distributed fuel cells (as in fuel cell vehicles) can be used to supply local electricity in emergencies;
- Zero CO_2 emissions at point of use and potentially zero emissions overall depending on method of hydrogen production.

In order to reach their goal of market introduction of fuel cell vehicles by 2015, more than 100 hydrogen refueling stations are being developed around Japan. It is envisaged that hydrogen will be produced centrally and distributed to the refueling stations, and that hydrogen will be imported into Japan as well as being produced locally [xviii].

Due to limited land availability, Japan will rely on imported hydrogen. Various means of transporting the fuel into Japan are under examination. A USD 20m "New Energy (hydrogen) carrier project" was commenced as a joint effort by the ministries of Education, Culture Sports, Science and Technology (MEXT) and Economy, Trade and Industry (METI) in April 2013. Various hydrogen transport approaches are being considered. Chiyoda Corporation is promoting a hydrogen transport system based on reversible hydrogenation of toluene. Kawasaki Heavy industries favor the use of cryogenic liquid hydrogen for international transport. They are currently engaged in a detailed study for a project that is intended to gasify Latrobe valley brown coal, converting all CO to CO_2 to maximize H_2 production, sequestering the CO_2 as part of the Carbon Net project and then liquefying the hydrogen for export using purpose-built ships. A system capable of 770 tons/day of hydrogen production is targeted (Figure 9).

The infrastructure for transport and storage of liquid hydrogen is conceptually similar to that used for LNG and Australia currently exports LNG to Japan from the North West shelf. The temperatures needed for hydrogen liquefaction are however considerably lower and harder to achieve than LNG.

There may be an opportunity for hydrogen production using solar brown coal gasification, although the DNI in the Latrobe valley is relatively low other deposits in South Australia may be more favorable[xx,xvi].

A third alternative is to use the Haber-Bosch process to synthesis ammonia from hydrogen and transport ammonia liquid. There is a large ammonia production facility in the Pilbara that already exports liquid ammonia around the world, including to Japan. Mitsubishi Corporation is a major ammonia customer / trader and is understood to have an interest in this approach to hydrogen trade. Conventional ammonia production, as it currently operates, uses steam reforming of natural gas to provide the input hydrogen for the Haber Bosch process. This offers an immediate opening for solar driven natural gas reforming as a route to a solar fuel hybrid that could address the Japanese hydrogen market.

Figure 9: Kawasaki Heavy industries vision for the cryogenic liquid hydrogen market.

China is pursuing coal to liquids development, where the main product is methanol. Methanol is currently used in China as a transportation fuel blend. Fuels containing 100% and 85% methanol are available, but these require engine conversion. As methanol is less expensive than petroleum, it is often blended illegally without the motorist's knowledge. Some reports have the use of methanol in transportation as much as 5.8% of total fuel use. There has been discussion of introducing a 15% methanol blend, but this has not yet occurred. Methanol is also used in China as a base chemical, for producing plastics, paint, solvents, refrigerants and pigments.

Demand for methanol in China continues to increase, with global demand expected to increase from 60.7 million tons per year to 109 million tons per year by 2023. This increase in demand is driven by China.

Development of CTL plants has slowed in China due to issues around water supply and contamination[xxi]. Therefore, Chinese companies are looking at investing in methanol plants outside of China. Much of this growth is happening in North America, because of access to cheap natural gas, which can be used to produce methanol.

A Chinese company is investing 1.8 billion Canadian dollars in construction of a GTL methanol plant in Canada, which will supply export methanol to China[xxii]. Another Chinese company is looking to invest in a 4.5 billion USD methanol manufacturing and exporting plant in Texas. This plant would produce 7.2 million tons/year all for export to China, becoming one of the world's largest methanol export facilities. To put this into perspective, 7.2 million tons/year of methanol is equivalent to 142 PJ, which is ~10% of LNG exports from Gladstone – from one methanol plant.

There may be some interest in producing methanol from CO_2 waste streams, as China holds many of the patents for this technology. This, combined with Australia's solar resource, may provide an opportunity for a CO_2/H_2O splitting solar fuels process to produce methanol, in the longer term as the technology matures. Other opportunities for importing solar fuels to China may be limited. Currently, China does not import ammonia, and it has no transport policies focused on fuel cells/use of hydrogen or alternative fuel technologies. Also methanol, even though there is high demand, does not have a national policy for use in transport – rather, it is driven at a regional level. It has been suggested that China may be more interested in pursuing electrification of its fleet to reduce local GHG pollution.

Based on the present position of the Australian energy economy, the logical way is to continue firstly the work on the hybrid solar fuels mainly produced by reforming (steam or dry) of natural gas. CO_2/H_2O based solar thermochemical fuels should follow when the emerging markets consolidate and the customers are requesting even cleaner fuels.

The R&D basis in Australia is among the best in the world. The solar fuels roadmap (Figure 10) must therefore mainly describe how to bring policy and industry together with R&D and the changing needs of the main customers. Critical to this is the ASTRI program which has been implemented by the Australian Renewable Energy Agency (ARENA) which is supporting education programs developing post grad programs for future solar leaders.

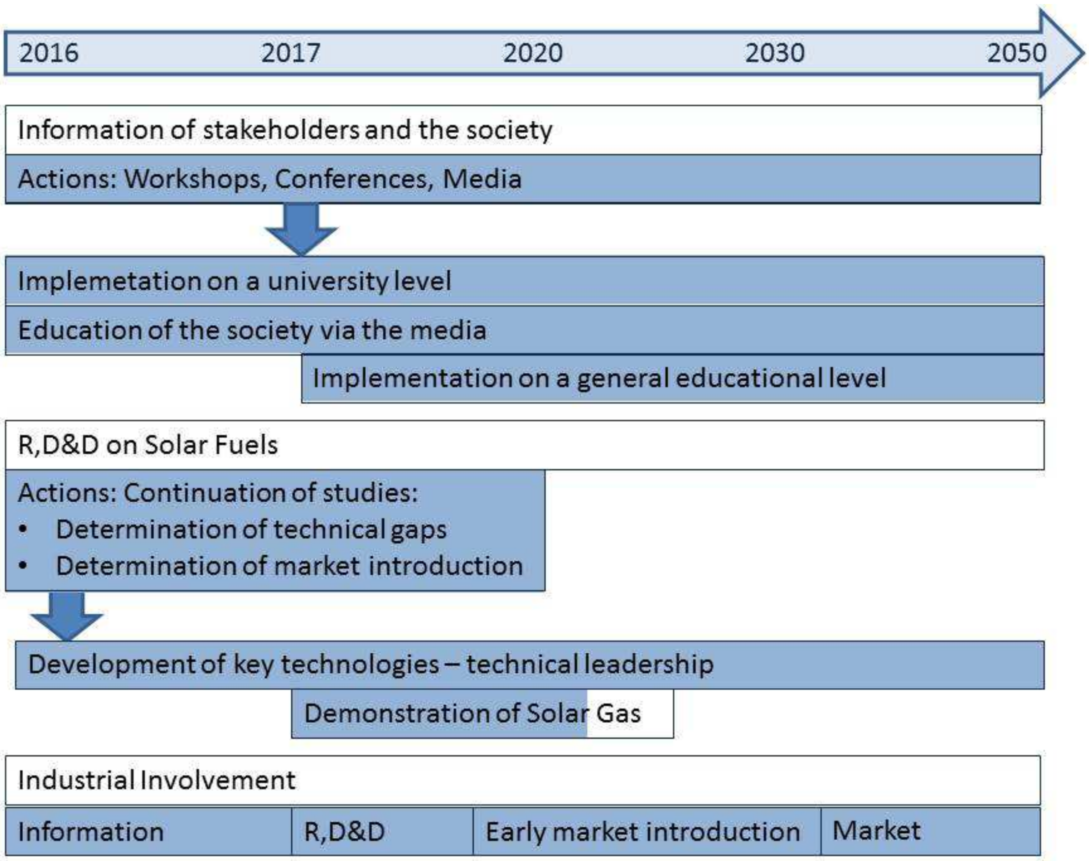

Figure 10: Timeline for the Australian Roadmap

This is already in action as described by the reports on the workshops in Australia. Further workshops and actions were carried out in Japan, China, and India. These efforts need to be continued. In parallel, a demonstration of a solar reforming plant should be installed to show the viability of the technology. A proposed program of development is shown in Figure 11.

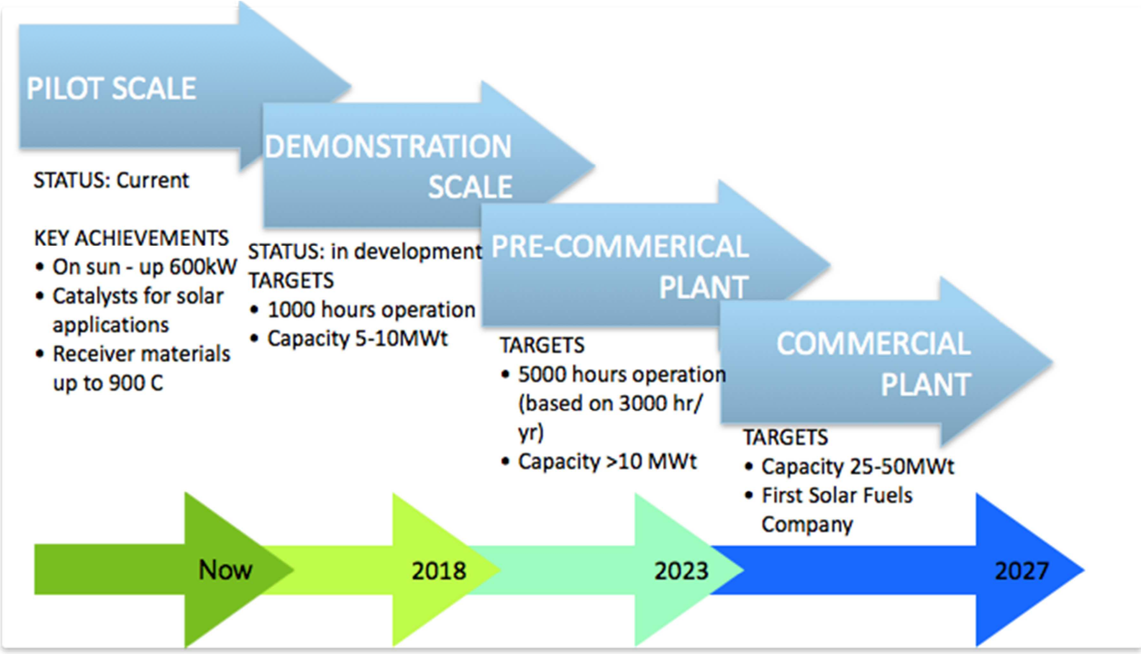

Figure 11: Development program for solar reforming plant.

6.2. Roadmap Proposal for South Africa

South Africa's energy economy is – like in Australia – largely based on fossil fuels, also mainly on coal (see Figure 12) and natural gas. However, the situation is different as South Africa is using a much larger share of its resources inside the country. As mentioned by SANEDI[viii], the introduction of renewable energy takes place supported by intensive programs. CSP is already implemented in South Africa, however it looks like PV and wind are seen as the main sources for a more electricity-based energy economy in the future.

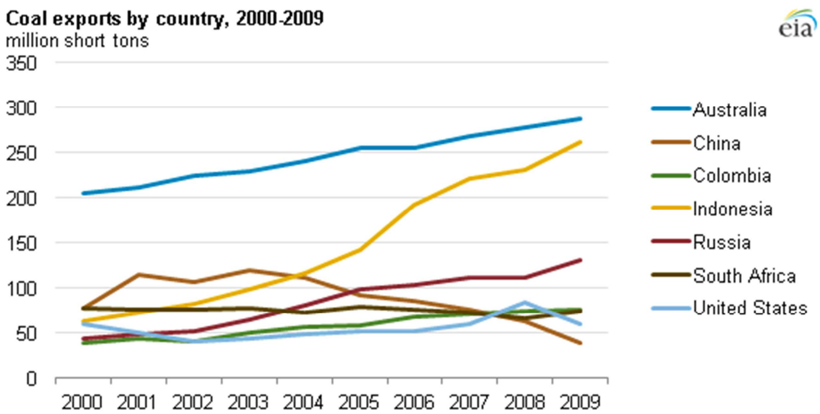

Figure 12: Coal export by country (Source: U.S. Energy Information Administration, International Energy Statistics).

To further raise the awareness and discuss the possibilities and benefits of solar fuels, more actions like workshops and conferences on different levels (policy, industry, academia, society) are necessary.

As discussed during the second workshop in Johannesburg in 2014, there are technical starting points that might be further discussed and developed to get a better understanding on the possibilities for the country.

South Africa has implemented with HySA a very strong program on hydrogen technologies [xi]. Industry, universities, and R&D organizations are world class. The action to be done here is to connect the South African stakeholders more closely to similar efforts on other continents (e.g. the European Hydrogen and Fuel Cells Joint Undertaking FCH-JU[xxiii]).

A participation of South African partners in international programs and projects would help very much to strengthen the connection and demonstrate the already outstanding level of knowledge.

An internationally supported technology demonstration would further improve the position as it could not only get the technologies to the next level but would also be a bridge between the participating countries.

The technology should be chosen based on the political and economic view of South Africa. Taking the actual situation into account, solar natural gas reforming or solar coal gasification would be the most obvious choice. But since HySA has already set up a strong basis on hydrogen technologies and since South Africa was a leader in high temperature nuclear technologies, a demonstration of a solar heated thermochemical cycle (maybe the Hybrid Sulfur Cycle) would also be an option.

A timeline for the South African Roadmap is presented in Figure 13.

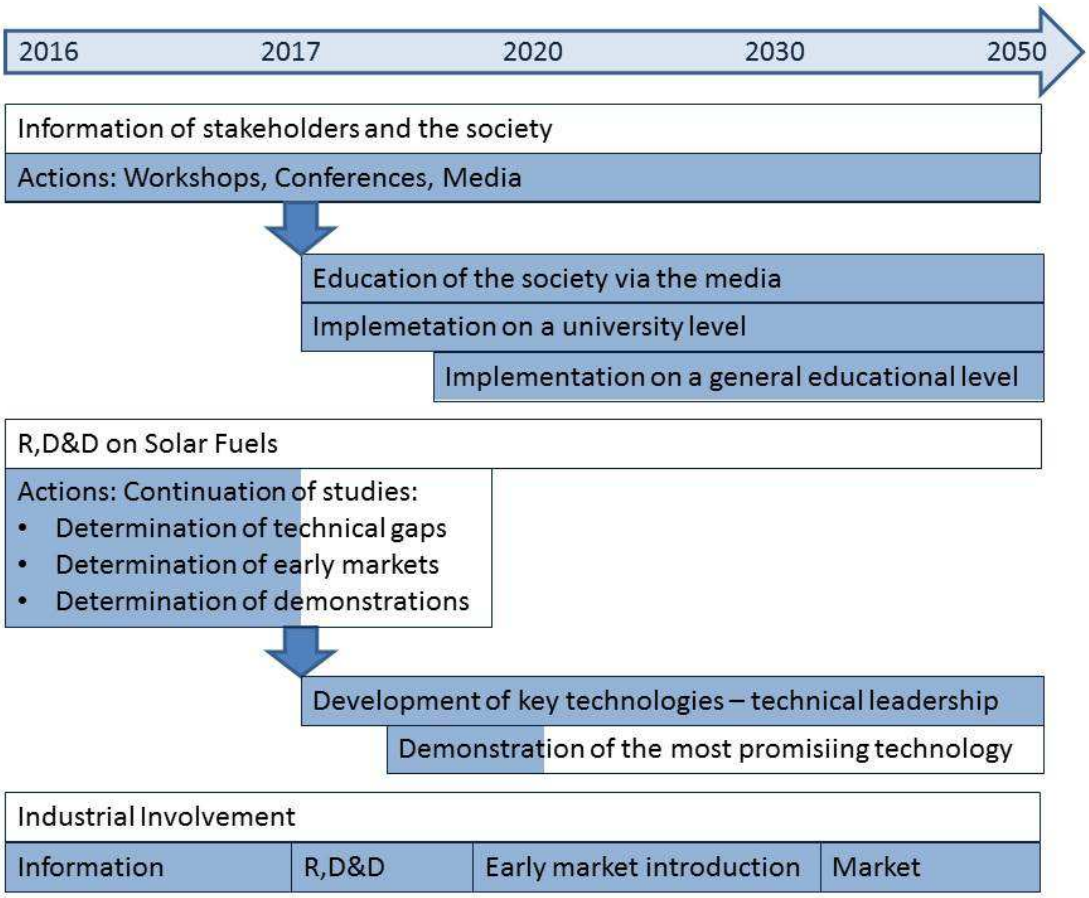

Figure 13: Timeline for the South African Roadmap

THIRD PHASE

Integration of China
and
Early Market Proposals

(January 2015 – April 2016)

7. Phase 3: Integration of China

China is the perfect country to roll out the effort on solar fuels using the results and knowledge gained on the starting partners Australia and South Africa. It has similarities like very good solar insulation in the northern and western part of the country (Figure 14 and Figure 15) combined with fossil resources, especially coal (Figure 16 and Figure 17).

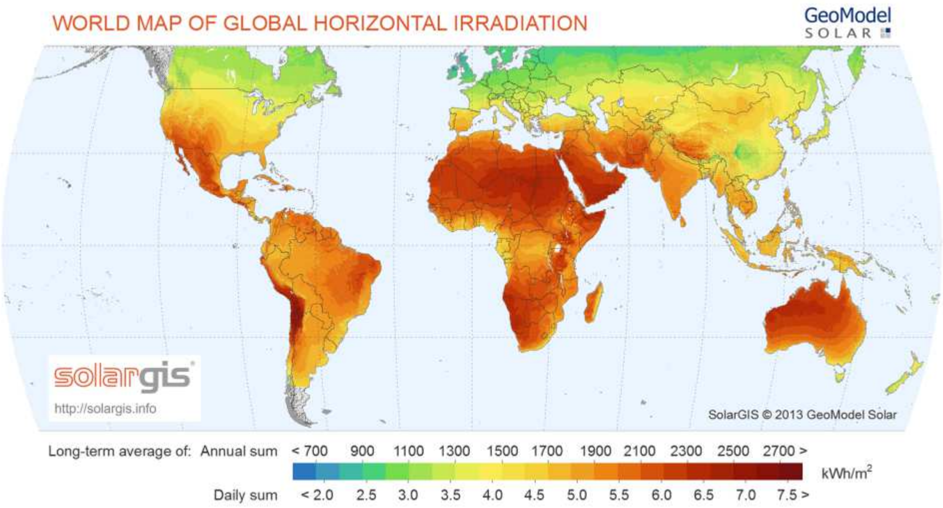

Figure 14: World Map of Global Horizontal Irradiation

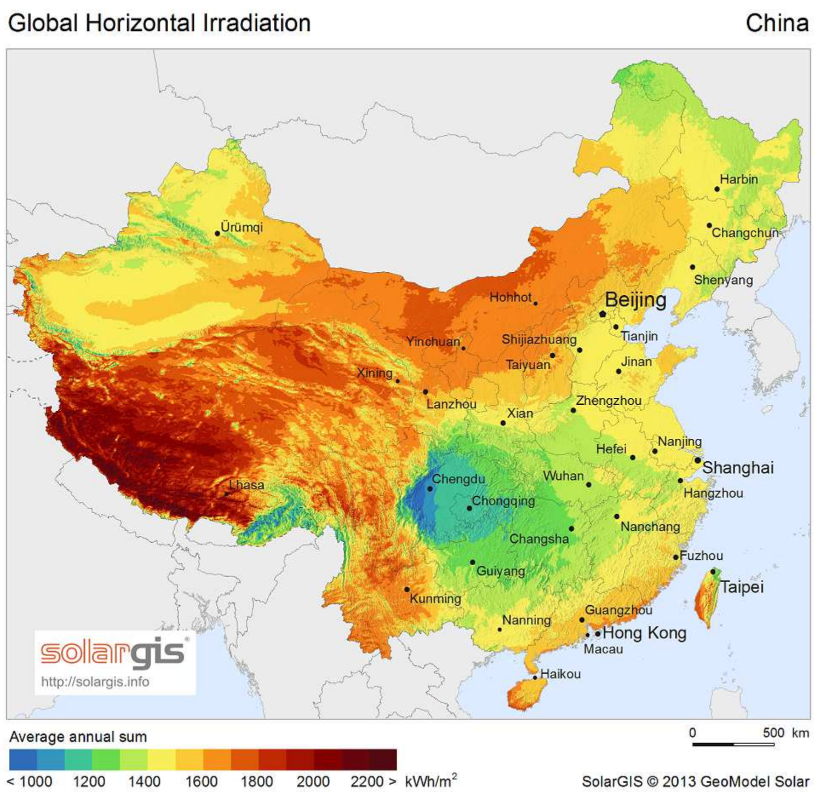

Figure 15: Global Horizontal Irradiation in China

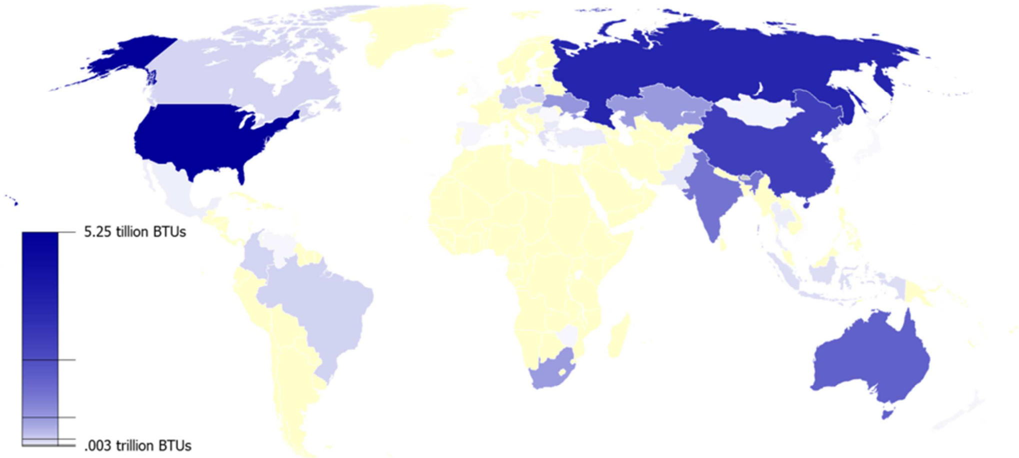

Figure 16: Global coal reserves in BTUs at end of year 2009. [xxiv,xxv,xxvi]
This map was created with GunnMap [xxvii]

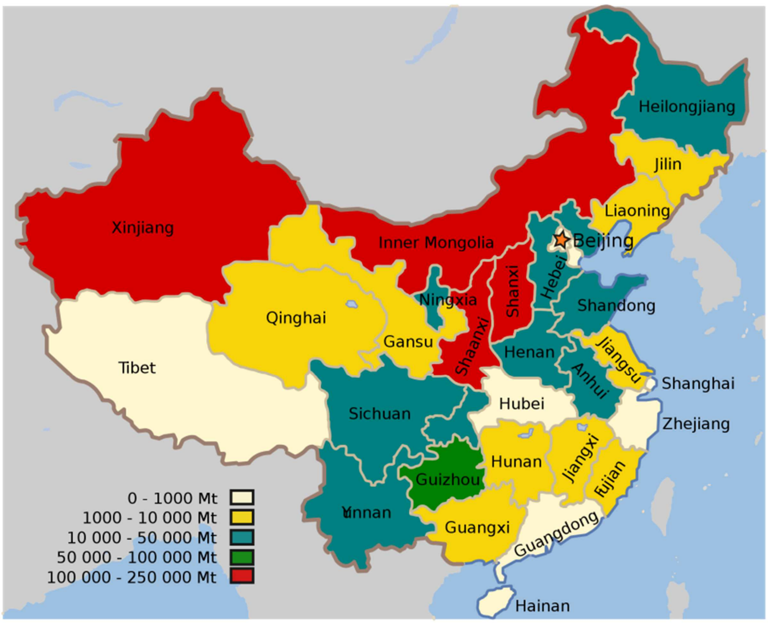

Figure 17: Coal resources in China - based on Barlow and Jonker (2001)[xxviii]

Other than South Africa and Australia, China is a net importer of coal and the largest user of coal in the world. The passing of the Renewable Energy Law (REL) in 2005 demonstrated China's commitment to renewable energy development[xxix]. Biomass had a significant role for fuel production in the REL. However, as the development of renewable energy applications continues, China is also developing alternatives, especially because the potential of biomass is rather limited.

The third phase of the SolarPACES solar fuels roadmap project will contribute to this by supporting to raise the awareness of concentrating solar technologies, inform stakeholders from academia, industry and policy on the state of the art and the perspectives, and develop a roadmap describing possible actions to intensify the effort to be put into solar thermochemical fuels.

8. Example 1 for an Early Market: Reduction of Aviation Emissions[xxx]

Aviation is one of the fastest-growing sources of greenhouse gas emissions. The European Union is taking action to reduce aviation emissions in Europe and working with the international community to develop measures with global reach.

Since the start of 2012, emissions from all flights from, to and within the European Economic Area (EEA) – the 28 EU Member States, plus Iceland, Liechtenstein and Norway – are included in the EU Emissions Trading System (EU ETS)[xxxi].

The legislation[xxxii], adopted in 2008, applies to EU and non-EU airlines alike.

8.1. Flights within EEA Covered for 2013-2016

To allow time for negotiations on a global market-based measure applying to aviation emissions, the EU ETS requirements were suspended[xxxiii] for flights in 2012 to and from non-European countries. For the period 2013-2016, the legislation has also been amended so that only emissions from flights within the EEA fall under the EU ETS. Exemptions for operators with low emissions have also been introduced. For details see the Documentation and FAQ tabs above (which also include information on the European Commission's initial proposal for emissions coverage within the European regional airspace)[xxxi]. The EU made this change following agreement by the International Civil Aviation Organization (ICAO) Assembly in October 2013 to develop a global market-based mechanism addressing international aviation emissions by 2016 and apply it by 2020. This agreement followed years of pressure from the EU for global action. The amended law provides for the Commission to report to the European Parliament and Council on the outcome of the 2016 ICAO Assembly and to propose measures as appropriate to take international developments into account with effect from 2017.

8.2. Market-based Measures are Most Cost-efficient Approach

Like industrial installations covered by the EU ETS, airlines receive tradeable allowances covering a certain level of CO_2 emissions from their flights per year. The Commission proposed the inclusion of aviation in the EU ETS after concluding that this was the most cost-efficient and environmentally effective option for controlling aviation emissions. Its decision was based on the results of a wide-ranging consultation of stakeholders and the public and analysis of several types of market-based solutions. Compared with alternatives such as a fuel tax, including aviation in the EU ETS provides the same environmental benefit at a lower cost to society - or a higher environmental benefit for the same cost. In addition to market-based measures, operational measures - such as modernizing and improving air traffic management technologies, procedures and systems – also contribute to reducing aviation emissions.

8.3. Compatible with International Law

The EU's 2008 legislation on aviation emissions is compatible with international law. This was confirmed by the European Court of Justice on 21 December 2011 in a legal case brought by some US airlines and their trade association against the inclusion of aviation in the EU ETS.

The Court stated that:

- the extension of the EU ETS to aviation infringes neither the principle of territoriality, nor the sovereignty of third countries;
- the EU ETS does not constitute a tax, fee or charge on fuel, which could be in breach of the EU-US Air Transport Agreement;
- the uniform application of the EU ETS to European and non-European airlines alike is consistent with provisions in the EU-US Air Transport Agreement prohibiting discriminatory treatment between aircraft operators on nationality grounds.

8.4. Aviation Emissions Growing Fast

Someone flying from London to New York and back generates roughly the same level of emissions as the average person in the EU does by heating their home for a whole year. Direct emissions from aviation account for about 3% of the EU's total greenhouse gas emissions. The large majority of these emissions come from international flights. By 2020, global international aviation emissions are projected to be around 70% higher than in 2005 even if fuel efficiency improves by 2% per year. ICAO forecasts that by 2050 they could grow by a further 300-700%.

8.5. Transfer to Solar Fuels

Generating aviation fuels using solar energy and CO_2 would have a large benefit for air traffic. It would also support the constant fuel prices and therefore reduce the economic risk of airlines. Promising projects like SolarJet [xxxiv] in the European Union or Sunshine to Petrol (S2P)[xxxv] in the USA demonstrate that the developments are real. A substantial contribution depends mainly on the investment in the technologies. Therefore it is very important to take this example in the definition of the roadmap timelines.

9. Example 2 for an Early Market: Use of CO_2 from Natural Gas Wells

As described above, methane reforming is a very promising technology for the production of hybrid solar fuels. It becomes even more attractive if not only natural gas but also waste CO_2 is used for a dry reforming process. This is especially the case if the CO_2 is mined from the same well as the natural gas. Often, highly CO_2 containing natural gas cannot be used energetically. An example was tackled by the European SOLREF project[xxxvi]. An economic evaluation of the process demonstrates this potential for the more conventional steam reforming process. In 2003, cost of hydrogen produced by solar reforming of natural gas was very close to conventionally produced[xxxvii], as seen in Figure 18.

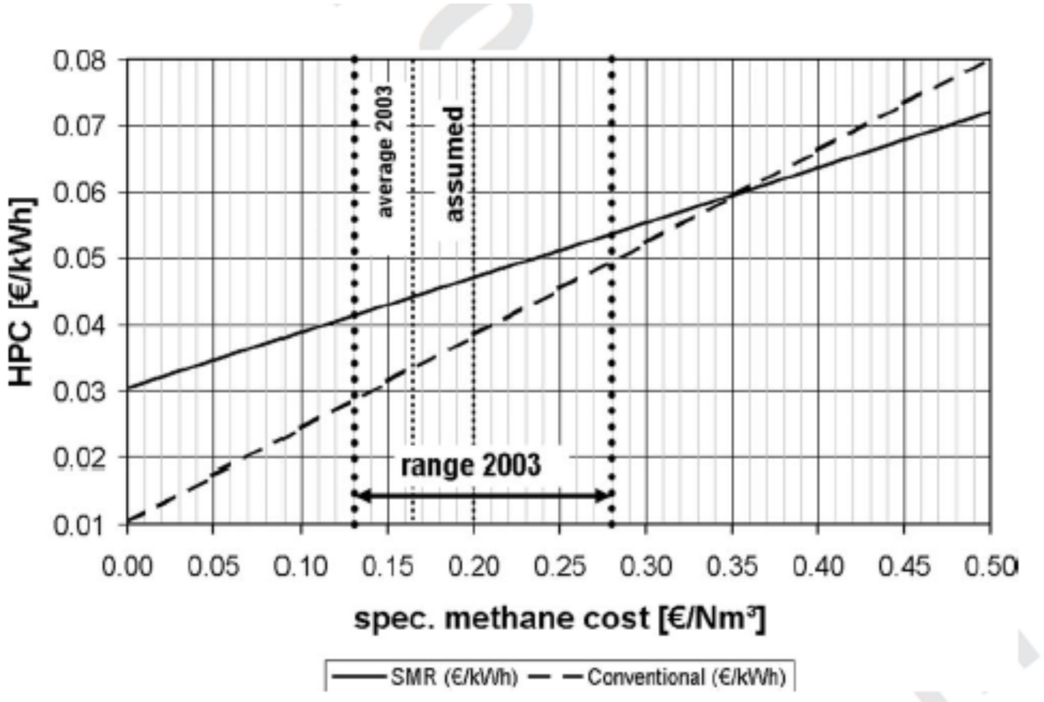

Figure 18: Comparison of hydrogen production cost for conventional and solar reforming of natural gas depending on the natural gas price (conversion rate is 1€ = 1.2 US$).

This promising starting point should be used – especially since natural gas will continue to have an important role in the future energy mix. Additional products derived by the storage of solar energy will have a beneficial influence on the CO_2 balance and most probably also on the economy of the product, including market positioning and cost.

A number of promising projects are carried out especially in the European Union, and Australia, but also in in Asia. Namely in China, Japan, and Korea, substantial work is carried out. Therefore, the solar hybrid fuel option is an important step into a solar based fuel economy as the risk is rather low and the products are conventional and can be used with existing infrastructure, but with reduced CO_2 emissions.

10. Closing remarks

The development of solar thermochemical fuels technologies is a global effort. This SolarPACES Task II roadmap to solar fuels activity shall provide ideas how such efforts can result in developments with a significant economic and ecological impact. However, the development even in the most advanced countries is still in its beginning. Therefore, international cooperation might be suitable to reduce the burden on each participant. The European HORIZON 2020 program has a particular share for such cooperation[xxxviii]. Other comparable national and international programs are heading in the same direction. Especially since the Leaders Declaration of the G7 summit June 7^{th} and 8^{th} 2015, in Elmau, Germany states on climate change:

G7 GERMANY
2015 | Schloss Elmau

"The G7 welcomes the announcement or proposal of post-2020 emission targets by all its members, as well as the submission of intended nationally determined contributions (INDC) and calls upon all countries to do so well in advance of COP21. We reaffirm our strong commitment to the Copenhagen Accord to mobilizing jointly USD 100 billion a year by 2020 from a wide variety of sources, both public and private in the context of meaningful mitigation actions and transparency on implementation.

Climate finance is already flowing at higher levels. We will continue our efforts to provide and mobilize increased finance, from public and private sources, and to demonstrate that we and others are well on our way to meet the USD 100 bn goal and that we stand ready to engage proactively in the negotiations of the finance provisions of the Paris outcome. We recognize the potential of multilateral development banks (MDBs) in delivering climate finance and helping countries transition to low carbon economies. We call on MDBs to use to the fullest extent possible their balance sheets and their capacity to mobilize other partners in support of country-led programs to meet this goal. We thank the presidency for the publication of the Background Report on Long-Term Climate Finance and call for a further exchange in all relevant fora in view of COP21.

Mobilization of private sector capital is also crucial for achieving this commitment and unlocking the required investments in low-carbon technologies as well as in building resilience against the effects of climate change. To overcome existing investment barriers finance models with high mobilization effects are needed." [xxxix] This statement will raise the economic importance in putting more effort on technologies like solar thermochemical fuel production. SolarPACES will continue to work in a direction to support its members to be on the forefront of this development.

11. Annex A: Questionnaire

Cluster 1: Technology

- What would put CSF on the radar from a technological point of view?
- What are competing technologies to handle storage/intermittency?
- How to factor uncertainty and risk into planning?
- How far can the competing technologies be scaled up?
- How precise are the predictions of the solar resources (volcanic ash, climate change)?

Cluster 2: Policy

- What would put CSF on the radar from a political point of view?
- What would be the measures for the country?
- What sort of support mechanism is needed?
- How to best leverage international opportunities?
- Is there a possibility and bilateral and multilateral for joint efforts as well on industrial, economic cooperation as on research, development, and deployment?
- Uncertainty and risk: How to factor it into planning?
- A techno-economic risk assessment has to be provided to explain how the sizing of a CSF plant takes risks and uncertainties into account.
- Check carbon accounting
- Presently there are no mechanisms in Australia but as CSF will be mainly export goods the key markets have to be evaluated for that.
- Is there need for more international coordination?
- This can be approached from different sides:
- Is there already international coordination available which could be used by the country?
- What is the position of the government?
- How can additional coordination help to strengthen the countries position?
- What are the needs of the major stakeholders?
- How to get a coherent message from CSF advocates?
- How can SolarPACES act to get the CSF advocates together?
- Are community acceptance and decommissioning issues addressed sufficiently?
- Who must be informed or educated?
- Who could act as multipliers?

Cluster 3: Economy

- What would put CSF on the radar?
- How to get more industry involved?
- What are early/niche opportunities?
- How to best leverage international opportunities?
- How to factor uncertainty and risk into planning?
- How fast can it be scaled up?
- How much money would be available for such an effort?
- Based on TCA, what would the CO_2 price have to be to make a plant economic?
- What is required to get break even CO2 price down to X?
- Are the markets different for the different approaches?

- Is there value in coal to CH4?
- How about chemical products?
- Can common industrial processes be redesigned for batching?

Cluster 4: Ecology

- Check carbon accounting
- Can the ecological benefit of the technology be quantified?
- Can the CO_2 balance be compared to other technologies?

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