ENERGY BUSINESS UNIT CONCENTRATING SOLAR POWER CASE STUDY

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BOX 1 CONCENTRATING SOLAR POWER CASE STUDY - EXECUTIVE SUMMARY

Key findings

The Concentrating Solar Power (CSP) project has produced the following outcomes:

— Software that optimises the design and positioning of heliostat collector fields and receivers
— Larger, lower cost heliostats that are suitable for mass manufacture
— A high temperature receiver that operates at a thermal efficiency of 90% or more
— The NPV of the estimated benefits to 2036 is $188.1 million in 2017 dollars under a 7 per cent real discount rate
— The project has an estimated benefit cost ratio (BCR) of 36.1

Innovation impact

The development of a heliostat design that is potentially suited for mass manufacturing is an important outcome as 'learning by doing', through higher production numbers, will help drive down unit costs. The software to optimise the design and positioning of a heliostat collector field and receiver in a way that best matches the terrain and the scale of the system required has already demonstrated that it can provide significant cost savings and there is considerable potential for its use worldwide.

In the longer term, there is the potential for Australia to make a significant contribution towards the development of the next generation CSP power plant utilising the high efficiency CO_2 Brayton cycle turbine.

The Concentrating Solar Power (CSP) case study uses the evaluation framework outlined in the CSIRO Impact Evaluation Guide.[1] The results of applying that framework to the CSP case study are summarised in **Figure 1.1**.

[1] https://www.csiro.au/en/About/Our-impact/Evaluating-our-impact

FIGURE 1.1 CSP CASE STUDY – IMPACT FRAMEWORK DIAGRAM

INPUTS	ACTIVITIES	OUTPUTS	OUTCOMES	IMPACTS
– Total support for low cost heliostat project was $2.108 million in cash and in-kind contributions (from ARENA, CSIRO Rio Glass and Diver Consolidated Industries) – Total support for the project to optimise central receivers was $2.108 million in cash and in-kind contributions (from ASI/ARENA, CSIRO, Sandia National Laboratories, NREL and Vast Solar)	– R&D into the design and operation of heliostats – developing a calibration system that can calibrate many heliostats simultaneously – developing improved software control systems – developing point focus receivers, storage, associated heat transfer and material considerations and high efficiency cycles that maximise the benefits of using supercritical CO_2 as a heat transfer fluid	– lower cost heliostats suitable for mass manufacture – an improved software control system – small footprint thermal storage – high efficiency receivers – modelling software used to optimise the lay out of the heliostat field and receiver – journal articles	– larger mirrors with the same unit costs for foundations, support structures, control and actuation – software to optimise the design and positioning of a heliostat collector field and receiver to best match the terrain and the required scale of the system – better CSP system planning and more rapid and cost effective installation – a high temperature receiver that operates at a thermal efficiency of 90% or more	– a non-exclusive licence to Heliostat SA to manufacture CSIRO heliostats for the Australian market – a separate licensing agreement with Thermal Focus (in China) – Thermal Focus can suggest design and manufacturing improvements to create a lower cost product – faster and lower cost installation – the opportunity to partner with others to build CSP systems which utilise supercritical CO_2 Brayton cycle turbines – licence fees – export opportunities – employment opportunities

SOURCE: ACIL ALLEN

1.1 Purpose and audience for case study

This case study describes the economic, environmental and social benefits arising from the CSP project.

This evaluation is being undertaken to assess (to a range of stakeholders) the positive impacts arising from the CSP project undertaken by CSIRO. This case study can be read as a standalone report or aggregated with other case studies to substantiate the impact and value of the Energy Business Unit's activities as a whole relative to the funds invested in these activities.

This information in this case study is provided for accountability, communication and continual improvement purposes. Audiences for this report may include Members of Parliament, Government Departments, CSIRO and the general public.

1.2 Background

CSIRO has a comprehensive portfolio of R&D into Concentrating Solar Power (CSP). That portfolio spans the spectrum of temperatures that CSP can provide. It includes R&D into thermal storage, heliostats and receivers associated with using CSP to produce and use:

— high temperature heat for industrial processes
— high temperature heat for electricity generation using advanced fluids such as supercritical CO_2

— very high temperature heat to produce solar gas, hydrogen or electricity.

The CSIRO's research into electricity generation using very high temperature heat was initially focussed on the air Brayton cycle due to its reduced requirements for water. However, gas turbines only achieve around 30 per cent efficiency at such temperatures. In addition, the relatively rapid cost reductions for PV's reduced the relative economic competitiveness of this technology. Hence the focus of the research program was shifted towards studying the supercritical CO_2 Brayton cycle. The aim of the CSIRO's research in this area is to achieve around 50 per cent turbine efficiency. CSIRO is currently regarded as the world leader in this field of research. Recently, the US Department of Energy awarded over US$160M funding towards this cycle.

This case study is focussed on two different streams of CSP research. One is R&D into low cost, small heliostats where the aim of the research effort is to reduce the cost of heliostats to around $100/m^2 while maintaining high optical performance. The other is research into advanced central receiver technology. The aim of the research is to increase the receiver temperature from around 600 degrees to 700 degrees while maintaining (or increasing) receiver efficiency. Improving the efficiency of conversion is one of the most important ways to reduce the cost of solar electricity. Efficiency improvements reduce costs across the board as it not only means a reduction in solar field size, but also a reduction in number (or size of) receivers, towers (in case of central receiver systems), land area and associated balance of plant, etc. The reduction in the amount of installed plant also translates to a reduction in operating and maintenance costs.

1.3 Impact Pathway

1.3.1 Project Inputs

The total cost for the low cost heliostat project was about $2.108 million in cash and in-kind contributions (see **Table 1.1**).[2] The vast majority of CSIRO's contribution was provided as in-kind support. CSIRO's in-kind support included providing access to the two solar towers and heliostat fields in Newcastle. The main source of cash contributions to the project was ARENA and CSIRO. Rio Glass and Diver Consolidated Industries (DCI) provided $150,000[3] and $114,200 of in-kind support respectively.

TABLE 1.1 SUPPORT FOR THE LOW COST HELIOSTAT PROJECT

Contributor / type of support	2014 ($)	2015 ($)	2016 ($)	2017 ($)	Total ($)
Cash					
Support from CSIRO, and ARENA	53,030	408,385	580,251	25,413	**1,067,079**
In-kind					
Support from CSIRO, Rio Glass and DCI	53,441	448,465	529,537	9,549	**1,040,992**
Grand Total	**106,471**	**856,850**	**1,109,788**	**34,962**	**2,108,071**

The total cost for the project to optimise central receivers for use with advanced power cycles was $2.85 million in cash and in-kind contributions (see **Table 1.2**). [4] The majority of the cash contribution was provided by ASI/ARENA. CSIRO contributed $1.41 million as in-kind support (around 50 per cent of the total cost). In-kind support was also provided by Sandia National Laboratories, National Renewable Energy Laboratories (NREL) and Vast Solar.

TABLE 1.2 SUPPORT FOR THE PROJECT TO OPTIMISE HIGH TEMPERATURE RECEIVERS

Contributor / type of support	2013 ($)	2014 ($)	2015 ($)	2016 ($)	2017 ($)	Total($)
Cash						
External contributions (including by ASI[5])	103,658	155,340	249,207	628,855	13,819	**1,150,879**
In-kind						

[2] Data shown in Table 1.1 based on information provided in an email from CSIRO on 12 July 2017.
[3] CSIRO application for ARENA grant.
[4] Data shown in Table 1.2 based on information provided in an email from CSIRO on 12 July 2017.
[5] In November 2012, the Australian Solar Institute (ASI) entered into a funding agreement with the CSIRO to establish and deliver the Australian Solar Thermal Research Initiative (ASTRI). The agreement provided funding of $35 million over 8 years for ASTRI. Funding consisted of ASI funds for the first four years, with the balance provided by ARENA (subject to the satisfactory outcome of a midterm review). The funding was provided as support for a range of solar thermal projects.

Contributor / type of support	2013 ($)	2014 ($)	2015 ($)	2016 ($)	2017 ($)	Total($)
Total in-kind support (from CSIRO, National Renewable Energy Laboratories (NREL), Sandia, and Vast Solar)	104,531	170,427	287,085	618,168	518,308	**1,698,519**
Grand Total	**208,189**	**325,767**	**536,292**	**1,247,023**	**532,127**	**2,849,398**

1.3.2 Project activities

The activities for each of the two elements of work considered for this case study are briefly described below.

Low cost heliostats

CSIRO's work on heliostats began in 2006. CSIRO Energy Technology (CET) has developed and patented a heliostat for use in a high accuracy, high flux collector field. This heliostat was used to refurbish the original solar field installed for CSIRO by Solar Heat and Power in Newcastle. Various prototypes were deployed in the first field, and in 2011, the first complete version of the CSIRO heliostat was deployed for the ASI demonstration field in Newcastle. For this project, the price of the heliostats was around $\$500/m^2$.

The ARENA funded Low Cost Heliostat project started in 2014 to reduce the cost of the CSIRO heliostat design, and address technical barriers that make small heliostats, which can achieve a higher theoretical optical efficiency, impractical for large installations. The aims of the current project include further developing the mechanical design of the heliostats to facilitate mass manufacturing to achieve a cost of $\$200/m^2$ (fully installed and commissioned in remote Australian locations). The project will also seek to develop the next generation of actuators for the mirrors, an advanced calibration system that can calibrate many heliostats simultaneously, and improved software control systems for the heliostats. The ultimate objective of the research is to reduce the cost of the heliostats by a further 50 per cent to $\$100/m^2$ without any loss in performance.

The project builds on the experience, equipment and facilities developed by CSIRO for past projects, such as experience in building research heliostat fields in Cyprus and Japan, and experience designing low-cost actuation based on existing supply chains. High volume manufacturing and knowhow from research partners and the solar industry will be crucial for developing solutions that enable rapid deployment of collector fields in remote locations. The existing solar receiver installations can of course be used to validate experimental developments, along with existing solar thermal testing infrastructure, such as cooling water loops, cameras, data acquisition and processing software.

Part of the effort is to develop a $7.22m^2$ heliostat (the versions deployed in Newcastle are $4.8m^2$ and in Cyprus and Japan they are $5.1\ m^2$). This is the maximum mirror size possible from float glass lines that can be easily transported in containers. Diver Consolidated Industries (DCI) and Rio Glass are providing in-kind support for the research effort.

CSIRO has also been in discussions with industry partners to examine options for supplying heliostat components rather that the entire heliostat system.

Optimisation of Central Receiver Systems

The aim of this element of the project is to produce a levelised cost of solar electricity below 10 cents per kWh. The project aims to develop new technology based on a closed loop supercritical CO_2 Brayton turbine, small footprint thermal storage and high efficiency receivers in order to drive this step change in the cost of electricity from CSP.

The focus of CSIRO's research has been on the latter two of the above three elements. In particular CSIRO has concentrated on the development of point focus receivers, storage, associated heat transfer and material considerations and high efficiency cycles that maximise the benefits of using supercritical CO_2 as a heat transfer fluid. CSIRO has and will continue to design, fabricate and test receivers on the solar tower facilities at the CSIRO Energy Centre in Newcastle.

Another important element of CSIRO's work on this project will be to further develop the modelling software that is used to optimise the receiver and field lay out.

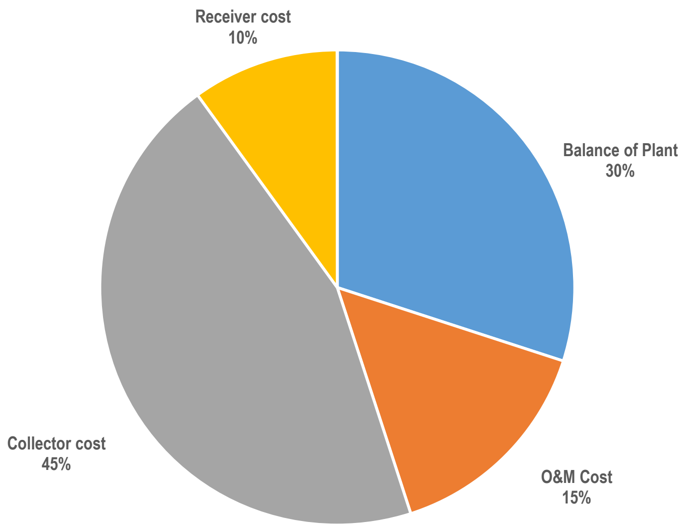
1.3.3 Project outputs

The research by CSIRO as part of these two projects should, if successful, lead to significant cost reductions in the Levelised Cost of Electricity (LCOE) from a CSP power plant. The commercial cost of CSP has decreased significantly over the past 5 years and is likely to be in the range of 14-17 cents/kWh, depending on size, storage capacity and location, in Australia without any subsidies or incentives. Recent modelling has suggested that the LCOE needs to be reduced to less than 10 cents/kWh for CSP to be competitive, and thus CSIRO's strategy has been to focus on component and process technologies that realise this goal. **Figure 1.2** shows the relative contribution of different cost elements to the LCOE of a CSP power plant. There are a number of elements of CSIRO's research with the potential to collectively contribute towards a reduction in costs for CSP. They include:

- 40 per cent larger mirrors with the same unit costs for foundations, support structures, control and actuation.
- Modelling software that will allow the optimisation of the design and positioning of a heliostat collector field and receiver in a way that best matches the terrain and the scale of the system required.
- Better CSP system planning and more rapid and cost effective installation.
- A receiver that operates at high temperatures (around 700 degrees), but maintains a thermal receiver efficiency of 90 per cent or above.

Ultimately the aim will be apply all of the above research outputs with those of other research partners to build CSP systems which utilise supercritical CO_2 Brayton cycle turbines with an efficiency of around 50 per cent compared to the current efficiency of around 40 per cent.

FIGURE 1.2 RELATIVE CONTRIBUTION TO CSP LIFECYCLE ELECTRICITY COSTS



SOURCE: CSIRO PROPOSAL TO ASI FOR AN ADVANCED RECEIVER RESEARCH PROJECT, 2011 (DOES NOT INCLUDE STORAGE)

Publications

This project has produced a number of publications, such as the ones listed below:

- Lovegrove, K., Stein, W., Editors "*Concentrating Solar Power Technology – Principles, Developments and Applications*", Woodhead Publishing, 2013
- Kim J, Kim J, Stein W (2015) *Simplified heat loss model for central tower solar receivers. Solar Energy*, 116, 314-322.
- Padilla RV, Too YCS, Beath A, McNaughton R, Stein W (2015) *Effect of Pressure Drop and Reheating on Thermal and Exergetic Performance of Supercritical Carbon Dioxide Brayton Cycles Integrated With a Solar Central Receiver*. Journal of Solar Energy Engineering-Transactions of the ASME, 137(5).
- Schramek P, Mills DR, Stein W, Le Lievre P (2009) *Design of the Heliostat Field of the CSIRO Solar Tower*, J. Sol. Energy Eng 131(2), 024505.
- Beath AC (2012) *Energy Industrial energy usage in Australia and the potential for implementation of solar thermal heat and power Energy*, 43, 261-272.
- Collins M, Potter D, Burton A (2017) *Design and simulation of a sensor for heliostat field closed loop control*, AIP Conference Proceedings 1850, 030009
- Olivares RI, Young DJ, Marvig P, Stein W (2015) *Alloys SS316 and Hastelloy-C276 in Supercritical CO2 at High Temperature*. Oxidation of Metals*, 84*(5-6), 585-606.

- Padilla RV, Too YCS, Benito R, Stein W (2015*) Exergetic analysis of supercritical CO2 Brayton cycles integrated with solar central receivers*. Applied Energy*, 148*, 348-365.

Patents

CSIRO Energy Technology (CET) has developed and patented a heliostat for use in a high accuracy, high intensity collector field. A series of patents relating to heliostat and receiver design and control have been filed, with some granted, including:

- **Heliostat control** Burton, Alexander Ian (2012) AU2012203234 (GRANTED)
- **Heliostat control** Burton, Alexander Ian (2012) AU2012203231 (GRANTED)
- **Heliostat calibration and control** Burton, Alexander Ian (2012) AU2012203230 (GRANTED)
- **Heliostat construction** Burton, Alexander Ian; Andrews, Glenn (2011) AU2011349053 (GRANTED)
- **Closed loop control system for heliostats** Burton, Alexander Ian (2016) AU2016208290 (FILED)
- **Monitoring and measuring of multiple light sources especially heliostats** Burton, Alexander Ian; Collins, Michael (2015) AU2015213474 (FILED)
- **Method of designing a concentrated solar cavity receiver** Burton, Alexander Ian (2015) AU2015201631 (FILED)

Awards

CSIRO's Solar Tower at their CSP facility in Newcastle was highly commended at the 2006 Newcastle Division Engineering Excellence Awards.

In December 2016 Mr Mike Collins was awarded the John Philip Award for the Promotion of Excellence in Young Scientists. This award provides opportunities for young scientists to extend their professional development by gaining further career related training and experience.

Innovation / commercialisation

Low cost heliostats

As CSIRO has existing capability in the area of heliostats and field design and control, should the novel concepts being developed and tested as part of this project be proven to be cost-effective, then CSIRO is well placed to integrate them into a commercial ready product for CSP projects in Australia.

CSIRO has granted a non-exclusive licence to Heliostat SA to manufacture its heliostats for the Australian market. For the purposes of its analysis ACIL Allen has assumed that the licence fee is 3 per cent. A one off licence was also given to the same firm to build 150 heliostats for a CSP research facility in Yokohama, Japan. No royalties were paid by Heliostat SA on this occasion. Instead CSIRO provided its support for the construction of the facility on a fee for service basis.

A Chinese firm, Thermal Focus, have been granted a separate licensing agreement for the use of CSIRO heliostat (and related) technology and know-how in concentrating solar power projects in China. The firm already envisages heliostat cost reductions of 30 per cent in China.

Under the terms of the present agreement between Thermal Focus and CSIRO, the latter has the rights to manufacture and install CSIRO heliostats in China for a small pilot facility (approx. 10-20 heliostats) and a 5MW (thermal) project. Thermal Focus also has the rights to run a stand-alone executable version of field layout optimisation software for a restricted region. Thermal Focus is currently tendering to build three collector fields, each with a capacity of 50 MW_e (these plants would each require approximately 700,000m^2 of collectors).

As part of the agreement between CSIRO and Thermal Focus there has been close collaboration between the two organisations. Thermal Focus staff will make a number of visits to CSIRO in Newcastle for training and CSIRO staff will visit Thermal Focus in China to support the technology transfer. Thermal Focus will pay CSIRO a license fee for access to its technology and know-how. That fee will vary depending on the size of the project. For the purposes of our analysis, ACIL Allen has assumed that on average the licence fee will be around 3 per cent of the value of the heliostats.

The three projects that Thermal Focus have tendered for are part China's current Five Year Plan to build 5 GW of concentrating solar power plants capacity by 2021.

Stemming from the collaboration with Thermal Focus, CSIRO has recently signed a letter of intent with Elion, a large Chinese company, to develop and demonstrate CSIRO CSP technology based on supercritical CO_2 turbines.

Optimisation of high temperature receivers

CSIRO expects that the benefits of this project will be realised by "advertising" the outcomes by incorporating public versions of the models used to optimise collector field and receiver design into the analytical tools used to plan CSP plants. The public model available in this manner would represent accurate simulations, but to utilise the full breadth and scope of the modelling capability organisations would need contract on a consultancy basis with CSIRO.

The benefits will also be realised by developing recommended boundary conditions or parameters for designers, developers and manufacturers of heliostats and receivers. These would be published through normal channels. However, access to the detailed capability of the modelling software would only be available through a consultancy with CSIRO. This is partly because every developer will have a slightly different configuration.

1.3.4 Project Outcomes

The modelling software used to optimise the layout of the heliostat collector field and the receiver has demonstrated that it is able to improve the cost efficiency of a CSP plant. For example, the software was used to determine the optimal design of a possible 1 MW thermal liquid sodium central receiver system at Perenjori in Western Australia. It is assumed that the system is designed to provide an annual thermal energy output of 2500 MWh.

The original layout of the collector field required 600 heliostats, each approximately 5 m^2 in area, to produce the required annual thermal energy output. The modelling software was able to optimise the design of the system to produce the same thermal output with only 413 heliostats.

If we assume that the heliostats cost $200/$m^2$ this reduction in the required number of heliostats implies a cost saving of just over $189,000 for the same thermal output, or just over a 30 per cent reduction in heliostat field costs. A reduction in the number of heliostats will also lead to a reduction in operation and maintenance (O&M) costs since operating and cleaning the heliostats are the main contributors to O&M costs.

The cost of the collector field contributes roughly 40 per cent to the LCOE of a CSP plant and the plant O&M costs contribute a further 15 per cent to the LCOE (see **Figure 1.2**). If we assume the software enables a 30 per cent reduction in the number of heliostats and a similar reduction in O&M costs this implies the modelling software could reduce the LCOE of a CSP plant by 18 per cent.

If the current LCOE is between 14 and 17 cents/kWh, then this would imply a reduction in the LCOE for CSP to between 11.5 and 14 cents/kWh.

If the research being done to optimise the receiver and solar field in an integrated way enables the use of the CO_2 Brayton cycle with the higher efficiency of conversion of steam energy to turbine energy, then this again reduces the number of heliostats needed for the same electricity production by 20 per cent. Based on the same arguments as presented above in the case of the field optimisation software, this would imply a reduction in the LCOE of a CSP plant to between 9.2 and 11.2 cents/kWh if combined with the field optimisation software.

Finally, CSIRO is conducting research to enable the use of 7.2m^2 heliostats (rather than 5 m^2). If successful, the larger heliostats would enable the same energy production with 40 per cent fewer heliostats. The larger heliostats are intended to use the same supporting infrastructure, which would reduce the cost of the collectors needed for a given power output. It is worth noting that the cost of footings for the heliostat supports can vary considerably. For some sites the cost for footings could be considerable and being able to reduce the number of footings by 40 per cent could provide an important cost reduction. However, some of this reduction would be lost due to the need to purchase larger mirrors. For the purposes of our analysis we have assumed that half the resulting cost reduction could be captured. This would further reduce the LCOE to between 7.4 and 9 cents/kWh.

The above calculations all assume that there is no change in the contributions that the receiver and the balance of systems items make to the LCOE.

The integrated modelling capability developed and demonstrated in the project became one of the core components for heliostat technology transfer as the customers need to know how to design the solar filed using the heliostat to meet a specific design requirement. The outcomes of both low cost heliostat and central receiver optimization project provided a combined package of technology including both hardware and software, which enhances the value and the chance of technology transfer opportunity.

1.3.5 Adoption

There is little doubt that if the research effort by CSIRO (and others) was successful in reducing the LCOE of CSP plants to below 10 cents/kWh this would be a very significant outcome. Such a reduction in the LCOE would mark a paradigm shift in the economic viability of CSP plants. Such an outcome would be likely to lead to an increase in the number of CSP plants constructed in Australia and elsewhere in the world.

The efforts to reduce the cost of heliostats from around $200/m^2 to around $100/m^2 are well advanced. The cost reduction achieved depends to some extent on the scale of production of heliostats. It is anticipated that the targeted cost reduction might be achieved by the time heliostat fields with some 50 MW_e of capacity have been built. The cost reduction depends on industry mass production and it is testament to CSIRO's work that industry has been approaching CSIRO for licenses.

In the case of the high temperature, high efficiency receiver needed to utilise the supercritical CO_2 Brayton cycle, this is a longer term objective. CSIRO estimates that a commercial supercritical CO_2 Brayton cycle turbine might be available to the market around 2025.

1.3.6 Impacts

One impact of a successful outcome of CSIRO's research into low cost heliostats would be the potential growth in the market for the heliostat support frames by Heliostat SA. Heliostat SA currently has a licence to manufacture the CSIRO developed heliostats. Heliostat SA also has the rights to use the software developed by CSIRO to optimise the layout of the collector field. The efficiency gains provided by this software should considerably strengthen Heliostat SA's ability to market their heliostats.

ACIL Allen has spoken to Heliostat SA about the prospects for heliostat sales. They advised that their current focus is to try to supply the market for industrial heat. The view is that the current high gas and power price helps improve the economic viability of a hybrid system that includes CSP to provide industrial heat. These would be smaller scale CSP plants (around 3 to 10 MW_{th}), which are ideally suited to the technology. Heliostat SA is currently in discussions with four or five firms in South Australia who use industrial heat in the temperature range of 300 to 600 degrees.[6]

A 2008 study commissioned by the IEA found that in several industrial sectors, including food, wine and beverage, transport equipment, machinery, textile, pulp and paper, about 27 per cent of heat is required at medium temperature (100–400 degrees C) and 43 per cent at above 400 degrees C.[7] The deployment of solar thermal in industrial applications is increasing rapidly, albeit from a very low base. In 2010, the IEA-SHC[8] reported about 42 MW_{th} worldwide (60,000 m^2).[9] By 2014, 132 solar thermal plants for industrial applications were reported worldwide with a total capacity of over 95.5 MW_{th} (over136,500 m^2).[10]

Heliostat SA's strategy is to seek public support from an organisation like ARENA to help construct the proposed CSP plants. They envisage that the level of external support required might be of the order of 50 to 60 per cent of the cost for the first plant. The external support required would progressively decline to around 10 per cent for the fourth or fifth plant. The intention is to use the production of the heliostats needed to supply these first contracts to drive unit cost reductions for the heliostat support frames. The firm anticipates that learning by doing can help drive down the unit costs of the heliostat support frames from the current cost of around $850 per frame to around $250 per frame.[11]

Heliostat SA believes that the total cost of supplying heliostats to the companies they are currently in negotiations with would be around $50 million. If so, this would imply a licence payment of the order to $2 million to CSIRO.

The firm is also fielding an increasing number of enquiries from potential customers from around the world. The most recent was an inquiry from a potential Argentinian client for 6,600 heliostats.

A joint study in 2016 by the European Solar Thermal Electricity Association (ESTELA), Greenpeace International and the IEA's SolarPACES estimated that under a moderate growth scenario the market for CSP would increase from around 4,900 MW in 2015 to 20,000 MW by 2020 and 80,000 MW by 2050.[12] This additional capacity is likely to be supplied by a mix of CSP technologies (parabolic trough collectors, Fresnel lens collectors and heliostats with central tower receivers). If we assume that the proportion of the market supplied by solar tower CSP technology remains at the current share of around 12 per cent of the total market for CSP and that Heliostat SA captures 0.5 per cent of the global market from 2018 onwards this suggests that Heliostat SA's share of the global market could be some 8.4 MW of CSP capacity in 2018. Their share could increase to around 28 MW in 2020 and 91 MW by 2025.

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[6] Heliostat SA is also developing a single axis tracker to use with its support frames when they are used for PV panels.

[7] Vannoni, Battisti and Drigo, 2008, Department of Mechanics and Aeronautics - University of Rome "La Sapienza". Potential for Solar Heat in Industrial Processes, Commissioned by Solar Heating and Cooling Executive Committee of the International Energy Agency.

[8] The IEA Solar Heating and Cooling Program (IEA-SHC) was established in 1977. It was one of the first collaborative research programs established by the IEA.

[9] Lauterbach, C. et al,, "Solar heat for industrial processes –Technology and potential", http://www.solarthermalworld.org/sites/gstec/files/solar-heat-for-ind-processes-christoph-lauterbach.pdf

[10] Christoph, Brunner, 2014, "Solar Heat for Industrial Production Processes - Latest Research and Large Scale Installations", AEE INTEC.

[11] The impact of 'learning curves' is well established. A recent example of this effect is the very significant drop in the unit cost of PV panels following the dramatic increase in the production of PV panels, to the point where the economic viability of the panels is now less dependent on subsidies or other forms of government support.

[12] Dr. Luis Crespo, Marcel Bial, Elena Dufour, Dr. Christoph Richter, Solar Thermal Electricity - Global Outlook 2016,

A 2012 study found that the construction and operation of CSP plant can generate significant employment opportunities. The study concluded that seven jobs were created during the construction of the CSP plant for each MW of capacity installed.[13] If the same figures were true for Australia then the construction of the CSP plants to provide industrial heat that Heliostat SA is currently discussing with several potential clients could generate around 200 jobs during construction.

Based on the assumptions above about the growth in the global market for CSP, Heliostat SA's estimated share of the market could increase employment for the construction of CSP plants from around 60 in 2018 to over 600 in 2025.

With regard to CSIRO's work to optimise the high temperature receiver, the impacts of this research, if successful, are only likely to be seen some time after 2025 as the research to develop the supercritical CO_2 Brayton cycle is unlikely to be completed before then. In view of the uncertainty about when a commercial product might be available, we have not sought to value the outcomes of CSIRO's research in this area.

1.4 Clarifying the Impacts

1.4.1 Counterfactual

The research done by CSIRO to reduce the cost of heliostats and develop the software to optimise the layout of the collector field should improve the ability of Heliostat SA (HSA) and other licensees to market CSIRO heliostats in Australia and overseas. In the absence of the competitive advantage provided by that research, Heliostat SA's share of the global market is likely to have been significantly less than assumed above. In fact, HSA may not even have considered constructing CSP heliostats at all were it not for the CSIRO pilot demonstration plant. For the purpose of our analysis we have assumed that HSA's market share would have been 10% of the market share assumed above in the absence of the CSIRO research.

CSIRO are currently in discussions with General Electric about CSIRO's possible participation in the project to develop a supercritical CO_2 Brayton cycle turbine. The conditions under which CSIRO might participate in the project are yet to be agreed.

1.4.2 Attribution

CSIRO suggests that the attribution of benefits from the work done to reduce the cost of heliostats should be around 65 per cent.

We have not sought to assign any attribution for possible future benefits associated with the research being conducted by CSIRO to optimise the high temperature receiver.

1.5 Evaluating the Impacts

1.5.1 Cost-Benefit Analysis

Costs

Based on the year-by-year costs shown in **Table 1.1** and **Table 1.2**, the present value of R&D costs for the low cost heliostat project and the project to optimise high temperature receivers is $5.21 million in 2017 dollars under a 7 per cent real discount rate.

ACIL Allen was unable to obtain information about Heliostat SA's commercialisation costs.

Benefits

Three strands of benefits associated with the low cost heliostat project are assessed in the cost-benefit analysis:

— the revenues generated by Heliostat SA for CSP used in industrial heat applications
— the revenues generated by Heliostat SA for CSP used in power applications
— royalties paid by Thermal Focus to CSIRO.

Revenues generated by Heliostat SA for CSP used in industrial heat applications

As discussed in Section 1.3.6, the deployment of CSP to produce thermal energy for use in industrial applications increased from 42 MW_{th} worldwide (60,000 m^2) in 2010 to over 95.5 MW_{th} (over 136,500 m^2) in 2014, a compound annual growth rate of 23 per cent. This annual growth rate is assumed to persist over the next 20 years. However, the industrial heat market covers a wide range of temperatures. It is likely that technologies other than heliostats will be used in some cases (e.g. troughs or linear Fresnel).

[13] Deloitte 'Impacto Macroeconómico del Sector Solar Termoeléctrico en España', 2012

Taking the above point into consideration, it is assumed that Heliostat SA's share of the global CSP market for industrial heat applications will rise from zero in 2017 to 1.0 per cent in 2022 in 0.2 per cent annual increments, and remains at 1.0 per cent thereafter. Heliostat SA's price per square metre in real terms (that is, in 2017 dollars) is assumed to decline by $10 per m^2 each year from $200 per m^2 in 2018 to $100 per m^2 in 2028, and then remains at $100 per m^2 thereafter.

Under these assumptions, the annual revenues generated by Heliostat SA for CSP used in industrial heat applications is projected to rise from $124,000 in 2018 to $12.5 million by the end of the analysis period in 2036 (both figures in 2017 dollars).

Revenues generated by Heliostat SA for CSP used in power applications

As discussed in Section 1.3.6, the market for CSP for power applications is projected to grow from around 4,900 MW in 2015 to 20,000 MW by 2020 and 80,000 MW by 2050. The projected growth between 2020 and 2050 is assumed to be linear (that is, with a declining growth rate). Total collector area is projected to reach 73.4 million m^2 in 2036, assuming 700 Wth/m^2.

It is assumed that Heliostat SA's share of the global CSP market for power applications rises from zero in 2022 to 0.5 per cent in 2027 in 0.1 per cent annual increments, and remains at 0.5 per cent thereafter. Again, Heliostat SA's price per square metre is assumed to decline by $10 per m^2 each year from $200 per m^2 in 2018 to $100 per m^2 in 2028, and to remain at $100 per m^2 thereafter.

Under these assumptions, the annual revenues generated by Heliostat SA for CSP used in power applications is projected to rise from $2.5 million in 2023 to $37.7 million by the end of the analysis period in 2036 (both figures in 2017 dollars).

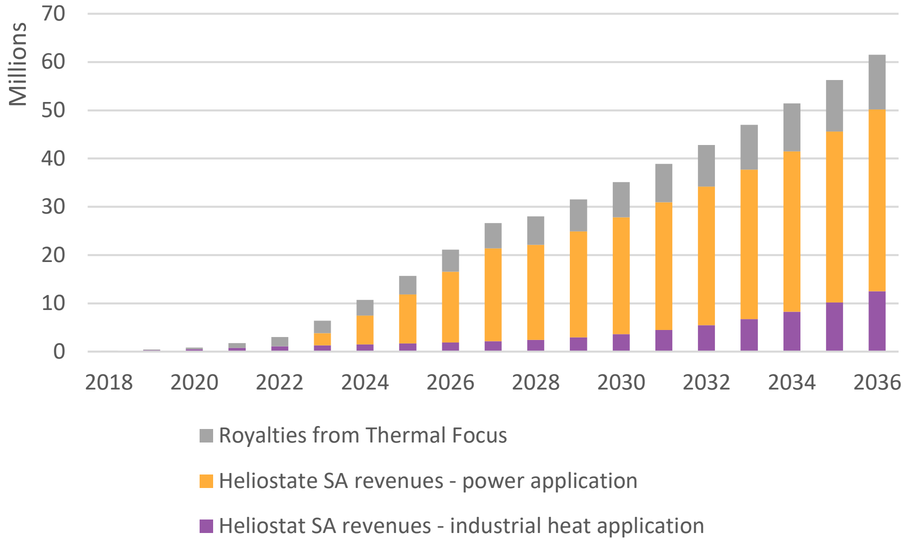
Thermal Focus royalties

It is assumed that Thermal Focus' share of the global CSP market for power application rises from 1 per cent in 2018 to 5 per cent in 2022 in 1 per cent annual increments, and then remains at 5 per cent thereafter. Thermal Focus' price per square metre is assumed to remain constant in real terms at $100 per m^2 in 2017 dollars. Thermal Focus' current price is assumed to be lower than Heliostat SA's due to scale economies and lower labour costs.

Assuming a 3 per cent royalty rate, the royalties paid by Thermal Focus to CSIRO are projected to increase from $72,400 in 2018 to $11.3 million by the end of the analysis period in 2036 (both figures in 2017 dollars).

The annual benefits of the low cost heliostat project from the three sources described above are shown in **Figure 1.3**.

FIGURE 1.3 BENEFITS OF THE LOW COST HELIOSTAT PROJECT



SOURCE: ACIL ALLEN CONSULTING

The present value of all project benefits to 2036 is estimated at $188.1 million in 2017 dollars under a 7 per cent real discount rate.

Assessment of benefits against costs

The net benefit or net present value (NPV) of the low cost heliostat project is estimated to be $182.9 million in 2017 dollars under a 7 per cent real discount rate. The benefit-cost ratio (BCR) is estimated to be 36.1.

Note that the above calculations do not take into account commercialisation costs.

Sensitivity analysis

In the central case of the cost-benefit analysis, it is assumed that Heliostat SA's share of the global CSP market for industrial heat applications rises from zero in 2017 to 1.0 per cent in 2022 in 0.2 per cent annual increments, and remains at 1.0 per cent thereafter. If Heliostat SA's share of the global CSP market for industrial heat applications rises from zero in 2017 to 2.0 per cent in 2022 in 0.4 per cent annual increments (and remains at 2.0 per cent thereafter), the BCR increases from 36.1 to 41.1.

In the central case of the cost-benefit analysis, it is assumed that Heliostat SA's share of the global CSP market for power applications rises from zero in 2022 to 0.5 per cent in 2027 in 0.1 per cent annual increments, and remains at 0.5 per cent thereafter. If Heliostat SA's share of the global CSP market for power applications rises from zero in 2022 to 1.0 per cent in 2027 in 0.2 per cent annual increments (and remains at 1.0 per cent thereafter), the BCR increases from 36.1 to 59.2.

In the central case of the cost-benefit analysis, it is assumed that Thermal Focus' share of the global CSP market for power application rises from 1 per cent in 2018 to 5 per cent in 2022 in 1 per cent annual increments, and then remains at 5 per cent thereafter. If Thermal Focus' share of the global CSP market for power application rises from 2 per cent in 2018 to 10 per cent in 2022 in 2 per cent annual increments (and then remains at 10 per cent thereafter), the BCR increases from 36.1 to 44.0.

A 7 per cent real discount rate has been used in the cost-benefit analysis. The use of a 4 per cent real discount rate would increase the BCR from 36.1 to 55.2, while the use of a 10 per cent real discount rate would reduce the BCR to 24.2.

1.5.2 Potential future impacts

Heliostats contribute almost half the lifecycle electricity costs of a CSP power plant. Hence any reductions in unit costs for heliostats will have a significant impact on the competitiveness of CSP power plants. CSIRO's work to improve the design and operation of heliostats to make them easier to mass manufacture should help boost the number of heliostats built and gradually lead to a reduction in unit costs. The adoption of CSIRO's heliostat design by Australian and Chinese firms suggests that heliostat production is likely to increase.

Similarly the software that CSIRO has developed that can be used to optimise the design and positioning of heliostat collector fields and receivers, will also help to reduce the construction costs of CSP power plants.

In the longer term, the partnership with others to build CSP systems, which utilise high efficiency supercritical CO_2 Brayton cycle turbines has the potential to further improve the competitiveness of CSP power plants.

1.5.3 CSIRO's role as an Innovation Catalyst

CSIRO's research and development into lower cost heliostats suitable for high volume manufacturing is being used by several firms.

The heliostat field optimisation software has the potential for adoption worldwide.

The CSIRO's research into high temperature receivers has opened the door to collaboration with major international research groups seeking to develop next generation CSP plants.

1.5.4 Distribution effects on users

CSIRO stands to receive royalties from the users of its research. There is the potential for additional employment opportunities with Australian manufacturers of CSIRO designed heliostats.

1.5.5 Externalities or other flow-on effects on non-users

Greater use of CSP plants will help Australia and other countries to reduce the emissions associated with the generation of electricity and thus help them to meet any commitments they may have to reduce their emissions.