ASI funded Solar Thermal Storage and Steam Programs at the CSIRO and ANU

R. McNaughton[1], R. Benito[1], G Burgess[2], G.J. Duffy[1], J.H. Edwards[1], J.S. Kim[1], K Lovegrove[2], J Pye[2], and W. Stein[1]

[1]CSIRO Energy Technology
10 Murray Dwyer Circuit Mayfield West NSW 2304 Australia
Robbie.Mcnaughton@csiro.au
[2]Department of Engineering, Australian National University, Canberra, ACT 0200, Australia

ABSTRACT

The use of concentrated solar thermal energy for the production of electricity has been achieved commercially with the generation of steam in trough or tower concentrating systems. More recently, solar power stations such as the AndaSol 1 have also included 1,010 MW·h of heat storage, enough to run the turbine for about 7.5 hours at full-load. The thermal storage in the AnderSol 1 solar power station is a molten salt mixture of 60% sodium nitrate and 40% potassium nitrate that is stored in large insulated tanks at temperatures up to 380 º C.

These first generation commercial systems have some limitations in their operation when compared to state of the art fossil fuelled generators; the most significant of these is the temperature and pressure of the resultant steam that is generated and the types of steam turbines that can be utilised. Other major limitations are the ability of the solar system to produce a consistent steam quality required for operation of a steam turbine, and the upper temperature limit that molten salt can be safely stored before it begins to decompose.

The CSIRO and Australian National University (ANU) have recently begun two Australian Solar Institute (ASI) funded projects, one looking at development of high temperature thermal storage systems, and a second investigating techniques for the generation of high pressure and temperature steam. These projects will be undertaken over the next three years.

The high temperature thermal storage project will examine a wide range of techniques, fluids, materials and process designs that will enable the storage of solar thermal heat at temperatures beyond the limitations of the salts used in current solar power generation facilities.

The advanced steam generation project will address the challenges of producing steam at the conditions required to couple solar thermal with state of the art power generation turbines, and through the use of storage technologies enable production of reliable, consistent and high quality steam.

This paper outlines the research directions and the areas of focus of the two projects.

Keywords — solar, concentrating solar, CSP, steam, storage

Introduction

The Australian Solar Institute has recently approved support for two projects to enable the development of critical solar thermal technologies that can make substantial advancements in the ability of solar thermal systems to produce clean reliable electricity.

The projects involve the storage of the heat produced by concentrating solar energy and the conversion of the heat to electricity via the production of steam.

The projects have many areas of interaction.

The thermal storage project

Cost-effective thermal storage systems are required for solar thermal energy to make a significant contribution to Australia's electricity generating sector and to supply the energy requirements of its energy-intensive industries. Such storage systems are required to accommodate periods of cloud cover, overnight operation and, in the case of electricity generation, meet peak power needs that occur outside the hours of maximum insolation rates. In doing so, thermal storage removes many of the intermittent characteristics of solar electricity generation, improves its dispatchability, thereby increasing its level of contribution to total electricity supply.

About half the cost of a solar central tower power generation system is associated with the heliostat field that focuses sunlight on the high temperature receiver located on the tower. The remainder of the cost is associated with absorbing the heat and converting it into electricity. The heliostat system is almost independent of the power conversion technology and thus improvements in power conversion efficiency through the use of higher temperature steam cycles can have a major impact on total power plant costs per unit of electricity generated.

Most electricity generation technologies are based on the Carnot thermodynamic cycle (eg. Brayton gas turbine and Rankine steam cycles) and their theoretical thermal efficiencies increase with increasing the inlet or peak temperature at which the cycle operates. As demonstrated in large solar applications overseas (e.g. Solar One, Solar Two and SEGS and most recently Andasol 1), solar thermal energy storage technologies can provide a continuous supply of high grade, high temperature energy for electricity generation, although the reliability of such systems has been problematic. New solar plants for electricity generation are now also being developed or under construction overseas (e.g. Solar Tres) to implement improvements to earlier designs, but with conventional molten nitrate salts these are restricted to maximum storage temperatures of 565^{o}C, which limits the maximum temperature of the steam produced to 538^{o}C, typical of coal-fired subcritical plants. However, new steam-based power generation technology has advanced to the use of supercritical (566^{o}C) and ultra-supercritical (605^{o}C) steam cycles, as these higher steam temperatures result in higher thermodynamic efficiency. If solar thermal power generation plants are to take advantage of such developments, maintain their compatibility with existing fossil fuel-fired plants and to generate power when the sun is not available there is a need for solar thermal storage systems that can operate well above 565^{o}C.

To date the highest temperature thermal storage systems have used nitrate salts. However, with conventional molten nitrate salts the maximum storage temperature is around 565^{o}C, which limits the maximum temperature of the steam produced to 538^{o}C and thus restricts the options for power generation to the use of lower efficiency subcritical steam cycles. There is a need to look at means of increasing the storage temperature for the solar energy collected to around 750°C to make possible the use of thermodynamic cycles that operate at higher temperatures and achieve higher efficiencies, hence increasing the power output per unit of capital invested.

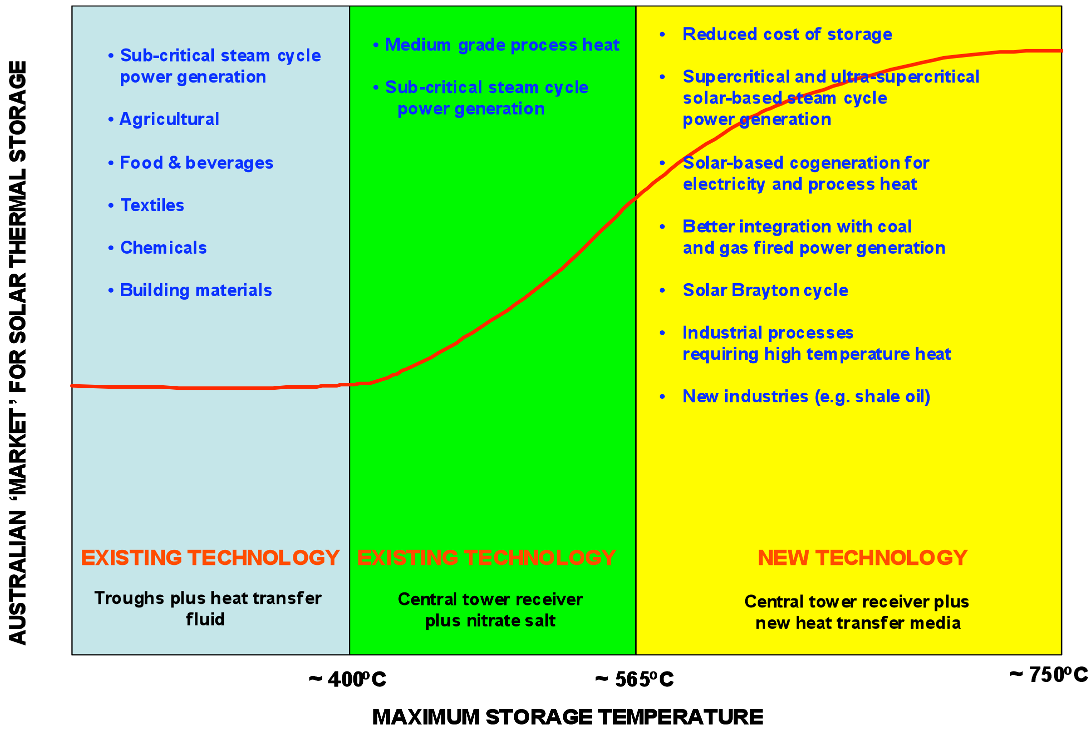

Figure 1 – Benefits of existing and new solar thermal energy storage technologies

This storage project will therefore identify, develop and demonstrate solar thermal energy storage technologies that can operate at as high a temperature as can be reliably achieved (up to 750°C) in order to encourage the widespread use of solar thermal energy by Australian industry and make possible some of the benefits shown in Figure 1.

An important aspect of this project will be to show proof-of-concept of the integration of a solar thermal storage system with a solar energy concentrator/receiver facility to store high grade heat that can be subsequently used on demand by electricity generators and industrial processes relevant to the Australian situation. While new molten salts such as fluorides and fluoroborates will be investigated, other processes utilising gases or solids as the heat transfer media will also be considered. Integration of the heat transfer medium with storage media, such as graphite blocks or other suitable solids or phase change materials, will also be investigated. Results from this phase of the project will then lead to a decision on the type of solar thermal storage loop to be constructed for integration with CSIRO's central tower facility at Newcastle.

Outcomes from this project will be quantification of the potential for integrating solar thermal storage with Australian electricity generation and industrial processes, development of a system that can store solar thermal energy at temperatures up to 750°C, proof-of-concept performance assessment of the optimized storage system under real solar conditions and development of the paths to commercialization for most prospective applications of this technology in Australia. This project will obviously have a strong link to the steam generation project and will play a crucial role in ensuring the early uptake of solar thermal technologies by Australian industry.

The steam generation project

Rankine cycle power generation is the basis of the production for the majority of the world's electricity normally with thermal energy supply from either coal , oil or nuclear sources. There is a natural fit with CST technology and consequently by far the bulk of commercial CST activity and plant construction uses steam Rankine cycles. This link is a major enabling factor that should allow the level of installed capacity in CST power generation to grow extremely fast. Many of the systems currently being installed use Rankine cycle systems that are less efficient than might otherwise be the case due to the use of steam of limited pressure and temperature. This is a limitation of the linear reflector, whether trough or Fresnel, and the use of oil as the heat transfer medium, mandated by the difficulties of a two-phase fluid over long receiver lengths. Given the high capital cost associated with the collector field, a power conversion efficiency improvement afforded by higher temperature steam means less cost associated with the oil system, less required mirror area and subsequent reduction in levelised energy cost of the output.

The advanced steam project has identified four areas to address:

- To maximise the efficiency of solar receiver systems that produce superheated steam for Rankine cycle power generation
- To produce optimal combinations of heat source and steam temperature such that linear concentrators or geothermal heat sources can be complemented by high concentration collectors.
- To match steam from CST systems to the highest efficiency turbines available.
- To explore the possibility of integrating other energy conversion cycles to produce a higher efficiency combined cycle system, without compromising the reliability of the Rankine cycle approach.

The project will test Steam receivers designed to match the highest efficiency commercial turbines, including supercritical steam turbines (ie more advanced Rankine cycles such as those in the coal-fired power stations most recently deployed in Queensland). It will also test the concept of developing superheating receivers and associated systems suitable for increasing the temperature and efficiency of low temperature thermal technologies such as linear Fresnel or geothermal to above 500°C. Going beyond this the technical and economic feasibility of adding Thermoelectric generating elements to receiver tubes for additional electricity production will be investigated.

The optical, material and heat transfer principles associated with the development of high temperature solar steam generation will translate to most other CST technologies and as such this project can also form a backbone for future CST work.

Strategies for the thermal energy storage project

The objectives for this project are :

1. To assess the Australian market potential for solar thermal energy storage systems that can supply heat at appropriate temperatures (up to 750°C) for both power generation and industrial process applications on a dispatchable basis.

2. To identify suitable heat transfer and storage media for operation at temperatures required in applications identified in Objective 1.
3. To design a solar thermal energy storage system to meet the requirements determined in Objectives 1 and 2.
4. To design receiver systems for tower and dish concentrators suitable for transferring solar energy to the heat transfer medium at temperatures up to 750^{o}C.
5. To construct and operate a proof-of-concept solar thermal energy storage loop, integrated with one of CSIRO's Newcastle solar concentrating field/tower facilities.
6. In conjunction with the steam generation project to evaluate methods for heat recovery from the solar thermal energy storage system.

The strategies to achieve these objectives involve the following activities:

1. A study evaluating the requirements for process heat in Australian industries.

   This will involve identification of the geographic distribution of energy-intensive Australian industries, both current and future (e.g. oil shale processing) and for each significant industrial site, quantification of the demand for process heat, it will include assessment of on-site daily, seasonal and annual insolation rates and other issues (e.g. land availability) to determine the potential for co-locating solar thermal generation adjacent to the industrial site. Economic and systems modelling studies will be carried out to quantify the benefits that solar thermal storage can have on increasing the market penetration of solar thermal energy in Australia. This would include quantifying the curve shown in Figure 1.
2. Identification of the most appropriate heat transfer and storage media suitable for the applications

   From our review of the literature to date on thermal storage it is clear that each of the basic types of thermal storage (sensible heat, latent heat and thermochemical) has its own advantages and limitations. However, what is not yet clear is which one has the best potential for extending the upper storage temperature limit from its current level of 565^{o}C to something approaching 750^{o}C.

   Preparation and characterisation of the preferred heat transfer and storage media in the laboratory will be performed to determine operating envelopes as will the assessment of the impact of such media on the selection of the materials of construction of heat transfer loops and containment vessels. Various system configurations will be simulated using a range of heat transfer and storage media to establish the optimum system that can proceed to detailed design. The design study will be guided by previous CSIRO experience in reactor and heat exchanger design using computational fluid dynamics (CFD) and finite element analysis (FEA).
3. Design of solar receiver systems for tower and dish concentrators unit for the effective collection and transfer of solar energy to the heat transfer medium

   The designs will be guided by previous CSIRO experience in reactor and heat exchanger design using CFD and FEA. Control strategies will need to be developed to link control of receiver temperature with the heliostat operating system.
4. Construction and operation of the solar thermal energy storage system fully integrated with the solar thermal concentrating facility at Newcastle

   This will see the construction of a facility with a storage capacity of around 750 kWh. This stored heat will then be used within the steam project to generate high temperature and pressure steam that can drive a steam turbine.

Strategies for advanced steam generation project

The broad objective of this project is to develop high temperature (>540°C) steam generating solar receivers that maximise the efficiency and cost performance of solar towers or distributed dish systems in the near to medium term.

Each case below incorporates the development and assessment of the receiver in the context of overall plant thermo-economic performance. It is not the intention to develop receivers in isolation.

The specific objectives are:

1. Steam receivers with outputs to match highest efficiency commercial turbines
2. Superheating steam receivers
3. Thermo-economic of solar steam systems
4. Feasibility studies of hybrid steam/thermoelectric receivers

Objective 1

Conventional Rankine cycles have used subcritical steam conditions and this remains the receiver which would be most readily developed under this project. However these steam conditions are still 540°C and 16MPa at the turbine inlet (so higher at the receiver) and no commercial solar plants are operating at this condition in the world. State of the art large scale Rankine cycle power generation utilises supercritical steam for the highest possible conversion efficiencies. This means steam at over 22.5MPa, with temperatures up to 600^{o}C or higher. Under these conditions water does not “boil” in the traditional sense, rather the distinction between liquid and gas is progressive. These temperatures and pressures have been explored in solar receivers in the course of previous work. High strength nickel alloys are required and new approaches to construction geometry must be developed.

Specific strategies to address the first objective will be:

- Establish methods for design and performance modelling of steam receivers and confirm their validity against experimental data
- Develop and test high efficiency receivers for once through to superheat operation at pressures in excess of 10MPa for large dish or tower concentrators. This may include subcritical and supercritical.
    - Review of steam turbines on the market in terms of their allowable inlet condition parameters and subsequent impact on receiver design, including transient temperatures, start-up and shut-down and combination solar/coal –fired operation. This will provide the boundary conditions for receiver design.
    - Assessment of boiler materials - allowable creep/fatigue life, radiant flux, heat transfer, and temperature excursion. This invokes the real-world limitation of available materials, and will investigate more novel possibilities.
    - Consideration of above in relation to recirculation and once-through-type boilers and selection of preferred design/s. Both types of receivers are technically feasible for subcritical, and only once through for supercritical. Both offer various advantages in relation to operational control and cost. These will be assessed in relation to dish and tower systems.

- Use proven models to explore performance of possible geometric arrangements
- Use proven transient models to examine the tradeoffs associated with increased receiver thermal mass

Objective 2

The value of high concentration systems such as dishes and towers lies in their ability to convert energy at higher temperatures than linear concentrators. Consequently in the context of steam based conversion, the feedwater heating and boiling stages underutilise their potential. Other sources such as Geothermal HDR heat or linear concentrators can effectively provide the lower temperatures in bulk. The motivation for consideration of superheat only receivers is the high exergy value gained from introducing only a small level of energy, but at high temperature. The information gained from the once through receivers will be the starting point for these investigations.

Specific strategies anticipated are:

- Determine the most appropriate operating parameters for a receiver designed to superheat saturated steam produced by other sources.
    - Conduct a review in three areas that will provide the design parameters for a superheat steam receiver:
        1. linear reflectors
        2. geothermal technologies
        3. complete system models
    - Construct and test receiver including a front-end system capable of emulating the condition that would be provided by the linear reflector or geothermal heat source in practice.
- Develop and test a receiver system for large dish concentrators suitable for superheating at the required pressures and to > 500°C the saturated steam produced by other lower temperature thermal systems for both dish an tower concentrators
    - Use proven models to explore performance of possible geometric arrangements and transient models to examine the tradeoffs associated with increased receiver thermal mass
    - Model the thermodynamics of integration of the two systems in terms of controlling variable pressure drop, flows and temperatures at the inlet to the superheater.
    - Optimise design including geometry and aperture and complete structural analysis and technical drawings
    - Fabricate, including full instrumentation. Consider use of superheated steam outlet with heat exchanger to simulate the variable low temperature inlet.
    - Test, analyse data, verify and calibrate models.

Objective 3

Each of the receivers above will exhibit different characteristics in relation to operation of large-scale systems. Past steam generation projects in Australia have exhibited issues with aggregation of steam from multiple point sources. This stream will develop a combined thermodynamic and economic model of complete systems for towers and dishes. This will allow optimisation of tower size vs steam transport path to be conducted.

- Complete analysis of the superheat receiver and thermo-economic modelling in conjunction with industry developers of the low temperature technology.
- Modelling and annual thermo-economic assessment of a supercritical receiver in a complete system and analysis of any refinements that might be recommended.

Objective 4

The intention of this stream is to conduct high level modelling of the potential for thermoelectric devices incorporated into steam receivers. This will provide the framework for another project where devices will be developed, fabricated and tested on sun at small scale.

- Assess the technical and economic feasibility of improving system performance of steam receivers by incorporating thermo-electric elements.
- Provide feedback to researchers working on device development and fabrication in other projects.

Concluding remarks

Over the next 3 years these two projects will develop and demonstrate technologies that will enable solar thermal to be a realistic option for the production on solar thermal based electricity in both the peaking and baseload markets for Australia.

The high temperature thermal storage project will examine a wide range of techniques, fluids, materials and process designs that will enable the storage of solar thermal heat at temperatures beyond the limitations of the salts used in current solar power generation facilities.

The advanced steam generation project will address the challenges of producing steam at the conditions required to couple solar thermal with state of the art power generation turbines, and through the use of storage technologies enable production of reliable, consistent and high quality steam.

Together these projects address the critical issues to allow deployment of solar thermal power in Australia.

This project has been supported by the Australian Government through the Australian Solar Institute (ASI), part of the Clean Energy Initiative. The Australian Government, through the ASI, is supporting Australian research and development in solar photovoltaic and solar thermal technologies to help solar power become cost competitive with other energy sources."