



2-A015 Development of a Thermoelectric Generator for Application in a CST Topping Cycle

Final report: project results

Lead organisation: Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Project commencement date: 1 March 2011 **Completion date:** 12 January 2015

Date published: 12 January 2015

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Executive Summary

The project aims to investigate the combination of a medium temperature thermoelectric generator with an absorption chiller in a concentrated solar thermal system. Thermoelectrics are materials which can generate electrical power when exposed to a thermal gradient, and absorption chillers produce chilled air from a thermal source, in this case water superheated to 180°C. The two technologies have been combined so that the thermoelectric generator (TEG) is heated on one face to greater than 400 °C by solar radiation concentrated at 200x with a parabolic mirror, and cooled on the opposite face by flowing superheated water which is fed to the absorption chiller. This configuration is envisaged to be useful in a variety of applications including remote communities without grid power operating as a Stand-alone Solar Cooling System (SASCS). A complete test bed was constructed and operated at the CSIRO Energy Centre. The system consists of two 15 m² solar concentrating dishes with cavity receivers and a 10 kW absorption chiller.

The technologies required for this system were developed under three tasks: (1) The development and process scale up of improved ceramic oxide thermoelectric materials, (2) The design and construction of cavity receivers which incorporated medium temperature TEGs, and (3) Design, construction and operation of the SASCS test bed.

The development of improved thermoelectric materials focused on ceramic oxides due to their stability in air. The research led to some improvements in the performance of both CaMnO₃ and Ca₃Co₄O₉. However, the overall thermal-to-electrical efficiency is seen as limited to around 3.5% which may limit the applicability of these materials, such that higher-performing and more expensive materials which would also require a protective atmosphere may be required to provide the necessary efficiency.

Two cavity receivers, one with a parabolic-shaped heated surface, and the other with a flat-plate heated surface, were produced and tested. The former yielded a more uniform heating of the hot face of the TEG than the latter, but proved more difficult to construct, whereas the flat plate design allowed the use of pre-constructed thermoelectric modules. Testing indicated that a single receiver was capable of delivering over 4 kW of thermal power to the carrier water with a 200 °C drop across the thermoelectric elements. A third flat plate system was then developed which allowed operation of the TEG in a protective atmosphere.

Operation of the completed SASCS test bed has led to a number of findings. First, the dish design is robust and can provide concentrated solar radiation reliably to the receiver over extended periods. Improvements were made in the design of dish to allow the second dish to operate more efficiently and smoothly. The thermal losses in both in the piping and water storage tank were found to be significant; however subsequent changes in the insulation have led to some reduction in heat losses. The novel 10 kW absorption chiller was proven to operate effectively.

Project Overview

Project summary

The project set out to better understand the applicability of thermoelectric power generation within a useful concentrated solar thermal (CST) technology. A mix of technologies are likely to be required for the successful application of CST. Specifically, the aim was to evaluate a small scale (~10 kW) CST system designed around the concept of incorporating a thermoelectric generator (TEG) into a solar receiver as a topping cycle having a hot side temperature of 400 °C. Thermoelectrics can turn heat to electricity, but operate at low efficiencies so that a large amount of heat is rejected. The present project shows how these can be used with solar heating in a more efficient manner where the rejected heat is at a higher temperature (~180 °C) than in previous systems. Waste heat from this TEG-receiver was used to power an absorption chiller solar cooling system operating as a bottoming cycle at 180 °C, thus providing a Stand-alone Solar Cooling System (SASCS). The SASCS concept is shown below in Figure 1.

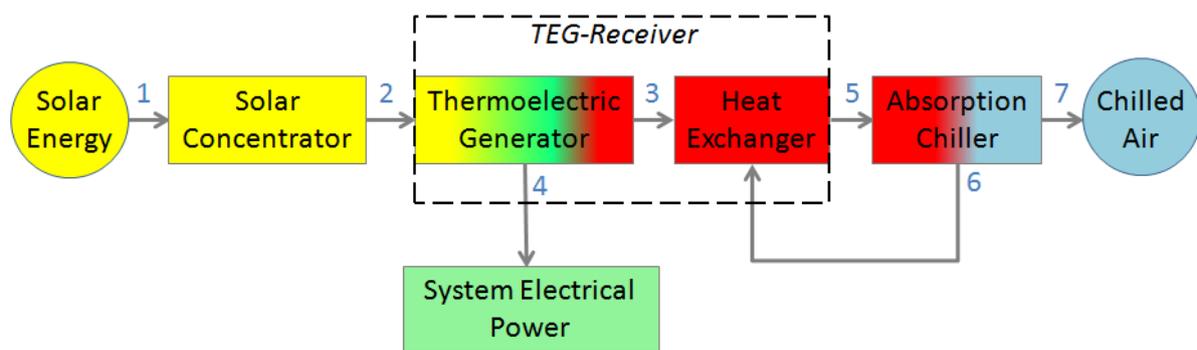


Figure 1. Process diagram representing the Stand-Alone Solar Cooling System (SASCS) concept. The system incorporates three primary components (Concentrator, Receiver and Chiller) and seven primary energy streams, numbered one to seven.

The key driver for this project was to design a generator which could serve as an off grid cooling system for remote communities where communal food storage is essential. The specific technologies for the primary components were selected at an early stage of the project; these are a parabolic dish solar concentrator, a cavity receiver incorporating an oxide-based TEG, and a double-effect absorption chiller. The areas requiring the most R&D effort were deemed to be the efficiency of the oxide-based thermoelectric materials and the design of the cavity receivers incorporating TEGs.

The project was divided into three distinct tasks as shown in Table 1. The materials research program in Task 1 focussed on the reduction of the electrical resistivity and thermal conductivity in known oxide-based thermoelectric materials such as In_2O_3 , CaMnO_3 and $\text{Ca}_3\text{Co}_4\text{O}_9$ in order to maximise their thermal-to-electrical efficiency at 400 °C. Suitable processes for the production of TEGs using these materials were developed and over 8,000 elements were produced. The research indicated that a maximum efficiency of 3.5% is likely to be achievable for these operating temperatures in the near term, which is less than the original target of 5 to 10%.

Table 1. Task structure for the CST Thermoelectric Development project.

Task	Participants
1) Thermoelectric materials and processes	UNSW, CSIRO
2) TEG-Receiver development	Thermax Ltd, CSIRO
3) System Design and testing	CSIRO, Thermax Ltd

Three distinct receiver designs were developed under Task 2. The 1st generation design utilised a parabolic-shaped hot face and TEG compartment which was intended to optimise the uniformity of illumination from the parabolic dish. This design required the development of novel interfaces and shaped thermoelectric elements. In the 2nd and 3rd generations the TEGs were housed between two parallel flat plates in a more conventional configuration. The 3rd generation design also incorporated a sealed system which allowed the use of metalloid thermoelectric materials protected by a cover gas. Such metalloid thermoelectric materials would allow for greater thermoelectric efficiency than the more robust oxide thermoelectric materials required by the 1st and 2nd generation receivers. Activities within Task 3 related to the development and operation of a prototype SASCS test station. A full-scale (10 kW nominal) SASCS testing station was designed and constructed to provide flexible operation so that the performance of the individual primary components could be studied. The system consisted of two 15 m² parabolic-type dishes with provisions for cavity receivers, a 10 kW absorption chiller and a fluid handling system to feed water heated in the receiver to a storage tank and the absorption chiller.



Figure 2. Front and rear view of the SASCS test station at the CSIRO Energy Centre located in Newcastle, NSW.

By the end of the project a fully operational test station based on the SASCS concept in Figure 1 was constructed at the CSIRO Energy Centre in Newcastle, NSW, and operated for hundreds of hours. From an overall system standpoint the tests have resulted in improvements to the performances of the individual components, including the reduction in thermal losses and improved dish focussing and tracking. The testing of oxide-based TEGs within cavity receivers was carried out to ascertain

their performance and to identify faults or problems. Trials were run in both the 1st and 2nd generation receivers, and electronic loading was used.

Project scope

Concentrated solar thermal (CST) technologies are seen to be part of the overall mix of technologies that will reduce greenhouse gas emissions and lessen our dependence on fossil fuels. At present, solar thermal applications are not widespread and it is believed that this is partly due to the inherent cost of the technologies as well as the intermittency of solar radiation. This project is a practical step towards the development of medium-to-high temperature thermoelectric-based technologies that are suitable for deployment in the large-scale concentrated solar power systems under development at CSIRO, as they could lead to an improvement in their overall efficiency. Both the stand alone solar cooling system and the large scale solar power applications were deemed to contribute to the Energy Transformed Flagship's goal to deliver cost-effective, low emission electricity in Australia.

The project aimed to assess the viability of the SASCS as a product, as well as to provide a useful test bed for CST technologies. The primary efforts were focussed on the thermoelectric materials and the TEG-receiver. The successful development of the thermoelectric semiconductor materials and the receiver technology would deliver cost-effective stand-alone cooling systems which would be invaluable in remote communities both here in Australia and in those developing countries where the electrical power delivery infrastructure (grid) is lacking, for example, India.

The project was a partnership between the University of New South Wales (UNSW), Thermax Ltd and CSIRO. Thermax Ltd is an engineering and manufacturing company with extensive knowledge in thermal processes including boilers and absorption chillers. The research group at UNSW has considerable experience in the physics of thermoelectric materials and specifically oxide-based materials.

Outcomes

The SASCS test bed is now fully operational and has been used to ascertain the behaviour of the various components. The system has been debugged and upgraded as required - for example, improvements in the focussing were implemented in construction of the second dish concentrator. Dish tracking methodologies were debugged as well. System heating times were found to be somewhat longer than the original design specification due to thermal losses in the superheated water lines and the water storage tank. Some improvements to system efficiency were achieved by improving the insulation on the piping and components - in a commercial system the length of piping would likely be minimised.

The novel 10 kW absorption chiller performed well. From an operational standpoint it would be beneficial to extend the range of operation to below 140 °C to allow the system to begin cooling earlier. The operating temperature range could be further extended if a water pump with a higher temperature rating than 180 °C were used.

The project has completed significant research into the performance of oxide thermoelectric materials by doping leading to seven publications in scientific journals. This research yielded an improved test methodology which can eliminate inaccuracies in the measurement of electrical conductivity and Seebeck coefficient caused by the loss of oxygen in $\text{Ca}_3\text{Co}_4\text{O}_9$. The materials research and development has led to the development of scalable processes, and over 8,000 thermoelectric elements and 70 TEGs were produced. Our research and that of others has led to the realisation that in the near term, the overall efficiency of oxide thermoelectric materials is likely to be around 3.5% which is below our target of 7% to 10%.

This project funded three PhD candidates at UNSW as well as related researchers at CSIRO. This effort resulted in a number of published works around the improvement of the thermoelectric efficiency of both n-type (CaMnO_3 and In_2O_3) as well as p type ($\text{Ca}_3\text{Co}_4\text{O}_9$) thermoelectric materials.

Transferability

Several technologies have been developed which may be applicable in other systems.

- The oxide thermoelectric materials developed here have proven to be reliable and could be applied where reliability is important and high efficiencies are not required, such as high temperature waste heat harvesting in remote applications. They may also be useful in series with the low temperature Bismuth Telluride-based thermoelectric elements to create TEGs capable of operating from high temperatures (e.g. 700 °C) down to room temperature.
- The solar concentrating dishes will be amenable to a variety of technologies, such as concentrated Photo-Voltaic systems which can produce electricity with higher efficiency. These systems may not be able to generate temperatures at 200°C to run an absorption chiller, but can provide hot water at 80° to 100°C which can be used for other processes.
- The absorption chillers are suitable for testing other solar small scale solar devices, and could also be used in conjunction with a Fluid Handling System as a test bed to check the performance of other renewable energy sources such as Geo-Thermal.
- The Newcastle test bed is ideal for pursuing further solar powered thermally activated technologies (e.g. gas reactors).
- This project is a sensible first step towards the development of thermoelectric-based technologies that are suitable for deployment in the large-scale concentrated solar power applications under development at CSIRO as these technologies could lead to an improvement their overall efficiency.
- The SASCS system provides a base case for a general solar-based cooling system. The components of the SASCS could also be replaced with different technologies as required. For example:
 - A Concentrated PV based system could replace the TEG.
 - The absorption chiller could be replaced by a heat pump to generate higher grade of heat instead of cooling.
- The thermal storage system can be improved with different materials.

Conclusion and next steps

The project has provided an improved understanding of the technical aspects of the path to market for a SASCS. In general terms the system does do what it set out to do by combining a TEG topping cycle with solar cooling, and future work would likely include the implementation of non-oxide thermoelectric materials and lessening the thermal losses in the system so as to increase the overall efficiency of the system. With such improvements in efficiency, the SASCS can become self-sufficient and thus deliver cooling in remote locations.

The test bed, and specifically the 10 kW scale dishes and the 10kW double effect absorption chiller, are already being proposed for use in future solar thermal projects in the areas of solar cooling and solar reforming of natural gas.

Lessons Learnt

Lessons Learnt Report (A): Design and Operation of Stand-alone Solar Cooling Systems Utilising Concentrated Solar Thermal Energy.

Project Name: 2-A015, Development of a Thermoelectric Generator for Application in a CST Topping Cycle

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar Thermal
State/Territory:	VIC, NSW

Key learnings

1. The overall system efficiency of a solar thermal system is highly dependent on the system thermal losses, especially from the hot water loops. These losses include those from heat loss from surface of the piping, heat loss from the exterior of the water storage tank and thermal requirements for initial heating of the components including losses from the receiver when off-sun or during cloudy periods.
2. Two key system requirements are compactness and efficiency of insulation. A compact system where the fluid handling system and absorption chiller are housed as close as possible to the solar collector and this is placed as close as possible to the building would have resulted in improvements in system efficiency. System efficiency can also be improved through reducing high temperature line lengths. During the design stage, however, these issues needed to be balanced against the need for flexibility, access to items for assessment and repair since this was the first time a unit of this type had been constructed.
3. A broad range of operating temperatures for the absorption chiller would be better. Startup sequences are also deemed to be critical but may be limited by the thermal stresses in the TEG section of the receiver. Handling cloudy periods to prevent loss from the receiver will be helpful.
4. The overall system efficiency of a solar thermal system is highly dependent on the system thermal losses, especially from the hot water loops. A large proportion of total system losses originate from the high temperature piping as well as the storage tanks for water which is used as the medium for thermal storage.
5. Normally designed insulation thicknesses are inadequate since they allow too high a loss percentage and are detrimental to its performance. Reducing the piping length, diameter and incorporating a highly efficient thermal barrier on these piping is one of the key requirements for a solar system. Reducing the pipeline is not an easy task as it should also be flexible to connect to a Solar Dish which has a 180° rotation and frequent changes in elevation.
6. The current SASCS uses a water tank as a thermal storage device. This was selected for its flexibility and also for eliminating an intermediate heat exchanger. The use of thermal salts and other storage devices can make the system more compact and could reduce storage device surface area and thus the losses originating from the SASCS system. The use of a salt based system would also reduce the

components of the SASCS which are required to maintain the pressure of the water system and additional safety features associated with high pressure equipment.

Implications for future projects

The present system can deliver hot water, cooling and electricity. Many challenges were encountered and overcome with regards to (a) thermal losses, (b) start-up time, and (c) absorption chiller operation at lower temperatures.

The following points can be taken as learning which can be implemented in future projects.

1. Better designed thermal storage and piping systems: The current system employs a traditionally designed thermal storage system (water based) and traditional piping with insulation. A salt based storage and thermal oil or other such conveying medium can be considered.
2. A small size absorption chiller was specifically designed for use with the SASCS. This absorption chiller operates at 180°C with a good COP (coefficient of performance). An absorption chiller having a broader range of operation (120-200°C) with minor variation in COP could give better overall SASCS performance.

Knowledge gaps

Key technological gaps currently identified are:

1. Low cost, high efficiency, high temperature pump.
2. An absorption chiller having a broad operating range with minimal change in COP.
3. High heat capacity thermal storage systems which can be used with minimal loss

Background

Objectives or project requirements

The system is designed to take the heat from the cold side of the TEG section of the Receiver and deliver it to the absorption chiller. It also has provisions to store the heat in terms of a thermal storage and to reject excess heat using a heat exchanger and cooling tower. The system needed to be compact and incorporate all the necessary safety features that are required for a high pressure water based system.

Process undertaken

A process flow diagram of the system was prepared including all the components of the system. It was found that a pump operating at high pressure and temperature (i.e. of the order of 25 Bar, and 200°C) was not commercially available. Standard pumps for water were either for high pressure, low

temperature systems, or for low pressure, high temperature systems. Based on available pumps, the process temperatures were altered to allow the incorporation of a pump which operated at 25 bar at a maximum temperature of 180 °C.

Once the components were selected, a HAZ-OP study was conducted on the system and the necessary safety features and components were added. The final system and components were designed / selected to fit into a 20' long container which was useful for shipping purposes.

The system was manufactured and certified by Lloyd's Register to be compliant with the AS standards and operable in Australia. The system includes all the necessary components for managing the fluid side of the SASCS. It incorporated the necessary instruments and control devices for managing the system and for data recording and monitoring.

Supporting information

The two figures show the fluid handling system in a 3-D view as well as the fluid handling system before the application of paneling. The fluid handling system incorporates all the components for the fluid side management.

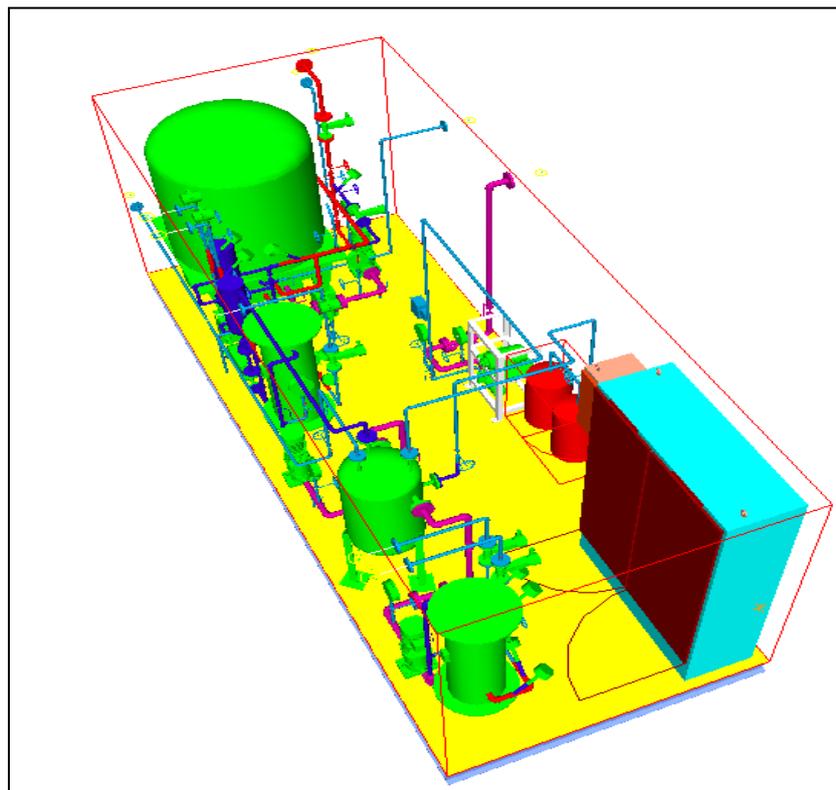


Figure 1: A 3D view of the fluid handling system



Figure 2: The fluid handling system during construction

Lessons Learnt Report (B): Thermoelectric Receivers

Project Name: 2-A015: Development of a Thermoelectric Generator for Application in a CST Topping Cycle

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar Thermal
State/Territory:	VIC, NSW

Key learnings

1. From literature searches and analysis of physics of solar thermal radiation, it was found that a dish concentrator and cavity receiver were most suitable combination for the desired hot face temperature of 400 °C to 500°C, which could be attained with a parabolic dish utilising two axis solar tracking. Analysis via ray tracing showed that a parabolically curved solar radiation receiving plate (hot plate) provided the most uniform illumination across the surface, but created difficulties with respect to installation of thermo-electric generators (TEGs) between this and the correspondingly curved cooling plate. This necessitated a laborious in-situ installation of the TEG elements, rather than a much simpler modular installation, as could be used in flat plate receiver assemblies.
2. Solid calcium silicate insulation allowed for easier rebuilding as opposed to fibre insulation.
3. Finite element analysis showed that the magnitude of the stress in the hot plate, due to clamping at installation and differential thermal expansion when heated, was extremely sensitive to the way the hot plate was designed and located, and that accurate design and manufacturing processes would be required to minimise/eliminate these stresses. To maximise efficiency of the receiver, a minimised resistance to heat flow was required, thereby requiring the thinnest possible hot plate. However, the hot plate needed to be thick enough that static (cool) clamping pressures could be attained reliably at the TEG interface as to allow heat to flow to the TEG. Thicker the hot plate sections allowed for a greater temperature differential between each side of the plate at temperature, and consequently higher stress due to differential thermal expansion. Therefore, thick hot plate sections could lead to mechanical failure once heated and poor performance due to thermal resistance. On the other hand, thin hot plate sections could also lead to mechanical failure and poor performance due to irregular clamping pressure (noting also that all suitable materials weaken as the temperature rises to many hundreds of degrees).

Implications for future projects

Future projects using TEG devices should use receivers designed with improved hot plate attachment and location methods; the aims of which are to maximise mechanical reliability and clamping pressure distribution, and minimise resistance to heat flow. Ultimately this will maximise

performance, through minimisation of the hot plate thickness. If a method could be envisaged to eliminate the hot plate and allow direct irradiance of the TEG, it should be investigated.

Knowledge gaps

1. TEGs use a thin outer layer which acts as an electrical insulator between the electrical junctions in the device and the outside world. However, this also acts as a thermal insulator which limits heat flow. Thinner coatings or sheets would minimise the thermal drop and allow the curved system to be more easily built.
2. Achieving uniform pressure across the TEG is paramount for good performance, so a method to determine the pressure distribution once assembled is required. Determining the pressure distribution during operation is also a further challenge.
3. A knowledge gap that was not explored during this project was the effect on performance of the inclusion of a window or lensing on the front of the receiver.

Background

Objectives or project requirements

This project aimed to demonstrate a hybrid solar thermal system that could both generate electrical energy via a solid state thermoelectric generator, and heat water to a high enough temperature to power a solar air conditioning and heating unit.

This necessitated the design and construction of a receiver incorporating a TEG that provided good thermal connections via good clamping between the TEG and surrounding surfaces (plates), and that could accommodate a number of different TEG materials/thicknesses for scientific comparison. It also required the receiver to provide adequate uniformity of heating, and flux receiving capabilities consistent with a Direct Normal Irradiance (DNI) of 700 to 900 W/m², coupled with a solar concentration ratio of approximately 200:1.

Process undertaken

Three iterations of hybrid solar thermal receiver were designed, built and tested. Ray tracing and finite element analysis predicated the first design utilising the circular parabolic receiving plate.

From lessons learned through the manufacture, testing and further analysis of the first receiver, including the use of a camera to assess light distribution in the receiver, the second design was conceived and built. It used two rectangular flat hot plates and cooling plates in the receiver assembly.

A third design was then conceived, designed and built, which utilised the knowledge gained from the first two designs, and incorporated a sealed section to allow further TEG materials to be incorporated in an oxygen free environment. It used a single circular flat plate receiver assembly.