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ARENA

3-A018 Solar Hybrid Fuels (Stream 2)

Summary report: project results and lessons learnt

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Executive Summary

Imagine using Australia' abundant solar energy to create low emissions, sustainable, and low cost solar fuels that could be used to run your car engine, power aircraft, and create a sustainable export industry in Australia.

Concentrated Solar Fuels (CSF) are combustible fuels (liquid and gas) that are created utilising concentrated solar energy. The solar energy is transformed into chemical energy for use in a variety of applications. Potential CSF products include synthetic diesel, gasoline (petrol), methanol, ammonia and hydrogen.

There are a number of potential technologies that could enable a CSF Industry in Australia. However, until recently, no comprehensive study has ever been completed looking at the opportunity in Australia.

In this project we examined the challenges and solutions to the implementation of a CSF industry by considering; technology development, societal acceptance, market development and customer demand. From this a detailed list of R&D priorities has been developed. Successful establishment of a CSF industry in Australia would be aided by suitable actions across stakeholder groups that include; Research organisations, State governments, Federal government, Funding agencies and existing industrial players. A detailed listing of suggested actions for each group has been assembled. These can be broadly summarised as:

- CSF R&D should be a priority and should target

  Parallel development of multiple technology options to enable a staged approach to reducing carbon intensity. It makes best sense to use solar energy to upgrade fossil fuels in the short to medium term, allowing fully renewable technologies to develop in the longer term.

  More detailed R&D recommendations can be found in the full report, but key areas include storage of thermal energy, the development of high temperature materials and heat transfer fluids, and low cost storage solutions for hydrogen and or the synthesis gas (a mixture of carbon monoxide and hydrogen used to make fuels) produced from solar processes.

  Demonstration of full production chain full to CSF products. This is essential to show that the technologies work right through to the delivery of a useful fuel. Imagine holding a Gerry can of fuel bursting with energy from the sun!

- Australian Renewable Energy Agency could adopt renewable fuels as a new priority area. This would provide the context for R&D and industry to work more closely together to bring CSF to the market.

- State mandates for biofuels could be generalised to include all renewable fuels. This would provide a market pull, and has been effective for biofuel development.

- The Renewable Energy Target could be expanded or replicated to include renewable fuels, providing a policy driver for developing the industry.
- Removal of fossil fuel subsidies (e.g. diesel excise rebates) and/or consideration of appropriate carbon pricing measures. Renewable technologies should enjoy the same level of support in their early stage development as incumbent fossil alternatives.
- A pipeline of Australian CSP deployment is needed to build capability and supply chain that can be leveraged for a CSF industry in future. A CSF industry will be based on the same tower and heliostat technology as CSP, and thus can piggyback on the growth and cost learnings of this industry.
- Establish a regional test platform at 5-10 MW scale for a range of CST technologies including a demonstration of solar steam methane reforming. With its superlative solar resource and engineering nous, Australia is uniquely placed to be the host of a world class research and demonstration facility which could support research and technology development in Japan, Korea, China and other Asian countries.
- Bilateral government negotiations with Japan and others could establish international renewable fuels trade. Japan in particular has stated that it intends to transition to a hydrogen economy, and CSF such as ammonia and hydrogen are highly prospective options for Australia to transition its energy exports to lower emissions products in the future.

The analysis carried out in this study suggests that CSF approaches to pure solar hydrogen production are likely to be less than half the cost of PV plus electrolysis, and similar to conventional fossil based alternatives at oil prices around $100/barrel. The competitiveness against advanced biofuels options will very much depend on the cost of biomass available. There is only a limited supply potential for cheap biomass so both approaches have a role. Competiveness against fossil plus CCS is hard to determine at this stage. Overall it would be suggested that major policy initiatives should be made in a technology neutral manner such that all approaches can compete in new zero emission fuel markets.

With suitable strategic initiatives in these directions, an Australian CSF industry established over the next 2 decades, could grow to be of equal or larger value to the economy than the fossil fuel industry is today.

Project Overview

Project summary

The concentrated solar fuels (CSF) roadmap study was established to identify what would be needed for Australia to become a world leader in this area. The key outcomes of the project were reports that detailed the:

- Australian context for solar fuels and state of the art for solar technologies
- Evaluation and ranking of solar fuel technologies in consultation with industry
- Techno-economic analysis and commercial assessment
- Roadmap and strategic recommendations for solar hybrid fuel technology options and opportunities suitable for Australia, including future research necessary to build on and expand the then current capability base in Australia

What are Concentrated Solar Fuels?

CSF are fuels that are made from – in part or in whole – concentrated solar energy. Solar energy is concentrated using mirrors to provide temperatures high enough to drive reactions that are able to store this thermal energy in a chemical form. This could be in the form of synthetic diesel, gasoline (petrol), methanol, ammonia and hydrogen. An overview of the various processes follows.

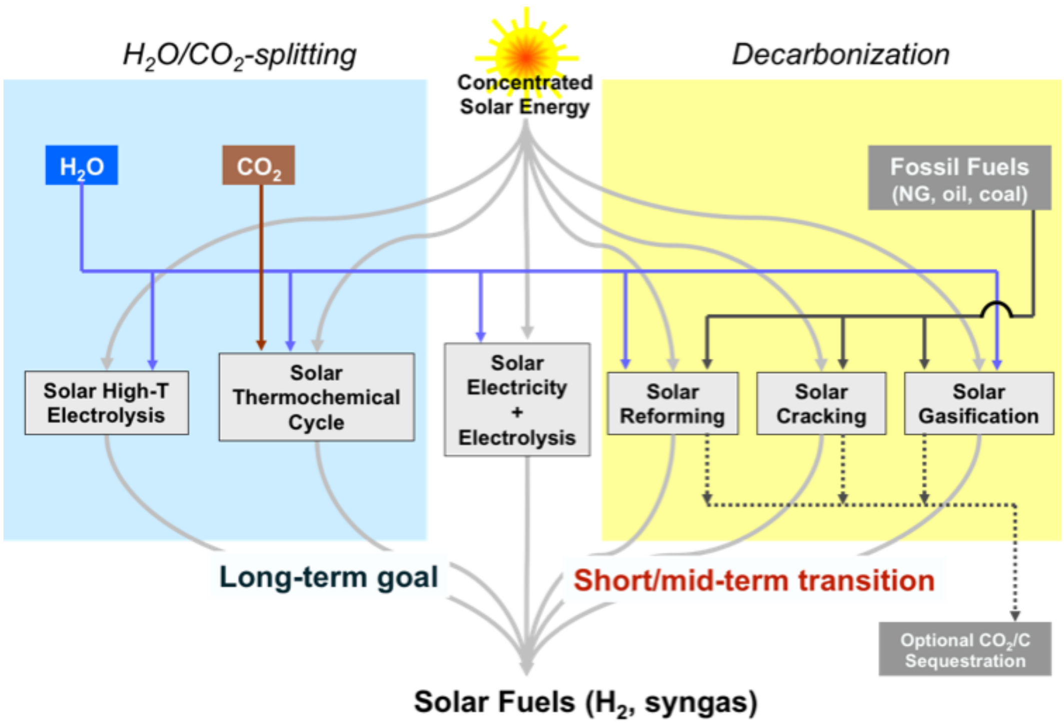

Figure 1: Summary of solar fuel options
Source: Paul Scherrer Institute

Syngas is a mixture of carbon monoxide and hydrogen that is widely used in the chemical industry for the synthesis of many chemicals, and can be used to make synthetic diesel, gasoline or methanol. Syngas can also be readily converted to hydrogen which is a fuel in its own right as well as the essential feedstock for petroleum refining and ammonia synthesis. Ammonia is manufactured in vast quantities for fertiliser and explosive production.

Project scope

The initial scope was clearly focussed on concentrating solar thermal technologies, and while the importance of industry engagement was clear, the level of market analysis was limited. This was partly because fuel security was a looming issue at the commencement of the project, with growing unease about escalating fuel prices and a growing shortfall between indigenous liquid fuel production and consumption. As the project has progressed, the oil price has dropped unexpectedly, and several additional activities have been included in the project, including assessments of:

- Markets and opportunities both domestic and export
- The likely cost of hydrogen from PV and electrolysis

The potential role of CSF in reducing carbon emissions

While tremendous advances have been made in the development and deployment of renewable energy technologies, what is not always recognised is that while most popular attention is given too renewable technologies that produce electricity, **around 80% of global and Australian primary energy demand is currently supplied by petroleum and gas (Figure 2) and this is largely used for transport and heat**. Renewable technologies as they are currently deployed are thus only tackling part of the problem, and tackling the carbon dioxide emission reductions needed for … will require either a significant change in energy consumption (e.g. electrified transport) or the identification of lower carbon intensity sources of combustible fuels. Carbon capture and storage is also likely to play some role, it is widely recognised that a portfolio approach with multiple technologies is likely to be needed. Concentrating Solar Fuels (CSF) technologies have the potential to provide a variety of low emissions fuels from conventional liquids like diesel and gasoline to more disruptive fuels like hydrogen.

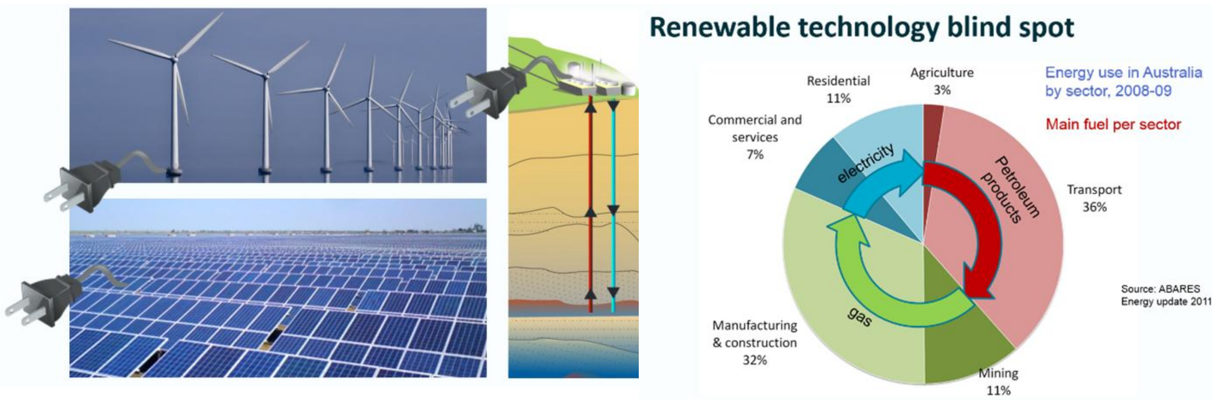

Figure 2: Renewable energy technologies as currently deployed do not address a large fraction of energy demand

Oil still provides approximately 30% of global primary energy and is the largest single contributor. More significantly trade in oil accounts for around 70% of the financial turnover in the energy sector as a whole, reflecting its higher value that follows from its versatility, high energy density and key role in transport. To date world efforts to expand renewable energy contributions have largely been in the electricity sector and rapid progress is being made. However if international efforts such as those agreed in COP21 to limit global warming to below 2°C are to succeed, low emissions alternatives to fossil oil and natural gas are urgently needed, particularly for transport applications.

Electrification of transport via passenger vehicles and trains will increase over time and contribute to a solution. However the advantages of high energy density storage, quick refuelling and efficient distribution infrastructure, make the continued use of fluid fuels very attractive and arguably essential for air travel and long distance freight.

Options for producing such fuels in an emissions free manner include; fossil fuels combined with CCS, biofuels, renewable electricity driven electrolysis, and Concentrating Solar Fuels.

Outcomes

This roadmap has examined the CSF options in detail and concluded that hybrid options are very attractive in the medium term and pure solar driven thermochemical processes for water and CO2 splitting appear very promising in the long term.

CSF technologies will be deployed as a natural evolution of the growth and diversification of a Concentrated Solar Thermal sector, which is currently almost exclusively devoted to Concentrated Solar Thermal Power. CSP globally is growing strongly, with the same growth trajectory as PV but about 1 decade behind. Its growth will drive the cost reductions in solar field components that will make CSF competitive as the new receiver technologies mature.

This roadmap has carried out possibly the most complete review ever of the published literature in the CSF area. 1322 publications have been reviewed, examining key operating parameters, Technology readiness, limits to conversion efficiencies and other factors. Technologies range from hybrid solar plus gas, biomass or coal options with technical readiness levels (TRL) in the range 1 to 6 to advanced multistep water splitting processes with TRLs in the range 1 to 5.

There are many different solar to syngas and then syngas to fuels technologies available, however many are still in the demonstration or R&D phases and thus require support to continue their development so they may become a commercial reality. The process of creating a CSF for market involves a primary solar driven stage that produces either pure hydrogen or a mixture of hydrogen, CO and CO2 (syngas). This is followed by a range of possible secondary processes to produce one of a range of possible saleable fuels.

An innovative and comprehensive approach to evaluating the levelised cost of firstly the solar process gases, followed by the final synthesised CSF has been developed and applied to an extensive generalised range of solar receiver reactor plus reaction system combinations. Aside from the cost of feedstock, the key driver of cost effectiveness is the solar to chemical conversion efficiency that can be achieved. The calculation method adopted uses key parameters of operating temperature and overall mass-flow rates of species passing through the reactor system to evaluate the optimistic / realistic values that could be achieved from each receiver / reaction system combination in a consistent manner such that a meaningful ranking was produced. In doing this the importance of minimising thermodynamically unnecessary mass-flow streams and maximising the recuperation of sensible heat was clearly demonstrated.

A systematic screening process that combines the solar LCOF with criteria that determine the relative prospects for commercialisation, such as the current technology readiness and the difficulty of unsolved hurdles plus GHG reduction potential has been carried out.

1. The screening analysis indicated that **solar reforming of natural gas** was the highest ranked process, due to its good economics (~$10/GJ for solar syngas), current high TRL and relatively low score for unsolved hurdles. Developing this technology to a higher TRL level will require a reasonably significant investment in a plant that can operate on a more or less continuous basis to build up the hours of operation needed to make the process "bankable".

- **Solar thermal water splitting** with redox cycles also scored well in the screening, despite having a much higher product fuel cost (~$35-50/GJ). This was because it has a reasonable TRL score, having been demonstrated at 100 kW_t scale, and the fact that there is quite a significant amount of international effort being spent on R&D, plus it offers zero GHG emissions. This technology is also applicable to carbon dioxide splitting to enable the production of syngas for hydrocarbon fuel synthesis.
- **Solar coal and biomass gasification** scored slightly worse than water splitting, due to higher greenhouse gas intensity (CCS was not considered in the screening), lower R&D effort and a higher score on the unsolved hurdles associated with the difficulty of handling solids as opposed to gases. However, brown coal did have a very low syngas production cost (~$5/GJ) due to the very low feedstock costs.

The final fuel LCOF is projected to be competitive with conventional oil derived fuels for solar processing of carbon containing feedstock such as coal and natural gas by around 2020 (Table 1). The production of hydrogen from water splitting is projected to be 2-3 times more expensive, although significant cost reduction can be anticipated beyond 2020.

Table 1: Projected 2020 levelised cost of fuel (LCOF), technology readiness level and greenhouse gas (GHG) intensity for key concentrating solar fuels technologies

Process	Input fuel cost	Solar product gas LCOF	Final fuel LCOF	Final fuel LCOF	Technology readiness	GHG intensity
Conventional crude oil at $100/barrel	$16/GJ	–	$20/GJ	$0.56/L	Current technology	High
Solar gasification of brown coal	$1/GJ	$3.45/GJ	$11/GJ	$0.31/L	Medium	High
Solar reforming of natural gas	$8.4/GJ	$10.30/GJ	$17/GJ	$0.48/L	High	Medium
Solar gasification of biomass	$8/GJ	$9.75/GJ	$17/GJ	$0.48/L	Medium	Zero-low
Solar water splitting	Zero	$29–46/GJ	$34-51 /GJ	$4-6/kg H_2	Low	Zero

Different technologies are clearly at different levels of maturity and require very different activities in terms of research and or demonstration projects (and levels of funding) to continue development. Solar gasification technologies – and redox cycles – require more work at the laboratory and pilot demonstration scale before they can be built at the pre-commercial demonstration plant scale, while solar reforming is ready for a larger scale demonstration. It is recommended that continued development in solar gasification and redox is conducted in parallel with demonstration of natural gas reforming at a larger scale. This will result in a suite of technologies being developed over time to offer progressively greater reductions in the GHG intensity of the CSF products. It is important also to realise that a CSF industry cannot be created overnight, as finance for commercial scale projects will only be available to projects that have been proven at pilot and pre-commercial scale. This requires several years of continuous operation using essentially the same engineering designs that would be commercialised, and therefore requires sustained investment over a period of 5-10 years depending on the maturity of the technology.

Transferability

The key potential markets for solar fuels are offsetting oil imports for transport fuel in Australia and potential export opportunities to Japan, China and Korea. In Australia, net oil imports are one of the most significant import costs for the country, and growing rapidly as a result of declining domestic production and growing demand together with what was an upward trend to international oil prices and will likely be so again in future decades.

Australia has ample solar, coal and biomass resources to produce pure solar fuels and/or solar hybrid fuels. The transport costs of final fuels products to international markets are more than justified by Australia's superior resources.

Japan is Australia's most important trading partner for energy, and is the largest destination for the coal and LNG exports that figure as a major share of Australia's export income. At the same time, Japan is dependent on imported energy and actively looking to diversify, improve efficiency, reduce its dependence on Middle East oil, and reduce its GHG emissions. Japan has also recently moved to actively promote a hydrogen economy and develop supply chains for renewable hydrogen. Japan has no significant solar resource compared to Australia's world leading position. These factors combined make Japan an ideal target market for solar fuels.

Ammonia and methanol are two key chemical commodities already traded globally, which may in future grow to become major fuel commodities and a way of transporting solar energy. Projected costs for solar driven production based on solar driven reforming suggest that a solar derived product could be competitive in 2020 even before consideration of GHG costs.

Domestically near term markets could be created with suitable government action via blending. 20% methanol additions to gasoline, blending of DME with LPG and up to 20% additions of hydrogen to natural gas can all be contemplated without vehicle and end use infrastructure changes. Importantly, the solarised versions of these commodities are indistinguishable from those derived from conventional fossil sources. This blending approach would be expected to gradually evolve into a future where new emissions free standard fuels may completely replace crude oil derived diesel and gasoline.

Conclusions and next steps

The challenges and solutions to implementation of a CSF industry have been examined, considering; technology development, societal acceptance, market development and customer demand. From this a detailed list of R&D priorities has been developed. Successful establishment of a CSF industry in Australia would be aided by suitable actions across stakeholder groups that include; Research organisations, State governments, Federal government, funding agencies and existing industrial players. A detailed listing of suggested actions for each group has been assembled. These can be broadly summarised as:

- CSF R&D should be a priority and should target
  - Reactor lifetimes
  - Recuperation of heat from reactants to maximise efficiency
  - Low cost underground storage of hydrogen / syngas mixtures
- Australian Renewable Energy Agency could adopt renewable fuels as a new priority area
- State mandates for biofuels could be generalised to include all renewable fuels
- Renewable Energy Target could be expanded or replicated to include renewable fuels
- Removal of fossil fuel subsidies (e.g. diesel excise rebates) and/or consideration of appropriate carbon pricing measures
- A pipeline of Australian CSP deployment is needed to build capability and supply chain that can be leveraged for a CSF industry in future
- Establish a regional test platform at 5-10 MW scale for a range of CST technologies including a demonstration of solar steam methane reforming
- Bilateral government negotiations with Japan and others could establish international renewable fuels trade

The analysis carried out in this study suggests that CSF approaches to pure solar hydrogen production are likely to be less than half the cost of PV plus electrolysis. The competitiveness against advanced biofuels options will very much depend on the cost of biomass available. There is only a limited supply potential for cheap biomass so both approaches have a role. Competiveness against fossil plus CCS is hard to determine at this stage. Overall it would be suggested that major policy initiatives should be made in a technology neutral manner such that all approaches can compete in new zero emission fuel markets.

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Lessons Learnt

Lessons Learnt Report: Risk is not just technical risk

Project Name: *Concentrated solar fuels road map*

Knowledge Category:	Financial
Knowledge Type:	Risk Management
Technology Type:	Solar Thermal
State/Territory:	All

Key learning

A key comment from participants at the stakeholders' workshops was that industry is very risk averse and needs to have good drivers to invest. The project team, mainly engineers and scientists, was reminded that addressing technical risk was only part of the issue, and that externalities such as carbon pricing, environmental credentials, incentives or mandates and public perception were all equally if not more important.

Implications for future projects

Clearly engaging with industry and government on all levels is important for understanding the drivers for and barriers to action.

Knowledge gap

While not really a knowledge gap as such, it is recognised that the development of biofuels for instance has important parallels and potential synergies.

Background

Objectives or project requirements

We wanted to understand the viewpoint of various stakeholders and what their thoughts were on our methodology in screening and analysing the cost of various technology options.

Process undertaken

Three stakeholder workshops were held in all, each with a different focus. The first was primarily knowledge sharing on the state of the art, the second discussed the economic analysis and explored the risk of developing new technologies, and the third explored the needs and attitudes of a particular market – Japan.