Project report: Development of Combined Cycle using solar reformed gas in North Western Australia

Final report: project results and lessons learnt

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Executive Summary

This project launched in March 2013 and ran for a 12 month period, with the final outcome being a detailed assessment of the potential for solar thermal steam reforming to be integrated into a combined cycle power station. The project is led by CSIRO, with project partners GE Global research (GE GRC) and GE Australia (GE AUS).

The project is structured into three stages, with the three stages having significant overlap and interactions:

- Stage 1 - six months design of the solar thermal reformer system (CSIRO) and combined cycle power system (GE GRC);
- Stage 2 - an overlapping six month stage where the two system designs were integrated (CSIRO/GE GRC); and
- Stage 3 – a three month economic feasibility completed (GE AUS).

The reformer was developed with a capacity of 15 MWt at peak thermal input. The design utilises a surround field and cavity receiver developed specially for this application, taking into account the expected solar flux density for the site. The system utilised combusts a mix of solar derived syngas and natural gas in the gas turbine component of the combined cycle.

The design presented a number of challengers that impacted both the final power station characteristics as well as the solar reformer design. As a result, the combustion characteristics of the fuel were investigated in significant detail. The most critical of these are the operating pressure of the turbines ranging from 25---46 bar, and the ability of a combustion system to accept varying fuel compositions, keeping the flame stable, while meeting emission limits. The final design configuration includes a GE 206B Turbine in combined cycle mode, with a solar field design point capacity of 15MWt.

The project economics presented a case where the Levelized Cost of Energy (LCOE) remains effectively unchanged, despite the addition of a solar field and reactor system, Capital cost increases were offset by improvements in thermal efficiency. The assessment highlights that the risks involved in developing such a system out-way the benefits at this point in time. A number of barriers were highlighted to take the project to the next stage.

Project Overview

Project summary

The project, a technical and economic feasibility study of the potential for a solar thermal steam reformer to be hybridised into a combined cycle power station, is led by the CSIRO with project partners in GE Australia (GEA) and GE Global Research (GEGR).

The solar hybrid power system design utilises a solar thermal heliostat (large mirror) field to drive a steam reformer at 750^{0}C. The solar steam reforming process was developed at the CSIRO to chemically embed solar energy into a fuel supply.

The process to embed solar thermal energy into the fuel gas is known as steam reforming and is a common industrial chemical reaction used to convert natural gas into hydrogen. The solarised fuel gas is blended with natural gas before it is fed into a gas turbine; this ensures that the combustion is stable and reliable for consistent power generation.

This solar fuel gas containing up to 25% embedded solar energy is then combusted in a combined cycle power station, replacing natural gas during the day, while keeping the electricity flowing overnight using traditional natural gas. A key challenge in the development of the solar combined cycle design was enabling this fuel flexibility, allowing combustion of the solar and natural gases, while maintaining performance, fuel economy and operational reliability of the power station.

The project examined a site in the north west of Australia, prime solar territory with growing need for power generation. The sites annualised solar exposure, a combination of the sun position during the day and its movement through the year, was used to define the solar thermal receiver design.

This project was the first to look at the detailed engineering required to scale-up the CSIRO developed solar steam reformer for use in the power generation industry. The project assessed the project economics including the capital costs and ongoing running costs of the system.

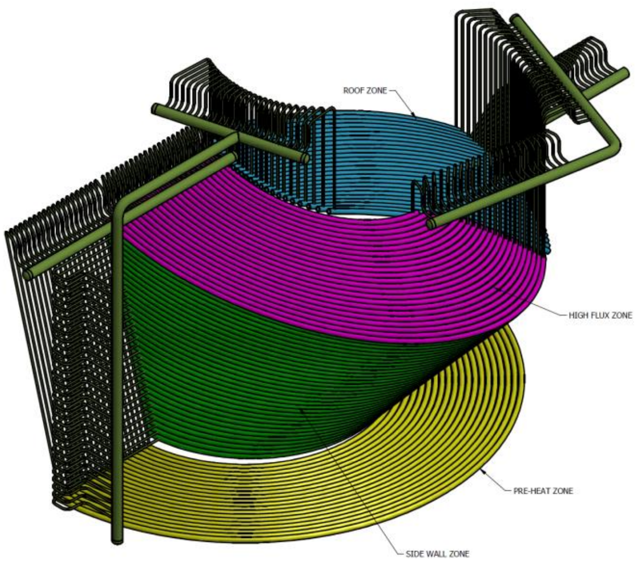


Figure 1 Isometric drawing of the receiver/reactor system

Project scope

The project was undertaken to examine a novel approach to utilising solar energy, using a chemical reaction to embed solar energy into a traditional fuel, thereby reducing the amount of traditional fuel required. This approach has several advantages**:**

- It enables the use of traditional power generating technology; in this case gas turbine based combined cycles. These have over 100 years of development and are in operation worldwide;
- Continuous operating potential; the turbine is able to combust a wide range of fuel from the solarised fuel to the regular natural gas and blends between the gas turbine;
- The system is able to run 24 hours a day, every day of the year; and
- Full utilisation of the solar, as the turbine always is spinning, and the solar system can be fully utilised without the need to wait for the turbine to warm up or get up to speed.

While the CSIRO has developed and tested suitable solar reactor systems and GE has experience in turbine operations, this project required a large step-up in scale for the solar component, with GE to closely look at the operational impacts of such a combustion system.

The project established a design for the solar component, including laying out a field of heliostats to enable the concentration of solar energy to a single point in the sky. At this point a receiver was designed to accept the concentrated solar radiation. The receiver, operating at close to 900^0C, contains the reactor system that converts the natural gas to a solar boosted fuel.

The next stage was to analyse GE's range of turbines to identify the most suitable. Engineers at GE's Global Research Centre began a detailed examination of the impact of burning the solarised fuel during the day and normal natural gas during the night. They took into account reliability, flame stability and the impact the varying fuel had on the emissions from the turbine.

The project addressed a number of challenges in building a solar thermal reformer which can be attributed to the following major novel differences for this solar reformer compared to a conventional reformer. These are:

1. Thermal cycling caused by intermittent daily operation as opposed to continuous around the clock operation;
2. Uneven tube wall heating;
3. Catalyst position and lifetime; and
4. The reformer tubes are exposed to air at elevated temperatures.

Outcomes

The project successfully developed a new solar steam reformer system suitable to convert natural gas to a solar enhanced fuel gas. The new reactor design is able to embed 15MW of solar thermal energy into the fuel gas, thereby reducing the amount of natural gas used for the same amount of electricity out. The solarised fuel gas changes chemical composition with the solar input, with regular natural gas making up any shortfall. This can be seen in figure 2 below, the black line showing the solar radiance or direct normal insolation (DNI) and the coloured regions showing the changing chemical composition.

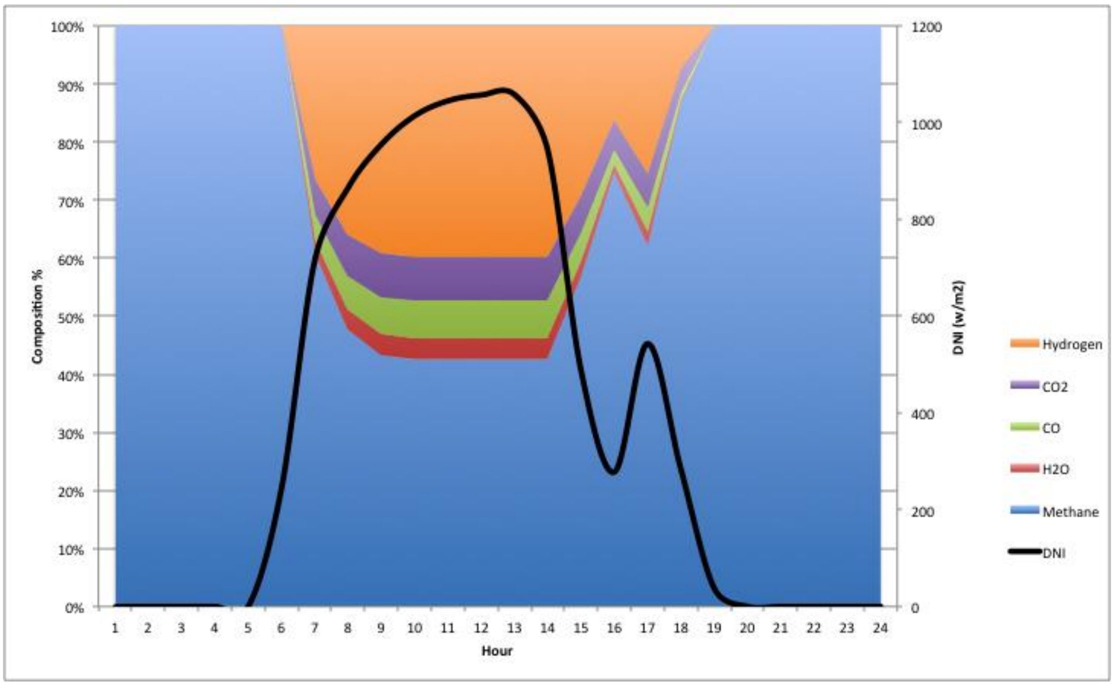


Figure 2 Changing Composition of the fuel gas over a 24 hour period, with Solar input (w/m2) on the RHS axis

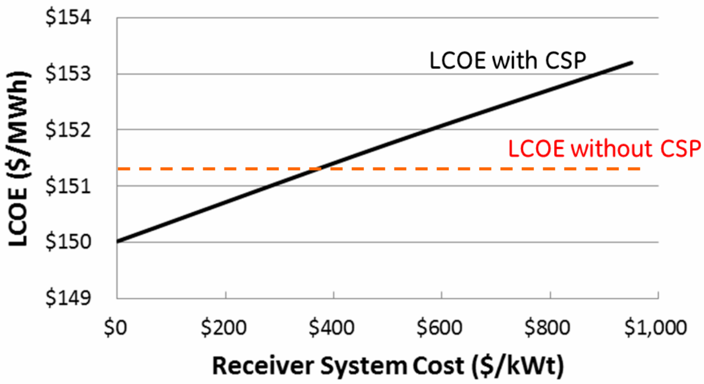
Based on CSIRO's transient simulations of the solar field, receiver, and Balance of Plant (BOP), the annual solar capacity factor at a solar multiple of 1.2 is found to be 30.63%. Using an overall gas turbine annual capacity factor of 90%, the results of the simulations are shown in the Table 1 below. The results show the addition of a solar thermal steam reformer increases efficiency with a corresponding decrease in CO_2 emissions.

Table 1 Summary of performance with and without a CSP system.

							Annual Averages				
	Nominal Rating (MWe)	Absorbed Solar (MWt)	Fuel MWI	Peak Output (MWe)	Nat Gas Use (GJ)	AEP (GWhe)	Heat Rate (kJ/kWh LHV)	Nat Gas Efficiency	CO2 Rate (kg/MWh)	Water (m3/MWh)	NOx (mg/Nm3 @15%O2)
206B	99.48	0	42.3	99.5	6030.6	784	7689	46.8%	445	0.03	31
+ Solar		13.1	33.6	101.2	5988.9	789	7591	47.4%	439	0.04	31
DELTA w/Solar				**1.8%**	**-0.7%**	**0.6%**	**-1.3%**	**0.6%**	**-1.3%**	**59.5%**	**0.0%**

Sensitivity analysis for cost of the system, with a cost neutral position being $400/kWt, is shown in Table 2 below.

Table 2 Sensitivity analysis for the cost of the solar thermal system.



The estimated cost of the system, specifically a first of kind in remote Western Australia, has the solar thermal system at $948/kWt. However looking at the breakdown of the costs of that system, almost half are attributed to the cost of the tower system. The tower design report suggests that the cost of the tower is high due to the remote location. If the site had access to a suitable crane, cost reductions could be achieved.

Two key areas that need to be addressed:

- Customers (e.g. Mining companies) will seek the most reliable and proven technology for non-core business. In this case electricity is a critical input to the business of processing ores for export.
- The technology has higher capital cost for a small abatement of CO_2.

The first point is a difficulty any new technology will face. In this case the project addressed this risk by enabling a true hybrid design. GE GRC spent considerable effort with their combustion engineers to select the correct turbine that could seamlessly move from a natural gas fuel to a hydrogen rich fuel, and in the process identified new barriers that limited the integration potential of solar thermal energy into the power generation process, such as wobbe index and NOx emission limits.

The lower than expected carbon dioxide emission reductions are the result of the limits that these new barriers introduce. These effectively capped the allowable contribution that the solar thermal system could make. In order to boost the emission reductions one possible path would be to introduce a SOLARGAS storage system, “a pressure vessel”, allowing the Combined cycle power generation system to operate on SOLARGAS 24hr/day, enabling the annual emission reductions to approach the maximum daily value of greater than 20%. This could be achieved with an increase in the capital cost of the solar system and relies on a value of carbon offset to be introduced.

Transferability

The commercial assessment performed by GE Australia has highlighted a number of barriers to taking the project to the next stage. The market for power generation has not developed as predicted when the project was first proposed. The hybrid nature of the fuel and solar has operation limits in the turbine combustor (Wobbe index and NOx Emissions) resulting in minimal savings in CO_2 emissions. There are also factors associated with introduction of new technology and the risk burden they present to a mining customer.

The high level economic analysis of adding a solar steam reformer results in a 0.3% increase in LCOE over a standard combined cycle system, based on this turbine. Given the assumptions in this analysis, the LCOE can be considered unaffected by the addition of the solar thermal steam reformer. An annual drop in CO_2 Emissions of 1.3% has been predicted.

The low impact of the solar thermal system has two main drivers, (1) the limitation within the combustion system to burn large amounts of solar fuel, and (2) the lack of suitable storage to enable the solar fuel to be produced during sunlight hours while being burned continuously.

The assessment by GE Australia highlighted the following barriers:

- Proven technology with long demonstration of operation has typically been used to meet requirements, as it offers security and reliability above all else.
- There is no reason to alter the current power generation mix – including augmentation or improvement – and especially not using ‘speculative’ technology.
- For the most part, except for utilities, customers core business is not power generation.
- Increasing the complexity of power generation assets is highly unappealing to potential partners
- The addition of more moving parts, including changing gas supplies twice per day, increases risk of failure in the system.

The steam reforming reactor system does have a positive outlook outside of this project, with opportunities in other applications currently being developed. These projects will utilise the unique design of the reformer from this project to boost production in large hydrogen facilities. The patented design technique has application to any high temperature solar thermal process.

Conclusion and next steps

The project has demonstrated that hybridisation of power generation with a solar thermochemical process is achievable, with technical challenges addressed.

However, the scale up of solar thermal processes needs to be taken in a stage-wise fashion. The reforming technology that was the key to this project was demonstrated at 600kW scale, however the combined jump to 15MW and regular daily operation was highlighted as too high on the risk-scale for a power generation facility. It should be noted that power is only one application of steam reforming and opportunities exist for use of the same reactor system in the production of hydrogen and the development of other solar fuel products.