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ARENA

Advanced Steam Generating Receivers for High-Concentration Solar Collectors
Final report: project results

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Executive Summary

The project is a detailed investigation into steam generation using solar thermal technology. High pressure and temperature steam drive the majority of the world's electricity producing turbines and the development of technology suitable for implementation into solar thermal systems is critical to the continued uptake of concentrating solar thermal power technology.

This project achieved steam conditions comparable to state-of-the-art fossil-fuelled power stations, using large scale Concentrating Solar thermal Power (CSP) stations, something that has not been achieved in all other commercial CSP plants in the world today. This represents a world record for the combined temperature and pressure of steam using solar thermal technology.

The project successfully demonstrated that significant reductions in the capital costs of the system can be achieved through higher thermal efficiencies and a resulting reduction in the total area of the solar collector required.

At the time of project conception, commercial concentrating solar-based steam power systems had a thermal efficiency below 30% (in the conversion of solar energy to electricity). Using steam at higher temperatures and pressures increases the thermal efficiency, meaning that for the same amount of collected solar energy you can produce more electricity. Typical subcritical power stations have thermal efficiencies of approximately 35%, while supercritical power cycles can have thermal efficiencies above 40%. This means that if a concentrating solar thermal power station could operate with supercritical steam the electricity output could be boosted by 20-30%, providing a substantial increase in sellable electricity for the same capital investment, resulting in a significant reduction in Levelised Cost of Energy (LCOE) against the current concentrating solar power stations.

This work also showed that geothermal sources were unsuitable for use in a steam power system designed to operate at the temperatures and pressure comparable to traditional fossil fuelled power stations, due to the low pressure of the steam able to be generated.

Hybridising with other solar technologies was also examined; these showed more promise with estimated LCOE values of between 20-25c/kWh.

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Project Overview

Project summary

The project is a detailed investigation into steam generation using solar thermal technology. High pressure and temperature steam drive the majority of the world's electricity producing turbines and the development of technology suitable for implementation into solar thermal systems is critical to the continued uptake of concentrating solar thermal power technology.

The project was broken into 4 streams of research ensuring a complete system analysis could be undertaken. The first stream was focused on the development and demonstration of steam receivers suitable for current turbine technology and advanced supercritical turbines. The second stream looked at specific applications of superheating steam receivers to address whether solar thermal systems could be improved by innovative hybridisation with other thermal heat sources. The third stream was focused on the development of modelling tools to guide the experimental programs and the fourth stream looked at how high temperature steam could be generated using a unique thermal storage system.

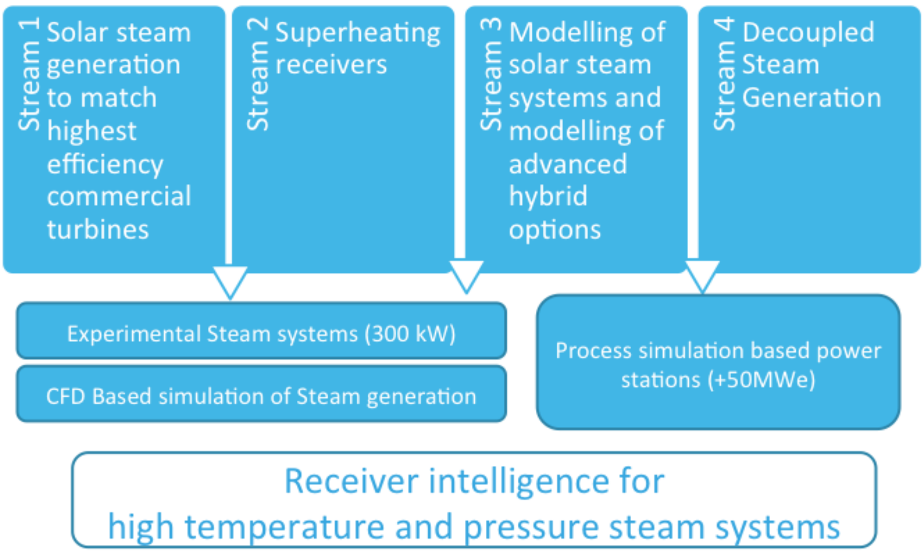

Figure 1. Advanced steam receiver project structure.

Activities within stream one featured the design and experimental examination of steam generation from a concentrating solar thermal field. Steam is used to generate 90% of the world electricity and when at high pressures and temperatures contains large amounts of stored energy. As a result, the design of the experimental system was required to meet high standards of safety. This resulted in significant challenges in sourcing key components and materials required to construct the system. The system components were designed to accept 300kWt of solar thermal energy, enabling large-scale models of heat transfer to be confirmed. These experimental findings are suitable for scaling to commercial scale systems, as the mass fluxes were selected to be the same as what is found in industrial boiler tubes.

The key outcome from this stage of the work was to achieve steam conditions comparable to state-of-the-art fossil-fuelled power stations. These fall in into two distinct categories; subcritical and supercritical steam. Subcritical steam represents the bulk of current fossil power stations and is characterised by temperature of 540°C and pressures from 12-18MPa. All of the current concentrating solar thermal power stations in the world operate in the subcritical range, usually with lower temperatures and pressures at the lower end of the operating range. This experimental program targeted steam production at 540°C and 17MPa, higher than all other commercial CSP plants in the world today.

Supercritical [1]steam exists at pressures and temperatures above the critical point, therefore supercritical steam has unique properties that enable vastly simpler boiler layouts, as the conversion of water to supercritical steam doesn't pass through a distinct "boiling" zone. Power generated using supercritical steam achieves higher thermal efficiencies than subcritical systems; this is seen as advantageous to solar thermal systems as the area of the solar collectors can be reduced and subsequently lower capital costs of the system. The target conditions for supercritical steam were 23MPa and 570°C; this represents the highest energy steam produced using concentrating solar thermal anywhere in the world.

Activities in stream 2, where initially focused on development of models to represent a solar thermal tower system superheating saturated steam. These models where then coupled to a variety of "boilers" such as solar trough systems, solar linear Fresnel systems, and geothermal sources. The basis for this is that tower systems are capable of producing high quality steam and, when coupled with a lower cost and lower temperature system, a cheaper solution to power systems could be developed. In parallel with these activities a steam superheater design was developed and tested. This was again at an operating duty of 300kWt.

Outcomes from this work showed that geothermal sources were unsuitable for use in a steam power system designed to operate at the temperatures and pressure comparable to traditional fossil fuelled power stations. The maximum pressure of saturated steam able to be generated was limited to approximately 2-2.5MPa, resulting in a non-optimal system when connected to a solar thermal tower system with a superheater. Geothermal systems remain best suited to organic Rankine and mixed fluid cycles that operate with more volatile fluids than water. Hybridising with other solar technologies were examined, these showed more promise with estimated LCOE values of between 20-25c/kWh. The true values are very much the development of near future technologies for deployment, as this will provide both firmer cost predictions and realise cost reductions through learning from the experiences of an operating plant. In the experimental field; a superheater was demonstrated at the target conditions of 540°C and 17MPa. This 300kWt system was also operated with a gas power boiler on the ground, in the same way that a hybrid system could be developed.

Stream 3 was focused on the development of models to examine the current and future performance of large-scale concentrating solar thermal power systems. IPSEpro, a commercial power turbine simulation package was selected as the basis for the models. Models where developed for a range of solar systems including subcritical and supercritical direct steam towers as well as molten salt towers.

[1] A supercritical fluid is any substance at a temperature and pressure above its critical point, where distinct liquid and gas phases do not exist. It can effuse through solids like a gas, and dissolve materials like a liquid.

Stream 4 developed a solution for interfacing steam generation with a unique thermal storage solution, using a gaseous heat transfer fluid with a solid thermal storage bed. The steam generation in this application utilised a modified shell and tube heat exchanger to transfer energy from the heat transfer fluid to the water/steam system. This system is able to generate steam at 10 MPa and up to 650°C.

Project scope

The project was undertaken to show that concentrated solar thermal energy was capable of producing steam at conditions equivalent to modern fossil-fuelled boilers. The majority of power stations in Australia operate with steam turbine conditions of 540°C, and pressures between 14-17MPa, there are only 4 examples of supercritical power stations in Australia, with these operating at conditions above the critical point of water, typically 565-600°C and pressures from 23-25MPa.

At the time of project conception, commercial concentrating solar-based steam power systems were either based on trough or tower systems producing saturated steam at pressures of approximately 10 MPa and temperatures between 250-350°C. These conditions limit the thermal efficiency of the conversion of solar energy to electricity to below 30%. Using steam at higher temperatures and pressures increases the thermal efficiency, meaning that for the same amount of collected solar energy you can produce more electricity. Typical subcritical power stations have thermal efficiencies of approximately 35%, while supercritical power cycles can have thermal efficiencies above 40%. This means that if a concentrating solar thermal power station could operate with supercritical steam, the electricity output could be boosted by 20-30%, or a substantial increase in sellable electricity for the same capital investment, resulting in a significant reduction in LCOE against the current concentrating solar power stations.

The main barrier to moving to higher operating conditions is the materials that form the solar receiver. The solar receiver is the area where the focused solar thermal energy is targeted, and consists of high quality steel tubing that has been designed to withstand the thermal stresses from operating under these conditions. In the case of traditional fossil fuelled boiler, these tubes are subjected to tightly controlled heat fluxes, which enable continuous operation over many years. In the solar scenario, the tubes are subjected to changing conditions, as the sun moves through the day and through cycling overnight back to ambient temperatures, additionally the tubes are exposed to the elements and air can result in faster corrosion.

The project addressed these challenges through a number of ways;

- Development of heat transfer models to predict how the steam is generated given a thermal input.
- Adopting a once through boiler design. Traditional boilers separate the boiler area from the area where the steam is superheated to the maximum operating temperature. Using a once through boiler eliminates the steam drum, however requires constant adjustment of how heat is applied. This was enabled by the CSIRO heliostat control system.
- With the unique CSIRO heliostat technology these heliostats are a fraction of the size of current heliostats and, when combined with CSIRO-developed control methods, enables very fine control of the concentrated solar energy. This resulted in the project running much closer to the design limits of the materials.

Outcomes

The project successfully demonstrated through development of thermodynamics models of large-scale CSP stations that significant reductions in LCOE can be achieved by moving operation of CSP to higher temperatures and pressures. Additionally, the project has shown that using once through boiler designs is suitable in concentrating solar thermal receivers.

The experimental program achieved world leading results, highlighted by the supercritical steam system operating at world record conditions for a solar thermal concentrator.

- Subcritical steam generation at pressures from 0.1 MPa to 17MPa and temperatures of 580°C, with flows of 316kg/hr collecting 310 kWt of solar thermal energy
- Supercritical steam generation at pressures from 22.5MPa to 23.5MPa and temperatures of 570°C, with flows of 334kg/hr collecting 309 kWt of solar thermal energy. **This represents a world record for the combined temperature and pressure of steam using solar thermal technology.**
- Superheater steam generation at pressures from 0.1 MPa to 17.6MPa and temperatures of 552°C, with flows of 1152kg/hr collecting 281k Wt of solar thermal energy.

Figure 2 Subcritical steam generation at the CSIRO Newcastle

By completing these experiments CSIRO has demonstrated that once-through boiler designs are suitable for solar thermal systems operating over a wide range of operating conditions. The ability of the CSIRO control system, with small heliostats to customise the solar flux pattern on the receiver, is pivotal to achieving the supercritical operating conditions. The experiments were designed in such way that the mass fluxes during the experiments were comparable to those expected in a large-scale design.

With the success in demonstrating that these conditions are technically achievable, further work now needs to be undertaken to demonstrate that robustness of the material of construction to prove that are able to withstand the operating conditions and daily cycling from ambient to full power.

The critical Intellectual Property to achieve these outcomes lies in the development of the heliostat control systems, which allows fine adjustments to the heat flux to the receiver. This is covered by a number of patents. Additionally there has been significant knowledge gained in the design and operation of these high temperature receivers, as CSIRO have made advances in preparation and joining of new materials suitable for solar thermal applications.

The achievement of supercritical steam conditions was a world first and will be used as the base for a large number of peer reviewed journals, conferences and public dissemination activities. There have already been a number of conference presentations on early outcomes of the project covering modelling and experimental design.

Transferability

The project was executed by CSIRO with funding from ARENA and Abengoa Solar. The relationship with Abengoa Solar has been strengthened through this project and new joint projects are underway or in development.

The achievement of world record steam conditions has received a large volume of media attention on the project, and highlighted the work ongoing at the CSIRO in Newcastle. The suite of CSIRO heliostat and control technologies was critical to this success and this achievement is a great advertisement for that capability.

As the first specific solar steam project in Australia, the project has also attracted unexpected interest from a number of Small Medium Enterprises in regional Australia. These enterprises had seen the costs of generating steam escalating with increasing fuel costs. The enterprises, typically running batch operations, are ideally suited to small solar trough concentrator systems. The project was able to highlight that solar generated steam is a possible solution and provide general advice towards these types of steam systems.

Conclusion and next steps

The project has shown that producing steam conditions equal to that which is generated in a fossil-fuelled boiler is achievable across a wide range of conditions including subcritical and supercritical power cycles. These results were achieved by coupling CSIRO's unique heliostats and control systems to a well-engineered setup and careful experimental design. Furthermore modelling within the project has shown that costs for systems based on these steam conditions should fall within LCOE values of 20-25c/kWh. These values represent the benefits of the improved thermal efficiency from operating at higher temperatures and current estimates of component costs. Critical to achieving these in real installations are incorporating learning benefits from recently commissioned plants in the USA (Ivanpah) where cost savings where achieved in manufacturing from construction of tower 1 through to tower 3. In order to meet more aggressive targets such as those from the USA Sunshot initiative or the Australian Solar Thermal Research Initiative continued deployment is critical as well as successful ongoing operation of existing CSP plants.

In order to realise these outcomes future work needs to focus on receiver materials, while this project has demonstrated that materials exist that are suitable for experimentation, continued work needs to be completed to ensure that the receiver materials are able to withstand daily thermal cycles and exposure to atmospheric conditions.