The Feasibility of Grid Connected Solar Dish Stirling Generators within the South West Interconnected System of Western Australia

By

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A dissertation submitted in partial fulfilment of the requirements for the degree of...

MASTER OF SCIENCE (RENEWABLE ENERGY)

Murdoch University School of Energy and Engineering, 2010

PEC624
Declaration and Acknowledgements

Except where other sources have been referenced, this dissertation is a product of my own research.

I gratefully acknowledge the assistance and support of the following people, who helped with the provision of research data and advice;

- Charles Andraka, Sandia National Laboratories, New Mexico USA
- John Relf, Bureau of Meteorology, WA
- Peter Jefferies, 20 kW PV system owner/operator Tenterden, WA
- Ben Williams, System Capacity Analyst, Independent Market Operator, WA

I would also like to acknowledge the input and support of my project supervisor, Trevor Pryor, and of my mother, Caron O’Connor, who passed away during the preparation of this report.
Abstract

The feasibility of using Solar Dish Stirling (SDS) generators to supply renewable energy from distributed installations connected to the South West Interconnected System of Western Australia is assessed using solar resource models for seven sites within the region, and a financial model that calculates payback times and Levelised Cost of Electricity using a Net Present Value methodology for two quasi-commercial SDS systems.

An overview of SDS technology, addressing kinematic and free piston engine designs, maintenance requirements, hybrid operation, heat pipe receivers and system capital costs is presented.

The safety, environmental and social implications of SDS installations, including the potential impacts upon bird life, and the value of a supplementary income stream for rural stakeholders is explored, along with suitable sites for system installation, such as salt affected land.

Grid connection requirements within the SWIS network, including network capacity constraints, network protection, network performance and the structure of the wholesale electricity market, are discussed in the context of distributed SDS deployment. Analysis of the SWIS market data form 2006 to
2010 provides an average daytime balancing price or Marginal Cost Administered Price (MCAP) $0.08AUD/kWh, which is subsequently used in the financial modelling.

Financial modelling using a worksheet developed for this dissertation indicates system payback periods of between 13.4 and 19.2 years and a Levelised Cost of Electricity (LCOE) for Kalbarri of between $0.1184 and $0.3495 AUD/kWh, depending on factors that include the amount of direct solar radiation received, system output and efficiency, maintenance costs, export tariff, government subsidies, and exchange rate.

A series of sensitivity analyses, describing the effects on the results of changes in sunlight hours, export tariff and exchange rate, indicate the feasibility of the systems is most strongly influenced by variations in export tariff and sunlight hours.
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## Glossary

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<thead>
<tr>
<th>Acronym</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUD</td>
<td>Australian Dollar</td>
</tr>
<tr>
<td>CPV</td>
<td>Concentrated Photovoltaic</td>
</tr>
<tr>
<td>DIR</td>
<td>Directly Illuminated Receiver</td>
</tr>
<tr>
<td>DNI</td>
<td>Direct Normal Incident</td>
</tr>
<tr>
<td>FIT</td>
<td>Feed-in Tariff</td>
</tr>
<tr>
<td>IC</td>
<td>Internal Combustion</td>
</tr>
<tr>
<td>IMO</td>
<td>Independent Market Operator</td>
</tr>
<tr>
<td>LCOE</td>
<td>Levelised Cost of Electricity</td>
</tr>
<tr>
<td>MCAP</td>
<td>Marginal Cost Administered Price</td>
</tr>
<tr>
<td>NEMMCO</td>
<td>National Electricity Market Management Company</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratories (US)</td>
</tr>
<tr>
<td>PCU</td>
<td>Power Conversion Unit</td>
</tr>
<tr>
<td>PPA</td>
<td>Power Purchase Agreement</td>
</tr>
<tr>
<td>SAM</td>
<td>Solar Advisor Model</td>
</tr>
<tr>
<td>SDS</td>
<td>Solar Dish Stirling</td>
</tr>
<tr>
<td>SES</td>
<td>Stirling Energy Systems</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>STEM</td>
<td>Short Term Energy Market</td>
</tr>
<tr>
<td>SWIS</td>
<td>South West Interconnected System</td>
</tr>
<tr>
<td>USD</td>
<td>United States Dollar</td>
</tr>
</tbody>
</table>
1. Introduction

Companies in the USA are poised to begin mass production Solar Dish Stirling (SDS) generators and deployment in large installations within the United States by the end of 2010. If the systems prove successful in the US, opportunities exist for their use in Western Australia.

This study aims to assess the feasibility of SDS generators within the South West Interconnected System (SWIS) in Western Australia. In particular, it aims to assess the feasibility of the systems when deployed in small distributed privately owned installations on farmland within the region.

The study consists of an overview of the SWIS network, a solar resource assessment for seven locations located near the margins of the network, an overview of current SDS technology and systems, and a financial model that assesses system payback times and Levelised Costs of Electricity (LCOE) using a discounted cash flow methodology.

A discussion of the potential safety, environmental and social impacts of the systems, suitable sites for installation, and merits of hybrid operation is also included.
1.1 SWIS overview

The South West Interconnected System (SWIS) is the largest interconnected electricity grid in Western Australia. It operates in isolation from NEMMCO, the National Electricity Market Management Company, which administers the electricity transmission grid in the eastern states of Australia. A distance of 1500 km separates the SWIS from the NEMMCO network, making integration of the networks unlikely in the short to medium term.

The SWIS network extends from Kalbarri in the north to Albany in the south, and east to the mining communities in the Kalgoorlie area, effectively encompassing the entire wheat-belt region of WA less the area around Esperance (See Figure 2).

With an installed capacity of 6200 MW (Office of Energy 2008), the SWIS system is small by international standards. Power is supplied dominantly by coal and natural gas, but in the past decade renewable capacity has begun to appear on the system.

A number of wind farms are now in operation, including facilities in Albany (22 MW), Emu Downs (79.2 MW) and Walkaway (90 MW). Together these produce around 5% of peak demand (Morton 2005), a figure that is expected to increase
to 8.9% when the 206 MW Collgar wind project near Merredin comes online in 2011.

Small-scale distributed PV generation, mostly residential grid interactive units, are making a growing contribution to supply. However, as of 2008, PV contributes only 1.7% of the total electricity generation in the SWIS (See Figure 1) (SEDO 2008).

Figure 1: Electricity Generation from Renewable Energy in the SWIS by Source
Source: (Office of Energy 2010)
Figure 2: Regional Extent & Transmission Structure of the South West Interconnected System (SWIS) (Office of Energy 2010)
2. Solar Resource Assessment, SWIS Area

2.1 Climate Overview.

The wheat-belt region of Western Australia is located in the south-west corner of the State between latitudes 28 and 35 degrees south, and has a temperate climate, characterised by cool wet winters and warm to hot dry summers. (See Figure 3)

Rainfall is highest near the west and south coasts, dropping away steadily as distance from the coast increases (See Figure 4). Cold fronts moving up from a
southern westerly direction bring most of the winter rain, resulting in increased cloudiness during the winter months.

Mid-latitude high pressure cells dominate during the summer bringing generally clear, dry conditions.

Tropical cyclones have occasionally affected the region, but are significantly degraded in intensity by the time they reach the area. The last major event was cyclone Ably in April 1978, which skirted the west coast, and brought wind...
gusts of 130km/h to Perth and a maximum recorded gust for the south west region of 150km/h at Albany.

Figure 5 indicates the average number of tropical cyclones affecting the Australian region and shows wheatbelt region of Western Australia receives fewer than 0.1 cyclones annually.

Figure 5: Tropical Cyclone Frequency

Source: BOM (2011)

The strongest winds to affect the region have historically been associated with powerful cold fronts, not tropical cyclones. The Natural Hazard Risk Report for Perth (Xun Guo Lin 2005) indicates a maximum gust for the Perth metropolitan area of 156km/h during the passage of a cold front in August 1963. They also
report wind velocities become significantly attenuated as distance from the coast increases.

Strong wind loadings deform the parabolic structure of dish concentrators, causing flux spillage at the receiver, and reducing system output. If wind speeds continue to rise, the concentrator moves to a stow position to avoid structural damage. The maximum survivable wind speeds vary from system to system, but are generally near 150km/h (O’Grady 2010). Given this, deployment in the wheat belt should be physically practical, with recorded wind speeds being within design limits.

### 2.2 Model Locations

Seven discreet locations were selected for analysis. Sites were selected along the margins of the SWIS where the benefits of distributed generation were likely to be greatest, and real cost of grid electricity highest.

The locations selected are;

- Kalbarri
- Mullewa
- Dalwallinu
- Southern Cross
Kalgoorlie

Hyden

Kendenup

These locations are shown on Figure 6. The sites have a range of latitudes extending from 27° S for Kalbarri, to 34° S for Kendenup. Geographic coordinates for all the sites are contained within Table 1.

Although the climate for all sites is broadly similar, important differences in $K_t$, or clearness index, exist from site to site. Generally northern locations receive more sunlight than those further south, due to clearer sky conditions.

Specific details of the solar resource for each site are contained within the solar resource assessment in the following section.
Figure 6: Model Locations. Map Source: (Google 2010)
### Table 1: Geographic Coordinates of Site Locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude (Decimal Degrees South)</th>
<th>Longitude (Decimal Degrees East)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalbarri</td>
<td>27.71</td>
<td>114.16</td>
</tr>
<tr>
<td>Mullewa</td>
<td>28.54</td>
<td>115.51</td>
</tr>
<tr>
<td>Dalwallinu</td>
<td>30.27</td>
<td>116.66</td>
</tr>
<tr>
<td>Kalgoorlie</td>
<td>30.75</td>
<td>121.47</td>
</tr>
<tr>
<td>Southern Cross</td>
<td>31.25</td>
<td>119.34</td>
</tr>
<tr>
<td>Hyden</td>
<td>32.45</td>
<td>118.86</td>
</tr>
<tr>
<td>Kendenup</td>
<td>34.49</td>
<td>117.63</td>
</tr>
</tbody>
</table>

Figure 7: Average Daily Sunshine Hours.
Source: (BOM 2010)
Figure 8: Average Annual Direct Solar Radiation
Source: (NASA 2010)
### Table 2: Average Direct Solar Radiation for the South West of Western Australia by Latitude and Longitude.

Source: (NASA 2010)

#### 2.3 Assessment Methodology

Incident solar radiation contains direct beam, diffuse and reflected components. Of these only the direct beam component can be concentrated for use in solar dish applications. Therefore, estimating this component for each location is the
first step in assessing the magnitude of the resource available, and ultimately the electrical output of the device.

Three separate methods were used to estimate the direct solar radiation available at each site, in order to provide redundancy and confidence in the data. Each is elaborated below.

**Method 1:**
Method 1 utilised NASA’s online solar resource model to estimate the amount of direct solar radiation received at each of the seven selected locations. The latitude and longitude of each location was entered into the database and direct radiation component retrieved. (See Table 2 & Figure 8)

The direct radiation figures for each location represent the average direct radiation that has been received at the site based on data collected since 1980. The data is satellite acquired, and accounts for cloud conditions. It therefore represents the average daily amount of direct beam radiation, expressed in kWh/m², that could be expected at the site over the year.

**Method 2:**
This approach also used NASA’s online solar resource model, this time applying a cloudiness index to the number of daylight hours at each site. When the daylight hour figure is multiplied by 1-Kt the number of clear sky sunlight hours is produced.
**Method 3:**
This approach used average annual sunshine hours data from the Australian Bureau of Meteorology, logged using Campbell Stokes sunshine recorders. The average sunlight hours for each site was estimated using Figure 7. The BOM methodology uses a 120 W/m² cut off for this measurement.

SDS systems do not require cloud free conditions in order to operate. Unlike some other solar thermal systems, the relatively small thermal inertia of the engine allows it to operate at irradiances as low as 200 watts per square metre, with proportionally reduced output and efficiency (Mancini 2002) (See Figure 9).
2.4 Assessment Results

Data from the Campbell Stokes sunshine hours recorder provides an approximation of SDS system daily engine run times due to a direct physical relationship between the concentrated beam radiation focus by the Campbell Stokes concentrator sphere, and the focus of the parabolic dish concentrator used in solar dish Stirling systems.

However, as mentioned earlier, the BOM sunshine hours measurement has a threshold value of 120 W/m², whereas Stirling engines require a minimum of 200 W/m² to run. Data from the sunshine hours recorder will therefore tend to overestimate the daily 100% output engine run time.

Data collected using Method Two, which is a product of daily sunlight hours and cloudiness percentage for each site, produces the most useful figure for the purposes of this study. It provides an approximation of daily average engine run time at 100% output for each location.
This figure accounts for cloudiness. However, it does not account for periods of low direct radiation early in the morning or late in the afternoon, and so somewhat overestimates the daily run times.

Given the systems all track the sun, these periods are of short duration, and for the purposes of this study are assumed to be of minor significance.

A sensitivity analysis, examining variation in this parameter is presented in Figure 33. It shows that although the sensitivity increases strongly as runtimes are decreased significantly, minor changes of 10% cause variations in payback periods of between 12.7 at 17%, which is not enough to significantly alter the results.

Consequently, the figure produced by Method Two is used in the modelling.

<table>
<thead>
<tr>
<th>Location</th>
<th>Average Annual Daylight Hours</th>
<th>Average Daylight Cloudiness</th>
<th>Average Daily Runtime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalbarri</td>
<td>12.05</td>
<td>44.6</td>
<td>6.68</td>
</tr>
<tr>
<td>Kalgoorlie</td>
<td>12.04</td>
<td>44.9</td>
<td>6.63</td>
</tr>
<tr>
<td>Southern Cross</td>
<td>12.05</td>
<td>48.1</td>
<td>6.25</td>
</tr>
<tr>
<td>Dalwallinu</td>
<td>12.06</td>
<td>43.3</td>
<td>6.84</td>
</tr>
<tr>
<td>Mullewa</td>
<td>12.08</td>
<td>45.2</td>
<td>6.62</td>
</tr>
<tr>
<td>Hyden</td>
<td>12.05</td>
<td>50.8</td>
<td>5.93</td>
</tr>
<tr>
<td>Kendenup</td>
<td>12.05</td>
<td>55.5</td>
<td>5.36</td>
</tr>
</tbody>
</table>

Table 3: Solar Resource Assessment Results
Figure 10 compares the results from the different methods. All produce broadly similar estimates of output.

Figure 10: Solar Resource Assessment Method Comparison Chart
3. Stirling Cycle Overview

The Stirling engine, a type of reciprocating heat engine, is an emerging technology for prime mover applications in the field of distributed power generation.

In a Stirling engine, heat is transferred through the hot end cylinder walls, from an external heat source, to a confined working gas, commonly hydrogen, helium, nitrogen or air. The heat causes the working gas to expand, driving a power piston and converting the expansion to mechanical work via the Stirling thermodynamic cycle (Figures 11 and 12). The hot gas is then passed to the cold end cylinder where heat is absorbed through the cylinder walls causing the gas to contract as heat is transferred to the coolant for rejection. The cool gas is then transferred back to the hot end of the engine allowing the cycle to repeat (Majeski 2002).

A regenerator is used between the hot and cold ends of the engine to temporarily store and release heat from the working gas, maximizing engine efficiency.
Figure 11: Pressure/Volume Diagram of the Stirling Cycle.

Source: Majeski 2002

Figure 12: Temperature/Entropy Diagram of the Stirling Cycle.

Source: Majeski 2002
A large number of discrete engine designs exist, but they may be grouped into two main types, the Alpha type, which uses pistons in independent cylinders to transfer the working gas from hot to cold spaces, and the displacement type engines (Beta or Gamma type) which use a loose fitting displacer piston to push the working gas from hot to cold parts of the engine (Majeski 2002). See Figures 13, 14 and 15 below.

Figure 13. Alpha Configuration.

Source: (Majeski 2002)
Kinematic Stirling engines, which include linkages and a rotating camshaft, may be Alpha or Beta types. Free piston Stirling engines, which have the power
piston, displacer and linear alternator on a single oscillating central shaft, are a 
Beta type of engine (See Figure 16).

What is now termed the Stirling engine, was not invented by Robert Stirling as 
often believed. It is a type of Air engine, that had been developed as early as 
1699, but it is unclear exactly when or by whom it was originally invented 
(SESUSA 2011).
The engine was improved by Robert Stirling in 1816, with a patent that added an ‘economiser’ or regenerator to the engine, increasing efficiency. However, high temperatures at the hot end of the engine and the material constraints of the time made the machines unreliable, and when steam technology began to rapidly progress after the patenting of Bessemer process steel in 1855, interest in the engines waned.

Phillips revived interest in the engine in the 1950s, with a research program to develop a compact, flexibly fuelled generator intended to run the valve radios of the time in remote off-grid areas. Working gases other than air began to be used in the engines, prompting Dr. Rolf Meijer, project manager, to rename them as ‘Stirling’ in honour of Robert Stirling’s contribution (SESUSA 2011).

Although this project greatly improved on Stirling engine design and efficiency, the invention of the transistor eroded the market for such a device, and the program was eventually dropped.

Many of today's kinematic Stirling engines can trace their heritage to engines designed by Phillips during the 1950s (Majeski 2002).
3.1 Efficiency

The large difference between input and output temperatures in Stirling cycle engines allows potentially high engine efficiencies.

In SDS engines concentrated solar radiation is directed at the receiver, heating it to temperatures of up to 1000°C. This heat is then passed through the engine, performing work through the thermal expansion of the working gas, before being rejected from the motor at about 80°C, often using an automotive style radiator system (Majeski 2002).

Efficiency improves as input temperature is increased and coolant temperatures are reduced (See Figure 17). Accordingly, there are ongoing attempts to increase the input temperature. However, material costs increase significantly as temperatures exceed 1000°C, compromising engine affordability.
3.2 Hybrid Operation – Fuel Versatility.

Since Stirling engines are powered by external heat sources, they have outstanding fuel versatility, and when suitably configured are capable of hybrid operation. This capability greatly enhances the flexibility and usefulness of the systems, as when solar energy is available, power can be produced at low cost, while dispatchability and supply can be ensured regardless of cloud conditions or time of day by switching to a different fuel source.
Because heat is applied externally, and combustion occurs steadily at adiabatic conditions, it is possible to use low grade fuels, including material normally regarded as waste to power the engine. Impurities within the fuel, which would result in damage or deposits within spark or compression ignition internal combustion engines can be used to run Stirling engines efficiently and without damage (Majeski 2002). However, some cleaning of the burner surface may be required if dirty fuels are used.

To date solar hybrid operation has been achieved with natural gas, landfill gas, diesel and biofuels, including agricultural waste materials. Such operation requires the use of a specially designed receiver that must be optimised for the characteristics of the selected fuel. However, once this has been achieved the system is able to provide power on demand (Majeski 2002).

In addition to electrical power production, SDS systems can be used in combined heat and power applications, providing additional versatility when installed in suitable locations (Majeski 2002). Similar arrangements have already been made in some of the CPV installations installed in central Australia, where process heat for sewage treatment facilities is provided by the system cooling water.
3.3 Reliability Issues

In order to maximize engine efficiency, engineers aim to operate the engines at the highest possible temperatures. High performance materials are required at these temperatures, and these can present challenges in preparation and fabrication.

High temperature gradients exist across the engine itself, with the hot end often exceeding 730°C, while the cold end is near 80°C. Such strong gradients create stress in materials due to differing rates of thermal expansion.

Such problems can be especially severe in systems with directly illuminated engine heater tubes. In this case any variation in the intensity of the incoming solar flux distribution causes differential heating of the tubes and subsequent variation in their thermal expansion. This reduces the efficiency of the engine as its maximum operating temperature is set by the highest temperature present on the heater tubes, not the average temperature (Moreno 2001). In addition, such uneven heating stresses the tubes themselves as they experience multiple cycles of uneven expansion and contraction over time.

Variations in flux intensity on the receiver can be a result of a number of factors, including mirror slope angle errors, mirror alignment errors, partial shading,
and wind loadings on the concentrator dish causing transient spillage. Reports of uneven flux intensity have also been attributed to patchy dew accumulation on the concentrator at morning startup, although this had only a brief effect and was not considered to be damaging due to the relatively low solar intensity at that time of day (Stone et al. 1999).

More problematic are issues with the internal seals for kinematic engine types. As most commercial Stirling engines utilize pressurised hydrogen or helium as a working gas, materials with a very small nuclear radius, sealing the engine pistons, and for that matter the engine itself can be challenging, and requires exacting tolerances. The high working temperatures and pressures compound the challenges, and to date issues with kinematic engine sealing have been the main constraint in achieving long-term reliable operation (Majeski 2002).

3.4 Kinematic Designs

Kinematic Stirling engine types are the oldest and most developed designs. The power piston in kinematic engines is mechanically connected to an output shaft though a series a camshafts and linkages. The output shaft then drives an alternator to supply electrical output.

Many kinematic different engine designs exist, and this remains an active area of research and development as engineers attempt to improve power transfer
and durability. Within kinematic engines, the oscillation of the moving parts is mechanically coordinated to ensure the proper reciprocating motion during start-up, operation and during load fluctuations, making control easier.

Kinematic engines also have a number of disadvantages. The presence of cranks and rotating parts generate lateral forces inside the motor, and require lubrication, necessitating periodic maintenance. The larger number of moving parts in this design implies a greater maintenance frequency, and potentially reduced reliability.

As described earlier, moving seals are required between the working gas and the crankcase, and this too has implications for service frequency and durability.

3.5 Free Piston Designs

Free Piston Stirling engines are a relatively new design, and were invented in 1971. This engine uses flexure mountings or a gas-filled bounce space to create an oscillating motion, which is transferred along a central shaft to a linear alternator where electricity is produced (See Figure 16). The frequency of the engines oscillation determines the frequency of the linear alternators electrical output.
The Free Piston design has far fewer moving parts than the kinematic design, and does not require moving seals between the working gas and the crankcase. In addition, the linear alternator is enclosed within the engine bell, allowing the entire engine, including the working gas, to be hermetically sealed. Some commercial designs, such as Infinia’s PowerDish system, claim zero maintenance operation over the 25 year life of the engine (Infinia 2010).

The main disadvantages of this design are control and cost. It is essential that the frequency of oscillation within the engine remains within certain specified limits, otherwise the quality of the electrical output is compromised. This can be difficult to achieve, especially when variations in electrical load are encountered.

Nevertheless the simplicity and reliability of free piston designs are compelling, and intensive research in this sector is underway. Infinias 3 kW PowerDish has recently become commercially available for utility scale customers, making free piston systems the first SDS system design to market.

3.6 Heat Pipe and Pool Boiler Receivers

In addition to Directly Illuminated Receivers (DIR), which were discussed on page 26, a number of more advanced receivers are under development.
In order to further enhance the efficiency of SDS systems, and to optimise hybrid fuel operational flexibility, research has focused in recent years on increasing the input temperatures at the receiver. Material constraints prevent a simple increase in solar flux. However, it is possible to increase the average temperature of the receiver by reducing the variations in flux level, allowing the average temperature to increase to the maximum that material properties will allow (Moreno et al. 2001).

Heat Pipe and Pool Boiler receivers attempt to even flux intensity levels over the engines heater tubes. They act as a heat exchange interface between the receiver and the engine, and utilize the evaporation and subsequent condensation of a Sodium or Sodium/Potassium mixture to transfer heat evenly from the receiver to the engine’s heater tubes.

In the case of the Heat Pipe receiver, this is achieved by placing a nickel or stainless steel felted wick within a vacuum enclosure containing a sodium, or sodium/potassium mixture. Heating the receiver melts the alkali metal contained within, allowing it to be drawn up the wick by capillary action, where it is subsequently vaporized. The metal vapour travels across the heat pipe and condenses on the engine heater tubes where temperatures are lower, liberating heat (See Figure 18).
Gravity then returns the condensate to the sodium pool at base of the heat pipe, where is re-used.

This process allows isothermal heating of the engine heater tubes, increasing their average temperature. Engine efficiency improvements of up to 20% are possible (Moreno 2001).

The development of heat pipe systems has proved challenging, and some engineering issues still remain to be solved. The thin metal fibres within the wick tend to become crushed under the weight of the sodium column, creating hot spots, which eventually cause the wick to fail. Problems with the interface
between the heat pipe and the engine itself have also occurred, and are being researched.

The pool boiler receiver operates in a similar fashion to the heat pipe, however instead of using a wick to transport the molten sodium, a pool of sodium, in contact with the absorber surface is heated. The evaporation/condensation heat transfer mechanism is the same in each system, but the sodium inventories differ significantly.

Pool boiler receivers typically contain 5 to 8 kg of sodium, whereas heat pipes generally require under 2 kg (Stine 1994).
4. Prospective Current SDS Systems

Several SDS systems are under development, and one has reached the commercial market, the Infinia 3 kW PowerDish™. Other systems, such as Stirling Energy Systems 25 kW Suncatcher are close to commercial release and are expected to be deployed in large numbers within the south western United States beginning at the end of 2010.

Final approval to deploy Suncatcher™ systems on federally managed land in the Imperial Valley California, was given by the US Interior Department on the 6th of October 2010 (Barringer 2010). However, project commencement is awaiting US federal government loan guarantees, which are expected before the end of 2010.

A US District Court preliminary injunction, placed on the Imperial Valley project on the 16th of December 2010 by the Quechan tribe has further delayed project commencement (Tessera 2010) and it is currently unclear when this issue will be resolved.

Whether these systems are able to be successfully deployed commercially has a large bearing on the feasibility of similar systems within the SWIS in WA, and
therefore a brief review of each, highlighting their strengths and weaknesses, is appropriate here.

4.1 Infinia PowerDish™

4.1.1 Technical Overview

The 3 kW PowerDish™ system uses a propriety free-piston engine with flexure bearings driving a 240 volt 50 or 60 hertz linear alternator.

The dish concentrator has a diameter of 4.7 meters and has an approximate parabola configuration (See Figure 19).

4.1.2 Capital Costs

The 3 kW PowerDish™ retails for $US26,000, and this figure has been utilised in the system modelling worksheet.

Infinia claims the system requires no maintenance over its 25 year life apart from mirror cleaning, which is nominally required once per month, depending on the system location. System modelling assumes mirror cleaning is conducted monthly.

The PowerDish™ parks itself in a mirror down position after sunset to reduce dust accumulation and extend the period between mirror washings. It also
detects wind loads upon the concentrator, putting itself into a low drag position when wind speeds exceed a threshold value for a defined period of time.

In addition to the PowerDish™, Infinia is developing a 30 kW system based on its free-piston engine design. The larger system utilizes a series of discrete 3 kW engines arranged in a vertical radial cluster to achieve the higher power output.

The PowerDish™ began commercial deployment in July 2010.
4.2 SES Suncatcher™

The Suncatcher™ has a long developmental history. Concentrators developed by McDonnell Douglas and a 4 cylinder Kockums 4-95 kinematic Stirling engine were first mated in 1983 as part of a US Department of Energy program, which
saw eight 25 kW units constructed and deployed in various locations within the United States.

By 1984 the systems had set the world record for solar conversion efficiency at 28.25% a record which stood until 2008 when a highly precise Suncatcher set a new record of 31.25% on an extremely bright and cold Arizona day (Sandia 2008).

McDonnell Douglas divested itself from the development of the systems in 1988, and ownership was passed to Southern California Edison, who after several years left the systems idle. In 1996 the rights to the technology were sold to SES who began a program of intense development, with a view towards the commercialisation of the technology (Andraka 2008).

SES obtained the rights to solarize the 4-95 engine from Kockums, and embarked on a program, together with Sandia National Laboratory, to simplify the motor and concentrator to increase reliability and reduce costs. This program produced a new Mk2 version of the Suncatcher™ with a lighter, simpler concentrator and enhanced motor. Sixty of these devices, producing 1.5 MW, have been commercially deployed in Peoria, near Phoenix, Arizona, and are presently in operation.
Mass production of the Mk2 Suncatcher™ is expected to begin towards the end of 2010 in order to supply the units needed for two large scale SDS power developments in southern California.

Construction of the 709 MW Imperial Valley facility, requiring 28,360 Suncatchers™ is expected to commence in 2011, with completion scheduled for 2012. An additional 100 MW facility at Calico in California is will also use Suncatchers™ during Phase 2 of the project, although, as of January 2011, it is unclear when construction will begin.

4.2.1 Technical Overview

The Suncatcher™ utilizes a solarized version of the 25 kW 4 cylinder Kockums 4-95 kinematic Stirling engine, originally developed for stationary power applications. The Mk2 unit uses a simplified 10 meter diameter concentrator dish, with 40 mirror facets, of 2 discreet types, arranged radially, and covering an area of 91 square meters (See Figure 20).
The power conversion unit, comprising the receiver, Stirling engine, cooling system and control electronics, is mounted on a boom at the focal point of the dish. The system uses directly illuminated engine heater tubes, which heat the hydrogen working gas to 730°C before passing it into the cylinders. Cooling is provided by an adapted automotive radiator system running at 80°C.

System control is provided by a microprocessor driven monitor and control system which supplies data in real time to a remote operator. Often system error
messages and problems can be addressed remotely, without on ground intervention.

4.2.2 Capital Costs

Accurate costings for the pre-production models are not publicly available, however several studies have been able to estimate system capital costs, and most agree the prototype units cost close to $US250,000.

The $US2.1 billion Imperial Valley project will use 28,360 Mk2 Suncatcher™ units in a 26 km² area, to generate 709 MW (Renewable Energy World, 2010), giving an installed cost of $US74,048 per 25 kW Suncatcher™ unit. This figure is utilised within the modelling worksheets.

4.2.3 Availability

A total of 68 Suncatchers™ have been produced (as of September 2010), 60 of which are Mk2 units commercially on-line at a 1 MW facility outside of Phoenix Arizona. The other 8 are prototype units built during the 1980s and installed for research purposes at Sandia National Laboratories in Arizona and at Huntington Beach California.

Commercial production of the Mk2 units has not yet commenced, although based on SES press releases it is imminent. Large scale orders, consisting of tens of thousands of units have been placed by power utilities within California and
Texas. However orders are not yet being taken from the general public or other small-scale consumers.

Assuming mass production does go ahead as planned, and system performance is as anticipated, expanded availability could be expected within several years, and the potential for Australian deployment increases.

4.2.4 Maintenance Requirements

- **Oil change requirements.** The Kockums 4-95 Stirling engine is a reciprocating kinematic design, and has a number of internal moving parts including piston rods and a camshaft. It uses a synthetic oil for lubrication, which is tolerant of the high temperatures that exist within parts of the motor.

As with all reciprocating engines, regular oil changes are required. Kockums states that the 4-95 can operate for up to 18,000 hours before service is required, although this refers to a non-solarized version of the engine, and actual service intervals are likely to be more frequent. Nevertheless 18,000 hours represents over 8 years of operation assuming a run time of 6 hours per day in a solar application (Majeski 2002).
For the purposes of system modelling oil changes are assumed to
occur monthly.

**Coolant.** The PCU on the Suncatcher™ uses a modified ethyl glycol
automotive radiator for cooling. As such, periodic changes of coolant
will be required, at approximately the same intervals as would be
expected in automotive applications. For the purposes of system
modelling coolant changes are assumed to occur monthly.

- **Engine overhaul frequency.** The sliding seals within the engine
  require overhaul when they become worn. This can be detected by
  monitoring working gas pressure. If hydrogen pressure begins to
  build up within the crankcase, when the system is offline, it is likely
  the seals need to be replaced. This is best achieved by the removal of
  the PCU, and its replacement with another unit, as opposed to
  attempting to fix the seals on site.

  The exact frequency of seal replacement is unclear, but is likely to be
  approximately once every 5 to 10 years. For the purpose of modelling
  PCU overhauls are assumed to occur every 10 years.
- **Mirror cleaning.** Keeping the mirrors clean has a direct tangible relationship to system efficiency and performance. The frequency with which mirror cleaning is required is highly site specific and varies with atmospheric dust levels, wind conditions, frequency and intensity of rainfall events, and the off-sun stow position of the concentrator.

Generally, mirror cleaning is required about once per month, when mirror reflectivity drops below a threshold value, commonly 75%. More frequent cleaning enhances system output, but increases O&M costs. Therefore, a site specific optimal point exists for each facility.

Modelling assumes mirror cleaning is conducted once per month.

Cleaning is performed using a high pressure cleaner mounted in a truck, and controlled by the driver. This method is quick and efficient, taking several minutes to complete per dish. Cleaning agents contained within the water enhance the effectiveness of the operation.

- **Specialised personnel requirement.** Although specialist personnel are required to overhaul and troubleshoot the engines, most regular maintenance tasks can be performed by non-specialized trained
personnel. Engine oil changes, coolant changes and mirror washing require no detailed knowledge of Stirling engine design and operation, and can be carried out by site-trained personnel.

Even tasks such as removal and installation of PCUs, do not require specialized personnel. However training would be necessary to ensure reliable and consistent results.

- **Tracker maintenance.** The concentrator tracks the sun in two axes to ensure optimal performance. Regular maintenance of the tracker entails the lubrication of moving parts, and could be expected once every 12 months.

**4.3 Opportunities for Energy Storage**

Because Stirling engines are capable of hybrid operation, and are, as a result, potentially dispatchable, energy storage is not as critical as it is for some other renewable technologies, such as wind or PV.

Using a hybrid receiver, a Solar Dish Stirling system can, if strategically positioned, utilize another fuel source, such as natural gas, landfill gas or diesel, to provide power regardless of weather conditions or time of day. The high efficiency of the system is achievable regardless of the fuel utilized.
Additionally, combustion used to heat an engine’s receiver occurs as a continual process, at a chosen temperature and pressure, providing predictable results.

In contrast, IC engines burn fuel in a series of explosions where the temperature and pressure in the cylinder are continually varying. As a result, combustion is less controlled and often less efficient.

Furthermore, the relatively poor combustion control in an IC engine results in increased emissions relative to that achievable using a hybrid Stirling engine (Majeski 2002).

Although not specifically tested in this study, it is likely that energy storage options for SDS generators are significantly more expensive than hybrid operation of the devices. However, if hybrid operation is not feasible, then a range of energy storage options, similar to those use in other renewable systems are possible. These include:

- Flywheel Storage.
- Thermal Storage
- Battery Storage
Research conducted into the economics of storage in grid connected concentrating solar thermal power stations (Johnson 2009) focuses on large scale solar trough and power tower approaches, which are unlikely to be necessary or economic in the case of relatively small scale Solar Dish Stirling generator installations.
5. Grid Connection Requirements

Connection to the SWIS network must be in accordance with Western Powers’ Technical Rules, which specify acceptable power quality parameters for grid connected generators.

Since most systems utilise conventional induction generators, with well known characteristics, power quality issues are unlikely to be problematic. The presence of harmonics within the power output, as is typical in inverter based renewable energy technologies, such as PV and CPV, is not an issue with Stirling engine based systems.

As a result of the thermal inertia present in Stirling engine solar generators, some degree of output variation smoothing occurs following the obstruction of direct sunlight in response to cloud passage. Instead of an extremely rapid change in power output, as would occur with PV or CPV, SDS generators wind down over several minutes as the engine cools (Lopez & Stone 1993).

When direct sunlight resumes, a similar thermal lag occurs, and output increases gradually as the engine returns to its nominal operating temperature.
Such gradual changes in output reduce transient power flows in the grid, enhancing power quality for consumers and reducing effects such as flicker. Performance in weaker areas of the grid is likely to be improved as a result making SDS systems a good candidate for installation near grid margins.

In small regional grids, isolated from the SWIS, gradual changes in output are particularly attractive, as they provide time for hybrid fuel burners or diesel generators to come on line to meet the load.

5.1 Network Constraints

The SWIS network has been designed to transport power from the main generating plants near Collie, to customers in the Perth metropolitan area, and to regional areas in a unidirectional fashion, for the lowest possible cost.

Consequently, the grid margins are weak in some areas, and are unlikely to be able to support the large bi-directional power flows that would be created by significant renewable capacity installed in these areas.

Assessment of the networks capability to support proposed renewable energy project development is vital, and will limit the size and location of these projects. Network augmentation, such as the Pinjar transmission line project,
adds capability to the system in the northern wheatbelt area, and makes this part of the SWIS more attractive for large scale projects.

In areas with weaker grids, smaller scale installations are still possible, and are likely to be beneficial, provided they are appropriately sized and located. A network analysis by Western Power to assess the capability of the local network to absorb renewable energy generation is required before undertaking project development.

5.2 Network Protection & Performance Standards

All distributed generation facilities are required to operate within the network protection and performance guidelines outlined in Western Powers Technical Rules document (Western Power 2007).

The rules specify a number of parameters which generating units are required meet to ensure the safe and reliable operation of the network. Issues including islanding avoidance and frequency and voltage limits are addressed in the rules.

Adapting SDS units to meet these requirements does not present a significant challenge, and should not cause delays to any potential deployment on the SWIS.
5.3 SWIS Electricity Market

Electricity market reform in Western Australia was carried out in 2006, and has introduced a market based system for the sale and pricing of electricity in the SWIS.

Provisions were included in the reforms to encourage generation from distributed renewable sources. Whilst major conventional suppliers must provide the Independent Market Operator (IMO) a statement of output days in advance, the intermittent nature of renewable generators is recognised by the legislation, and these suppliers are allowed to sell their full output to the market whenever it is being produced.

Electricity can be sold through negotiated Power Purchase Agreements (PPA), to power wholesalers, such as Synergy, or to the IMO for sale on the Short Term Energy Market (STEM).

PPAs provide renewable generators with greater financial certainty as the value of the power produced is negotiated in advance and applies for the term of the agreement.
As a negotiated agreement a PPA involves discussions with a number of interested energy wholesaler and requires substantial legal input. Agreements may take months to be concluded, specify amounts of electricity available for sale, and times when supply may be available.

Electricity may also be sold through the IMO on the STEM. This approach requires no contractual arrangements. However, the price paid is volatile, and financial security for suppliers is reduced.

The electricity spot price on the STEM varies with demand upon the SWIS. At times of elevated demand, such as during hot summer afternoons, the spot price increases reflecting the increased cost of generation using peak provision gas turbines.

In order to simplify economic analysis, this study assumes the SDS systems will operate in a solar only mode. The value of the electricity generated is therefore based on the MCAP during the period when the machines are likely to be operating, that is, during daylight hours, nominally from 0600 to 1800.

This period corresponds loosely with the morning peak and shoulder periods, and includes early portions of the summer peak.
6. Installation

6.1 Suitable sites

SDS units have a high degree of flexibility in where they are installed. Most systems, including the Suncatcher and PowerDish, are mounted on a single pole that stands several meters above the ground, reducing the footprint of the device, and making its presence more amenable to other land uses.

Some prototype research systems, such as the Eurodish, utilize a circular tracking ring, to enable azimuthal tracking. Although this is a simple and stable arrangement, it increases the footprint of the device, and restricts its installation to flat or nearly flat areas.

Because of the relatively small footprint of pole-mounted units, there is potential in a Western Australian context to allow some limited agricultural land use, such as sheep grazing, in the vicinity of the installation. Such multiple land uses would increase the attractiveness of the systems if they were to be deployed on agricultural land, as they would have less impact on the farmers’ core business.
Relatively low value salt-affected land may also be suitable for system installation, providing the site does not flood, and can be accessed effectively. In these locations site works may be more expensive. However, the land itself is cheap, and currently without a productive use.

Sloping land is also suitable for SDS installation, provided that the slope angle is not so extreme that it causes the concentrator to interact with the ground as it tracks the sun.

Suitable sites will be located within a reasonable distance from current power transmission infrastructure. This distance will vary as the size of the installation varies, with larger installations warranting longer transmission line runs. For small installations, with an output of under 100 kW per hour, suitable power lines should be no further than several hundred meters away.

If hybrid operation is desired, the fuel source must also be conveniently located. In Western Australia, areas within several kilometres of existing natural gas pipelines are especially attractive. Likewise, remote areas of the state, such as the Telfer Gold mine, which have large energy demands, high energy prices and access to natural gas, are likely to be potentially viable.
A very wide range of more exotic hybrid fuel sources are possible, including various types of biomass, sewerage sourced methane, diesel and biodiesel.

SDS also have the potential to supply process heat to a variety of applications as part of a CHP arrangement.

The mirrors used in solar dish concentrators are normally made of glass, as this material provides the highest level of reflectivity, with proven performance and durability over time. Some experimental systems such as the Cummins 10 kW Advanced Dish Project utilized a reflective stretched polymer membrane positioned over metal hoops, that when partially evacuated approximated a parabola to concentrate light.

This innovative system was found to have insufficient durability for commercial use, and problems due to the decoupling of the metallised reflective coating from the polymer, caused the technology to be dropped in the late 1990s.

Since that time materials have been improved, and future systems may again use polymer reflectors, however, current systems are based on glass or metal parabolas. The presence of glass mirrors raises the possibility of damage due to hail or vandalism. Some designs, including the PowerDish, park the dish in a facedown position after the sun sets, to reduce the risk of hail damage and rate
of mirror dusting. This approach also reduces the risk of mirror damage through vandalism, as the outside surface of the dish is a durable material.

Other systems, such as the Suncatcher, cannot park face down, and therefore are somewhat vulnerable to large hail events and to vandalism. It is unlikely that such devices would be placed in areas of uncontrolled public access, for reasons of safety and security, and this factor alone may reduce the risk of vandalism to acceptably low levels.

6.2 Methods and Technique

SES has provided a video documenting the installation of its Mk2 Suncatcher units on its website. The installation is extremely rapid with an adapted drill rig acting as a pile driver to ram the central mounting pole into the ground, without requiring the use of a concrete footing. A crane is subsequently used to lower the concentrator truss and boom on top of the pole, following which the PCU is installed on the boom and the mirror facets fixed.

Mirror alignment is checked after the installation of the facets to confirm its accuracy, prior to system commissioning.
6.3 Safety, Environmental and Social Impacts

Although SDS systems are a relatively benign electricity generation technology, some safety, environmental and social impacts would arise from their widespread deployment.

Extremely intense solar fluxes, which may exceed 7500 suns (Fraser 2008), exist near the focal point of the concentrator, close to the PCU. These represent a potential hazard to personnel when the system is on-sun, especially those who are unaware of the risk. Even transitory exposure to the flux near the focal point would result in serious burns, and the potential for fatal exposure exists if access to the devices was unconstrained.

The presence of intense concentrated sunlight is, however, obvious to ground observers. The receiver itself is brightly illuminated, and the concentration of the flux increases steadily as the focal point is approached, reducing the chances of unanticipated exposure to highly concentrated light.

A number of environmental risks also exist with the devices, again related to the presence of high intensity solar fluxes. Although no specific work has been conducted, there is a risk that wildlife, in particular birds, may be attracted to the mirrors arranged on the concentrator. If they were to interact with the
mirrors themselves, no significant danger would exist. However, if they flew too close to the focal point, they would be fatally burned.

Birds have good vision and may recognize the risk posed by the intense solar fluxes, but this has not been established, and the actual impact on birds, especially in an Australian context is currently unclear. Some experience may have been gained during the operation of the CPV systems in central Australia which face similar issues, but it is clear that careful monitoring prior to large-scale system deployment would be required.

Hydrogen or helium gases are commonly used as working gases in Stirling engines to maximize engine efficiency. Hydrogen in particular allows high efficiency operation. Leakage of hydrogen from the system occurs virtually on a continual basis, although the volume of gas released is extremely small and is rapidly dispersed (Byron and Renaud 2010). However, some risk of ignition does exist, especially if a leak develops in the gas line that runs from the make up tank to the engine. Therefore, it is important to put procedures in place to adequately manage this risk.

If an alkali metal heat pipe receiver is used with the system, there is a risk of a sodium fire if vacuum containment is breached. Exposure of the sodium to atmospheric oxygen will cause ignition, and destruction of the heat pipe.
Social impacts would vary with the scale, location, and nature of deployment. Large-scale plants consisting of hundreds or thousands of units, would require the employment of a number of workers to perform routine maintenance tasks, such as mirror cleaning. Specialised operators would be required to oversee the operation of the plant, however this task does not necessarily need to be based on site.

Smaller scale installations, perhaps privately owned and managed on rural land, could be owner managed. Routine maintenance could also be carried out by the owner. More specialized maintenance or service work could be outsourced to a qualified independent contractor.

It is difficult to predict the full scope of the social impact of such devices at such an early stage, however, if the devices prove to be commercially viable in Western Australia, then large numbers may begin to appear on the SWIS within the next 20 years, and private distributed power generation may become an important source of supplementary income, especially for rural land owners.

The possibility of a HVDC link connecting the SWIS and NEMMCO grids, although not likely for at least a decade, may make large scale renewable energy installations, including SDS systems, viable in the Nullarbor plain areas of
Western and South Australia, with consequent economic advantages for indigenous Australians and others.

The aesthetic impact of SDS installations is likely to be comparatively minor, as the devices are generally less than 11 meters tall, do not require positioning in elevated locations as is typical with wind farms, and present a form similar to a satellite dish, which is familiar and well received by the public. Installations do have the potential to be very large, and at this scale may draw public objection.

All Stirling engines produce some audible noise, although this is generally far less than comparable IC engines. As the Stirling engine has no valve train, explosions or exhaust, noise levels are generally less than 65 dB, the level of a normal conversation. Although this noise level may preclude the systems from suburban areas, in most locations it will be within acceptable limits.
7. Financial Modelling

Two approaches were used in the financial modelling.

As the paper was originally conceived in part to investigate the feasibility of small-scale, privately owned SDS systems deployed on farmland, it was decided to utilise payback period as the primary focus of the modelling. This approach provides an immediate, intuitive parameter with which to assess the feasibility, or otherwise, of the systems.

The second approach utilised LCOE to allow a comparison of the cost of power produced over the lifetime of the system with other technologies.

7.1 SDS System Selection

Financial modelling was conducted for two systems, the 25 kW SES Suncatcher™ and the 3 kW Infinia PowerDish™. These systems were selected due to their commercial or near commercial status, which allowed accurate system pricing to be obtained.

7.2 SDS System Cost Calculation Methodology

Acquiring costing data for the systems was problematic as figures are not supplied directly by the manufacturers. However, per unit costs were able to be
derived indirectly, through general and renewable energy industry press reports.

In the case of the SES Suncatcher, a story in the New York Times (Barringer 2010) quotes a total price for the 28,360 dish, 709 MW Imperial Valley SDS project of $US2.1 billion, equating to an installed per unit cost of $US74,047.

Costs for the Infinia PowerDish were obtained in a similar fashion, with the Tri-City Herald of Richland, Washington State USA reporting an agreement to install 14 PowerDish units at a cost of $US350,000, equating to an installed cost of $US26,000 per unit (Joshi 2010).

7.3 **SWIS STEM Electricity Price Calculation Methodology**

It was decided to use the Short Term Electricity Market MCAP for the financial modelling of both systems. This represents a realistic minimum price that could be obtained for the electricity produced by the units. The market data, divided into 30 minute trading intervals, was obtained from the Independent Market Operator (IMO) and sorted to provide an average STEM price and MCAP, from 0600 to 1800 for the period 20 September 2006 to 17 June 2010. This analysis indicated an MCAP of 8 cents per kilowatt hour could be expected and this figure was subsequently used in the models for each site.
7.4 Modelling Methodology

Two approaches were used to model the performance of SDS systems at selected rural locations within the SWIS in order to compare the results of both approaches and improve analysis confidence.

7.4.1 Solar Advisor Model (SAM)

The U.S. National Renewable Energy Laboratory (NREL) produces a renewable energy system modelling application, named Solar Advisor Model (SAM). This application contains a broad range of modelling tools for many types of solar energy systems, including for SES Suncatcher™ Solar Dish Stirling systems.

A large number of parameters can be entered into the model, including climatic, economic and technological variables, in order to produce data outputs including:

- Annual Electrical Production
- LCOE over entire system life
- System payback times
- NPV
- System output derating over time
The climatic data available for SAM covers the United States in detail. However, it is much more limited for sites outside the US. Western Australia is represented by two sites, Learmonth and Perth. In this case, the Perth climatic data was used for the analysis, as it is the most similar to the selected wheatbelt locations.

7.4.2 SDS Modelling Spreadsheet

The second technique used to model the performance of the SDS systems utilised a series of spreadsheets developed for this dissertation. The worksheets calculate and graph LCOE, system payback time and NPV from a series of inputs, which are outlined below:

- Capital Cost of PCU
- Capital Cost of Concentrator
- Installation Cost
- Peak output (kWh)
- PCU Service period (mth)
- PCU overhaul period (yr)
- Receiver lifetime (yr)
- Working Gas tank refill period (yr)
- Concentrator mirror cleaning period (yr)
- Currency exchange rate AUD/US
- Discount Rate
- Inflation Rate
- Analysis Period
- Electricity export tariff ($/kWh)
- REC Value $/MWh
- Tax Deductibility (on/off toggle)
- WA Govt FIT (@0.47$/kwh) (on/off toggle)
- Average Daily SDS Operating Hrs (hrs/d)

A worksheet was created for each of the selected locations using the results of solar resource assessment contained in Section 2.4, to provide an estimate of the average daily operating hours (@100% output) that could be expected at the site, and therefore the system power output.

The sensitivity of the model to changes in input parameters was investigated, and a series of charts summarising these changes produced. Special attention was paid to the effects of changes in electricity export tariff and exchange rate. These charts are included in the results section.

A digital copy of the worksheet is included in the appendix.
7.4.3 Levelised Cost of Electricity Methodology

Kalbarri was chosen for LCOE analysis. The LCOE calculations focus specifically on the costs of electricity production over the system life and therefore exclude earnings from the sales of electricity, RECs, tax deductions, and feed-in tariffs.

LCOE was calculated for the SES Suncatcher and the Infinia PowerDish systems.

An example calculation methodology follows, in this case for the Suncatcher system;

For a 30 year analysis period…

- Total Net Present Cost = $-83137
- Units produced over 30 years = 30(yrs) x 365(days) x 6.68(Kalbarri hours average daily runtime) x 25( kW output) = 1,828,650 kWh
- NPC of electricity = $-83,137 / 1,828,650 = $0.0455 / kWh
- The PWF with an analysis period of 30 years, a discount rate of 8% and an inflation rate of 2% = 11.483.
- The discounted number of units produced = 365 x 25 x 6.68 x 11.483 = 699,946 kWh.
Therefore the levelised cost of electricity is $83,137/699,946 = $0.1188/kWh.
8. Results & Discussion

The results of the analysis, focusing on the system payback times and LCOE are presented below as a series of charts and tables. It was decided to utilise the SDS modelling spreadsheet for the calculations and charting as it more readily accepts the available solar and climate data for the study region, and operates in a more transparent manner.

A comparison of the results between SAM and the SDS Modelling Spreadsheet indicated broad similarities between both approaches.

8.1 System Payback Times by Location

Table 4 shows the system payback times for each modelled location. A number of assumptions were made in the calculations. These are:

- Export tariff set at $0.08 per kWh
- System Run times @ 100% output = Direct sunlight hours
- $AUD/$USD set at parity. (accurate 20 October 2010)
- Systems are tax deductible, with equal annual deductions over 30 years
- REC value = $40/MWh
- WA state government FIT applies for 10 years @ $0.4/kWh (only for PowerDish + FIT model)
<table>
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<tr>
<th>Site</th>
<th>Suncatcher Payback years</th>
<th>Powerdish + FIT Payback years</th>
<th>Powerdish - FIT Payback years</th>
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<td>21.0</td>
<td>NA</td>
</tr>
<tr>
<td>Kendenup</td>
<td>19.2</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 4. System Payback Times

Figure 21. Years to System Payback for Modelled Locations.

(Note: The PowerDish System fails to achieve payback in Kendenup within the 30 year modelling period)
Payback times are a function of system cost, maintenance costs, system power output, value of power produced and amount of direct solar radiation received at a site. Given the assumptions outlined above, payback time is shortest at sites with the most solar radiation.

Among the sites modelled, Dalwallinu, in the northern wheat-belt has the shortest payback time, at 13.4 years for the Suncatcher™ and 14 years for the PowerDish™ + FIT.

The longest payback periods were found at the least sunny location, at Kendenup. Here, the payback time for the Suncatcher™ was 19.2 years. The PowerDish™ failed to achieve payback in this location, with or without a state government FIT.

In all other locations the PowerDish™ system achieved payback only when the state government FIT was applied. Without this subsidy, the system never breaks even when modelled using a discounted cash flow methodology.

A series of charts summarising the results for each location is presented in order of increasing payback time in the following section.
Figure 22. Payback Times at Dalwallinu

Figure 23. Payback Times at Kalbarri
Figure 24. Payback Times at Kalgoorlie

Figure 25. Payback Times at Mullewa
Figure 26. Payback Times at Southern Cross

Figure 27. Payback Times at Hyden
8.2 System LCOE at Kalbarri

The Levelised Cost of Electricity for Kalbarri was calculated to be $0.1188/kWh for the Suncatcher™, and $0.3506/kWh for the PowerDish™. The methodology used assumes 6.68 hours of run time per day, and no income, tax deductions, or government subsidies for the units.

Maintenance costs such as PCU and receiver overhauls and mirror cleaning are included.
8.3 System Payback Times when Export Tariff is Varied

A sensitivity analysis for the Kalbarri location was conducted to investigate the impact of changes in export tariff on the model. The tariff was changed relative to a nominal rate of $0.08/kWh, which the study of the Short Term Energy Market indicated was an average for the SWIS for the period 20 September 2006 to 17 June 2010 (See section 7.3).

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Figure 29. Sensitivity of Payback Period to Changes in Export Tariff at Kalbarri
Figure 29 shows that the Suncatcher™ is more sensitive to tariff changes compared with the PowerDish™ due to its higher capital costs, and greater power output, and higher maintenance costs.

Figure 30 displays how the payback period, as expressed in years, varies as the export tariff is changed. Both systems show fairly low sensitivity to changes in export tariffs from $0.12 to $0.25 cents per kilowatt hour, however sensitivity increases strongly as tariffs fall below $0.12/kWh.
8.4 Sensitivity of System Payback Times to Changes in Exchange Rate

The Australian dollar has appreciated strongly relative to the United States dollar during 2010. Since both the Suncatcher and PowerDish systems are manufactured in the United States, variations in the exchange rate impact upon the results of the study, and need to be considered in a sensitivity analysis.

Figure 31 summarises the sensitivity relationship. Changes in exchange rate relative to a nominal value of parity between the US and Australian dollars (accurate as of late October 2010) are plotted versus percent change in payback years for both the Suncatcher™ and PowerDish™ systems.

A reduction in the value of the Australian dollar has a strong effect on the system payback periods. When the AUD is reduced in value by 20%, the payback period of the Suncatcher increases by 29%. The PowerDish is affected even more strongly, with a similar reduction in the AUD producing a 50% increase in payback period.

The steady increase in the value of the Australian dollar during the period of the study has significantly increased the affordability of the systems within the Australian market.
Further increases in its value will continue to improve affordability, although at a reduced rate. A 10% increase in the value of the AUD will improve payback periods by 7% for both systems.

Figure 31. Sensitivity of Payback Period to Variations in Exchange Rate at Kalbarri

8.5 Sensitivity of LCOE to Variations in Exchange Rate

Variations in the exchange rate also impact upon the LCOE. The sensitivity of the LCOE to the exchange rate is described in Figure 32.
The relationship is nearly linear, with the effect being similar for both of the systems modelled. As the Australian dollar strengthens relative to the US currency, the LCOE falls. A 10% increase in the value of the AUD, produces a 7.5% reduction in LCOE.

![Sensitivity of LCOE to Changes in Exchange Rate](image)

Figure 32. Sensitivity of LCOE to Variations in Exchange Rate at Kalbarri

### 8.6 Sensitivity of LCOE to Variations in Direct Solar Radiation

Changes in amount of direct solar radiation have a large impact on LCOE, as can be seen in Figure 33.
The chart shows how the LCOE changes as the solar radiation is varied from its average daily value, in this case at Kalbarri.

The effect is especially strong when the solar radiation value is reduced by 50% or more, with the LCOE increasing at an exponential rate. Reductions in solar radiation of less than 50% have a far less dramatic impact.

Increases in solar radiation steadily reduce the LCOE, for both modelled systems. The Suncatcher™ has a consistently lower LCOE compared to the PowerDish™, with the effect being most pronounced at lower levels of solar radiation.

Figure 33. Sensitivity of LCOE to Variations in Exchange Rate
8.7 Sensitivity of Payback Years to Variations in Daily Runtime

Changes in daily engine run time, cause large changes in the time taken for system payback. This is illustrated in Figure 34. In this case, a 10% decrease in average daily runtime results in a 0.9 year increase in payback time (12.7%) for the Suncatcher™ and a 1.6 year increase for the PowerDish™ (17%).

This result indicates that assumptions made regarding the effects of disregarding low engine outputs for short periods early in the morning and late in the afternoon are probably justified.

Figure 34. Sensitivity of Payback Years to Variations in Sunlight Hours at Kalbarri
9. Conclusions, Risks & Further Studies

Solar Dish Stirling generators are moving from the research and development stage to being a commercially deployed power generating technology. Two sites in the desert southwest of the United States will soon begin producing 1.5 gigawatts of electricity from nearly 60,000 25 kW Suncatcher™ dish units.

Mass production of these systems will reduce their price and lead to availability outside of the United States, probably within the next few years.

Smaller free piston engine designs, such as the 3 kW Infinia PowerDish™, have reached commercial status and promise long service lives, with high reliability and low maintenance.

The available solar resource, especially in Western Australia’s Pilbara, northern wheatbelt and eastern goldfields regions, is broadly similar to that found in the areas where deployments are planned in the US, indicating installations in these regions are likely to be feasible.

Indicated payback times for Suncatcher™ units range from 13.4 years in Dalwallinu to 19.2 years in Kendenup, a site with significantly less solar radiation. For the PowerDish™, payback times range from 14 to over 30 years.
respectively, at the same locations. It should be noted that the PowerDish payback period is influenced by the application of WA state government FIT, which is not available for the larger Suncatcher unit. In cases where the subsidy is not applied, the PowerDish fails to achieve a positive NPV.

The payback periods indicated suggest marginal feasibility when the systems are deployed in rural wheatbelt locations. Increases in the wholesale electricity price, or a reduction in system capital costs would need to occur before investors would find the units attractive.

Large scale megawatt class deployments are more likely to be economic, especially in areas such as the eastern goldfields and northern wheatbelt, which have a good solar resource and are located far from conventional generation facilities.

The potential to run SDS systems using hybrid fuel operation has much potential, but is still a number of years off commercial viability. In particular, the development of reliable and durable commercial heat pipe receivers remains to be achieved.
Once such devices are ready for commercial operation, a huge range of fuels become available for SDS systems, providing dispatchability, versatility and increased system efficiency.

Many areas of Western Australia would benefit from the hybrid operation of the devices, especially considering the large natural gas resources and gas distribution network in the state.

**9.1 Risks**

As an emerging technology, SDS systems are not yet commercially field proven. Several years of operation at the Imperial Valley facility in California, and at other planned facilities, should help reduce uncertainty regarding the economic performance of the technology.

In particular, proving the long term reliability of the machines in commercial applications will reduce uncertainty regarding maintenance costs, and ultimately delivered energy costs.

Exchange rate variations have a significant impact on the cost of the technology in an Australian context. Continued strength in the Australian dollar relative to the US currency will make US manufactured units more attractive for deployment in Australia.
Falls in the value of the AUD after project commitment risks cost escalation, and a increases the LCOE and project payback periods.

9.2 Further Studies

Monitoring the success or otherwise of the facilities now approved for construction in the United States will help further establish the potential of SDS technology in WA.

Whilst this paper focused on the potential for grid deployment on the SWIS network, the systems may also be viable in remote parts of the State, including at some of the many mine sites and isolated communities, that currently have very high energy costs.

If the systems are to be considered for deployment on the SWIS, or in other WA locations, the installation of a demonstration unit would be the logical next step. This would enable the local performance of the systems to be tested and lead to increased confidence in their suitability for expanded use.
10. References

Andraka, C. (2008). Dish Stirling Reliability Improvement and Commercialisation, Sandia National Laboratories, Albuquerque, New Mexico, USA


Geoscience Australia. (2010). Australian Cyclone Tracks


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11. Appendix

A data disk containing the appendices is included with the bound copy of this document. It contains the following files:

- SDS_feasibility_SWIS.pdf
  An PDF version of this document.
- SDS Modelling.xls
  Amended solar resource, power cost, financial and sensitivity models.