AUSTRALIAN COMPANION GUIDE TO SAM FOR CONCENTRATING SOLAR POWER

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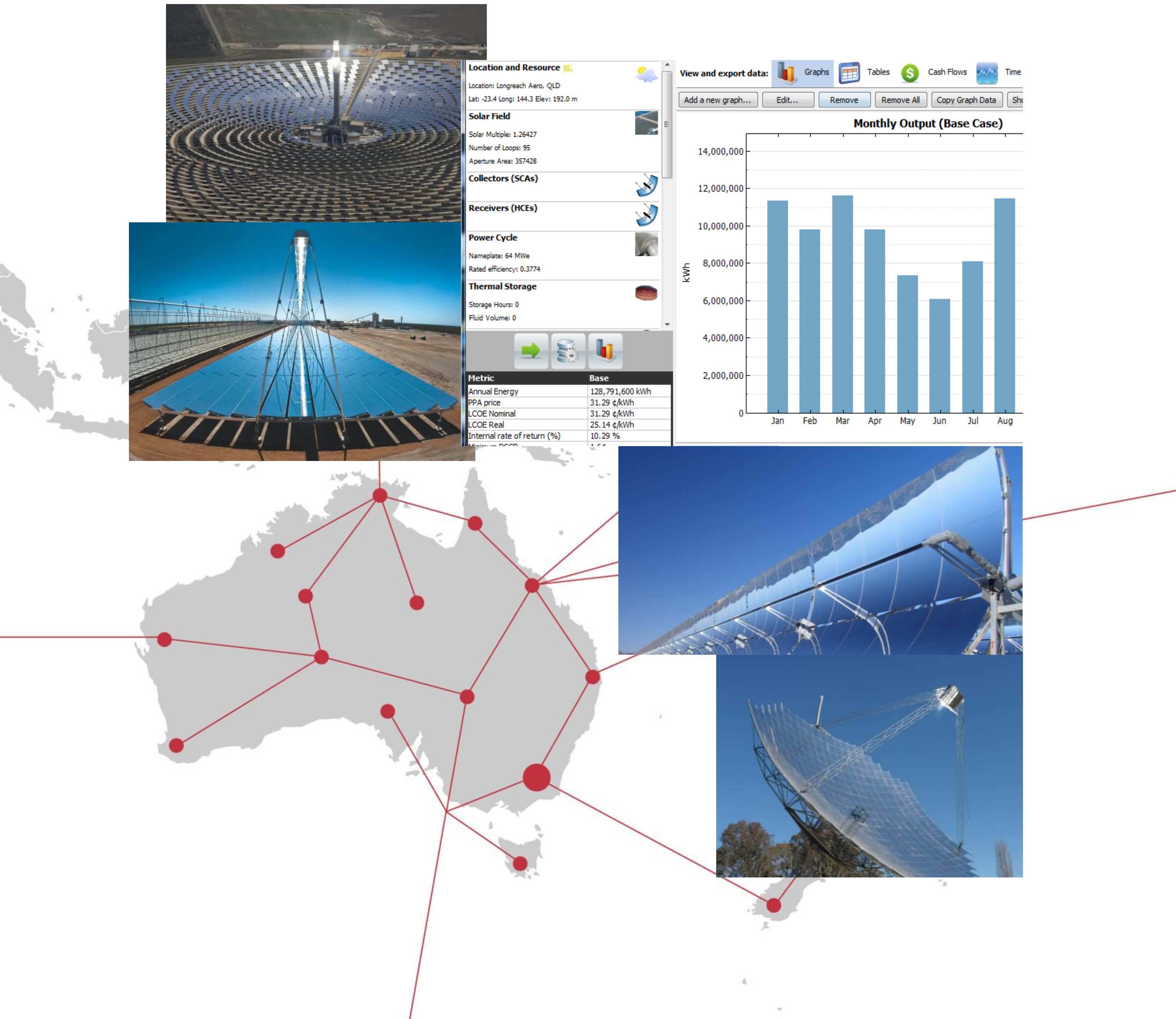

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Prepared by: IT Power (Australia) Pty Limited
Southern Cross House,
6/9 McKay St, Turner, ACT, 2612,
PO Box 6127, O'Connor, ACT, 2602, Australia.
Tel. +61 2 6257 3511
Fax. +61 2 6257 3611
E-mail: info@itpau.com.au
http://www.itpau.com.au

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Authors	Keith Lovegrove, Simon Franklin and Ben Elliston
Project Manager	Keith Lovegrove
Approved	Joe Wyder
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IT Power (Australia) was established in 2003 and has undertaken a wide range of projects, including designing grid-connected renewable power systems, providing advice for government policy, feasibility studies for large, off-grid power systems, developing micro-finance models for community-owned power systems in developing countries and modelling large-scale power systems for industrial use.

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Disclaimer

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Release Notes

Release number	Date	Solar Data files	SAM project files	Companion Guide
Original (1.0)	3 May 2013	File names end in 20130430	File names end in 20130503	File name ends in 20130503
1.1	23 October 2013	File names end in 20130430 Unchanged.	File names end in 20131023. All cases have been re run and saved using SAM 2013.9.20. An error in the “Gemasolar” case in the Tower_Models_Aus.. project file has been corrected. The previous version had incorrectly retained a 30% investment tax credit in the incentives settings, this is now set to zero and a higher LCOE results.	File name ends in 20131023. Addition of release notes. Acknowledgement of SAM 2013.9.20. Changes to text of section 5.5 to reflect the corrected error in the Gemasolar tower case.
1.2	6 March 2014	File names end in 20130430 Unchanged.	File names end in 20140306. All cases have been re run and saved using SAM 2014.1.14. An error in the Empirical trough, Nevada Solar 1 and Andasol cases within the trough project file that caused the cost scale factor exchange variable to be inactive has been fixed.	File name ends in 20140306. Update of release notes. Minor edits. Acknowledgement of SAM 2014.1.14.

Glossary

Acronym	Definition
SAM	System Advisor Model
CSP	Concentrating Solar Power (assumed to be thermal in this document)
NREL	National Renewable Energy Laboratory (USA)
CPV	Concentrating Photovoltaic
PV	Photovoltaic
ARENA	Australian Renewable Energy Agency
ASI	Australian Solar Institute
LCOE	Levelised Cost of Energy
O&M	Operation and Maintenance
DNI	Direct Normal Irradiation
SEGS	Solar Energy Generating Systems (California)
LFR	Linear Fresnel Reflector
NPV	Net Present Value
IRR	Internal Rate of Return
PPA	Power Purchase Agreement
DSCR	Debt Service Coverage Ratio
GST	Goods and Services Tax (Australia)
LGC	Large-scale Generation Certificate
TOD	Time of Day factors in SAM dispatch
HTF	Heat Transfer Fluid
BOM	Bureau of Meteorology (Australian Government)
TES	Thermal Energy Storage
TMY	Typical Meteorological Year
EPW	Energy Plus Weather, a file type for US building modelling software
ACDB	Australian Climate Data Bank

1. INTRODUCTION

The technology of Concentrating Solar Thermal Power (CSP) systems has reached a high level of commercial maturity and the level of deployment has been growing at around 40% per year since 2005. There are four basic approaches, trough concentrators, tower / heliostat systems, linear Fresnel concentrators and dish concentrators (in declining order of deployment and commercial maturity).

Overall the use of solar generation technologies, including photovoltaic systems, is growing fast and becoming a significant part of the future energy mix. CSP approaches, although only a small part of the present total, have claimed an important place in the future mix, because they offer large scale and proven energy storage as in inherent part of the system.

Predicting the output of a CSP system is a complex process. Thermal systems include multiple subsystems whose behaviour at any point in time depends not only on the instantaneous conditions the whole system experiences, but also the recent history of its operation.

There are a range of approaches to modelling CSP systems and it is an on-going area of research. One of the most respected is the freely available System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL) in the USA.

The SAM model is general purpose in nature and can predict hourly, monthly and annual output of CSP, CPV, flat plate PV and also a range of other renewable energy systems. There has been an extensive body of work around its application to CSP systems in particular.

This “Australian Companion Guide to SAM for Concentrating Solar Power” and the associated material was developed by Austela under a project supported by the Australian Renewable Energy Agency, (ARENA)[1]. The work was carried out by ITP working in collaboration with members of NREL’s SAM team.

This project has produced three resources for public use:

- This Guide.
- A collection of SAM project files with financial settings for Australian Conditions for modelling of trough, tower, linear Fresnel and dish based CSP systems.
- A selection of solar data files for input to SAM for selected representative Australian sites and years.

This guide includes step by step instructions on how to download and use SAM for Australian conditions and to open and use the project files and incorporate the new solar data files.

[1] At the commencement of the project, this support was provide by the Australian Solar Institute.

It also contains a discussion of the rationalisation of Levelised Cost of Energy calculations between the SAM cases and the previous study "The Potential for Concentrating Solar Power in Australia[2]" (Lovegrove et al 2012).

Detailed background information on the material and its origins is also included in appendices.

This guide together with the project and solar data files is available for download at http://austela.com/ . Any updates will also be available from that site.

This guide does not describe how CSP systems work or what their future market share might be. The reader is referred to the previous study by Lovegrove et al (2012) for a detailed discussion of such issues. Further, for a technical understanding of the principles of CSP systems and the state of technological development the reader is referred to Lovegrove and Stein (2012).

[2] This study is referred to on several occasions throughout this guide and for the sake of brevity is described as the "CSP in Australia Study".

2. SAM BASICS

2.1. Predicting system output

The SAM model is general purpose in nature and can predict hourly, monthly and annual output of CSP, CPV, flat plate PV and also a range of other renewable energy systems. There has been an extensive body of work around its application to CSP systems in particular. Quoting from NREL:

"SAM, originally called the "Solar Advisor Model" was developed by the National Renewable Energy Laboratory in collaboration with Sandia National Laboratories in 2005, and at first used internally by the U.S. Department of Energy's Solar Energy Technologies Program for systems-based analysis of solar technology improvement opportunities within the program. The first public version was released in August 2007 as Version 1, making it possible for solar energy professionals to analyze photovoltaic systems and concentrating solar power parabolic trough systems in the same modeling platform using consistent financial assumptions. Since 2007, two new versions have been released each year, adding new technologies and financing options. In 2010, the name changed to "System Advisor Model" to reflect the addition of non-solar technologies."

The SAM model has two roles;

- Given appropriate technical parameters and a set of Direct Normal Irradiance (DNI) data and associated weather related variables, the model will predict half hourly output from a system. This can be presented and exported in a range of graphical and tabular formats. There is scope for automated sensitivity analysis.
- Building on the system performance, if appropriate financial parameters are entered, the model further calculates financial performance including time series cashflows and Levelised Cost Of Energy (LCOE).

SAM produces a range of outputs related to the cost and performance of systems that include:

- System output.
- Peak and annual system efficiency.
- Levelized cost of electricity.
- System capital and operating and maintenance (O&M) costs.
- Hourly system production.

SAM's CSP models use the well-known TRNSYS software as an internal engine (University of Wisconsin 2013).

2.2. Installing SAM

NREL's System Advisor model is available at: https://sam.nrel.gov/ . According to the website when accessed as at 20 February 2013, SAM Version 2013.1.15 was the latest version and was the version utilised initially for this project. The current revision uses version SAM 2014.9.20.

Downloading the software from https://sam.nrel.gov/content/downloads is free, but requires the new user to register an account (which is subsequently used for notification of updates etc). The process of downloading and installing SAM is straightforward from that point.

The website includes an active user forum (https://sam.nrel.gov/forums/support-forum) with regular inputs from NREL's SAM team.

The learning page (https://sam.nrel.gov/content/resources-learning-sam) offers links to various presentations and webinair recordings. Most importantly it has a link to allow download of the SAM Help system (NREL 2012) as a PDF Document (https://sam.nrel.gov/sites/sam.nrel.gov/files/content/documents/pdf/sam-help.pdf).

This extremely detailed document should be treated as the primary reference source for using SAM and understanding input variables, models, outputs and features in detail. The "Australian Companion Guide to SAM for Concentrating Solar Power" is to be read and used in conjunction with this primary reference.

Having noted that, the Companion Guide can be read as a self standing document and will guide the new user through using and interpreting the Australian specific project files and solar data sets that are provided with it.

2.3. Running SAM with the Australian project files

SAM opens and saves the results and inputs for modelling runs in "project" files with the file extension ".zsam". Within a zsam project file are one or more specific system "cases" that can be edited and run in turn.

Cases can be established from first principles in a number of ways as detailed in the help document and from various menu options within the software[3]. Here we deal exclusively with the set of SAM project files for CSP in Australia that are available for download.

If the Australian SAM project files have been successfully downloaded and saved to a directory the listing should appear similar to Figure 1.

[3] Create cases from first principles from the front page via sample files, using the Solar Wizard or the Create case option in the Case menu. Refer to the help document for details.

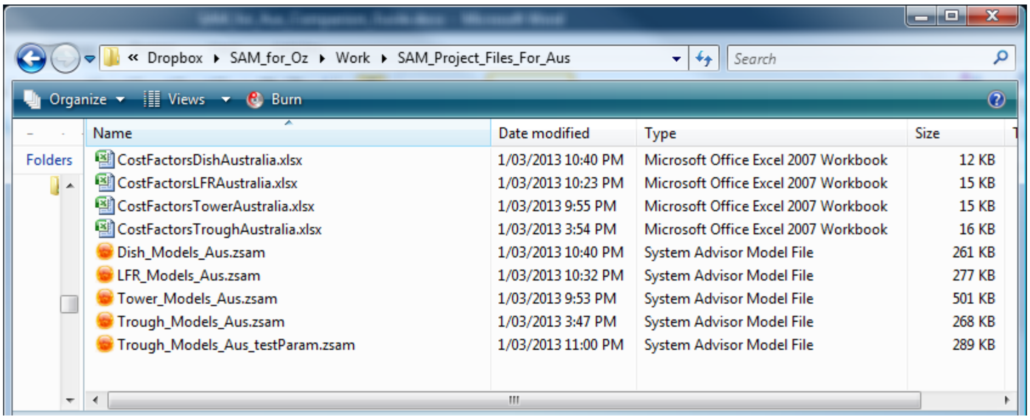


Figure 1: Project files and linked spreadsheets.

For the project files presented here, the Excel spread-sheets shown are linked and used by SAM during operation and so should be kept in the same directory as the .zsam files.

Once SAM has been installed, operation with one of these project files can be started in one of two ways. Start SAM from the program menu or icon, which will lead to a front page similar to Figure 2.

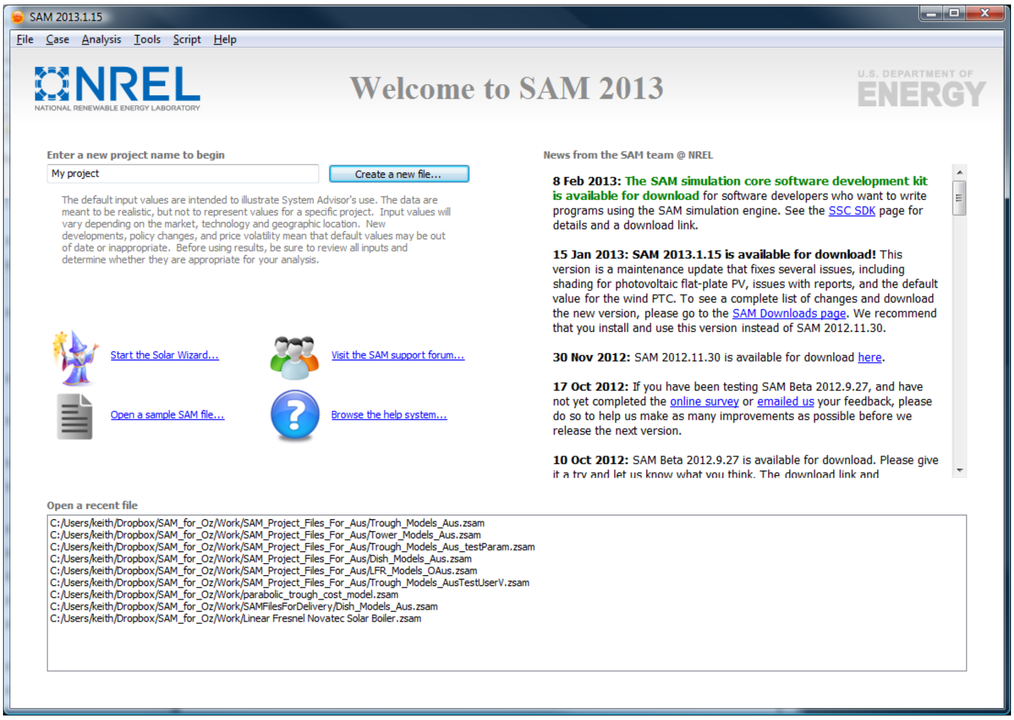


Figure 2: Front page of SAM.

Use the "File" menu, select "open", browse for the project (.zsam) file of interest and select / double click it (Figure 3). Alternatively the same result is obtained by simply double clicking the zsam file from its directory.

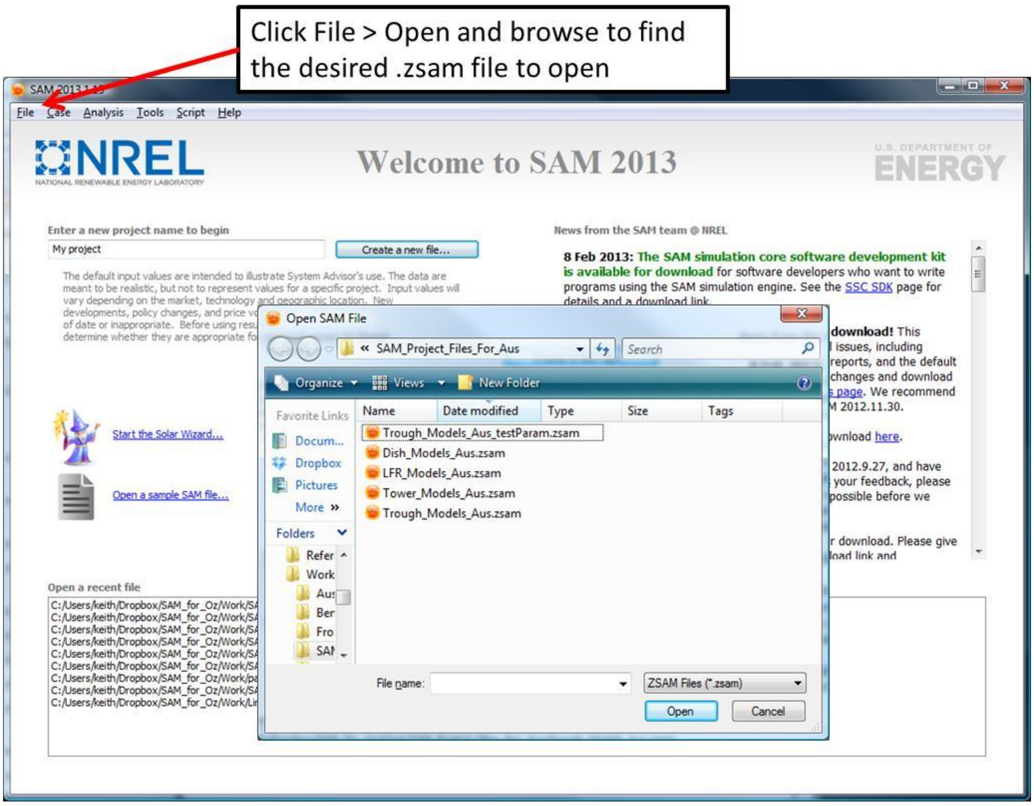


Figure 3: Opening a project file.

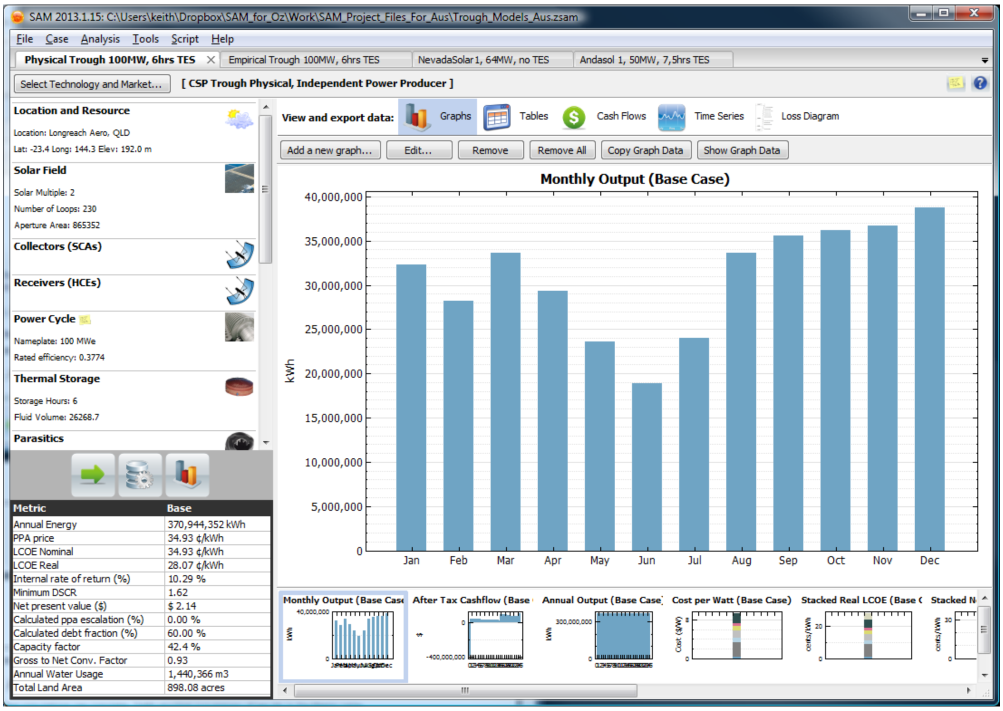


Figure 4: project file open to results page.

As an example, if the “Trough_Models” project file is chosen, after opening, the window will appear similar to Figure 4. It shows the results of the configuration / run for which it was saved. It is best to ignore these saved results and re-run it as shown in Figure 5.

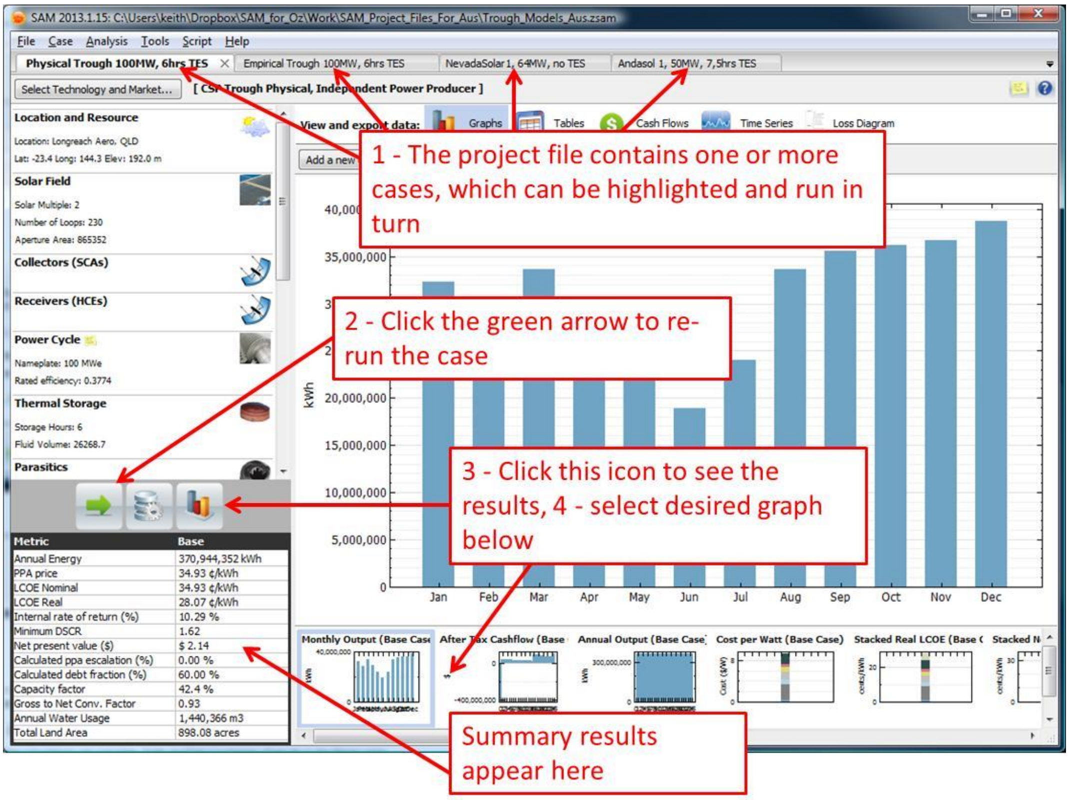


Figure 5: Steps to re-run a case and view results.

Running a case can take a minute or so depending on processing power available. At the beginning of the run a banner stating “exchanging data with Excel” should briefly appear. If there is an error message indicating a problem or absence of the Excel data, it is possible to run the case anyway using the data settings saved within the .zsam file. The exchange of data with the Excel files is discussed further below.

There are a number of options for creating new project files and cases within project files that will be self evident on investigation of the software. A common sense approach to modifying and saving files is needed to avoid losing track of changes. The following suggestions and observations may help:

- It is probably best to duplicate the entire directory of project files and associated Excel files to a backup location before any runs or changes are made (or else rely on repeating the download process if needed).
- Project (.zsam) files can be saved under a new name and the newly named versions should run in an identical manner. Note that the renamed / copied project files will

continue to access the same Excel file for data exchange and this file cannot be renamed without changing the appropriate file specification within each case. The Excel file (or a copy with the same name) also needs to be in the same directory as the new project file.

- To develop a quantitative understanding of both the SAM package and CSP systems, varying parameters and re-running in a case to see how results change serves well. Do not accidently "save" after such experiments, because the most recent setting will overwrite those you started with.
- Within the "Case" menu, the options to "import", "duplicate", "rename" and "delete" cases do as implied and allow project files to be organised appropriately. For example, to study the variation of a parameter in a systematic way[4];
    - Save the .zsam project file under a new name.
    - Choose a desired CSP plant configuration from among the existing cases.
    - Delete all the other cases.
    - Use "duplicate case", change the parameter (eg location) and run the new case.
    - Select the first case again and duplicate it and change to another parameter value as many times as desired (to the maximum 7 Cases allowed in a single project file[5]).

Various input parameters can be changed from the selected menu pages which are selected from the navigation menu on the left of the SAM window (Figure 6).

Many of the parameters that relate to physical plant operation require detailed understanding of the systems and model. If these are changed without being well understood it can result in specifying a physically impossible system that can either produce meaningless results or crash SAM. The user is referred to the SAM help documentation and the published literature on the various models if such understanding is sought. However there are a number of basic but important parameters than can be changed in a common sense way to provide informative results.

[4] Note that SAM has an internal feature for parameterised investigation that is recommended for thorough analysis and optimisation. Refer to the Help system. Parameterised runs can be quite time consuming so an initial manual investigation is beneficial.
[5] Computers with limited memory may experience problems with more than 3 or 4 cases.

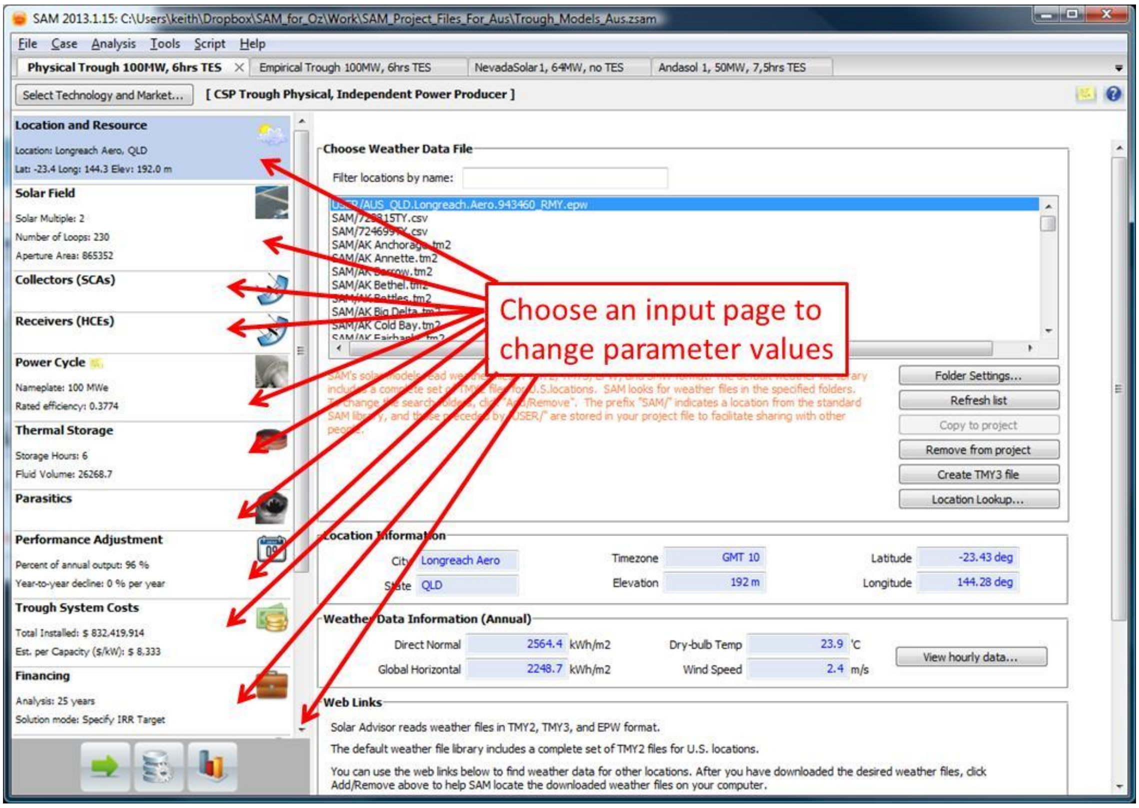


Figure 6: Selecting parameter input pages for a case.

In regard to changing parameters of the projects / cases that are presented here, the following suggestions are offered:

- Location can be changed to any of the options that appear in the menu list when the page is opened. There are only two Australian sites likely to be available in the default list until the new Australian solar data files provided are downloaded and installed as described in section 2.4.
- For cases that include selection of the “Solar Multiple” in the “Solar field” page, this can be changed and will scale the solar field relative to power block in a sensible manner.
- Within “Collectors” and “Receivers”, most parameters require detailed understanding, however choice of configuration from a library based drop down menu is straightforward if available.
- In “Power cycle”, changing the “Design Gross Output” can be instructive and physically meaningful. If all other aspects of a system are unchanged, it allows a system to be varied through base-load to peaking type configurations. It should be noted though that real turbines of arbitrary size may not exist on the market and different sizes and input characteristics of real turbines can have significantly different cycle conversion efficiencies.

- In “Thermal Storage” varying the specified “Full Load Hours” number is instructive and straightforward.
- In “Performance Adjustment” changing the “Percent of annual” output number allows investigation of different assumed levels of system availability and also an approximate way of scaling system performance to a site with similar but different annual DNI for which a solar data file is not available[6].
- In “System Costs” the input variables should not be changed because these are the variables that are contained in the associated spreadsheet and any changes will be overwritten by the Excel exchange feature. The spreadsheet however can be edited if desired. Alternatively one of the facilities provided, is the ability to apply a uniform scale factor to costs via the “User Variables” within the “Exchange Variables” page.
- “Financing”, “Incentives” and “Depreciation” settings can all be changed with care, however there are some potential sources of confusion and the section below on understanding LCOE in SAM should help in this regard.

2.4. Location specific Solar and Weather data for SAM

The key inputs for CSP system performance forecasting are the Direct Normal Irradiance (DNI) time series data, together with the associated ambient temperature, humidity and wind speeds. The SAM model accepts data files in several formats.

If the downloaded weather data zip file associated with the Companion Guide is opened, it is found to contain two directories which contain a collection of such files which can be saved for access from SAM.

The steps to link all the solar data files in a new directory to SAM are shown in Figure 7.

This need only be done from inside one case. After the change is saved, the new data files will then appear in the location menu list in all cases of all projects.

If the data files downloaded in this guide are installed in this way, it will be seen that a number of files for a number of representative prospective CSP locations in Australia will appear. There will be multiple files for a given location and these correspond to real years that are identified in the filenames. The actual locations, years and data types in this file set is discussed in detail in Chapter 6.

[6] Note though that as a rule system annual generation is varies in a non linear manner with DNI levels.

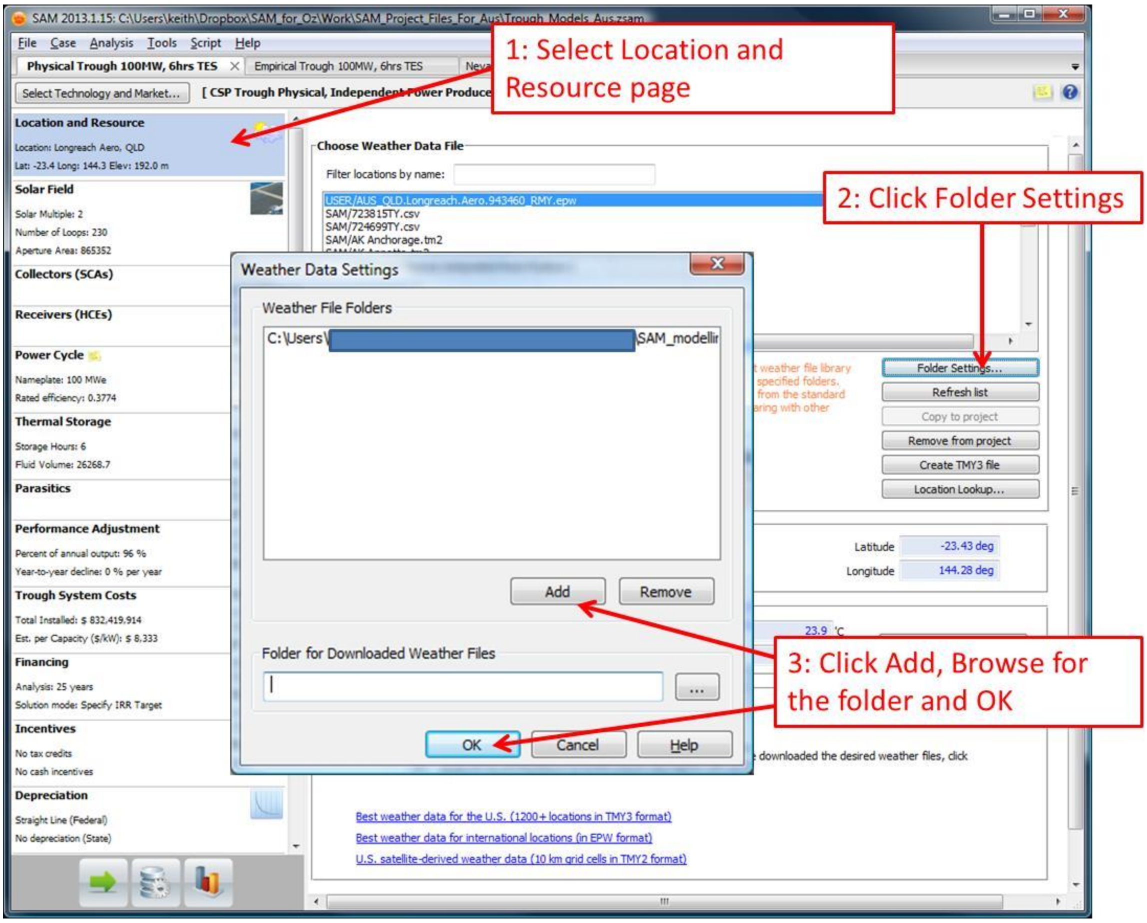


Figure 7: Steps for linking a new folder of solar data files.

3. CSP PROJECTS AND CASES FOR AUSTRALIA

The selection of project files and the cases they contain that have been assembled and customised for Australian purposes and made available for download have been chosen to:

- Be as transparent and easy to use as possible for a new SAM user.
- Provide examples from every CSP technology class.
- Offer a mix of cases that have been validated against real systems plus cases that represent likely realistic system configurations.

The cases chosen as a starting point for real systems are:

- “Nevada Solar 1” 64 MW_e no thermal storage physical trough model as used as the baseline system for the CSP in Australia Study.
- “Andasol 1”, calibrated physical trough model for the 50 MW_e, 7.5 hours storage, plant in Spain, typical of many such plants.
- “Gemasolar”, calibrated model for the 20 MW_e, 15 hours thermal storage, world first commercial salt tower plant in Spain
- “Novatec LFR Solar Boiler”, 47.5 MW_e, calibrated to Novatec GMBh KPI’s and configured in a similar manner to the PE2 plant in Spain.

The Andasol 1 case is discussed in detail in Appendix D and the Gemasolar case is discussed in detail in Appendix C.

The hypothetical cases offered are based on the default cases built in to the SAM program, specifically:

- Default “Physical Trough”, a 100 MW_e trough plant with 6 hours thermal energy storage.
- Default “Empirical Trough”, also a 100 MW_e trough plant with 6 hours storage.
- Default Salt tower, a 100 MW_e system with 10 hours thermal energy storage.
- Default Steam tower, a 100 MW_e system with no storage.
- Default Dish Stirling, 4000 x 25 kW_e units (100 MW_e total), no storage
- Default LFR, 100 MW_e, no storage.

These have been organised into zsam files by technology. Specifically[7]:

- Trough_Models_Aus_<release yyyymmdd#>.zsam
- Tower_Models_Aus_<release yyyymmdd #>.zsam

[7] New releases of SAM appear periodically, they should continue to open and run project files created previously. These projects and cases created for this project may be updated at some time in the future.

- LFR_Models_Aus_<release yyyymmdd#>.zsam
- Dish_Models_Aus_<release yyyymmdd#>.zsam

All the physical input variables are unchanged from the NREL original versions for the cases in these project files. All cases use the “Utility Independent Power Producer” financing option as the most appropriate for consideration of a large plant selling power in the market place or to a customer such as an electricity retailer. The financing and cost parameters however have been adapted for the purposes of an appropriate starting point for Australian use.

The NREL “physical trough model” is the basis for the Nevada Solar 1 and Andasol 1 cases as well as the default physical trough case. As its name suggests, it is a detailed model developed from the bottom up based on the physical principles of the components. For a detailed explanation of the physical trough model, see Wagner and Gilman (2011). By contrast the empirical trough model is simpler and based directly on performance characteristics of the Californian SEGs plants (Price 2003).

The direct steam power tower model is described by Neises and Wagner (2012) and the molten salt tower model by Wagner (2008). Field optimimisation issues for the tower models are described in Kistler (1986) and aspects of cavity receiver modelling in Feierabend (2009).

Linear Fresnel modelling is addressed by Wagner and Zhu (2012) and Wagner (2012). The dish Stirling model is described by Fraser (2008). Missing from the set is a model for a distributed dish system with central power generation. Such a model is yet to be developed.

The Longreach Australian Climate Data Bank Representative Meteorological Year solar data file that was used for the CSP in Australia study has been attached to each of the zsam files and has been selected as the default site. Note that SAM has the facility to include one or more solar data files within the zsam file, however each one adds to the size of the file. Thus adding a single reference Australian file serves as a starting point, with users then uploading and installing the directory of other TMY format files for Australian representative sites separately.

All financial related parameters have been changed to match the baseline conditions used in the CSP in Australia study and to give a simple basic calculation of real and nominal Levelised Cost of Energy (LCOE).

The “Financing”, “Incentives” and “Depreciation” parameter settings are the same for all cases and all technologies and are as described in the following sections.

All “System Cost” parameters have been adjusted as discussed in Chapter 5, but also transferred to the zsam files from a corresponding Excel spread sheet using the Excel exchange feature in SAM. This requires no action of the new user, only that they download the spread sheets together with the zsam files into the same file directory. User variables 1 and 2 on the “Exchange Variables” SAM menu page (Figure 8), then allows cost variables to be scaled to reflect hypothetical cost structures in future years, or system size effects for example.

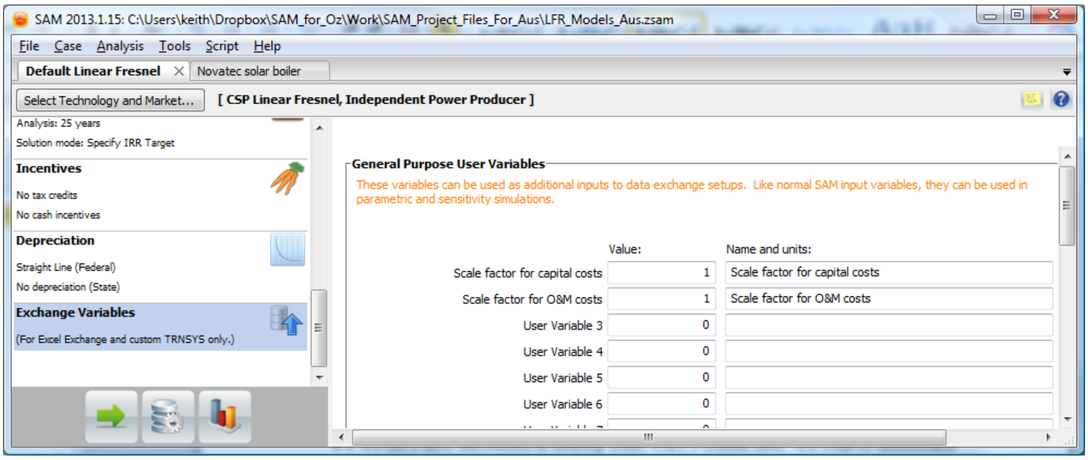


Figure 8: User variables that allow cost parameters to be scaled.

Users who wish to modify the Excel exchange arrangements are referred to section 25.5 of the SAM help document. However, a straightforward step is to simply switch Excel exchange off as shown in Figure 9.

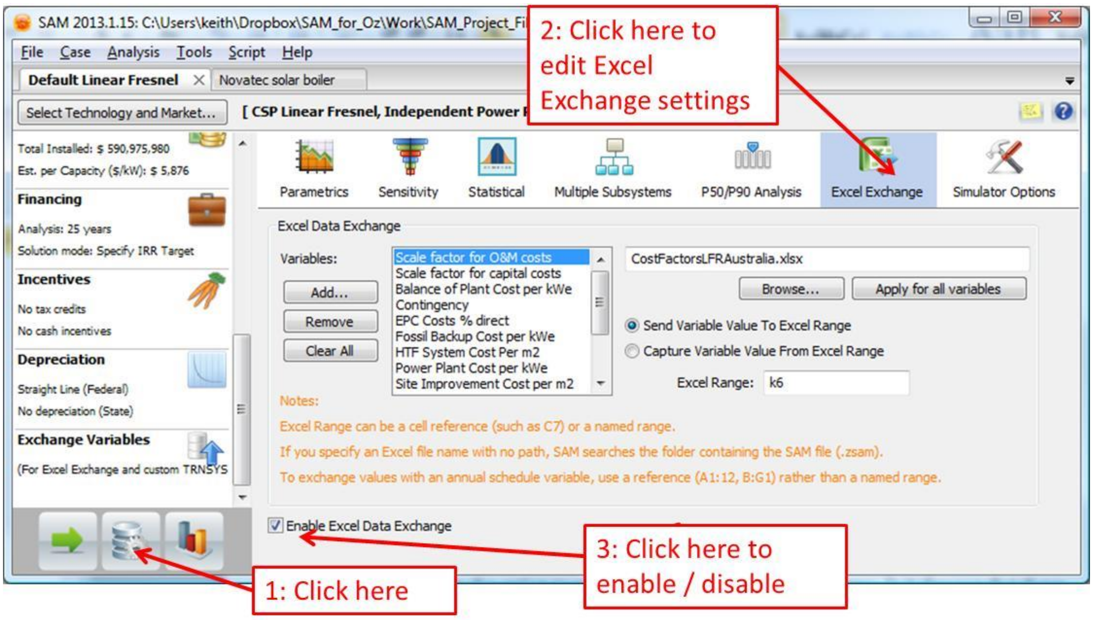


Figure 9: Steps for disabling Excel exchange.

In this case all the System Cost parameters will then keep the values they held at the end of the last run. They can then be individually edited if desired and will no longer be overwritten by the exchange feature when the case is run.

Important note: At the time of writing, the Excel exchange feature was not available for operation of SAM on Mac computers.

The project files / cases presented here should run anyway for a Mac, but with an initial warning message to indicate Excel exchange had not been carried out. For Mac users, disabling Excel exchange, as above, will remove the warning message each time the case is run.

4. LEVELISED COST OF ENERGY IN SAM

The Levelised Cost of Energy (LCOE) is the most frequently used economic performance metric for power generation plant. It is defined as the constant per unit price of energy which over the system's lifetime, will result in a total Net Present Value (NPV) for the system costs and income, of zero. In other words it is the "break even" constant sale price of energy.

LCOEs can be in real (inflation independent) or nominal terms, which can be confusing because they are expressed in year zero dollar values in either case. A nominal LCOE represents a hypothetical income that declines in real value year by year, whereas a real LCOE has a constant "value". Since the total NPV via either method must be the same by definition, the nominal LCOE will be the higher of the two. Real LCOEs are typically used for evaluation of future long term technology projections.

Appendix B explains the general principles of calculation of LCOE in more detail.

SAM provides as output a range of financial performance parameters, specifically; Power Purchase Agreement (PPA) price, LCOE nominal, LCOE real, Internal Rate of Return, and Net Present Value. These can be seen in the example summary table of results in Figure 10.

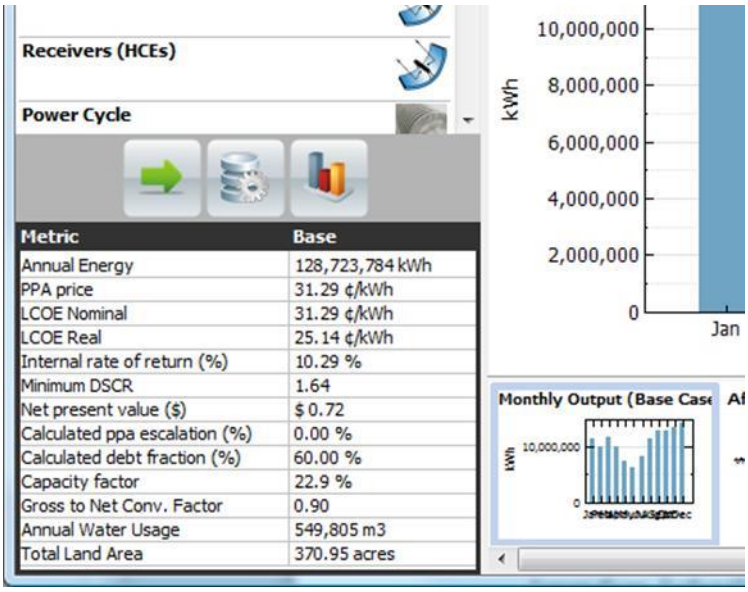


Figure 10: Summary of output parameters.

Whilst apparently self explanatory there are some details of SAM's implementation of these that need to be understood to avoid confusion.

Key observations that assist in interpretation are:

- All incentives of either a production or capacity based nature are included before either of the three financial metrics are calculated. In a sense, if incentives are included, they are not LCOE's in the general definition, but rather levelised costs of energy after subsidy.
    - For the set of projects / cases presented here, all incentives have been removed so true LCOE's are the result.
- The Internal Rate of Return (IRR) is included within the LCOE calculation in SAM. The target IRR effectively takes the place of the discount rate. To avoid any confusion, make the target IRR value and the nominal discount rate equal.
    - For the set of projects / cases presented here, "specify target IRR" is used and the IRR and nominal discount rate are made equal. A close to zero (ie very small fraction of system cost) project Net Present Value (NPV) should result with this approach.
- A Net Present Value of either the nominal LCOE x generation or the real LCOE x generation, summed over the project life, using the nominal and real discount rates respectively should have the same value. To get the same value from the PPA price, it must be escalated at its own escalation rate and multiplied by any Time of Day (TOD) factors (specified as input parameters in SAM) as well as the energy generated.
    - For the set of projects / cases presented here, all Time of Day factors have been set to one wherever they appear.
- If the Time of Day factors are 1 and the PPA escalation rate is zero then the PPA price will be the same as the nominal LCOE.
    - For the set of projects / cases presented here, PPA escalation rate is set to zero. Users may wish to change that if a PPA price escalation (that could be above or below estimated Consumer Price Index escalation) was to be examined. Doing this has no effect on other results.

4.1. Financial inputs for the SAM for Australia cases

4.1.1. Financing parameters

A screen shot of the financing inputs is shown in Figure 11. All inputs are the same for all cases. The calculated outputs of cost related numbers obviously vary between the systems modelled. It should be emphasised again that to calculate the correct real LCOE in SAM, the target IRR and the real discount rate must be the same. Target IRR is used inside the SAM LCOE calculation, it effectively is the project discount rate for equity. To achieve the desired nominal discount rate, the appropriate real discount rate must be provided since the nominal value is calculated from it.

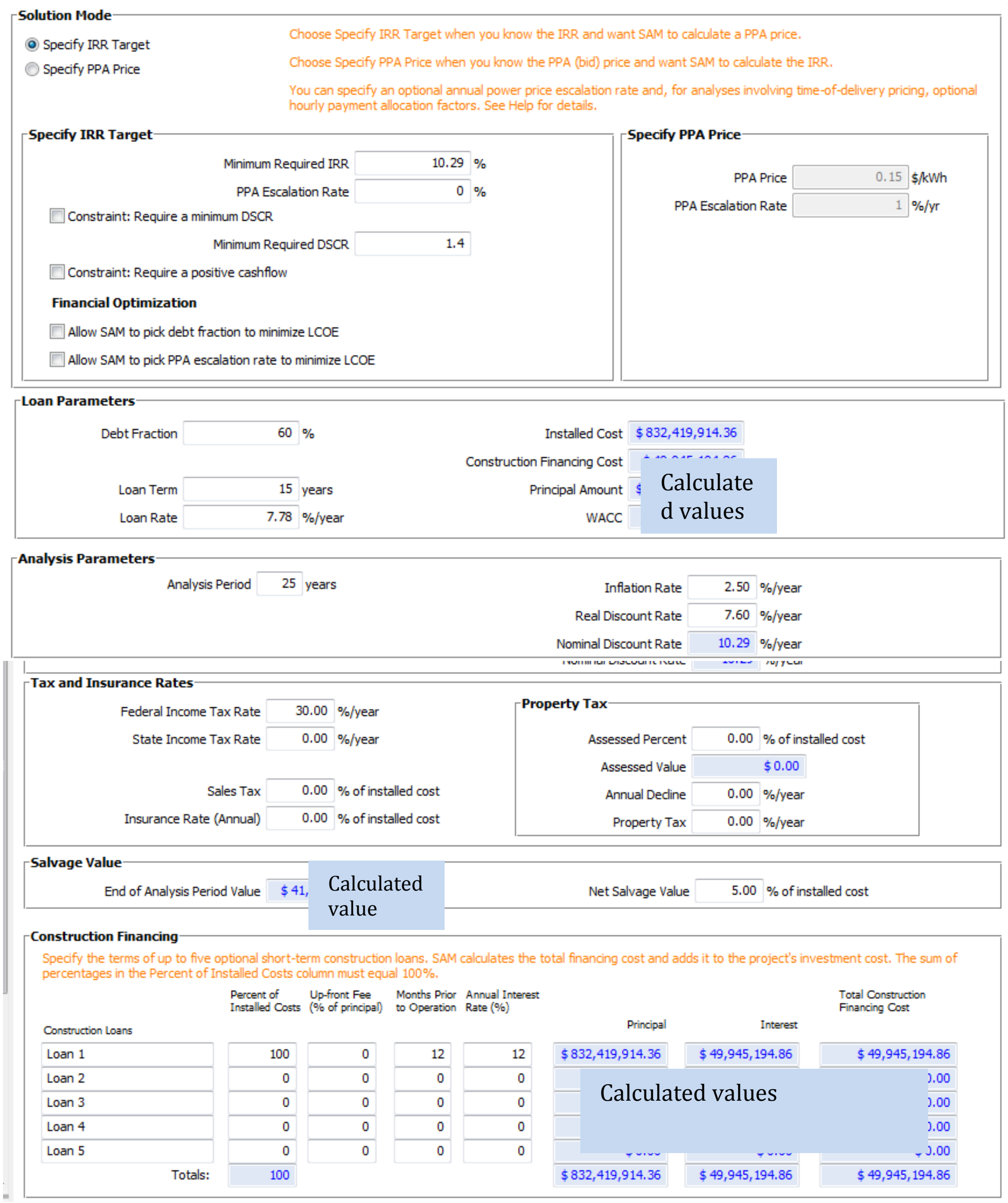


Figure 11: Financing input settings for CSP in Australia.

To ensure that the LCOE calculated by SAM is consistent with the definition above, the following conditions must be met:

- Use the “Utility IPP” financial model, and not one of the financial models listed under "Advanced Utility IPP Options" in the technology and market selection window that appears if you create a new file or case.
- On the Financing page, choose the "Specify IRR Target" solution mode option.
- On the Financing page, the Minimum Required IRR and Nominal Discount Rate are equal: Nominal Discount Rate = (1 + Real Discount Rate) × (1 + Inflation Rate) - 1

- On the Financing page the "Require a Minimum DSCR" and "Require a Positive Cashflow" constrain options are turned off (check boxes are clear).
- On the Results page, the Internal Rate of Return that SAM calculates and displays in the Metrics table is equal to the Minimum Required IRR on the Financing page[8].

The cases in the project files provided all meet these criteria in their default settings.

Federal income tax is set to 30% to match the assumed corporate tax rate used for the CSP in Australia study. State income tax and sales tax is not relevant for Australian conditions[9].

Insurance is set to zero since it is assumed to be part of the simplified indirect costs fraction in project costs. Other taxes / rates / charges that could be modelled as property tax and may be levied by local government are not considered in this analysis.

The system cost parameters are set to produce the appropriate "overnight cost"[10] rather than the cost inclusive of construction finance. Construction financing is shown as a single loan for 100% of capital cost for 12 months at 12% per year. The assumption in SAM is that a loan for a certain amount on average accrues interest for half of its duration. Thus the effect of these inputs is equivalent to a multiplier of 1.06 on the overnight capital cost, as was used in the CSP in Australia Study. In modelling it in this simple way, no comment is offered on the actual cash flow profile of construction. Best practice construction for a CSP plant can be around 18 months from ground breaking to grid connection.

4.1.2. Incentives

All the incentives inputs have been left at zero. The screen shot appears as shown in Figure 12.

[8] It is possible that for a given set of cost and financial assumptions that the iterative algorithm that SAM uses to calculate the IRR would not converge on the desired IRR, but on a different value. (For example, if project debt is too high or too low.) For this reason, it is important to verify that the IRR in the results is the same as the target IRR in the inputs to ensure that the LCOE meets your definition.

[9] Note an Australian system developer may have to cover GST on purchases for a period before later receiving a refund, the cost of managing this would be covered in construction financing.

[10] "Overnight cost" is a phrase that is used for the sum of all capital and construction costs (including labour) as if the system appeared instantly and there was no charge applied to the capital invested progressively to build the plant during the construction phase.

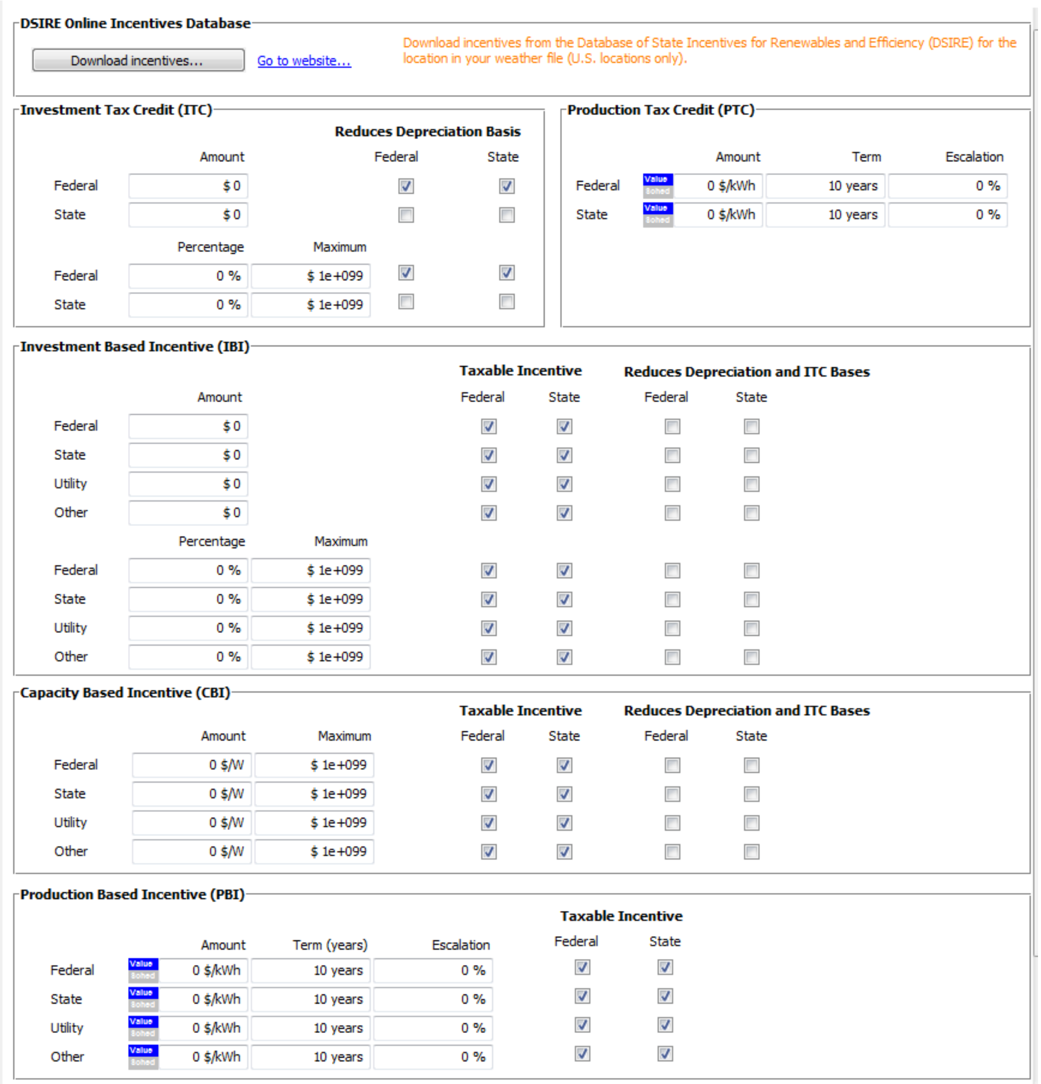


Figure 12: Default incentives input settings for CSP in Australia.

In SAM all incentives are considered inside the LCOE calculations, that is they have the effect of reducing the LCOE. In a strict interpretation that is not consistent with the definition of LCOE, but rather a levelised payment to break even after incentives.

In Australia, LGC[11] income from the Renewable Energy Target is a form of production based incentive with a term currently scheduled to end in 2030. A simple grant could be modelled as an investment based incentive. Other forms of incentive may be introduced by Australian Federal or State agencies in coming years. If users wished to calculate levelised energy values or required PPA tariff levels after incentives, they are referred to the SAM help manual to correctly interpret the incentive inputs that could be used to model them.

[11] Large-scale Generation Certificates earnt under the Renewable Energy Target scheme.

4.1.3. Depreciation

State depreciation is not relevant in the absence of a state income tax in Australia so is set to "no depreciation". Federal depreciation is set to a straight line over 20 years, as per the assumptions outlined in the CSP in Australia study (Figure 13). The Australian Tax Office may offer a more relevant ruling on depreciation period at some time in the future that could be used to vary this.

The option of "5 yr MACRS" refers to Modified Accelerated Cost Recover System, the current tax depreciation system in the United States, not relevant to Australia. The absence of such a scheme in Australia, is one of the reasons why LCOE's calculated for a system in Australia are significantly higher than the same system in the US.

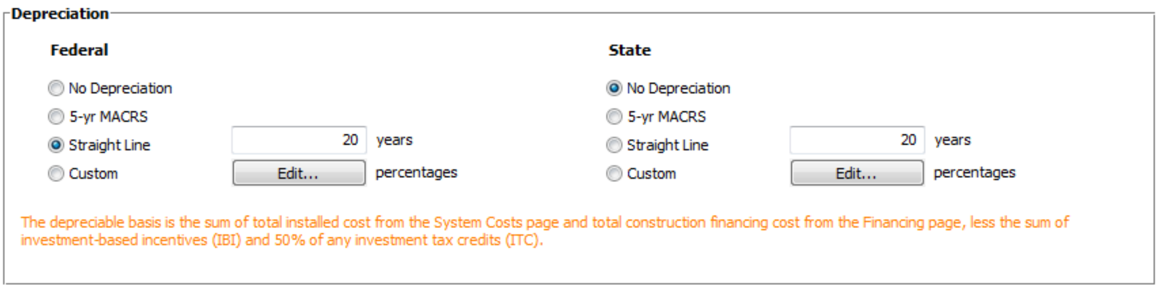


Figure 13: Depreciation input settings for CSP in Australia.

4.1.4. Dispatch Control

The CSP models have a feature for specifying dispatch control by hour and month, by specifying a range of parameters. It is somewhat confusing that this is usually found within the Thermal Storage input menu, yet has a significant effect on results for systems without storage.

- Turbine output fraction can be set as high as 110% and this is realistic for high solar peak demand times. This can increase total annual generation, particularly for a system with no storage.
- TOD (Time of Day) factors are multipliers to the assumed value of electricity sold. They are used to express a higher value for energy generated at times of assumed peak demand. They affect the calculated PPA price in the results, because the assumption is that a PPA would be a contract that specified a base PPA price and the TOD factors with actual revenue for a given hour, being energy x PPA price x TOD factor.

The use of TOD factors in this way reflects the current regulatory structure that applies in California. For the cases provided here, dispatch control has been turned off and appears as shown in Figure 14).

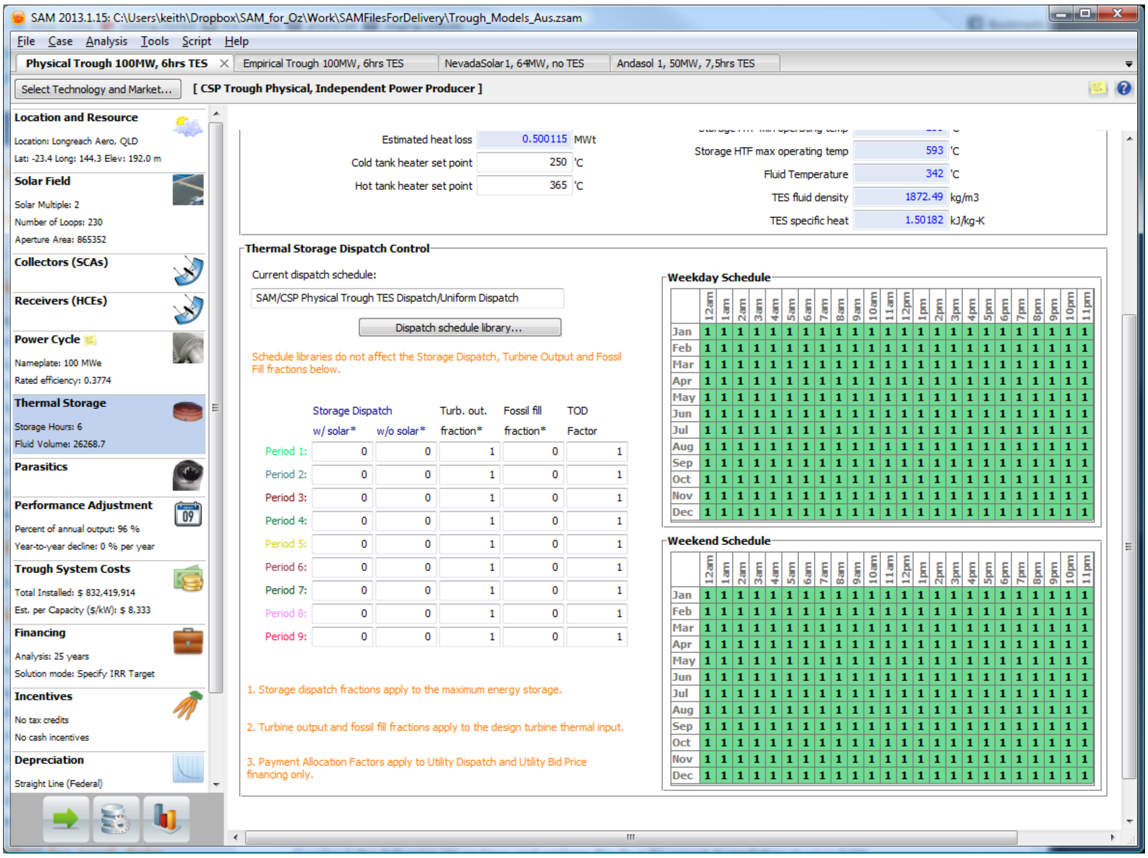


Figure 14: Uniform dispatch settings.

4.2. Reconciling LCOE with the CSP in Australia study

For the purposes of the CSP In Australia study, SAM was used to calculate annual generation for a range of systems at various sites. To establish a baseline 2012 LCOE for Australia, the annual generation from the 64 MW_e physical trough model with no storage (the Nevada Solar 1 case) was run using the ACDB RMY file for Longreach Queensland. The philosophy was to use “the most conservative plant configuration at a most favourable site”. LCOE was subsequently calculated using a separate spread sheet using a calculated capital cost determined for Australian 2012 conditions together with the annual generation figure. Details of the method and assumptions are given in Appendix A. ITP’s spreadsheet was simpler than the calculation in SAM, it also allowed other issues to be investigated separately from SAM.

The Nevada Solar 1 case in the Trough_Models_Aus.zsam project file, has settings that reconcile the LCOE calculations with those quoted in the CSP in Australia study. In making the comparison it should be noted that rounding differences occur in different places. The cost factors in the CostFactorsTroughAustralia.xlsx spreadsheet are rounded to whole numbers. Inputs to the ITP LCOE spread sheet were also rounded. The inputs and results quoted in the CSP in Australia study were also appropriately rounded from the multiple significant figures in the spread sheet.

A more significant factor in demonstrating the reconciliation is that the current release of SAM includes refinements to the physical trough model. A consequence of this is that when the Nevada Solar 1 case is re-run for the Longreach site, it is found that predicted annual generation had increased by approximately 6% over the value predicted with SAM version 2011.6.30[12].

To make the Nevada Solar 1 case in the Trough_Models_Aus.zsam project file reconcile as closely as possible with the original calculation, the annual output has been scaled back by changing the performance adjustment factor from the default of 96% to 90.8%. The exact comparison is shown in Table 1.

The 0.17% difference in calculated LCOE numbers is considered acceptable. The small difference is greater than the difference in input values, it can presumably be explained by small variations in the timing or method of accrual of one or more of the cashflows between the two calculations. It is noted that with PPA escalation set to zero, the PPA price and Nominal LCOE are equal in SAM.

If the financial settings are changed such that the loan is set at 100% of capital cost, the loan period is the same as the system life and construction finance costs and tax rate are set to zero, the simplified analytical formula quoted in Appendix A can be used as a comparison and exact agreement to more than 4 significant figures is found.

[12] This means that predicted LCOE has actually dropped by 6%. The models are all subject to debugging and refinement. This change in predicted output is within the levels of accuracy with which the results should be treated. The user is reminded of the disclaimers associated with both the SAM software and this project regarding not relying on the results for investment decisions.

USER INPUTS	Unit	Spread sheet calculation from CSP in Australia Study	Values in Nevada Solar 1 case in SAM (Australian parameter values)	Difference
Name plate capacity	kW_e	64,000	64,000	
Annual generation	kWh_e	128,794,000	128,791,480	-0.002%
Overnight Capital cost	$	$ 308,490,560	$ 308,558,260	0.022%
Capital cost after construction	$	$ 327,000,000[13]	$ 327,071,750	0.022%
Loan fraction of total		0.6	0.6	
Loan period	year	15	15	
Loan interest rate (nominal)	/year	7.78%	7.78%	
Discount rate for equity (nominal)	/year	10.29%	10.29%	
Tax Rate	/year	30.00%	30.00%	
Depreciation period	year	20	20	
Project Life	year	25	25	
Salvage value	$	$ 16,350,000	$ 16,353,588	0.022%
Variable o&m (year 1)	$/$kWh_e$	0.018	0.018	
Fixed O&M	/year	0	0	
Inflation	/year	2.50%	2.50%	
CALCULATED	.	.	.	.
Capacity factor		22.97%	22.9%	
Installed cost / unit capacity	$/$kW_e$	$ 5,109		
Loan amount	$	$ 196,200,000	$ 196,243,053	0.022%
Equity amount	$	$ 130,800,000		
Annualisation factor for loan	/year	11.53%		
Annual loan payment	$/year	$ 22,614,969		
Real discount rate for equity		7.60%	7.60%	
Nominal LCOE if energy sales taxed	**$/kWh**	**0.31344**	**0.3129**	**-0.174%**
Real LCOE energy sales taxed	**$/kWh**	**0.25185**	**0.2514**	**-0.177%**

Table 1: Reconciling the baseline LCOE calculation from the CSP in Australia study to the calculation in SAM.

[13] The table in the CSP in Australia report is unfortunately in error, showing the cost after construction as $318,000,000 when in fact the input was $327,000,000. The report does not articulate as clearly as it might that the cost after construction was calculated by assuming a 1.06 multiplier which was applied to “over night” costs of $308,490,000. The 1.06 multiplier was an estimate reaching in consultation with industry players and represents the effect of construction expenditure profiles and estimated cost of construction finance.

5. SYSTEM COST PARAMETERS FOR AUSTRALIA

In the CSP in Australia study it was determined that at the current stage of the CSP industry, there is insufficient data to differentiate in general terms between the LCOE of the various technology types if no storage was included and construction was at a good solar site. To a large extent this reflects the fact that publicly available cost data, largely reflects the experience with trough based systems. Other technologies really only have systems in the early commercial phase and are effectively price takers in a global market dominated by troughs. Not withstanding this, technology providers obviously attempt to analyse their own long term cost structure in great detail in the hope of offering the most competitive solution.

The individual cost breakdowns of the different technologies can be quite detailed and quite a high level of this detail is carried into the input parameters used by the SAM models for the different technologies.

In the CSP in Australia study, the approach taken was to gather up and simplify much of this detail and express it in a technology neutral manner.

The CSP in Australia Report has the costing factors shown in Table 2.

Subsystem	Per unit cost	Note / unit
Concentrator field (excluding receivers and Heat Transfer Fluid)	402	$/kWth capacity, delivered to power island at design point
Receiver/ transfer system (including receivers, HTF, piping, Tower as appropriate)	246	$/kWth capacity, delivered to power island at design point
Thermal Storage System	80	$kWhth of installed thermal energy storage capacity
Power block	882	$/kW$_e$ output capacity
BOP and Other	529	$/kW$_e$ output capacity
Indirect project costs	25%	Of subtotal of others (=20% of total)

Table 2: Estimated technology independent cost factors for a notional approximately 100MW$_e$ capacity CSP system with storage and Rankine cycle power generation in Australia (AUD 2012).

The costing estimation for storage is sensitive to the assumed temperature difference between hot a cold stores and so is adjusted to[14]:

Thermal Storage System Cost $(150/(T_h-T_c)) \times 80\$/kWh_{th}$

[14] In the CSP in Australia report, this scaling formula is shown in error with the scaling incorrectly inverted as $(T_h-T_c)/150$.

Overall, these cost factors are designed to be technology neutral. It is thus a different characterisation than normally applied to specific technologies and the solar field and receiver system components are expressed per kW_{th} delivered to the power island rather than per m^2 of field area. SAM produces a value for design point kW_{th} for the various solar field types. This allows equivalent capital cost parameters to be determined.

For the purpose of the CSP in Australia study, a simplifying assumption of treating all O&M costs as variable at a rate of AUD $0.015/kWh[15] for a 100 MW_e 40% capacity factor plant, was adopted.

To establish the cost parameters for the technology cost inputs for SAM these have been reverse analysed back to cost factors matching the required input units.

The principle adopted here, is to make the real LCOE close to matching the published 2012 value ($252/MWh) in the CSP Australia study using the Longreach Solar data file for any of the technologies for reasonably sized plants with no storage. Where the NREL default cost parameters offer greater detail, the fractional split has been maintained at the default level but normalised to the overall Australian number. Some parameters have been left at zero to avoid a false level of detail.

For the technology neutral numbers in Table 2, categories of 'Concentrator Field' excluding receivers and Heat Transfer Fluid (HTF) system, and 'Receiver System' including receivers, HTF system and Towers as needed, were adopted. In SAM different subsystem breakdowns are used for each technology type. For a trough system, the solar field includes the receivers, for a tower system the equivalent cost factor is for heliostats only.

The definition of power block assumed here is a narrower one than that assumed in the original NREL cases. Here it encompasses the turbine and gen-set and only such other components that would be common to all technologies using steam turbines. Ultimately it is the sum of power block costs and balance of plant costs that determine economic performance, so the absolute values of each should only be treated as indicative.

For systems with storage, the solar field and power block cost factors have been held at the same values as needed for the no storage case. Systems with storage consequently can have different LCOEs than the study benchmark.

In doing this it is emphasised that the benchmark LCOE is only sufficiently accurate for policy making purposes and the assessment that all technologies without storage are close to equivalent in LCOE at Longreach is only offered in the absence of better discoverable cost data.

The method applied for determining the new cost factors was:

- Scale the kW_{th} related costs from the CSP in Australia study back to per m^2, and divide them in the same proportions as the NREL originals.

[15] For the baseline conservative LCOE calculation this was increased to AUD $0.018/kWh.

- Scale the CSP in Australia kW_e related costs from nameplate to gross output, but keep them in the ratio as that study suggested.
- Set contingency to zero by assuming it is absorbed pro-rata in other cost factors.
- Simplify all in-directs to a single % multiplier at the 25% value quoted by the CSP in Australia study.
- Simplify all O&M to a single variable O&M approximation.
- Round all cost factors to the nearest whole dollar value and make manual adjustments to reproduce the baseline LCOE as close as possible.
- Make further common sense adjustments for logical consistency between the technology types.

5.1. Trough Cases

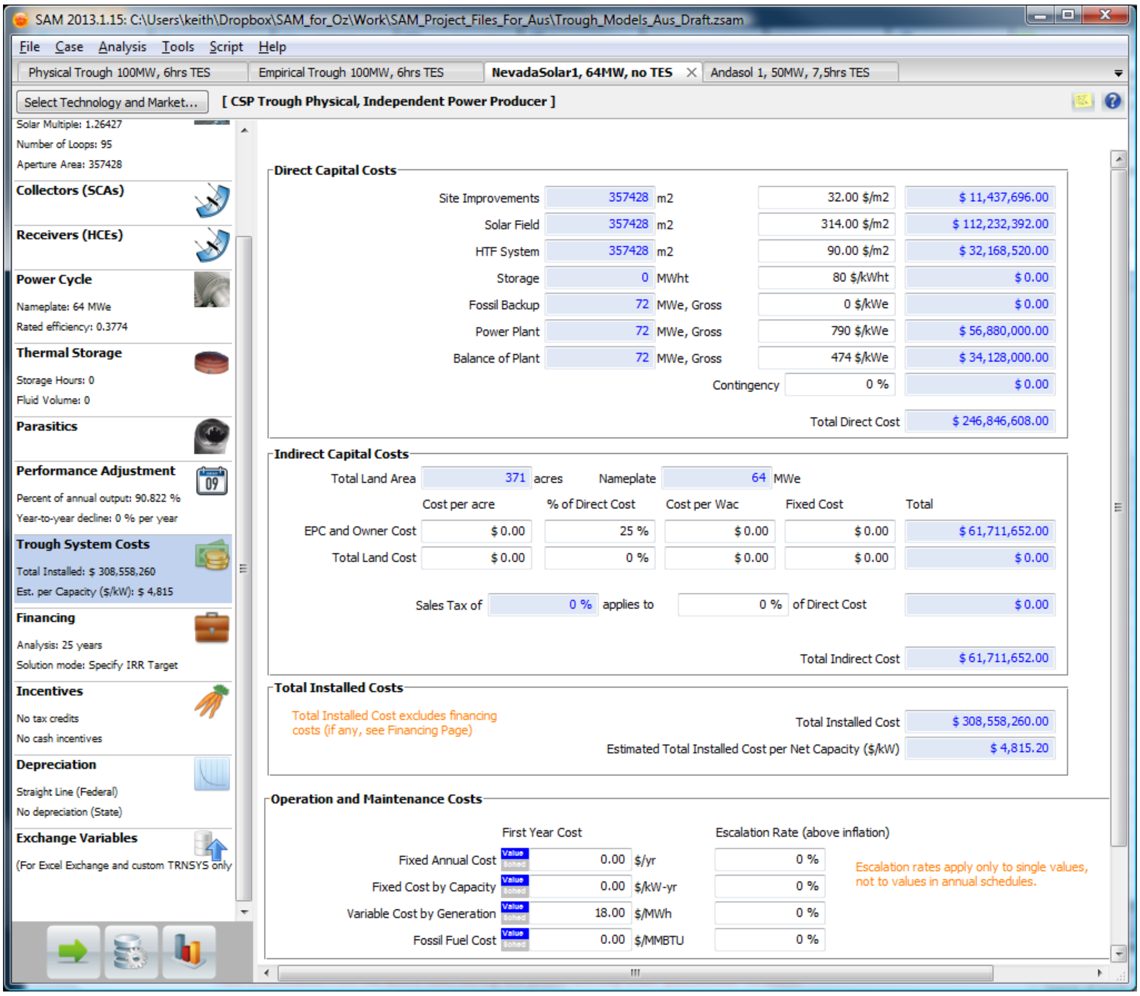


Figure 15: Trough system cost parameters.

For all cases the trough system cost input page appears as shown in Figure 15.

This screen shot is for the Nevada Solar 1, 64 MW_e simulation and so the calculated totals correspond to that. The input parameters (white cells) are the same for all the trough cases.

Table 3 compares the original and adjusted cost parameter values. It can be seen that the various original USD inputs are similar but slightly different across the 4 models.

Trough Case		**Nevada Solar 1, 64MW trough no TES**	**Physical Trough, 100MW, 6hrs TES**	**Empirica l Trough, 100MW, 6hrs TES**	**Andasol 1, 50MW, 7.5hrs TES**	**Base Adjusted parameter s**
Parameter	**Unit**	Original (USD)	Original (USD)	Original (USD)	Original (USD)	2012 AUD
Directs						
Site Improvements	$/m^2	28	30	30	28	32
Solar Field / heliostat field	$/m^2	271	270	270	270	314
HTF System	$/m^2	75	80	80	78	90
Subtotal area related	$/m^2	374	380	380	376	
Storage	$/kWh$_{th}$	0	80	80	80	80
Fossil Backup	$/kW$_e$	0	0	0	60	0
Power Plant	$/kW$_e$	916	830	830	850	790
Balance of Plant	$/kW$_e$	0	110	110	105	474
Contingency	%	10	7	7	7	0
Indirects						
EPC and owner	%	16.5	11	11	11	25
Land	$/acre	0	10000	10000	0	0
Land	%	7.40	0	0	2	0
Operation and Maintenance						
Fixed annual cost	$/yr	0	0	0	0	0
Fixed cost by capacity	$/kW-yr	65	65	65	65	0
Variable cost by generation	$/MWh	3	4	4	3	18
Fossil fuel cost		6	0	0	6	0

Table 3: Cost parameters for Trough cases, original and revised to Australian settings.

5.2. Tower Cases

For all cases the tower system cost input page appears as shown in Figure 16.

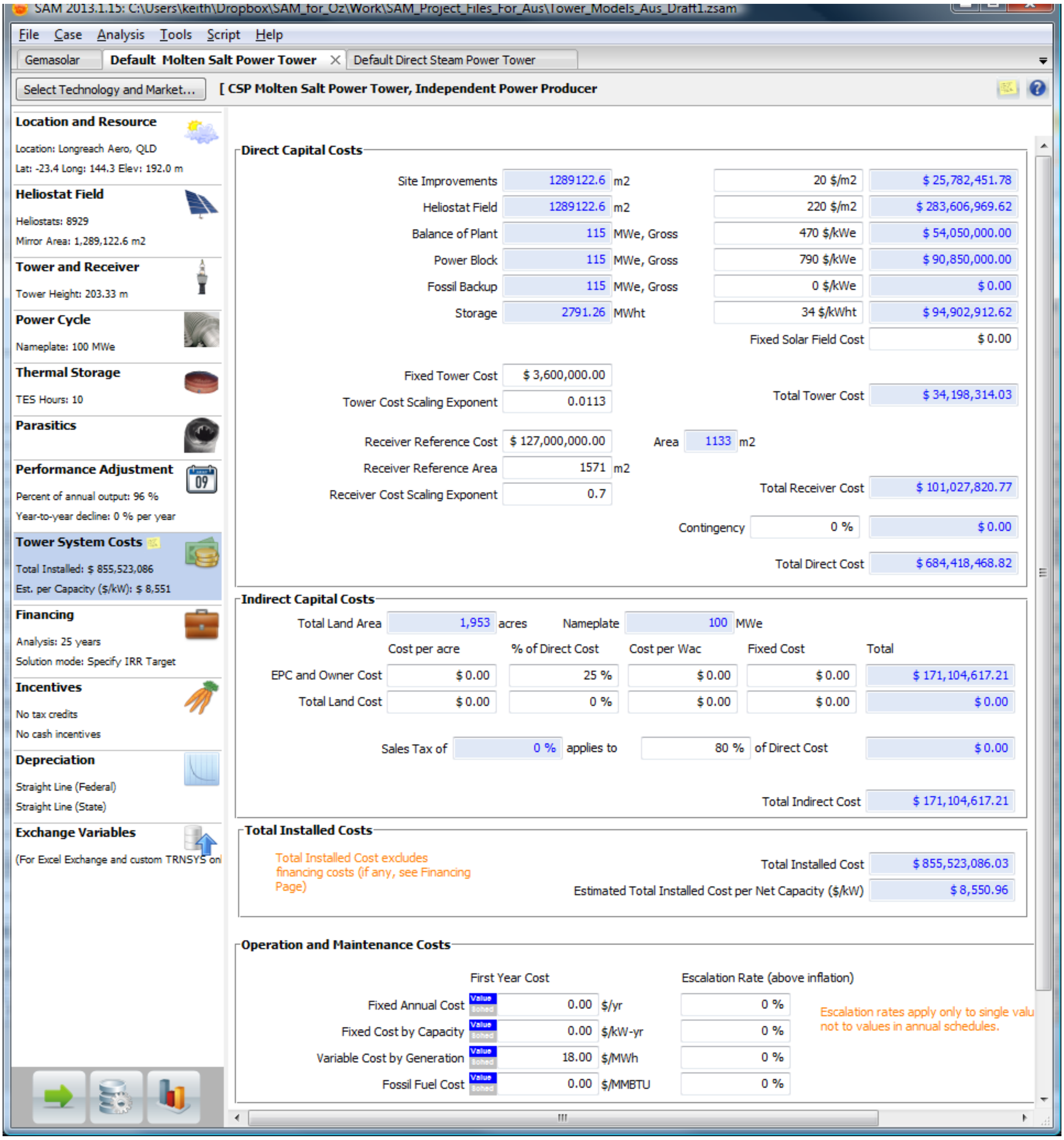


Figure 16: Tower system cost parameters.

This screen shot is for the Molten Salt tower, 100 MW 6 hrs Thermal Energy Storage (TES) simulation and so the calculated totals correspond to that. The input parameters (white cells) are the same for all the tower cases.

Table 4 compares the original and adjusted cost parameter values.

Tower Case		Salt Tower 100MW, 10hrs TES	Gemasolar, 20MW, 15hrs TES	Steam Tower 100MW no TES	Base Adjusted parameters
Parameter	**Unit**	Original	Original	Original	2012 AUD
Directs					
Site Improvements	$/m^2	15	15	15	20
Solar Field / heliostat field	$/m^2	180	160	180	220
Tower	$	28498595	14322823	17468431	
Tower receiver	$	87504412	42008310	62750917	
Tower	$/m^2	22.11	46.90	21.99	
Tower receiver	$/m^2	67.88	137.55	78.98	
Subtotal area related	$/m^2	284.99	359.45	295.97	
Tower fixed cost factor	$	3000000	30000000	3000000	3600000
Receiver fixed cost factor	$	110000000	110000000	11000000	127000000
Storage	$/kWh$_{th}$	27	27		34
Fossil Backup	$/kW$_e$				0
Power Plant	$/kW$_e$	1200	1200	1200	790
Balance of Plant	$/kW$_e$	350	350	0	470
Contingency	%	7	7	7	0
Indirects					
EPC and owner	%	11	11	11	25
Land	$/acre	10000	10000	10000	
Land	%	0	0	0	
Operation and Maintenance					
Fixed annual cost	$/yr	0	0	0	0
Fixed cost by capacity	$/kW-yr	65	65	65	0
Variable cost by generation	$/MWh	4	4	4	18
Fossil fuel cost		0	0	0	0

Table 4: Cost parameters for Tower cases, original and revised to Australian settings.

As with the troughs, It can be seen that the various original USD inputs are similar but slightly different across the 4 models.

5.3. Linear Fresnel Cases

For all cases the LFR system cost input page appears as shown in Figure 17.

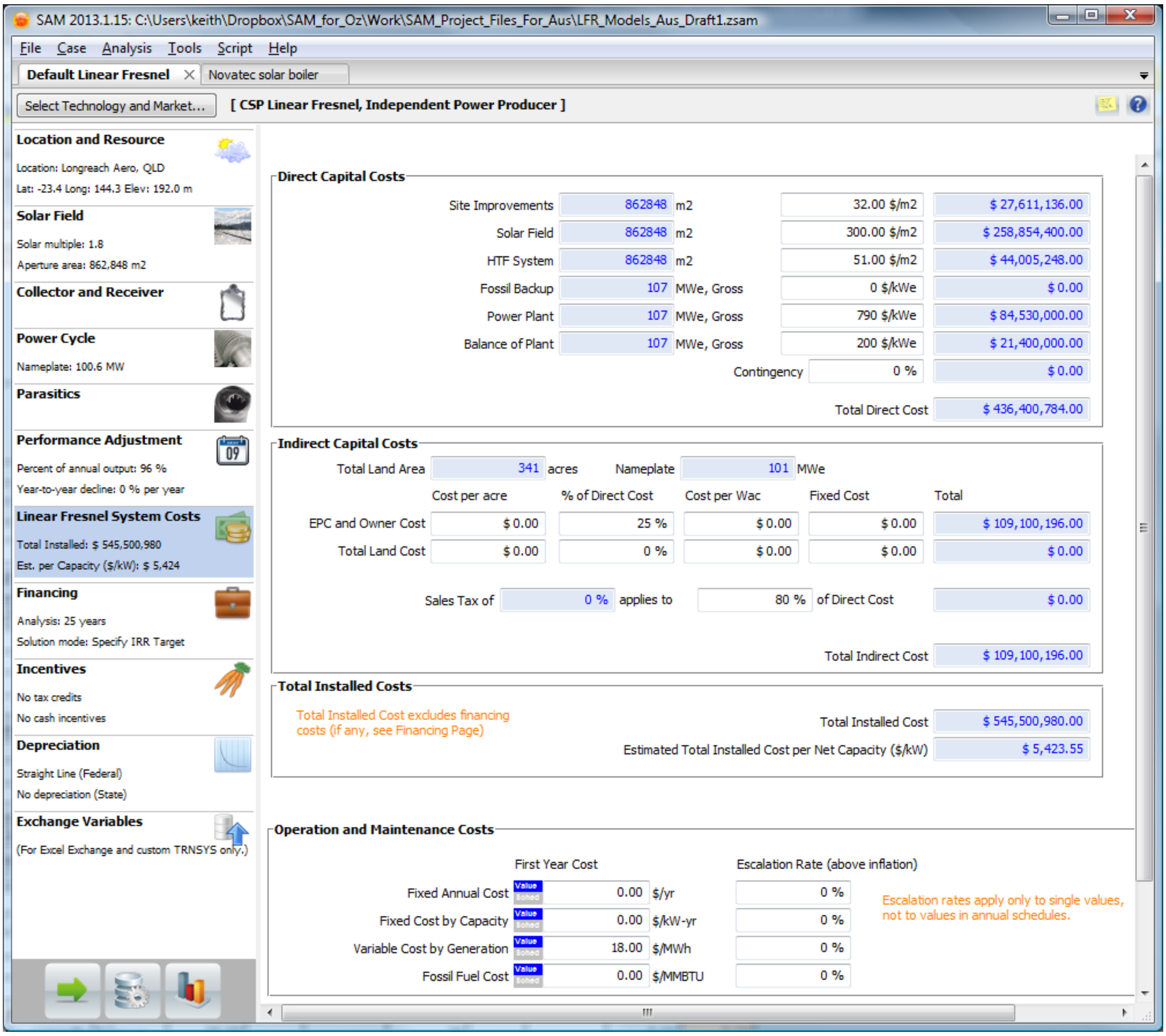


Figure 17: Linear Fresnel system cost parameters.

This screen shot is for the 100 MW default LFR simulation and so the calculated totals correspond to that. The input parameters (white cells) are the same for all the cases.

Table 5 compares the original and adjusted cost parameter values.

LFR Case	Unit	Default LFR 100MW no TES	Novatec Solar Boiler 47MW no TES	Base Adjusted parameters
Parameter		Original (USD)	Original (USD)	(2012 AUD)
Directs				
Site Improvements	$\$/m^2$	20	20	32
Solar Field / heliostat field	$\$/m^2$	210	210	300
HTF System	$\$/m^2$	35	35	51
Subtotal area related	$\$/m^2$	265	265	
Storage	$\$/kWh_{th}$			80
Fossil Backup	$\$/kW_e$			0
Power Plant	$\$/kW_e$	830	830	790
Balance of Plant	$\$/kW_e$	0	0	200
Contingency	%	7	7	0
Indirects				
EPC and owner	%	11	11	25
Land	$/acre	10000	10000	0
Land	%	0	0	0
Operation and Maintenance				
Fixed annual cost	$/yr	0	0	0
Fixed cost by capacity	$/kW-yr	55	35	0
Variable cost by generation	$/MWh	4	0	18
Fossil fuel cost			0	0

Table 5: Cost parameters for Linear Fresnel cases, original and revised to Australian settings.

5.4. Dish Case

For the dish system the cost input page appears as shown in Figure 17.

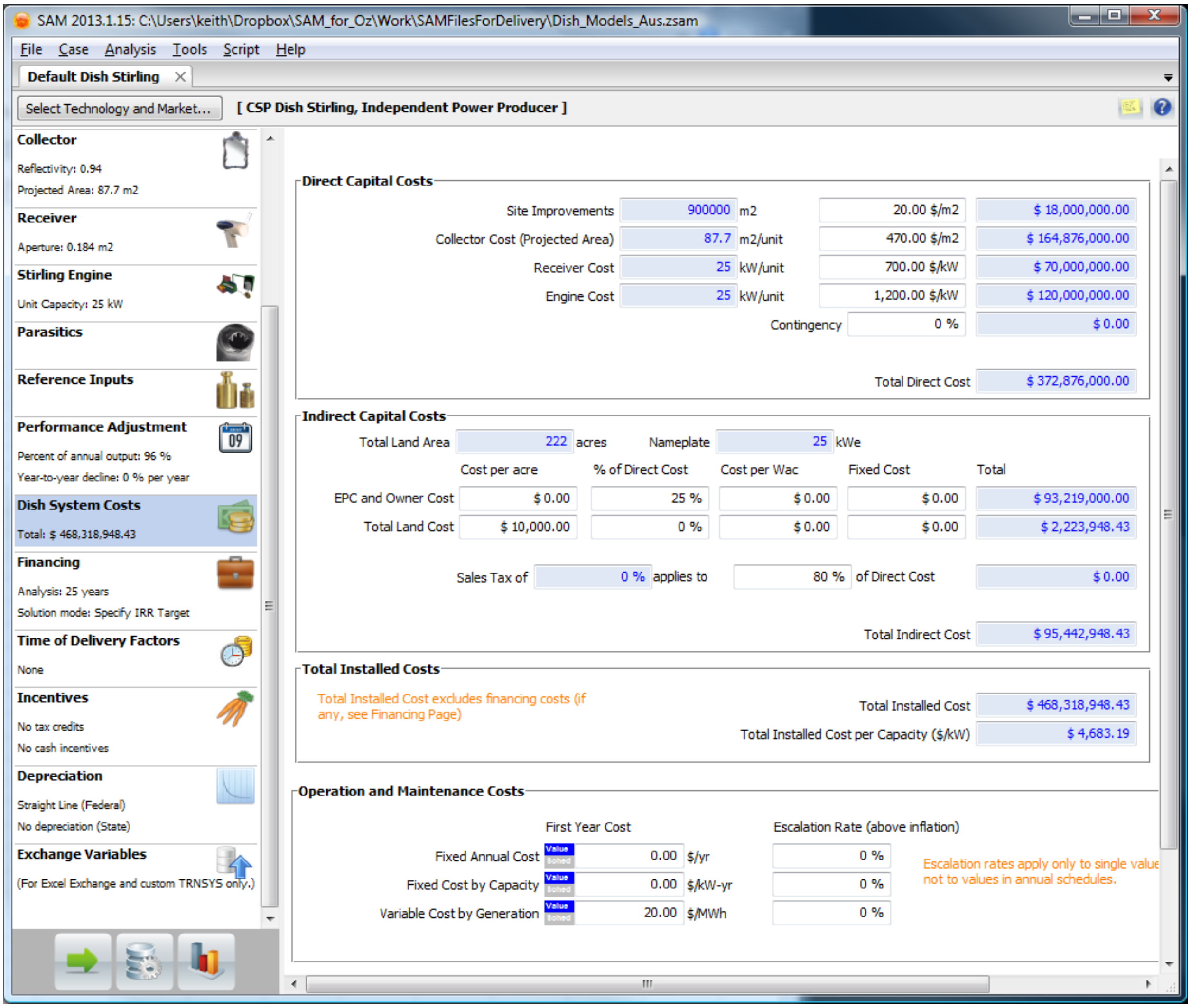


Figure 18: Dish system cost parameters.

The original and adjusted cost parameter values are shown in Table 6.

Dish case		Default Dish Stirling 100MW	Base Adjusted parameters
Parameter		Original USD	2012 AUD
Directs			
Site Improvements	$/m^2	20	20
Solar Field / heliostat field	$/m^2	400	470
HTF System	$/m^2		0
Subtotal area related	$/m^2	420	
Storage	$/kWh$_{th}$		
Fossil Backup	$/kW$_e$		
Power Plant	$/kW$_e$	550	1200
Balance of Plant	$/kW$_e$	225	700
Contingency	%	7	0
Indirects			
EPC and owner	%	11	25
Land	$/acre	10000	
Land	%	0	
Operation and Maintenance			
Fixed annual cost	$/yr	0	0
Fixed cost by capacity	$/kW-yr	75	0
Variable cost by generation	$/MWh	4	25
Fossil fuel cost		0	0

Table 6: Cost parameters for Dish case, original and revised to Australian settings.

It should be noted that the dish Stirling system cost factors carry the highest levels of uncertainty of all the technologies, due to the lack of commercial maturity.

5.5. LCOE's at the Longreach site

Having noted the basis for establishing the cost parameters above. It is instructive to consider the LCOE's that the various cases predict using the baseline RMY solar data file for Longreach. The values are shown in Table 7.

There is variation between these results, some of which has a real basis and some of which falls below the accuracy limits flowing from the various assumptions. The following observations can be made:

- Within the various trough cases, the systems with 6 or 7 hours storage show close to the same LCOE as the no storage case. This is in agreement with other analysis. The performance improvement from storage and the higher capacity factor for operation and hence amortisation of much of the system, offsets the investment in storage system. For trough plants with molten salt based storage, around 2 or 3 hours storage with the optimal solar field delivers the minimum LCOE.

- Whilst the underlying assumption is that at the present time, at a good solar site it is not currently possible to distinguish between the economic performance of the technologies without storage, the numbers show that the direct steam tower and the LFR systems are showing lower LCOEs than the trough without storage case. This arises from assumptions in the cost factors that the cost of the basic power block should be the same, but Balance of Plant costs are indicated as lower for tower and LFR in the absence of a separate HTF system. This is a real difference however it is smaller than the uncertainty of the estimates and until the Tower and LFR technologies are more widely deployed their true competitive position remains unknown.

Case	**Concentrator type**	**Real LCOE (2012 AUD $/MWh)**	**Nominal LCOE (2012 AUD $/MWh)**
Nevada Solar 1, 64MWe no TES	Trough	251.4	312.9
Physical Trough 100MW 6 hrs TES	Trough	234.4	291.8
Empirical Trough 100MW, 6 hrs TES	Trough	236.6	294.5
Andasol 1, 50MW, 7.5hrs TES	Trough	249.9	309.4
Direct Steam Power Tower 100MW	Tower	224.6	279.5
Molten Salt Tower 100MW, 10 hours TES	Tower	175.6	218.6
Gemasolar, 17MW, 15 Hours TES	Tower	212.9	264.9
Dish Stirling 100MW no storage	Dish	250.3	314.9
Linear Fresnel 100 MW no storage	LFR	232.3	289.1
Novatec Solar Boiler 42MW no storage	LFR	209.2	259.6

Table 7: LCOE results from the various cases using the Longreach RMY solar data file.

- In the physical and financial parameters in these cases, there is currently no recognition of the effect of system size. Thus the 50MW, 64 MW and 100MW trough cases are assumed to have the same cost parameters and the same turbine cycle efficiency. In fact smaller turbines are less efficient and smaller projects have higher proportional fixed costs. This is not captured.

- It is notable that the two molten salt tower plants have significantly lower LCOEs. This is a real differentiation. The molten salt energy storage technology is more cost effective in a Tower plant compared to a Trough plant because the larger temperature difference between hot and cold temperatures, means more energy is stored in the same volume of material. Thus while trough plants have an LCOE minimum at 2 – 3 hrs, Tower plants show progressively decreasing LCOE that is a minimum at around 10. However it needs to be noted that the Gemasolar 19MW plant is modelled with no size penalty in cost and efficiency relative to the 100MW hypothetical plant and so its costs are more representative of a larger plant with 15 hours storage. The fact that the predicted LCOE is higher for it than the 100MWe salt tower, is an indication that the increase in storage from 10 to 15 hours takes it past that of a minimum LCOE configuration. Whilst the case for Towers with storage seems very compelling, at the time of writing the Gemasolar system is the only example in the world, although the Crescent Dunes 100MW salt Tower system is nearing completion in Nevada. Hence this is still a technology at an early phase and although performance characteristics are becoming better known, cost data remains subject to a lot of uncertainty.
- If lower cost storage were modelled for any of the technology options, similar results to the salt Tower cases would be obtained.

6. SOLAR DATA FILES FOR AUSTRALIAN SITES

The most important input to modelling the performance of a CSP system is obviously a time series of Direct Normal Irradiance levels. Ambient temperature, windspeed and relative humidity are the other important variables. As well as determining thermal losses, they are also important for predicting system shut down and cooling tower performance.

Solar data in general is collected on various frequencies on various timescales from various sources. It could be categorised as:

- Direct site measurements that provide an exact assessment of a particular location at a particular time as reliably as the accuracy of the instruments.
- Satellite-derived data that, depending on the spatial resolution, provides an average assessment by grid cell, with data from a certain period, where its accuracy is dependent on the success of the algorithms used.
- Combined data, whereby a satellite data set is modified and calibrated using a range of ground-based measurements that have been accessed.

6.1. New data files for real years

SAM uses solar data / weather files in TMY3, TMY2 or EPW format. Generally the expectation is that the file will include hourly data. TMY3 and TMY2 have slightly different formats. EPW refers to the “Energy Plus Weather” file format developed for the US Department of Energy's Energy Plus building simulation software, and available from the Energy Plus website (Energy Plus 2012).

For locations outside of the United States, NREL suggests the US DOE’s Energy Plus weather files for use with SAM because they are readily available in a format that SAM can read for those locations. The Energy Plus website has weather data for all countries including Australia. It describes the source of the data for Australia as:

‘RMY Australia Representative Meteorological Year Climate Files Developed for the Australia Greenhouse Office for use in complying with the Building Code of Australia. These data are licensed through ACADS BSG Ltd for use by EnergyPlus users.’

It is understood that these “Australian Climate Data Base” (ACDB) data files were produced for the Australian Greenhouse Office, based on Bureau of Meteorology (BOM) satellite and ground station data and are now employed in “Accu-rate” and other building energy rating tools.

There is a known but little publicised fault with some of these data files, specifically those for sites for which ground-based data do not exist. In those cases, many of the daily profile shapes are not physically realistic, even though the integrated annual totals appear reasonable. Parsons

Brinkerhoff (2009) compared the EPS data to a range of other data sources, concluding that all sources were close, with the EPS data slightly underestimating totals compared to the others and so offering a conservative result. These files are also only statistically typical, strictly for the thermal behaviour of buildings.

Appendix E reviews possible sources of solar data for Australia, this project seeks to add to the range of options that is freely available. There are no other immediately available Australian site data files in TMY format although a revised version of the ACDB files is due to be released in 2013 by the Department of Climate Change.

TMY means “Typical Meteorological Year” meaning an artificial year that is claimed to be statistically representative of “average” weather patterns over a multi-year period. The TMY2, TMY3 or EPW file formats can also be used to present data for specific real years.

The methodology for Typical Meteorological Years (Wilcox and Marion 2008) is to assemble an artificial but representative year from real months from real years chosen such that each real month best reproduces the pattern that is considered typical in a long term average. The advantage of a Typical Meteorological Year is obviously that a system need only be modelled for that year to estimate its long term average output. Constructing a typical year in this way, requires the specification of weightings for the various variables such that the typical year will end up with the same weighted average value as the long term average for the site. The challenge is that not only do CSP systems suggest different weightings to, for example PV systems or buildings, even within CSP systems obvious factors such as threshold DNI and the use of dry vs wet cooling, mean that different system configurations should use different variable weightings (Wilcox and Marion 2008, Lee 2011).

In addition to this shortcoming, there are also the issues that as years go by, extra data years could lead to a revision of the long term average, because the long term data series better approaches a true average, or more significantly, because the long term average is actually changing due to climate change effects.

Thus the files presented here are instead real years chosen to be as close to the best, worst and average years for annual radiation levels as practicable. In addition to avoiding some of the pitfalls of Typical Years, these offer the additional advantages that:

- Modelling with three years provides a means for estimating the likely spread in annual generation values.
- If a real year is modelled, analysis to examine the exact correlation with electricity demand / price variation in the relevant market is possible.
- If subsequent years reveal a new best or worst year, then the old years still have validity in their own right, new real years can simply be added to the library going forward.

6.2. Choice of format

The new files presented here have been produced in TMY3 format. The TMY2 format has had the widest usage to date, however TMY3 is the newer format that appears increasingly favoured. TMY3 files are of the comma separated value (CSV) type, this has the major pragmatic advantage that they can easily be opened and inspected with Excel for example16. There is also the key point that SAM has a "create TMY3 file" facility built in to the location and resource menu page, that can be used to open an existing TMY3 and modify it if desired (Figure 19 and Figure 20).

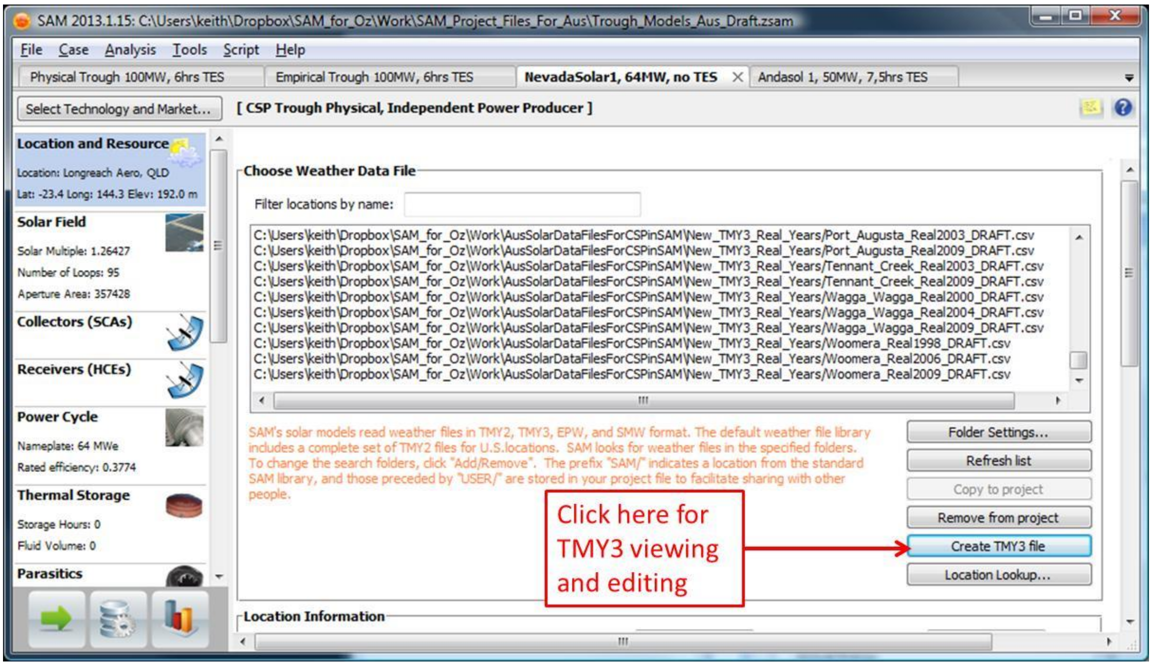


Figure 19: To view / edit a TMY3 solar data file.

While the format of TMY3 files is considerably different to that of TMY2 files there are only a small number of different fields contained in the files. The fundamental differences between the two file types are measurement units, which are SI or equivalent in the TMY3, the addition of three new fields for surface albedo and liquid precipitation, and the removal of the fields for present weather, snow-depth, and days since last snowfall that were present in the TMY2. The files include two leader rows and 8760 rows of data, each with 68 columns of data. SAMS's CSP models only use the first few columns, as seen in the TMY3 editor tool (Figure 20).

The files presented here have all the unused / unnecessary columns populated with the standard null placeholder of "-9900". These files should not be used for other purposes (modelling building systems for example) without checking whether the other data columns that are not used by SAM's CSP modelling are needed.

[16] Note, changing and saving from Excel can however lead to problems of format incompatibility. Use of the SAM tool is recommended instead for creation of custom files.

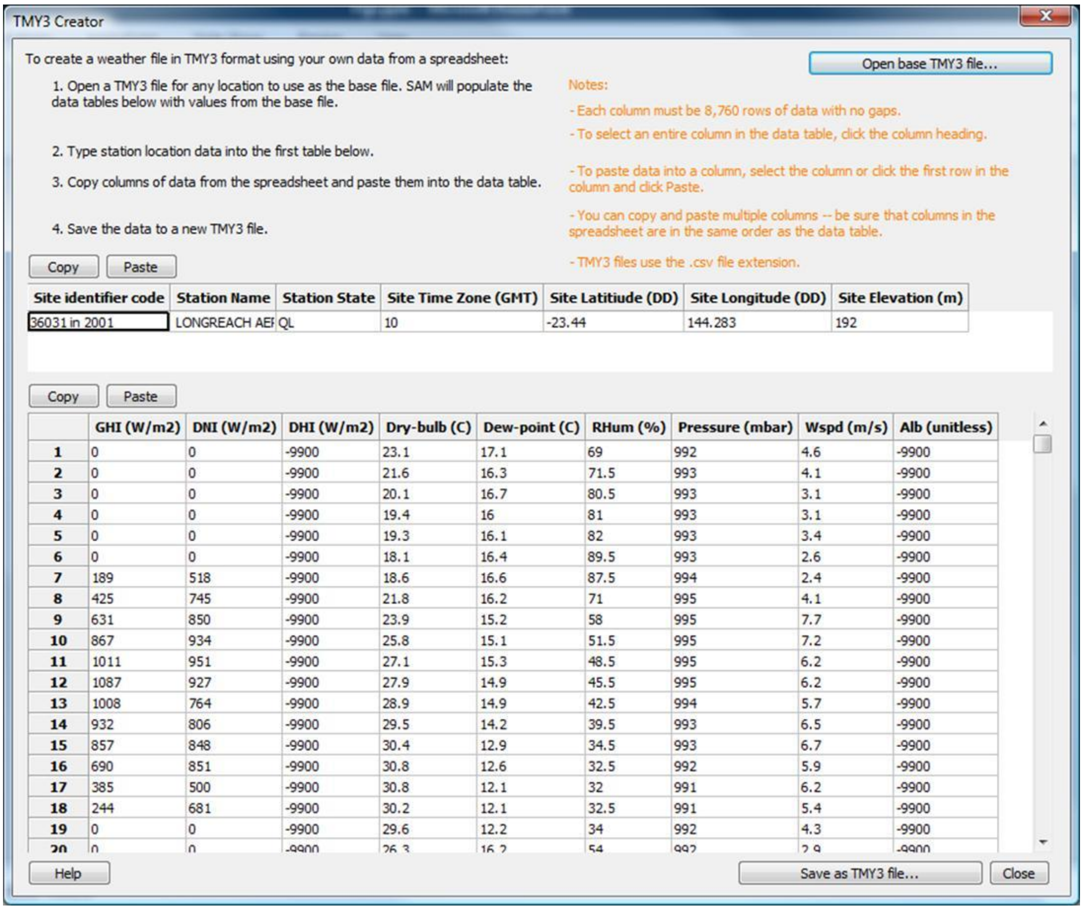


Figure 20: View of a TMY3 file in the TMY3 creation tool.

6.3. Sites and years

Figure 21, reproduced from the CSP in Australia report, shows the distribution of average DNI levels across Australia.

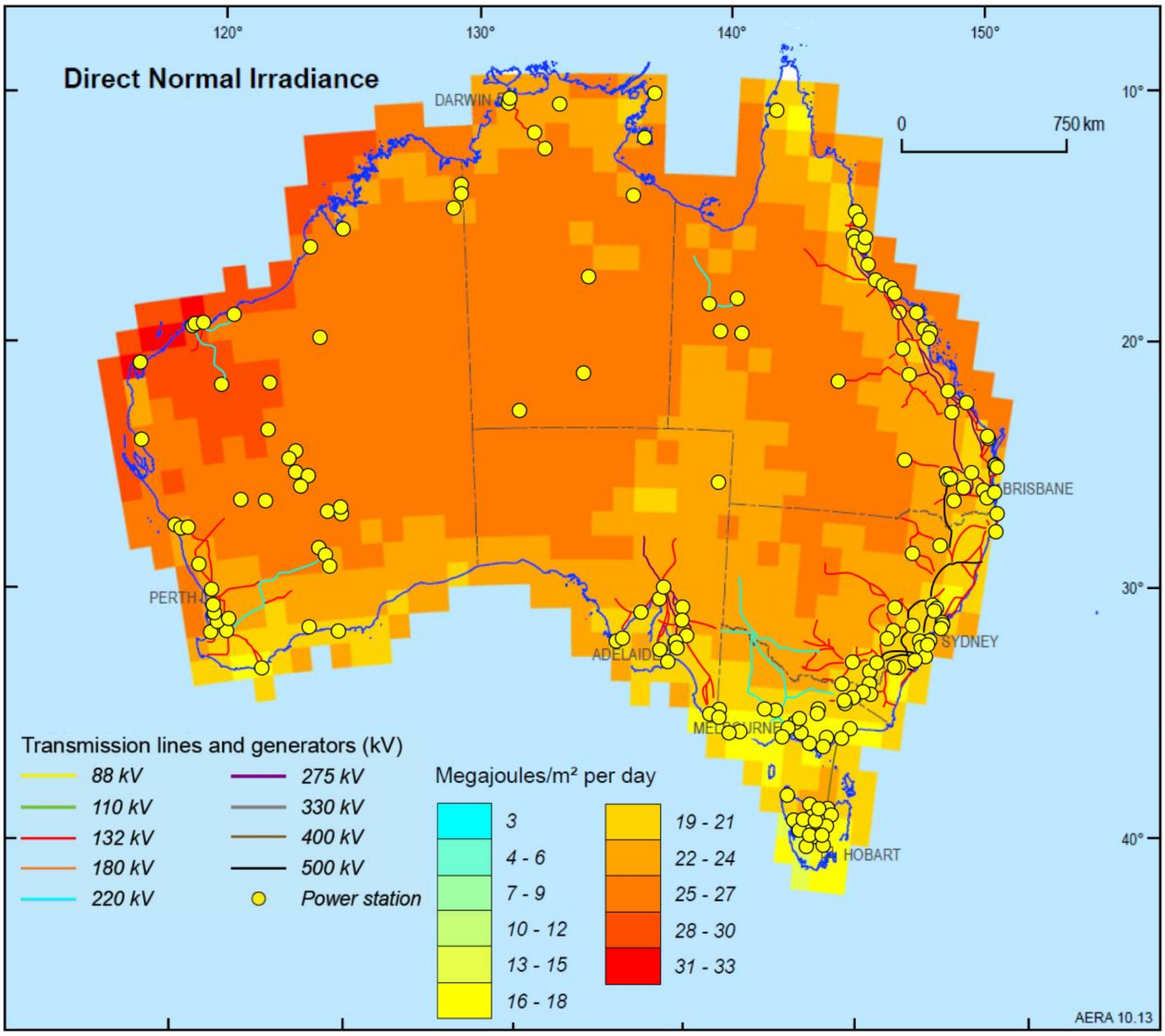


Figure 21: Transmission Network in Australia compared to average Direct Beam irradiation (based on two figures from Commonwealth of Australia (2010).

Figure 22 identifies likely locations of CSP systems targeted at large-scale grid connected (connected to the transmission network), medium-scale grid connected (connected to the distribution network) and off grid (connected to mini grids ie specific large local loads). This assessment suggests that Southern regions, the East Coast and any cyclone effected regions are not prospective for CSP purposes.

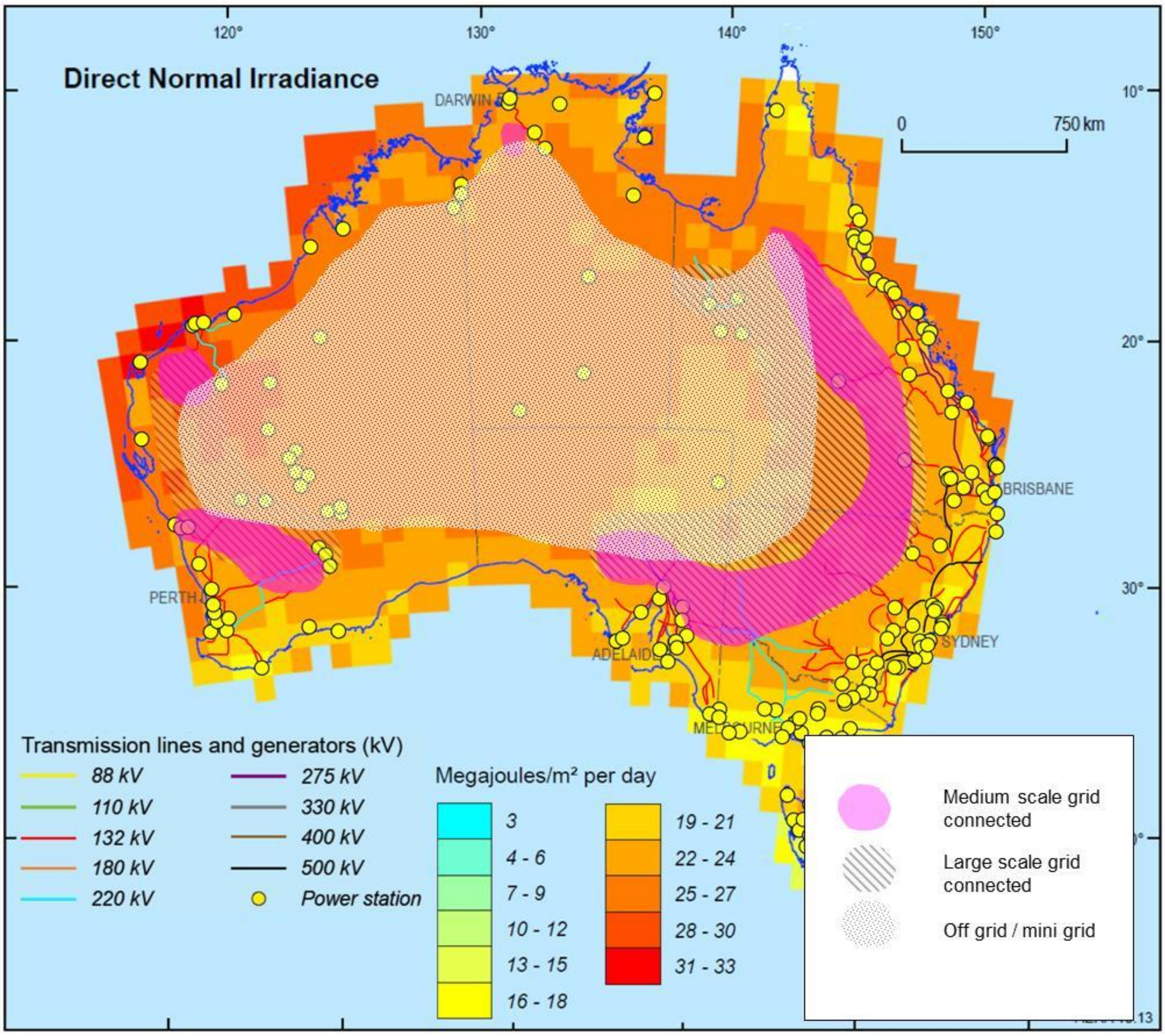


Figure 22: Market segments and approximate location for CSP in Australia.

The sites were chosen with the aim of limiting the number to around 10 whilst providing a representative location in each general prospective CSP suitable region in Australia.

The real year files are based on the Bureau of Meteorology gridded satellite data for solar radiation levels, combined with Automatic Weather station data for the other variables. Actual sites were chosen, for which some DNI based ground data is available for cross checking, or failing that some ground based data of any kind and failing that corresponding to an actual weather station in a location of critical interest.

The sites chosen are shown in Figure 23.

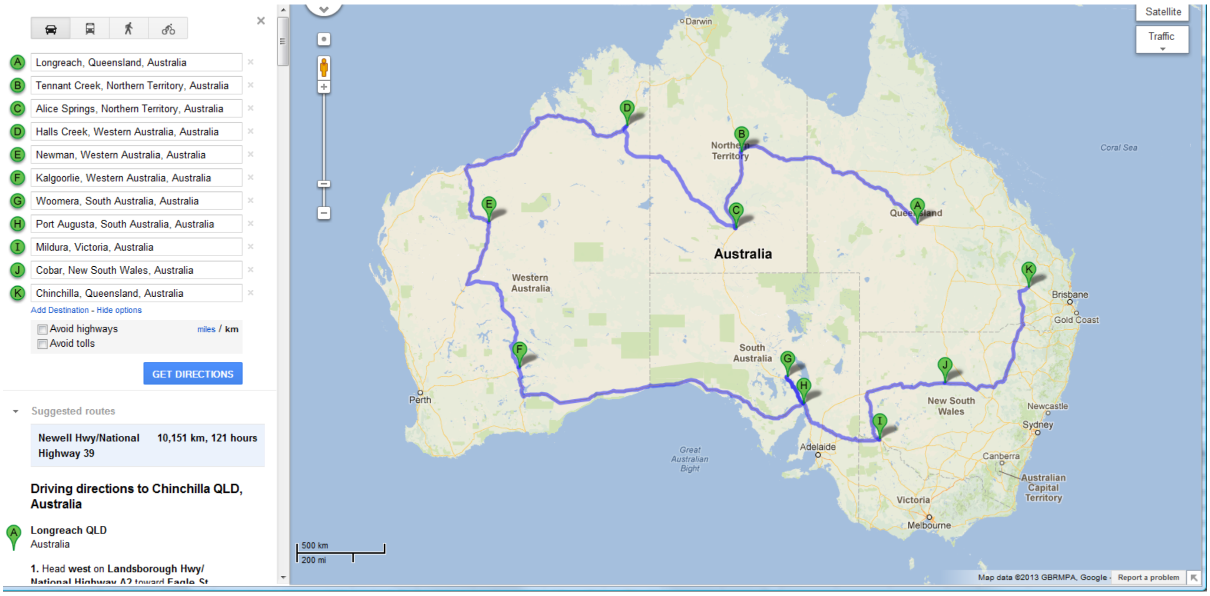


Figure 23: Representative sites for real year TMY3 format data files.

The years were chosen using the values for annual total Direct Normal irradiation integrated from the satellite data after interpolating for missing data points, for these locations for the years 1990 to 2012. All the satellite based data sets have missing data in various years, the worst years (1990 -1995 1992, and 2001- 2003) were avoided.

The comparison is shown in Table 8.

Year	Newman (stn#7176)	Kalgoorlie (stn#12038)	Tennant Creek (stn#15135)	Alice Springs (stn#15590)	Woomera (stn#16001)	Pt Augusta (stn#18201)	Cobar (Stn#48027)	Wagga Wagga (stn#72150)	Mildura (stn#76031)	Longreach (stn#36031)	Halls Creek (stn#2012)	Chinchilla (stn#41351)
1991			2523	2612			2534	2121	2264			
1992			2475	2367			2190	1813	1948			
1993			2428	2374	2415		2365	2054	2103			
1994	2453		2410	2543	2370		2373	2024	2124		2227	
1995	2517	2193	2552	2567	2308		2197	1921			2308	
1996	2576	2376	2708	2836	2567		2420	2102	2301	2630	2549	
1997	2543	2225	2522	2433	2384		2315	2275	2268	2371	2373	
1998	2269	2200	2470	2377	2200		2157	1954	2143	2290	2223	
1999	2359	2103	2475	2477	2264		2034	1970	2075	2283	2346	1925
2000	2426	2161	2249	2285	2279		2095	1917	2051	2215	2209	1958
2001	2360	1982	2145	2085	2148		2103	1798	1869		2082	
2002	2393	2186	2335	2322	2252	2128	2140	1997	2136		2250	
2003	2566	2238	2373	2449	2252	2176	2153	1907	2177		2392	

2004	2450	2243	2551	2516	2467	2381	2472	2131	2383	2573	2351	2348
2005	2688	2320	2486	2637	2515	2368	2460	2193	2262		2359	
2006	2452	2371	2513	2620	2480	2425	2428	2391	2394	2523	2375	2270
2007	2606	2430	2465	2604	2503	2412	2173	2164	2302	2358	2398	2106
2008	2512	2272	2579	2692	2456	2281	2330			2418	2401	2107
2009	2505	2298	2636	2744	2604	2456	2285	2129	2300	2410	2533	2207
2010	2553	2334	2238	2440	2317	2129	1995	1886	2018	2049	2245	1702
2011	2407	1889	2331	2439	2222	2153	2038	1903	2073	2361	2180	2006
2012	2346	2146	2479	2421	2317	2126	2183	1909	2040	2336	2336	2078
Aver.	2473	2220	2452	2493	2366	2276	2247	2027	2162	2371	2323	2071
Max	2688	2430	2708	2836	2604	2456	2534	2391	2394	2630	2549	2348
Min	2269	1889	2145	2085	2148	2126	1995	1798	1869	2049	2082	1702

Table 8: Summary of annual DNI levels and choice of best (red), worst (green) and close to typical (yellow) years.

Where necessary a "second closest" to Maximum, Minimum or Average year was chosen to avoid the years of poor satellite data coverage.

The final result is a set of TMY 3 format real year data files for sites and years as shown in Table 9.

	Newman (stn#7176)	Kalgoorlie (stn#12038)	Tennant Creek (stn#15135)	Alice Springs (stn#15590)	Woomera (stn#16001)	Pt Augusta (stn#18201)	Cobar (Stn#48027)	Wagga Wagga (stn#72150)	Mildura (stn#76031)	Longreach (stn#36031)	Halls Creek (stn#2012)	Chinchilla (stn#41351)
Representative min year	1998	2011	2010	2000	1998	2012	2010	2000	2010	2010	2011	2010
difference to actual min	0.0%	0.0%	4.9%	9.6%	2.4%	0.0%	0.0%	6.6%	8.0%	0.0%	4.7%	0.0%
Representative av year	2006	1997	2007	1999	1997	2008	2009	1996	1998	2009	2004	2011
difference to actual av	-0.8%	0.2%	0.5%	-0.6%	0.7%	0.2%	1.7%	3.7%	-0.8%	1.7%	1.2%	-3.1%
Representative max year	2005	2007	1996	1996	2009	2009	2004	2006	2006	1996	1996	2004
difference to actual max	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-2.4%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 9: Years and sites chosen.

7. CONCLUSION

At the completion of this project appropriate and readily understood financial input settings have been established to allow SAM to easily be used for Australian conditions to determine the real or nominal LCOE for a range of circumstances and system configurations.

The calculation of LCOE for the baseline case used in the CSP in Australia study has been successfully reconciled with a calculation within SAM, Results agree to within a fraction of a percent.

A selection of SAM cases has been identified and organised into technology specific projects (.zsam files) which will be placed on Austela and other websites. The financial parameters have been adjusted to appropriate AUD 2012 settings such that they are consistent with the baseline Longreach LCOE calculation. To aid new users in varying these financial settings, the Excel exchange feature has been employed to automatically load financial cost factors from an attached spreadsheet, which allows scaling of costs for learning effects or size dependence for example,

Approaches to providing a useful but limited set of TMY format solar data files for Australia have been reviewed. TMY3 was chosen as the preferred format. Rather than assemble statistically representative years in the face of no single clear determination of appropriate typical status, it has been assessed that providing close to best, worst and typical real years for representative sites in CSP prospective areas is the best approach.

The starting point for generating these solar TMY format files, is the most recent gridded satellite based data sets from the Australian Bureau of Meteorology. Unfortunately the process of data improvement and calibration that BOM is undertaking and that was expected to be finished prior to this project is still not complete. Re-running the process after the revised data is available later in 2013 is recommended. Any such updates would be available on the Austela website.

8. REFERENCES

Commonwealth of Australia, 2010, *Australian Energy Resources Assessment,* ISBN 978-1-921672-59-0 (hard copy)ISBN 978-1-921672-58-3 (web) Geoscience Australia and ABARE, 2010, Australian Energy Resource Assessment, Canberra, Commonwealth of Australia, 2010.

Energy Plus, 2012, *Energy Plus weather data,* http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data.cfm.

Feierabend, L., 2009, *Thermal Model Development and Simulation of Cavity-Type Solar Central Receiver Systems.,* University of Wisconsin-Madison. http://sel.me.wisc.edu/publications/theses/feierabend09.zip

Fraser, P., 2008, *Stirling Dish System Performance Prediction Model.l,* University of Wisconsin-Madison. https://sam.nrel.gov/webfm_send/75

Hammond G, 2011, *Solar Resource Mapping Program,,* presentation on behalf of Geoscience Australia at International Conference on Energy & Meteorology, 8-11 November 2011, Gold Coast Australia.

Kistler, B., 1986, *A User's Manual for DELSOL3: A Computer Code for Calculating the Optical Performance and Optimal System Design for Solar Thermal Central Receiver Plants.,* Sandia Report No. SAND86-8018. http://prod.sandia.gov/techlib/access-control.cgi/1986/868018.pdf

Lee, T, 2011, *Climate Data for Building Optimisation in Design and Operation in Australia.,* IBPSA conference paper 2011.

Lovegrove K, Watt M, Passey R, Pollock G, Wyder J, Dowse J., 2012, *Realising the potential of concentrating solar power in Australia,* Prepared by IT Power (Australia) Pty Ltd for the Australian Solar Institute, May 2012, www.australiansolarinstitute.com.au ISBN: 978-0-9873356-1-6.

Lovegrove L and Stein W, 2012, *Concentrating Solar Power Technology,* Woodhead publishing Limited, UK, isbn 978-1-84569-769-3, www.woodheadpublishing.com/7693

Neises, T.; Wagner, M., 2012, *Simulation of Direct Steam Power Tower Concentrated Solar Plant.,* ASME SE 2012 Conference.

NREL, 2012, *System Advisor model (SAM),* Version 2012.11.30, Manual Release data 11/29/2012, National Renewable Energy Laboratory.Colarado.

Parsons Brinckerhoff, 2010, *Queensland Concentrated Solar Power Pre-feasibility Report,* Pre-feasibility Report December 2009 Released October 2010 By Parsons Brinkerhoff for Queensland Government Office of Clean Energy Department of Employment, Economic Development and Industry.

Price, H., 2003, *Parabolic Trough Solar Power Plant Simulation Model.,* Proceedings of the ISEC 2003: International Solar Energy Conference, 15-18 March 2003, Kohala Coast, Hawaii. New York: American Society of Mechanical Engineers. 665-673 pp.; NREL Report No. CP-550-34742. http://www.nrel.gov/docs/fy03osti/33209.pdf

Short W, Daniel J. Packey, and Thomas Holt, 1995, *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies,* March 1995 □ NREL/TP-462-5173 National Renewable Energy Laboratory 1617 Cole Boulevard Golden, Colorado 80401-3393 http://www.nrel.gov/docs/legosti/old/5173.pdf .

University of Wisconsin, 2013, *TRNSYS official website,* http://sel.me.wisc.edu/trnsys/

Wagner, M., 2008, *Simulation and Predictive Performance Modeling of Utility-Scale Central Receiver System Power Plants.,* University of Wisconsin-Madison. https://sam.nrel.gov/webfm_send/79

Wagner, M., 2012, *Results and Comparison from the SAM Linear Fresnel Technology Performance Model.,* Preprint. NREL Conference Paper CP-5500-54758." http://www.nrel.gov/docs/fy12osti/54758.pdf

Wagner, M. J.; Gilman, P., 2011, *Technical Manual for the SAM Physical Trough Model.,* 124 pp.; NREL Report No. TP-5500-51825. https://sam.nrel.gov/webfm_send/106

Wagner, M.; Zhu, G., 2012, *A Direct-steam Linear Fresnel Performance Model for NREL's System Advisor Model.,* NREL Conference Paper CP-5500-55044. http://www.nrel.gov/docs/fy12osti/55044.pdf

Wilcox S and Marion W, 2008, *Users Manual for TMY3 Data Sets,* Technical Report NREL/TP-581-43156

9. APPENDIX B: LEVELISED COST OF ENERGY

The Levelised Cost of Energy (LCOE) is the most frequently used economic performance metric for power generation plant. It is defined as the constant per unit cost of energy which over the system's lifetime, will result in a total NPV of zero. In other words it is the "break even" constant sale price of energy. For a detailed presentation on the principles of financial evaluation of energy projects, refer to Short et al (1995).

The following discussion is reproduced from the CSP in Australia Study.

LCOEs can be in real or nominal terms, which can be confusing because they are expressed in year 0 dollar values in either case. A nominal LCOE represents a hypothetical income that declines in real value year by year, whereas a real LCOE has a constant "value". Since the total NPV via either method must be the same by definition, the nominal LCOE will be the higher of the two. Real LCOEs are typically used for future long term technology projections, whereas nominal ones are often used for short term actual projects.

$$LCOE = \frac{NPV(lifecyclecosts)}{\sum_1^N \left(\left(annual\_generation \times (1-T)\right) \big/ (1+DR)^j \right)}$$

Where T is the tax rate

From a pure societal perspective, it can be argued that tax issues can be left out of the LCOE. However for the perspective of a commercial entity owning a system, the prevailing assumption is that, to break even, it must be assumed that energy produced is taxed at the standard corporate tax rate. Against this, interest, depreciation and operating costs are tax deductible.

Detailed, project specific LCOE evaluations are based on complex spreadsheets summing every discounted cash flow over the system lifetime, which are then solved iteratively to establish the dollar value of energy which gives the total NPV of zero.

Issues that are typically encountered include:

- Debt financing may be paid off over a different time scale to equity
- Tax benefits may apply in different jurisdictions
- Tax deductible depreciation may apply over a shorter timescale than the project.
- Construction is staged over several years and subject to higher interest rates for finance
- System output may take some time to stabilise as commissioning processes proceed after first start up.

- System output may be subject to other predictable variations over time (such as a component with known degradation rate).
- Major overhaul type expenditures may be predicted at certain times in addition to overall continuous O&M.
- Various inputs may be subject to different escalation rates.

All these issues are project specific, depending on technology type, developer status and site chosen.

Studies that report LCOEs for CSP systems and other generation types are often poor at documenting all input parameter values and the methods used in a comprehensive way. In many cases, the methodology is actually intentionally withheld as it is embodied in proprietary financial models.

This study has adopted a methodology which is somewhat simplified but has sufficient complexity to allow issues of tax, cost of equity and cost of debt to be examined.

The life cycle NPV calculation is embodied in the following formula:

$$NPV_{LC\,\text{costs}} = EQ - \sum_{1}^{ND} \frac{DEP \times T}{(1+DR)^j} + \sum_{1}^{NL} \frac{LP}{(1+DR)^j} - \sum_{1}^{NL} \frac{INT \times T}{(1+DR)^j} + \sum_{1}^{N} \frac{AO \times (1-T)}{(1+DR)^j} - \frac{SV}{(1+DR)^N}$$

Where:

EQ is the initial equity contribution from the project developer

DR is the nominal discount rate

ND the period (number of years) over which the system can be depreciated for tax purposes

DEP is the amount of depreciation in a year

T is the tax rate applying

LP is the annual loan payment

INT is the reducing amount of Interest paid each year as the loan is paid off

NL is the term (number of years) of the loan

AO is the annual operations cost which could be calculated from fixed and variable contributions as needed

N is the project lifetime

SV is the end of project life salvage value.

The simplifying assumptions used are:

- The analysis begins from the time of plant commissioning.
- Annual energy production is assumed constant over project life.
- The Equity contribution is assessed at the beginning of year 1 and so is assumed to have all costs of construction finance rolled into it.
- Depreciation is linear in nominal dollars.
- Loan payments are constant for each year of the loan and are in nominal dollars based on amortisation of a debt across a loan term using the standard annualisation formula.
- Annual O&M costs are constant per year in nominal dollar terms across project life. (this is possibly the most significant, since it doesn't reflect the lumpy expenditure likely on component overhaul).

To aid in understanding, LCOE can be simplified further if tax is not considered and the cost of capital (both debt and equity) can be rolled into a single discount rate. The result is:

$$LCOE = \frac{(F_R + \mathrm{O\&M}_{fixed})C_0}{PF_c} + O\&M_{variable}$$

Where:

P is the nameplate capacity of the system

F_c is the capacity factor

C_o is the total initial capital cost and

$$F_R \equiv \left(\frac{DR(1+DR)^n}{(1+DR)^n - 1} \right)$$

is the 'capital recovery factor' and is dimensionally the same as the discount rate. The capital recovery factor represents a rate of repayment that covers 'interest' plus paying off the capital in the system's lifetime.

10. APPENDIX C - SAM CASE STUDY: GEMASOLAR, FUENTES DE ANDALUCÍA, SPAIN

The material in this appendix is reproduced verbatim from an NREL document of the same name. Authors Ezequiel Ferrer, Mark Mehos.

The SAM team is compiling a series of case studies to provide specific examples with the view to guide users in constructing their own SAM analyses. These case studies describe the process of acquiring data, generating a SAM file with explicit inputs, and analyzing the salient results. Each case study is accompanied by the SAM file (v2012.11.30) that has been used to model the case.

10.1. Abstract

Gemasolar, located in Fuentes de Andalucía, Spain, about 40 miles east of Sevilla, is the first commercial-scale plant in the world to apply central tower receiver and molten salt heat storage technology. The plant has a capacity of 19.9 MW_e (gross) and covers slightly less than 200 hectares. It is owned and operated by Torresol Energy, a joint venture between SENER and Masdar. Performance data from the plant is proprietary but even without a very accurate weather file the SAM model predicts an annual energy output proportional to the values reported in the media. In this case study we do not estimate the economics of the plant due to the lack of reliable data.

Figure C1: Gemasolar solar power tower plant

10.2. System Description

The Gemasolar power plant consists of 2,650 heliostats distributed in concentric rings around the tower, with a total reflective area of 304,750 m^2, in an immense 185-hectare circle. The 115 m^2 heliostats developed by SENER use proprietary technology to track the sun's location in order to maximize the collection of thermal energy, and their location was established by the SENSOL software. These heliostats reflect and concentrate sun radiation on a 120 MW_{th} solar receiver located on the upper part of 140 m tower. Molten salt is pumped from a cold storage tank through the receiver where is heated and then stored into a hot tank. From the hot tank the salt is pumped to a steam generation system. The superheated steam produced drives a 19.9 MW_e (gross) Siemens SST-600 two-cylinder reheat steam turbine, which is connected to a generator that produces electricity. The plant uses a wet-cooling system to condense the steam back to liquid. The Gemasolar power plant has a thermal storage system which stores part of the heat produced in the solar field during the day in a molten salt mixture of 60% sodium nitrate and 40% potassium nitrate. A full storage tank can be used to operate the turbine for about 15 hours at full-load when the sky is overcast or after sunset. The plant also utilizes a 15% fossil fuel back-up from a natural gas heater. Ground-breaking for Gemasolar plant began in February 2009 and after 26 months of construction, it went online in May 2011.

Figure C2: Aerial view of Gemasolar

10.3. Data Acquisition

This study used the Sevilla EPW climate file from the SAM database as the best representation of Fuentes de Andalucía due to the two locations being only 40 miles apart. The system specifications were primarily sourced from the NREL/ SolarPACES website [1] and from the Gemasolar plant fact sheet [2]. Torresol Energy released an estimated annual energy output for the plant in its website [3].

10.4. SAM Inputs

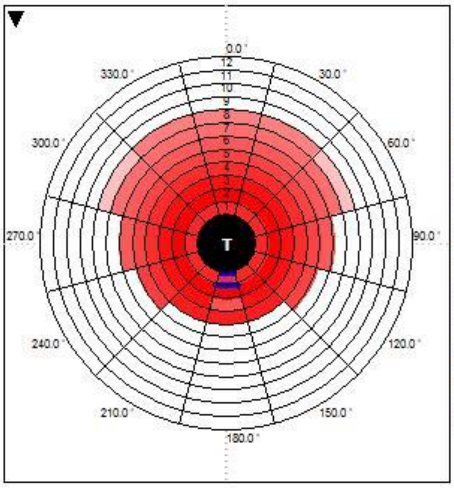
The SAM technology chosen for this system is CSP molten salt power tower. The market is Independent Power Producer since Torresol Energy sells the electricity to ENDESA at a price negotiated through a PPA that was established with the Spanish feed-in tariff. Table 1 shows all the changes from the default values based on the system description.

Table C1: SAM performance inputs for Gemasolar that differ from default values

Page	Variable	Default Value	Gemasolar
Climate	Location	CA Dagget (TMY2)	Sevilla (EPW)
Heliostat Field	Heliostat width	12.2 m	10.9 m
	Heliostat height	12.2 m	10.9 m
	Max heliostat distance to tower	7.5	8
	Solar field land area multiplier	1.3	1.4
Tower and Receiver	Receiver height	20.41 m	14.22 m
	Receiver diameter	17.67 m	8.89 m
	Number of panels	20	16
	Required HTF outlet temp.	574 °C	565 °C
	Solar multiple	2.4	2.5
	Tower height	203.33 m	140 m
Power Cycle	Design turbine gross output	115 MW	19.9 MW
	Estimated gross to net conv.	0.87	0.875
	Design HTF inlet temperature	574 °C	565 °C
	Aux heater outlet set temp.	594 °C	570 °C
	Min turbine operation	0.25	0.20
	Condenser type	Air cooled	Evaporative
	Ambient temp at design	43 °C	20 °C
Thermal Storage	Full load hours of TES	10	15
	Initial hot HTF temp.	574 °C	565 °C
	Current dispatch schedule	Summer peak	Uniform dispatch
	Fossil fill fraction (Period 1)	0	0.27
Parasitics	Piping loss coefficient	10,200 Wt/m	8,000 Wt/m

The Royal decree 661/2007 set an allowance for solar thermal plants to contain up to 12-15% natural gas back up. This increases the reliability of the plants, since natural gas can be used both to maintain the temperature of the heat storage during periods of interruption in solar thermal electricity generation and to continue generation during cloudy conditions or after sunset. We have adjusted the fossil fill fraction value in order to reach a 15% fossil fuel back up without specific criteria. Further research should be done in order to clarify how Gemasolar uses the 15% fossil fuel back up allowed.

The distribution of the heliostats in the solar field, receiver height and receiver diameter were calculated with the wizard. Once the wizard populated the zonal grid we adjusted the number of the heliostat to make them coincident with the 2,650 heliostat of the Gemasolar plant. Figure 3 (below) shows the final distribution of the heliostats in the solar field.



Span Angle: 360 Radial Zones: 12 Azimuthal Zones: 12

	0.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0
Rad.1	11	11	11	11	11	11	11	11	11	11	11	11
Rad.2	31	31	31	31	31	31	31	31	31	31	31	31
Rad.3	39	39	39	39	39	39	28	39	39	39	39	39
Rad.4	43	43	43	43	43	46	46	46	43	43	43	43
Rad.5	46	46	46	46	46	0	0	0	47	46	46	46
Rad.6	47	47	47	47	0	0	0	0	0	47	47	47
Rad.7	47	47	47	0	0	0	0	0	0	0	47	47
Rad.8	46	46	23	0	0	0	0	0	0	0	23	47
Rad.9	0	0	0	0	0	0	0	0	0	0	0	0
Rad.10	0	0	0	0	0	0	0	0	0	0	0	0
Rad.11	0	0	0	0	0	0	0	0	0	0	0	0
Rad.12	0	0	0	0	0	0	0	0	0	0	0	0

Import Export

Figure C3: Location of the heliostats in the solar field

10.5. Results and Discussion

Table 3 shows the key SAM metrics for the performance of the system along with reported values (when available) and the percent difference between the SAM estimates and the media reports.

Table C3: SAM metrics table

Metric	SAM value	Reported Value	Difference (%)
Annual Energy	107,356,960 kWh	110,000,000 kWh	2.4%
Capacity Factor	70.4%	74%	3.6%
Gross to Net Conv. Factor	0.88		
Total Land Area	438.18 acres	457.00 acres	4.1%
Annual Water Usage	368,347 m^3		

The simulation gave an energy output of approximately 107.4 GWh/year. The reported annual output for Gemasolar is estimated at 110 GWh/year, giving a 2.4% difference in the actual and simulated values. There was also a 4.1% difference between the simulated and reported values for the total land of the plant.

There are many practical graphs for the performance side of the model. Figure 4 (below) shows the annual energy flow. From this, we can see the energy losses associated with certain processes throughout the system. For example, we can see the inefficiency of converting thermal energy to electricity during the power cycle. We can also obtain a more precise picture of the system's output using DView, SAM's hourly time series data viewer. To launch DView, click on Time Series in the Results menu. Figure 5 (below) shows the gross power output of the plant at different times of the day and different days of the year. This is useful in determining peak output hours throughout the year and could be used to make a comparison between peak output and peak demand hours or to compare time series outputs in different locations.

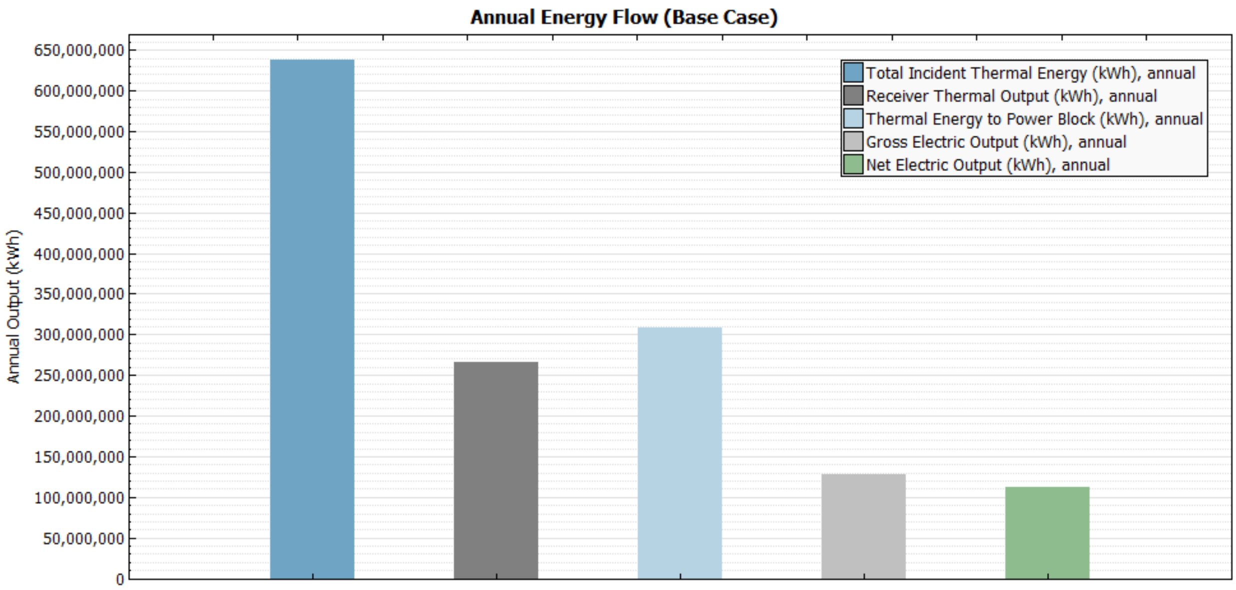


Figure C4: The annual energy flow shows the losses from different processes throughout the system.

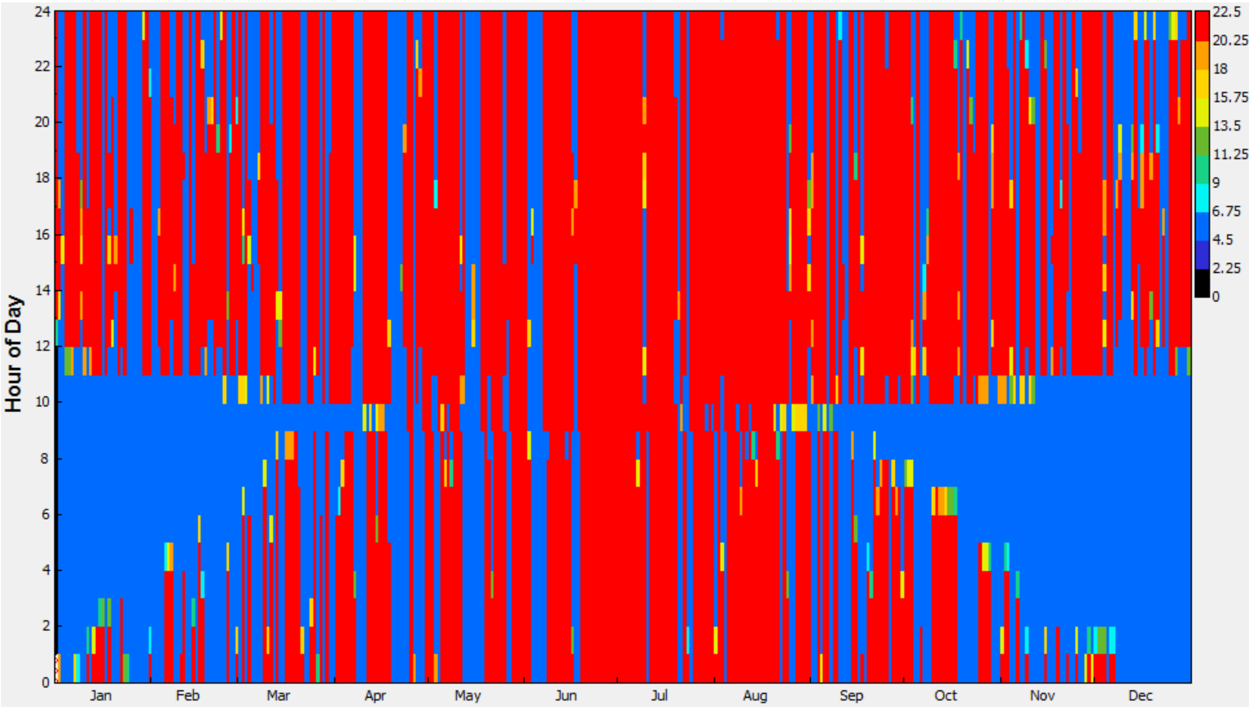


Figure C5: The gross power output of the system shows the peak times of year. Each pixel represents a single hour of the year.

10.6. Conclusion

Utilizing SAM's capabilities, we modeled Gemasolar, the first commercial-scale plant in the world to apply central tower receiver and molten salt heat storage technology. We were able to model the plant with minimal changes to the default values, using the limited information that has been made publicly available. Even with lacking performance data, we were able to get within 3% of the reported annual output. This case study is located in the SAM samples folder.

10.7. References

[1] "Gemasolar Thermosolar Plant" *SolarPACES. National Renewable Energy Laboratory*. <http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=40>

[2] "Gemasolar Plant (Solar-3)" *SENER Power and Process*. <http://www.sener-power- process.com/ENERGIA/ProjectsI/gemasolar/en>

[3] "Gemasolar" *Torresol Energy*. <http://www.torresolenergy.com/TORRESOL/gemasolar-plant/en>

[4] SAM templates available at: <https://www.nrel.gov/analysis/sam/templates.html>

11. APPENDIX D - SAM CASE STUDY: ANDASOL-1 ALDEIRE, SPAIN

The material in this appendix is reproduced verbatim from an NREL document of the same name. Authors Ezequiel Ferrer, Mark Mehos.

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The SAM team is compiling a series of case studies to provide specific examples with the view to guide users in constructing their own SAM analyses. These case studies describe the process of acquiring data, generating a SAM file with explicit inputs, and analyzing the salient results. Each case study is accompanied by the SAM file (v2012.11.30) that has been used to model the case.

11.1. Abstract

Andasol-1 is a parabolic trough concentrating solar power (CSP) plant in Aldeire, Spain about 40 km east of Granada. This was the first parabolic trough power plant built in Europe as well as the first trough plant in the world to incorporate thermal storage [1]. The plant has a nominal capacity of 50 MWe and covers slightly less than 500 acres. It is owned and operated by ACS-Cobra Energy, who invested around €310 million to build the plant. The feed-in tariff in Spain was set by Royal decree 661/2007 and offers a guaranteed power purchase agreement (PPA) for 25 years at a tariff rate of €0.27/kWh. Performance data from the plant is proprietary but even without a very accurate weather file the SAM model predicts an annual energy output and a PPA proportional to the values reported in the media [2,3].

Figure D1: South-facing view of Andasol-1 solar field [4]

11.2. System Description

Andasol-1 has a solar field aperture of 510,120 m^2, consisting of 624 Skal-ET parabolic trough collectors, including 156 parallel loops of four collectors in serial connection. The plant uses proprietary technology to track the sun's location in order to maximize the collection of thermal energy. The solar collectors are made up of more than 200,000 mirrors that concentrate the sun rays on 22,464 tube receivers. The receivers are both Schott PTR-70 and Solel UVAC models. The heat transfer fluid (HTF) in the receivers is Dowtherm A. This synthetic oil is heated to 393ºC and flows through the tubes in order to boil water in the heat exchangers. The steam produced from this process drives a 50 MW (net) Siemens SST-700 reheat steam turbine, which is connected to a generator that produces electricity. The plant uses a wet-cooling system to condense the steam back to liquid. The Andasol-1 power plant has a thermal storage system which stores part of the heat produced in the solar field during the day in a molten salt mixture of 60% sodium nitrate and 40% potassium nitrate. A full storage tank can be used to operate the turbine for about 7.5 hours at full-load when the sky is overcast or after sunset. The plant also utilizes a 12% fossil fuel back-up from a natural gas heater. Ground-breaking for Andasol-1 plant began in July 2006 and after 28 months of construction, it went online in November 2008.

Figure D2 View of the power block in Andasol-1

11.3. Data Acquisition

This study used the Granada EPW climate file [5] as the best representation of Aldeire due to the two locations being only 40 km apart. The system specifications were primarily sourced from the NREL/ SolarPACES website [6]. The financial assumptions for this study were compiled mainly from IDAE and Deutsche Bank technical studies [7,8]. ACS-Cobra Energy has not released performance data for the plant; therefore, the data provided in this case study was obtained from referenced public sources.

11.4. SAM Inputs

The SAM technology chosen for this system is CSP physical trough (as opposed to the empirical trough model) because the plant performance can be more accurately measured based on its physical characteristics. The market is Independent Power Producer because ACS-Cobra Energy sells the electricity at a price negotiated through a PPA that was established with the Spanish feed-in tariff. Table 1 shows all the changes from the default values based on the system description.

Table D1: SAM performance inputs for Andasol-1 that differ from default values

Page	Variable	Default Value	Andasol-1
Climate	Location	AZ Tucson (TMY2)	Granada (EPW)
Solar Field	Field aperture (Option 2)	861590 m²	510120 m²
	Irradiation at design	950 W/m²	700 W/m²
	Field HTF fluid	Therminol VP-1	User-defined (below)
	Design loop outlet temp	391°C	393°C
	Number of SCA per loop	8	4
Collector (SCAs)	Configuration name	Solargenix SGX-1	EuroTrough ET150
Receivers (HCEs)	Configuration name (Type 2)	No library match	Solel UVAC 3
Power Cycle	Capacity - Design gross output	111 MW	55 MW
	Rated cycle conversion efficiency	0.3774	0.381
	Aux heater outlet set temp	391°C	393°C
	Fossil dispatch mode	Minimum backup	Supplemental operation
Thermal Storage	Full load hours of TES	6 hr	7.5 hr
	Tank height	20 m	14 m
	Dispatch schedule	Summer Peak	Summer Peak
	TOD factor	Different values	All of them change to 1
	Fossil fill fraction (Period 1)	0	0.15
	Fossil fill fraction (Period 2)	0	0.20
	Fossil fill fraction (Period 3)	0	0.45
Performance Adjustment	Year-to-year decline in output	0	0.5

Since SAM does not have a heat transfer fluid model for Dowtherm A, we had to create a custom fluid. Using the “edit” button, we populated the table for each property at 10 different temperatures by using the DOW product technical data [9]. We changed the payment allocation factors to 1 because the Spanish feed-in tariff price is equal in all the periods. The Royal decree 661/2007 set an allowance for solar thermal plants to contain up to 12-15% natural gas back up. This increases the reliability of the plants, since natural gas can be used both to maintain the temperature of the heat storage during periods of interruption in solar thermal electricity generation and to continue generation during cloudy conditions or after sunset. We adjusted the fossil fill fraction values in order to reach a 12% fossil fuel back up without specific criteria. Further research should be done in order to clarify how Andasol-1 uses the 12% fossil fuel back up allowed.

As mentioned above, the financial inputs were compiled from two different studies, carried out for IDAE and Deutsche Bank. Screen shots of the Trough System Cost and Financing pages (with all of the adjusted inputs) are located in the Appendix. Table 2 shows the changes from the default values based on the system description.

Table D2: SAM financial inputs for Andasol-1 that differ from the default values

Page	Variable	Default Value	Andasol-1
Trough System Costs	Site Improvements	30.00 $/m^2	28.00 $/m^2
	HTF System	80.00 $/m^2	78.00 $/m^2
	Storage	80.00 $/kWht	78.00 $/kWht
	Fossil Backup	0.00 $/kWe	60.00 $/kWe
	Power Plant	830.00 $/kWe	850.00 $/kWe
	Balance of plant	110.00 $/kWe	105.00 $/kWe
	Fixed Cost by Capacity	65.00 $/kW-yr	66.00 $/kW-yr
	Variable Cost by Generation	4.00$/MWh	3.00$/MWh
	Fossil Fuel Cost	0.00 $/MMBTU	6.00 $/MMBTU
Financing	Minimum Required IRR	15%	12%
	PPA Escalation Rate	1%	0%
	Loan Rate	8%	7%
	Real Discount Rate	8.20%	8%
	Federal Income Tax	35%	30%
	State Income Tax	7%	0%
	Insurance Rate	0.5%	1%
	Up-front Fee	1%	3.5%
	Construction Period - Months	24	28
	Annual Interest Rate	5%	5.5%
	Allow SAM to pick debt fraction	❐	☑
Depreciation	Federal	5-yr MACRS	Straight line (25 yr)
	State	5-yr MACRS	No depreciation

11.5. Results and Discussion

Table 3 shows the key SAM metrics for the system along with reported values (when available) and the percent difference between the SAM estimates and the media reports.

Table D3: SAM metrics table

Metric	SAM value	Reported Value	Difference (%)
Annual Energy	174,511,024 kWh	179,103,000 kWh	2.6%

PPA price	36.67 ¢/kWh	37.05 ¢/kWh	1.0%
LCOE Nominal	36.67 ¢/kWh		
LCOE Real	29.72 ¢/kWh		
Internal Rate of Return	12.00%		
Minimum DSCR	1.40		
Net Present Value	$12,504,255		
Debt Fraction	71.43%		
Capacity Factor	40.20%	41.50%	1.3%
Gross to Net Conv. Factor	0.94		
Total Land Area	476.80 acres	481.85 acres	1.0%
Total Installed Cost (2006$)	$418,440,431	$411,690,000	1.6%

The simulation gave an energy output of approximately 174.5 GWh/year. The reported annual output for Andasol-1 is estimated at 179.1 GWh/year, giving a 2.6% difference in the actual and simulated values. There was also a 1.0% difference between the simulated and reported values for the total land of the plant, and a 1.6% difference in the total installed cost values. Furthermore, the SAM value for PPA price differ 1.0% with the Spanish feed-in tariff price per kWh. To further analyze the financial side of the model, the SAM graphs are very useful. The three standard financial graphs are shown below:

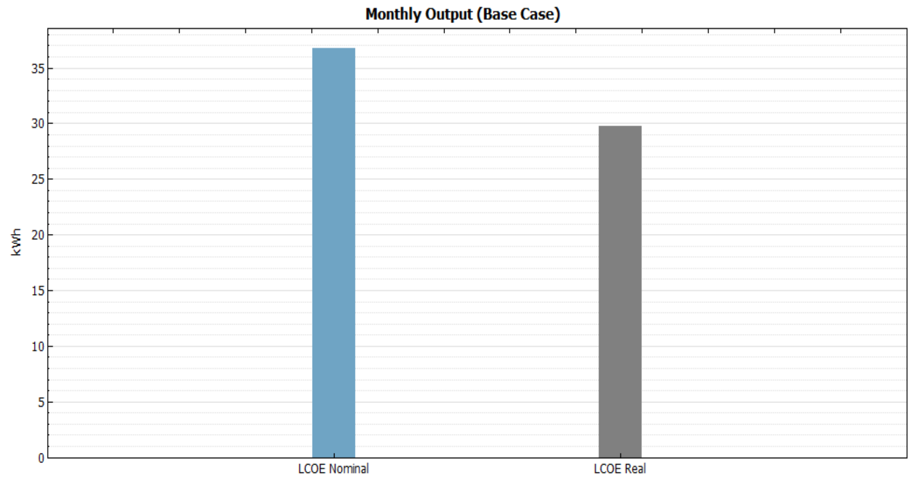

Figure D3: Simulated LCOE values for Andasol-1

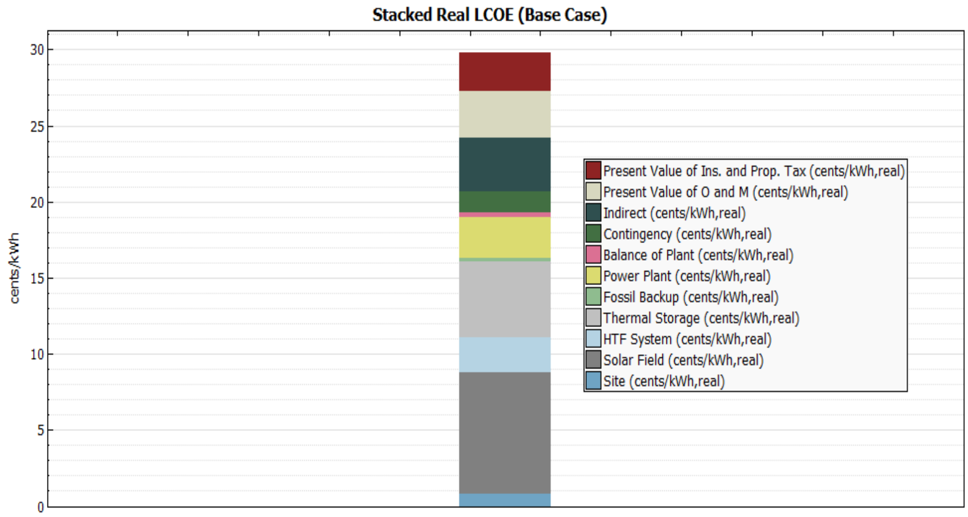

Figure D4: The stacked real LCOE shows the cost breakdown for different components of the system

From the stacked real LCOE (Figure 3), we can see how different components make up the LCOE for Andasol-1. For example, we can see the contribution of TES costs as well as the fossil fuel from the 12% fossil fuel back up costs. Figure 4 shows the after tax cash flow for the 25 year period analysis. We can see the negative payment for the installation of the project in year 0 as well as the diminishing profit until the 20-year loan term ends.

There are also many practical graphs for the performance side of the model. Figure 5 (below) shows the annual energy flow. From this, we can see the energy losses associated with certain processes throughout the system. For example, we can see the inefficiency of converting thermal energy to electricity during the power cycle (from over 500 GWh to less than 200 GWh). We can also obtain a more precise picture of the system’s output using DView, SAM’s hourly time series data viewer. To launch DView, click on Time Series in the Results menu. Figure 6 (below) shows the gross power output of the plant at different times of the day and different days of the year. This is useful in determining peak output hours throughout the year and could be used to make a comparison between peak output and peak demand hours or to compare time series outputs in different locations.

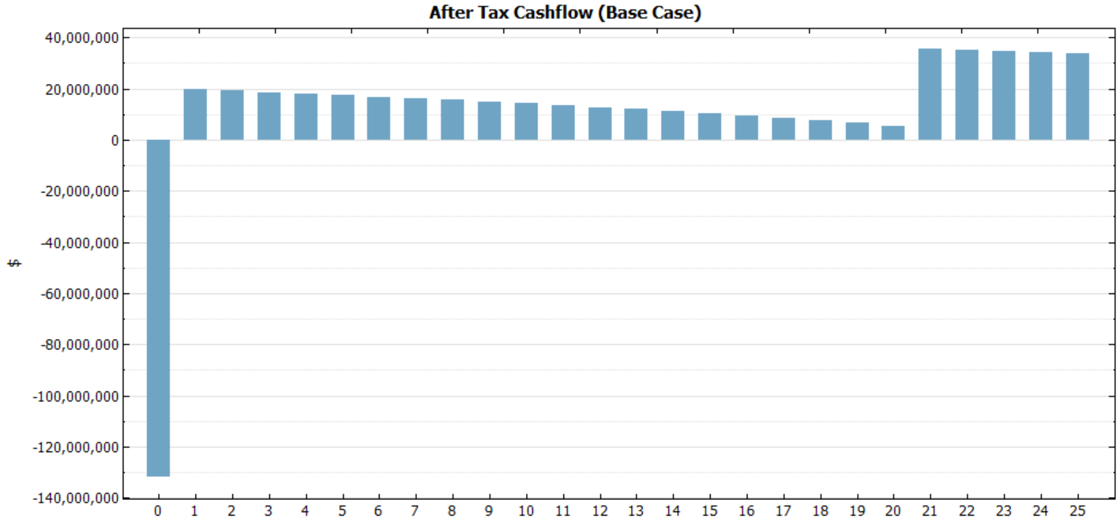

Figure D5: Shows the long-term financial profile for Andasol-1 over the 25 year period analysis. Positive values of cash flow represent an influx of money while negative values correspond to outgoing payments.

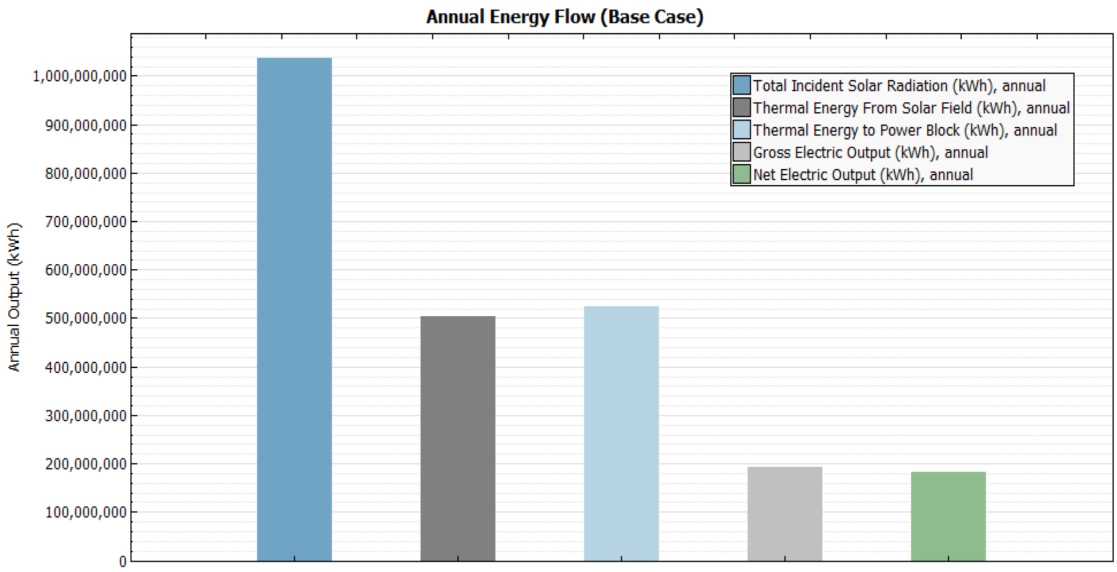

Figure D6: The annual energy flow shows the losses from different processes throughout the system

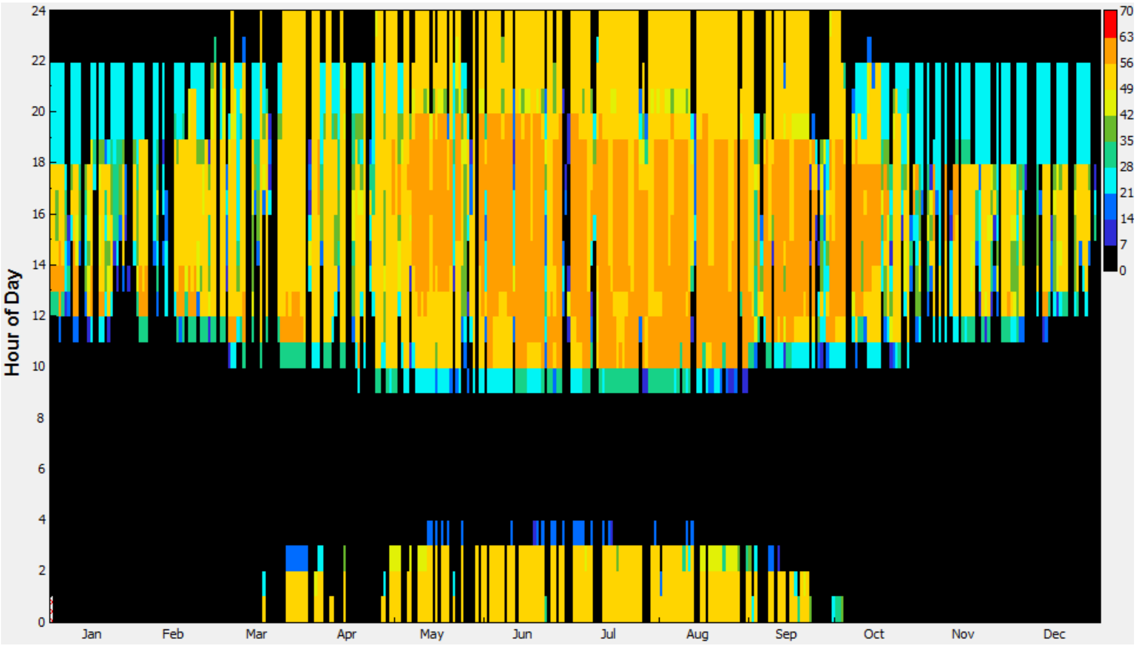

Figure D7: The gross power output of the system shows the peak times of year. Each pixel represents a single hour of the year.

11.6. Conclusion

Utilizing SAM's capabilities, we modeled Andasol-1, one of the first CSP trough plants constructed in the world. We were able to model the plant with minimal changes to the default values, using the limited information that has been made publicly available. Even with lacking performance data, we were able to get within 3% of the reported annual output and found a PPA close to the Spanish feed-in tariff price per kWh. This case study is located in the SAM samples folder.

11.7. References

[1] "Andasol Power Plants" Solar Millennium. <http://www.solarmillennium.de/Technologie/Referenzprojekte/Andasol/Die_Andasol_Kraftwerke_entstehen_%2Clang2%2C109%2C155.html>

[2] "Andasol 1 & 2" Estela Solar. <http://www.estelasolar.eu/index.php?id=32>

[3] "Andasol Solar Power Station" Clean Energy. <http://www.cleanenergyactionproject.com/CleanEnergyActionProject/CS.Andasol_Solar_Power_Station___Energy_Storage_Case_Study.html>

[4] Vincent, J. "The Future of Energy is Now." Greenpeace Australia Pacific Blog. 27 May 2009. <http://www.greenpeace.org.au/blog/?p=524>

[5] "Weather Data – Spain" US Department of Energy. <http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=6_europe_wmo_region_6/country=ESP/cname=Spain>

[6] "Andasol-1" SolarPACES. National Renewable Energy Laboratory. <http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=3>

[7] "Evaluación del potencial de energía solar termoeléctrica" IDAE. Madrid, 2011.

[8] "The CSP industry: An awakening giant" Deutsche Bank. Germany, March 2009.

[9] "Dowtherm A: Heat Transfer Fluid" Product Technical Data, Dow Chemical Company. March 1997.

[10] SAM templates available at: <https://www.nrel.gov/analysis/sam/templates.html>

12. APPENDIX E: EXISTING SOLAR DATA SOURCES FOR AUSTRALIA

Australia has a relatively small number of ground based weather stations, operated by the Australian Government's Bureau of Meteorology, that have collected DNI measurements. Sixteen operated prior to 2000, after which it was reduced to six. Eight new stations came online in 2011. There are a larger number of stations collecting diffuse radiation data. There have also been various ad hoc and private short duration data collection efforts. Overall, there is a strong dependence on Satellite based measurement, with calibration based on the limited ground data.

There are various sources of publically available data of varying spatial and temporal resolution. The following summarises them.

12.1. Bureau of Meteorology

http://www.bom.gov.au/climate/data-services/#tabs=3

The Australian Government's Bureau of Meteorology has satellite derived data sets of Direct normal Radiation (and other climate data) available. Hourly or Monthly average hourly direct normal solar exposure over the period 1998 to 2007 The resolution of the data is 0.05 degrees (approximately 5km). They also have ground station based DNI measured data for those stations that measure it.

12.2. The Australian Solar Radiation Data Handbook

The Australian Solar Radiation Data Handbook (ASRDH) and its companion software AusolRad, is marketed by the Australian Solar Energy Society.

http://auses.org.au/solarpedia/australian-solar-radiation-data-handbook-and-software/

It offers tabulated average data including DNI for a range of specific sites. Quoting from the Handbook:

*"*All data tabulated in this Handbook are drawn from the Australian Climatic Data Bank (ACDB). … The data bank sets consist of hourly records over numbers of years of climatic variables, including solar radiation. Measurements of global solar radiation are available for 22 locations, and of these, 16 locations have additional simultaneously measured diffuse solar radiation. A further 67 locations contain solar radiation data estimated from cloud cover records."

12.3. The Australian Climatic Data Bank (ACDB)

http://members.ozemail.com.au/~acadsbsg/

Quoting from the ACADS website:

"The Australian Climatic Data Bank, for use in air conditioning load estimation and building energy analysis and other HVAC applications, was established in the 1990's by CSIRO in association with AIRAH, ACADS-BSG Pty Ltd, the Australian Federal Government Construction Services, and the Australian Bureau of Meteorology. In 2006 the Australian Greenhouse Office funded the update and extension of the data bank to include data for 1967 to 2004 for most locations and a Reference Meteorological Year for each location being a composite of average months. For some locations only the original data is available."

As noted in Chapter 6, it is the ACDB RMY files that are offered by the US Energy Plus website for use with SAM. The same RMY files are found inside the "Accu-rate" building energy modelling software.

These are the files which have the identified faults. There is understood to be a revised version of the ACDB files using data to 2008, however this has not been released. The Australian Government's Department of Climate Change and Energy Efficiency is due to release a 2010 version of revised and corrected files and plans a further set including data to 2011 for release later in 2013.

A selection of relevant sites together with DNI totals and faults status is shown in Table 10.

Location [a]	Qualitative appearance of daily profiles	DNI [b] (kWh/ m^2/yr)	Lat-itude	Long-itude	Ave. ambient Temp °C	Ave. Wind-speed (m/s)
Oodnadatta	Satisfactory	2682	-27.5	135.4	21.9	3.7
Alice Springs	Satisfactory	2636.5	-23.8	133.88	21.2	2.3
Tennant Creek	Satisfactory	2615.4	-19.63	134.18	26	4.5
Longreach	Satisfactory	2564.4	-23.43	144.28	23.9	2.4
Mt Isa *	Faulty	2546.4	-20.68	139.48	24.5	2.8
Newman *	Faulty	2502.7	-23.42	119.8	24.1	2.1
Halls Creek	Satisfactory	2492.2	-18.2	127.6	26.4	2.1
Kalgoorlie	Satisfactory	2463.7	-30.78	121.45	18.3	3.8
Charleville *	Faulty	2418.8	-26.42	146.27	20.8	3.1
Geraldton	Satisfactory	2410.5	-28.8	114.7	19.2	4.8
Cobar *	Faulty	2381.1	-31.48	145.83	18.5	2.2
Woomera	Satisfactory	2368.9	-31.15	136.82	19.2	4.3
Moree *	Faulty	2254.6	-29.48	149.83	18.7	2.3
Mildura	Satisfactory	2124.6	-34.23	142.08	16.9	3.4
Wagga	Satisfactory	2038.4	-35.17	147.45	15.1	2.6

Table 10: Summary of selected sites from ACDB 2006 ranked by annual DNI.

12.4. UNSW TMY data

http://solar1.mech.unsw.edu.au/glm/trnaus/CLIMATIC%20DATA.htm

The University of NSW solar thermal group were the first in Australia to develop Typical Meteorological Year (TMY) files for Australian sites.

Quoting from the website:

“The generation of TMY records for Australia from long term measured solar radiation records is described in the STEL report "Condensed Solar Radiation Data Base for Australia" (http://solar1.mech.unsw.edu.au/glm/trnaus/tmy99.pdf) The long term hourly records for Sydney were a combination of measurements at the STEL and two years of measurements by the Bureau of Meteorology. Long term records for other locations were obtained from the Australian Climate Data Bank".

Eight Qld sites, ten NSW sites, three Victorian sites, six Western Australian sites and two NT sites are listed. It is understood that these have not however been updated with post 1999 data.

12.5. Australian Solar Energy Information System

Geoscience Australia is in the final stages of a joint Solar Resource Mapping project with BOM, that aims to:

- Improve solar data (including via the 8 new stations)
- Improve Infrastructure and topographic data
- Provide improved access to the data via the “Australian Solar Energy Information System”

http://www.icem2011.org/presentations2011/5_Friday/ASI_Workshop/1000_Graham_Hammond.pdf

Data sets for use with GIS software are now available from

https://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=71285

A web based tool is due for later in 2011 and promises to offer a major increase in utility for CSP feasibility study purposes.

12.6. NASA

http://eosweb.larc.nasa.gov/sse/

The NASA website service allows DNI data to be downloaded freely for any grid reference across the globe. The data is in the form of monthly averages and is derived from 22 years of satellite data with an effective 30km grid. Hourly data is derived using a calculation procedure based on an average day for each month.

12.7. Solemi

www.solemi.de

Solemi is a service run by the DLR (Deutsches Zentrum für Luft- und Raumfahrt), Germany's aerospace research centre. Solemi provides solar radiation data from the Metosat-5 and Meteosat-7 satellites with a nominal spatial resolution of 2.5 km and half-hourly temporal resolution. Solar radiation maps and hourly time series are available for approximately half the earth's surface including part of Western Australia. Approximately 10 years of data collected from the satellites is available. DNI data is derived from satellite data using a method of comparing a reference image (ground only) with the visual spectrum data collected by the satellite.

12.8. Meteonorm

www.meteonorm.com

Meteonorm is a commercial weather data and modelling tool that provides approximately 20 years of data for global solar radiation and other climate data including temperature, humidity and wind speed. The data is collected from ground based weather stations and supplemented with satellite data where there is a low density of weather stations. Hourly values are available but are calculated from collected data using a stochastic model.

12.9. 3Tier

www.3tier.com/en/products/solar/

The company 3Tier have modelled solar datasets available commercially that includes wind and temperature data. 3Tier have modeled hourly values of Global Horizontal Irradiance, Direct Normal Irradiance and Diffuse Horizontal Irradiance at a horizontal resolution of 2 arc-minutes, (approximately 3 kilometers).

12.10. Energy Partners

http://www.exemplary.com.au/

Energy Partners are the creators of the Australian Solar Radiation Data Handbook (ASRDH). They also created the 2006 set of TMY (RMY) files in the Australian Climate Data Bank, it is the ACDB RMY files that are offered by the US Energy Plus website for use with SAM. The same RMY files are found inside the "Accu-rate" building energy modelling software. They are also the creators of the un-released 2008 set.

Energy Partners have visual basic code that produces TMY (TMY2) files using BOM data input. They have the ability to enter any desired weighting to the variables that are used to calculate the value for an average month and then select the specific month to use. This is a service they provide on a commercial basis

Energy partners have prepared new TMY’s for 100 sites using their methods that they offer commercially.

13. APPENDIX F – PRODUCING NEW SOLAR DATA FILES

TMY3 is the newer format that is closest to an international standard and so will be used.

The starting point is a newly updated solar data set from the Australian Bureau of Metoerology.(BOM). This will be used in conjunction with other BOM weather data.

SAM USER Manual Section 4 on weather data offers detailed steps on creating a TMY3 file

"TMY is typical meteorological year data, and uses the National Solar Radiation Database's TMY weighting methodology described in the TMY3 User's Manual. These files were originally designed for use with building simulation models. The typical months in these files are based on bot hthe global horizontal and direct radiation in the long term data, and to a lesser degree on th etemperature and wind speed data. These files may be most suitable for modeling non-solar technologies that use the weather data in the file (biopower, geothermal) to estimate thermal losses from the steampower cycle, or for modeling solar technologies.

• TDY is typical direct-radiation-year data. For these files, only the direct normal radiation in the long-term radiation data set is analyzed to choose the months to include in the typical data file. These files maybe suitable for modeling solar technologies that use only the direct component of solar radiation incident on the collector such as the CSP technologies and concentrating solar power.

• TGY is typical global-radiation-year data with typical months chosen based only on the global horizontal radiation data in the long term data set. These files may be suitable for modeling solar technologies that use a flat collector such as photovoltaic and solar water heating."

The TMY3 file format is a comma-delimited text format with the extension *.csv*. The first row of a TMY3 file stores data describing the location's name, and the geographic coordinates, time zone, and elevation above sea level data required for sun angle calculations. The second row stores the column headings showing units for each data element. Rows 3-8762 store weather data elements used by SAM's performance models. Many of the data elements are not used by the SAM performance models.

13.1. New Solar data from the Australian Bureau of Meteorology (BOM)

The Bureau of Meteorology (BOM) in Australia offers a range of relevant data.

Specifically it is:

13.1.1. Satellite based "gridded solar data"

- A series of files for DNI, global and diffuse
- Each file is a matrix by position covering the continent in a 5km x 5km grid with a value for the solar metric.
- There is one file for every 1 hour time step from 1990 to end 2012
- The solar variables are calculated from satellite images using an algorithm from John Boland (UniSA).
- The latest data set is improved over previous versions in that “errors” have been removed. Unfortunately efforts to calibrate and remove bias against ground station data will not be complete until June 2013 at which time our data set will become redundant.
- There are folders for Time series hourly DNI and GHI, within these are subfolders for each year from 1990 – 2012.
- Whilst the files represent individual hours, many unambiguously darkness hours are omitted and hours that where faulty or rejected for some reason are not present. Thus each directory contains well less that 8760 files, and it ranges from 2,000 to above 5,000.

- Testing solar_dni_20000102_02UT.txt as an example:
  - The name indicates: DNI readings from year 2000, month 1, day 2, 02.00 Universal Time, this should correspond to around midday in SA. (UT = Universal Time or Greenwich Mean time Adelaide is GMT +10.30 (in Jan) thus 12.00 adelaide time is 1.30 GMT)
  - The top left of the file contains the following data:

NCOLS	839
NROWS	679
XLLCORNER	112.025
YLLCORNER	-43.975
CELLSIZE	0.05
NODATA_VALUE	-999

Table 11: Gridded satellite data coordinate information

  - The file has the listed number of rows and columns of possible data cells. The CELLSIZE specifications is 0.05degrees, corresponding to approximately five kilometre. On this basis, 839 columns means the grid area is around 4195km wide, around the width of the Australian continent. When the NODATA value cells are coloured, an outline of Australia is visible, when zoomed out.

- XLLCORNER, YLLCORNER are the coordinates of the (Lower Left) corner of the grid.

- One can expect that late afternoon or early morning files would show a limited patch on west or east of continent only.

- The following table provides a summary of the number of hourly files available for each year for both DNI and GHI.

Year	Number of hourly files for DNI	Number of hourly files for GHI
1990	3983	4499
1991	4326	4695
1992	3702	4780
1993	3966	4426
1994	4010	5056
1995	4629	5214
1996	5257	5440
1997	5117	5335
1998	5358	5492
1999	5241	5450
2000	5480	5528
2001	4131	4173
2002	2741	2806
2003	4401	4722
2004	5746	5758
2005	5857	5883
2006	5562	5571
2007	6491	6501
2008	6410	6429
2009	6286	6286
2010	6541	6556
2011	6556	6556
2012	6572	6572

Table 12: Summary of hourly DNI and GHI files

- Wish to avoid 1990, 1992, 1993 and 2002.

13.1.2. Automatic Weather station data (1990 – 2012)

- Includes all station data of temperatures relative humidity and windspeed etc every half hour
- There is a web page tool on BOM's site that allows the closest station to any given specified latitude longitude combination to be identified
- 556 files corresponding to 556 sites. Each file corresponds to a station number (station name not given within the file). There is data for each half hour but only against some time steps.
- There is a file of station data that gives name station number and latitude and longitude amongst other things.

13.1.3. Ground station solar data (1990 -2012)

- The number of ground stations has varied over time dropping from 22 to around 9. Recently 8 new ones have been added but data from these is not yet available
- The data is hourly.
- Available ground based data for either Direct Beam, Global or Diffuse solar irradiation levels on an hour by hour basis is summarised in the following table:
- The csv files in the top level of the directory, list the station numbers and names for which the various types of solar data are available.

Station Number	Station Name	Lat	Long	State	First year of Global data	Last year of Global data	First year of Direct Beam	Last year of Direct Beam	First year of Diffuse data	Last year of Diffuse data
70014	CANBERRA AIRPORT COMPARISON	-35.3	149.2	NSW	1983	1994			1983	1994
48027	COBAR MO	-31.5	145.8	NSW	2012	2012	2012	2012	2012	2012
66037	SYDNEY AIRPORT AMO	-33.9	151.2	NSW	1983	1994			1983	1994
72150	WAGGA WAGGA AMO	-35.2	147.5	NSW	1968	2012	1999	2012	1972	2012
61078	WILLIAMTOWN RAAF	-32.8	151.8	NSW	1968	1979				
15590	ALICE SPRINGS AIRPORT	-23.8	133.9	NT	1968	2012	1995	2012	1974	2012
14015	DARWIN AIRPORT	-12.4	130.9	NT	1968	2012	1999	2012	1999	2012
15135	TENNANT CREEK AIRPORT	-19.6	134.2	NT	1999	2006	1999	2006	1999	2006
40223	BRISBANE AERO	-27.4	153.1	QLD	1983	1995			1983	1995
31011	CAIRNS AERO	-16.9	145.7	QLD	1999	2004	1999	2004	1999	2004
32040	TOWNSVILLE AERO	-19.2	146.8	QLD						

36031	LONGREACH AERO	-23.4	144.3	QLD	1968	1980				
40282	NAMBOUR DPI	-26.6	152.9	QLD						
39083	ROCKHAMPTON AERO	-23.4	150.5	QLD	1973	2012				
200283	WILLIS ISLAND	-16.3	150	QLD	1977	1979				
23034	ADELAIDE AIRPORT	-35	138.5	SA	1983	2012	1999	2006	1983	2012
26021	MOUNT GAMBIER AERO	-37.7	140.8	SA	1968	2006			1971	2006
17043	OODNADATTA AIRPORT	-27.6	135.4	SA	1969	1980				
16001	WOOMERA AERODROME	-31.2	136.8	SA	1968	2012	1999	2012		
91148	CAPE GRIM RADIATION	-40.7	144.7	TAS	1999	2012			1999	2012
94008	HOBART AIRPORT	-42.8	147.5	TAS	1968	1980			1971	1980
87031	LAVERTON RAAF	-37.9	144.8	VIC	1968	1980	1999	2012	1975	1980
86282	MELBOURNE AIRPORT	-37.7	144.8	VIC	1999	2012			1999	2012
86071	MELBOURNE REGIONAL OFFICE	-37.8	145	VIC	1976	1980	1999	2012	1969	1974
76031	MILDURA AIRPORT	-34.2	142.1	VIC	1969	2012	1999	2012	1971	2012
9741	ALBANY AIRPORT COMPARISON	-34.9	117.8	WA	1968	1980			1971	1980
3003	BROOME AIRPORT	-17.9	122.2	WA	1986	2012			1986	2012
6011	CARNARVON AIRPORT	-24.9	113.7	WA	1986	1995	2004	2012	1986	1995
200284	COCOS ISLAND AIRPORT	-12.2	96.8	WA	2004	2012			2004	2012
9789	ESPERANCE	-33.8	121.9	WA	1987	1995			1987	1995
11004	FORREST AERO	-30.8	128.1	WA	1969	1980				
3003	BROOME AIRPORT	-17.9	122.2	WA			1999	2012		
8315	GERALDTON AIRPORT	-28.8	114.7	WA	2012	2012	1999	2006	2012	2012
8051	GERALDTON AIRPORT COMPARISON	-28.8	114.7	WA	1968	2006			1971	2006
2012	HALLS CREEK AIRPORT	-18.2	127.7	WA	1969	1980	1999	2012	1979	2012
12038	KALGOORLIE-BOULDER AIRPORT	-30.8	121.5	WA	1979	2012	1999	2012		
5007	LEARMONTH AIRPORT	-22.2	114.1	WA	1986	2012			1986	2012
7045	MEEKATHARRA AIRPORT	-26.6	118.5	WA	1985	1995			1986	1995
9053	PEARCE RAAF	-31.7	116	WA	1972	1975			1974	1975
9021	PERTH AIRPORT	-31.9	116	WA	1975	1980			1975	1980
4032	PORT HEDLAND AIRPORT	-20.4	118.6	WA	1968	1980			1971	1980

Table 13: Station details for ground based solar data provided by BOM

13.2. Process for creating TMY3 files from BOM data

ITP has proceeded by developing code and processes to carry out the required processing steps to populate the essential columns in a TMY3 format CSV data file using BOM data as input.

There are three key sets required to process the raw BOM data into real year TMY3 format files. The first step required is to create a CSV file containing the AWS data for the year of interest. This file must contain exactly 8761 rows (i.e. one header row and one row for each hour of the year). The columns required for the file are hm, Station Number, Year (YYYY), Month (MM), Day (DD), Hour (HH24), Minutes (MI), Air Temperature in degrees C, Wet bulb temperature in degrees C, Dew point temperature in degrees C, Relative humidity in percentage %, Wind speed in m/s, Wind direction in degrees true, Speed of maximum windgust in last 10 minutes in m/s, Mean sea level pressure in hPa, Station level pressure in hPa, AWS Flag, #.

The raw AWS files from BOM are in txt format, contain data for all measured years and contain a number of columns not required to create the TMY3 file. As such the raw AWS files must be modified to create an appropriate CSV file for the year of interest. The extraction of the required AWS data is achieve by using an excel macro (an extract of the code is included in appendix G). The macro opens each of the raw AWS data files (from BOM in txt format) contained in the folder of interest, separates out each year and saves it as a CSV file.

As a standard TMY3 formatted file expects 8760 rows for weather data it is important to account for leap years in the source AWS files. Where an AWS file is created for a leap year the data for the 29th of February must be removed to ensure step 2 can be completed successfully.

Step 2: Once the AWS file is created the Python language code can be used to extract the solar radiation data from the gridded solar data provided by BOM. The Python code (weather-maker.py and latlong.py) can be run from the command line on a windows computer (extracts of the python code are contained in appendix G). The inputs required by the weather-maker script are; the path to the gridded solar data, the year of interest, the station number of the requested site, the location of the AWS file created in the above step, the location of the station details file (provided by BOM with the raw AWS data), the format of the output file (e.g. TMY3) and the name of the output file.

The weather-maker script opens the station details file and based on the provided station number extracts the latitude and longitude of the site. The scrip then opens all of the GHI and DNI gridded data files for the year of interest and based on the lat and long extracts the solar radiation values from the files. The script then opens the AWS file provided and extracts the required data from this file. Finally the script uses the collected data to produce a TMY3 format file.

Notes on the weather-maker.py script:

1. There are a number of columns in a standard TMY3 file for which the script does not collect data and as such these columns are filled with null values in the output file.
2. The TMY3 file should be saved in CSV format for later use with SAM (e.g. filename.csv)
3. The raw AWS data files from BOM are provided in 6 folders (100 files in each of the first 5 folders and 44 files in the final folder) and each of the folders contains is own station details file. As such, a single station details file should be created or the weather-maker script will need to be directed to the correct station details file each time it is run.
4. The weather-maker script requires the gridded solar data to be saved in the following data structure:

```
SOLAR DATA
|
+--- HOURLY_DNI
       |
       +- 1998
       +- etc.
+---  HOURLY_GHI
       |
       +- 1998
       +- etc.
```

Step 3: As there are significant gaps in the data provided by BOM these need to be addressed before the data can be used in SAM. These data gaps are filled using an excel macro (code included in appendix G). The macro parses each TMY3 file and looks for gaps in the data. Once a gap is found the macro determines how many consecutive data points are missing (i.e. for how many hours or days is data missing). Based on the number of consecutive data points missing the macro will fill the missing data by either using linear interpolation or by using an average of data from the proceeding and following days.

Unfortunately the process of filling the missing GHI and DNI values involves saving the TMY3 formatted CSV files from excel and this makes them incompatible with SAM. As such, additional steps are required to ensure the files work correctly. One way to create a compatible file is to use the create TMY3 feature in SAM to open the base TMY3 formatted file (i.e. before blanks have been filled) created in step 2, fill the missing data (by pasting values from the blanks filled file created above) and resave in TMY3 format. While inefficient this is an effective way to create compatible files for use with SAM. It is the intention of the authors to simplify the above process for creating TMY3 files by combining the code for each step into a single executable file.

A number of useful sites for CSP purposes do have data sets for DNI. DNI can also be deduced from the difference between Global and diffuse and it can be estimated from a single Global measurement also. However testing the DNI data sets reveals that many specific hours of data are missing and very complex interpolations would be needed to fill the gaps with valid approximated values.

13.3. VBA and Python Code extracts

13.3.1. Create AWS Files

```
Sub CreateAWS()
    Dim strFile As String
    Dim strFile2 As String
    Dim FilePath As String
    Dim i As Integer
    Dim maxyear As Integer
    Dim minyear As Integer
    Dim stnName As String
    Dim j As Integer
    Dim sheetName As String

    i = 1
    k = 1
    FilePath = "...\AWS Files\source files\"
    strFile = Dir(FilePath)
    Do While Len(strFile) > 0
        Workbooks.Open Filename:=FilePath & strFile

        Windows(strFile).Activate
        Columns("A:A").Select
        Selection.TextToColumns Destination:=Range("A1"),
DataType:=xlDelimited, _
        TextQualifier:=xlDoubleQuote, ConsecutiveDelimiter:=False,
Comma:=True, TrailingMinusNumbers:=True

        If Workbooks(strFile).Worksheets.Count = 1 Then
            For Each ws In Workbooks(strFile).Worksheets
                ws.Name = "Summary"
            Next ws
        End If

        stnName = Workbooks(strFile).Sheets("Summary").Range("B2")
        If stnName < 10000 Then
            stnName = "stn00" & stnName
        Else
            stnName = "stn0" & stnName
        End If

        minyear = Workbooks(strFile).Sheets("Summary").Range("C2")
        maxyear = 2012
```

```
        strFile2 = strFile
        For j = minyear To maxyear
            sheetName = selectData(j, stnName, strFile2)
            ThisWorkbook.Sheets("Sheet1").Cells(k, 1) = sheetName
            ThisWorkbook.Sheets("Sheet1").Cells(k, 2) =
FillBlanks(strFile2, sheetName)

            Application.DisplayAlerts = False
            Workbooks(strFile2).Sheets(sheetName).SaveAs "...\AWS
Files\" & sheetName & ".csv", xlCSV
            Application.DisplayAlerts = True
            strFile2 = sheetName & ".csv"
            k = k + 1
        Next j
        Application.DisplayAlerts = False
        Workbooks(strFile2).Sheets(sheetName).SaveAs "...\AWS
Files\source files\" & stnName & "AWS", xlCSV
        Workbooks(stnName & "AWS").Close
        Application.DisplayAlerts = True
        strFile = Dir
        i = i + 1
    Loop


End Sub

Function selectData(interestyear As Integer, stnName As String, strFile
As String) As String
Dim myYear As Integer
Dim mysheet As String
i = 2
j = 2
myYear = Workbooks(strFile).Sheets("Summary").Cells(i, 3)

Do Until myYear = interestyear
    i = i + 1
    myYear = Workbooks(strFile).Sheets("Summary").Cells(i, 3).Value
Loop
StartRow = i
Do Until myYear > interestyear
    j = j + 1
    myYear = Workbooks(strFile).Sheets("Summary").Cells(j, 3).Value
Loop
endrow = j - 1

mysheet = "Y" & interestyear
Workbooks(strFile).Sheets.Add.Name = mysheet

Workbooks(strFile).Sheets("Summary").Rows(1).Copy
Workbooks(strFile).Sheets(mysheet).Select
```

```
Range("A1").PasteSpecial (xlPasteAllUsingSourceTheme)

myRange = StartRow & ":" & endrow
Workbooks(strFile).Sheets("Summary").Rows(myRange).Copy

Workbooks(strFile).Sheets(mysheet).Select
Range("A2").PasteSpecial (xlPasteAllUsingSourceTheme)

Workbooks(strFile).Sheets(mysheet).Range("H:N, P:P, R:R, T:T, V:Z,
AB:AB, AD:AD, AF:BQ, BS:BS, BU:BU").Delete

selectData = tohourly(mysheet, stnName, strFile)

End Function
Function tohourly(mysheet As String, stnName As String, strFile As
String) As String
    Dim myval, myval2 As Double
    i = 2
    k = 2
    mysheet2 = stnName & "AWS" & mysheet
    Workbooks(strFile).Sheets.Add.Name = mysheet2
    Workbooks(strFile).Sheets(mysheet).Rows(1).Copy
    Workbooks(strFile).Sheets(mysheet2).Select
    Range("A1").PasteSpecial (xlPasteAllUsingSourceTheme)

    myMonth = Workbooks(strFile).Sheets(mysheet).Cells(i, 1)
    Do Until myMonth = ""
        For j = 1 To 16
        If j > 7 Then
            If IsNumeric(Workbooks(strFile).Sheets(mysheet).Cells(i,
j).Value) Then
                myval = Workbooks(strFile).Sheets(mysheet).Cells(i,
j).Value
                If IsNumeric(Workbooks(strFile).Sheets(mysheet).Cells(i
+ 1, j).Value) Then
                    myval2 = Workbooks(strFile).Sheets(mysheet).Cells(i
+ 1, j).Value
                    Workbooks(strFile).Sheets(mysheet2).Cells(k,
j).Value = (myval + myval2) / 2
                Else
                    Workbooks(strFile).Sheets(mysheet2).Cells(k,
j).Value = myval
                End If
            ElseIf IsNumeric(Workbooks(strFile).Sheets(mysheet).Cells(i
+ 1, j).Value) Then
                myval2 = Workbooks(strFile).Sheets(mysheet).Cells(i + 1,
j).Value
                Workbooks(strFile).Sheets(mysheet2).Cells(k, j).Value =
myval2
            End If
        Else
```

```
        Workbooks(strFile).Sheets(mysheet2).Cells(k, j).Value =
Workbooks(strFile).Sheets(mysheet).Cells(i, j).Value
        End If
        Next j
        Workbooks(strFile).Sheets(mysheet2).Cells(k, 17).Value =
Workbooks(strFile).Sheets(mysheet).Cells(i, 17).Value
        Workbooks(strFile).Sheets(mysheet2).Cells(k, 18).Value =
Workbooks(strFile).Sheets(mysheet).Cells(i, 18).Value

        k = k + 1
    i = i + 2
    myMonth = Workbooks(strFile).Sheets(mysheet).Cells(i, 1)
    Loop
    tohourly = mysheet2
End Function

Function FillBlanks(strFile As String, sheetName As String) As Integer
    Dim ws As Worksheet

    i = 2
    myMonth = Workbooks(strFile).Sheets(sheetName).Cells(i, 4)
    NumBlanks = 0
    Do Until myMonth = ""
        If Workbooks(strFile).Sheets(sheetName).Cells(i, 8).Value = ""
Then

            myval = Workbooks(strFile).Sheets(sheetName).Cells(i + 1,
8).Value
            consecBlanks = 1
            mymonth2 = Workbooks(strFile).Sheets(sheetName).Cells(i +
consecBlanks, 4)
            Do Until myval <> "" Or mymonth2 = ""
                If i + consecBlanks > 8761 Then
                    myval = 1
                Else
                    consecBlanks = consecBlanks + 1
                    myval = Workbooks(strFile).Sheets(sheetName).Cells(i
+ consecBlanks, 8).Value
                    mymonth2 =
Workbooks(strFile).Sheets(sheetName).Cells(i + consecBlanks, 4)
                End If
            Loop
            NumBlanks = NumBlanks + consecBlanks
            If consecBlanks < 5 Then
                For j = 0 To consecBlanks - 1
                    For k = 8 To 16
                    If i = 2 Then
                        Workbooks(strFile).Sheets(sheetName).Cells(i +
j, k) = Workbooks(strFile).Sheets(sheetName).Cells(i + consecBlanks,
k).Value
```

```
                        Workbooks(strFile).Sheets(sheetName).Cells(i +
j, k).Interior.Color = RGB(0, 255, 0)
                    ElseIf Workbooks(strFile).Sheets(sheetName).Cells(i
+ consecBlanks, k) = "" Then
                        Workbooks(strFile).Sheets(sheetName).Cells(i +
j, k) = Workbooks(strFile).Sheets(sheetName).Cells(i - 1, k).Value
                        Workbooks(strFile).Sheets(sheetName).Cells(i +
j, k).Interior.Color = RGB(0, 255, 0)
                    Else
                        Workbooks(strFile).Sheets(sheetName).Cells(i +
j, k) = (j + 1) * (Workbooks(strFile).Sheets(sheetName).Cells(i +
consecBlanks, k).Value - Workbooks(strFile).Sheets(sheetName).Cells(i -
1, k).Value) / (consecBlanks + 1) +
Workbooks(strFile).Sheets(sheetName).Cells(i - 1, k).Value
                        Workbooks(strFile).Sheets(sheetName).Cells(i +
j, k).Interior.Color = RGB(0, 255, 0)
                    End If
                    Next k
                Next j
            Else
                For j = 0 To consecBlanks - 1
                    For k = 8 To 16
                    If i + j - 24 < 2 Then
                        If Workbooks(strFile).Sheets(sheetName).Cells(i
+ j + 24, k).Value = "" Then
                            If i = 2 Then

Workbooks(strFile).Sheets(sheetName).Cells(i + j, k) =
Workbooks(strFile).Sheets(sheetName).Cells(i + consecBlanks, k).Value
                            ElseIf
Workbooks(strFile).Sheets(sheetName).Cells(i + consecBlanks, k) = ""
Then

Workbooks(strFile).Sheets(sheetName).Cells(i + j, k) =
Workbooks(strFile).Sheets(sheetName).Cells(i - 1, k).Value
                            Else

Workbooks(strFile).Sheets(sheetName).Cells(i + j, k) = (j + 1) *
(Workbooks(strFile).Sheets(sheetName).Cells(i + consecBlanks, k).Value -
Workbooks(strFile).Sheets(sheetName).Cells(i - 1, k).Value) /
(consecBlanks + 1) + Workbooks(strFile).Sheets(sheetName).Cells(i - 1,
k).Value
                            End If
                            Workbooks(strFile).Sheets(sheetName).Cells(i
+ j, k).Interior.Color = RGB(0, 255, 0)
                        Else
                            Workbooks(strFile).Sheets(sheetName).Cells(i
+ j, k) = Workbooks(strFile).Sheets(sheetName).Cells(i + j + 24,
k).Value
                            Workbooks(strFile).Sheets(sheetName).Cells(i
+ j, k).Interior.Color = RGB(0, 0, 255)
```

```
                        End If
                    ElseIf Workbooks(strFile).Sheets(sheetName).Cells(i
+ j + 24, k) = "" Then
                        Workbooks(strFile).Sheets(sheetName).Cells(i +
j, k) = Workbooks(strFile).Sheets(sheetName).Cells(i + j - 24, k).Value
                        Workbooks(strFile).Sheets(sheetName).Cells(i +
j, k).Interior.Color = RGB(0, 0, 255)
                    Else
                        Workbooks(strFile).Sheets(sheetName).Cells(i +
j, k) = (Workbooks(strFile).Sheets(sheetName).Cells(i + j + 24, k).Value
+ Workbooks(strFile).Sheets(sheetName).Cells(i + j - 24, k).Value) / 2
                        Workbooks(strFile).Sheets(sheetName).Cells(i +
j, k).Interior.Color = RGB(0, 0, 255)
                    End If
                    Next k
                Next j

            End If
            i = i + consecBlanks - 1
        End If
        i = i + 1
        myMonth = Workbooks(strFile).Sheets(sheetName).Cells(i, 4)

    Loop
    FillBlanks = NumBlanks
End Function
```

13.3.2. Weather-maker.py

```
# -*- Python -*-
# Copyright (C) 2011, 2013 Ben Elliston
#
# This file is free software; you can redistribute it and/or modify it
# under the terms of the GNU General Public License as published by
# the Free Software Foundation; either version 3 of the License, or
# (at your option) any later version.
#
# If you find a bug or implement an enhancement, please send a patch
# to the author in the form of a unified context diff (diff -u) to
# <b.elliston@student.unsw.edu.au>.

import bz2
import math
import sys
import optparse
import datetime
import numpy as np
from latlong import LatLong

# PyEphem, from http://rhodesmill.org/pyephem/
```

```
# PyEphem provides scientific-grade astronomical computations
import ephem

# From Paul Gilman <Solar.Advisor.Support@nrel.gov>:
# The first list shows the data columns SAM reads from the weather file:

# Dry bulb temperature
# Dew point temperature
# Wet bulb temperature
# Percent relative humidity
# Wind velocity
# Wind direction
# Atmospheric pressure
# Global horizontal radiation (not interpolated)
# Direct normal radiation (not interpolated)
# Latitude
# Longitude
# Site elevation
# Hour of the day

### Sample row from the BoM weather data:
### hm, 48027,2009,01,01,00,00, 22.3,N, 13.1,N,  3.4,N, 29,N,   7.8,N,
26.9,N,  1.5,N,220,N,  2.1,N,1005.6,N, 975.6,N, 1,#

def verbose (s):
    if opts.verbose:
        print >>sys.stderr, s

def warn (s):
    if opts.verbose:
        print >>sys.stderr, 'warning:',
        print >>sys.stderr, s

def verify (items):
    # Verify that the line is valid.
    if items[0] != 'hm':
        warn ('non-hm record')

    st = items[1].strip().lstrip ('0')
    if st != stnumber:
        print '%s is a foreign station number' % st

def tmy3_preamble (f):
    # eg. 722287,"ANNISTON METROPOLITAN AP",AL,-6.0,33.583,-85.850,186
    print >>f, '%s in %s,\"%s\",%s,%.1f,%.3f,%.3f,%d' % \
        (stnumber, stname, opts.year, ststate[0:2], opts.tz, locn._lat,
locn._lon, elevation)
    print >>f, 'Date (MM/DD/YYYY),Time (HH:MM),ETR (W/m^2),ETRN
(W/m^2),GHI (W/m^2),GHI source,GHI uncert (%),DNI (W/m^2),DNI source,DNI
uncert (%),DHI (W/m^2),DHI source,DHI uncert (%),GH illum (lx),GH illum
source,Global illum uncert (%),DN illum (lx),DN illum source,DN illum
```

```
uncert (%),DH illum (lx),DH illum source,DH illum uncert (%),Zenith lum
(cd/m^2),Zenith lum source,Zenith lum uncert (%),TotCld (tenths),TotCld
source,TotCld uncert (code),OpqCld (tenths),OpqCld source,OpqCld uncert
(code),Dry-bulb (C),Dry-bulb source,Dry-bulb uncert (code),Dew-point
(C),Dew-point source,Dew-point uncert (code),RHum (%),RHum source,RHum
uncert (code),Pressure (mbar),Pressure source,Pressure uncert
(code),Wdir (degrees),Wdir source,Wdir uncert (code),Wspd (m/s),Wspd
source,Wspd uncert (code),Hvis (m),Hvis source,Hvis uncert
(code),CeilHgt (m),CeilHgt source,CeilHgt uncert (code),Pwat (cm),Pwat
source,Pwat uncert (code),AOD (unitless),AOD source,AOD uncert
(code),Alb (unitless),Alb source,Alb uncert (code),Lprecip depth
(mm),Lprecip quantity (hr),Lprecip source,Lprecip uncert (code)'

def epw_preamble (f):
    print >>f, 'LOCATION,%s (%s) in
%s,%s,AUS,BoM,%s,%.2f,%.2f,%.1f,%.1f' % \
        (stname, stnumber, opts.year, ststate, stnumber, locn._lat,
locn._lon, opts.tz, elevation)

    print >>f, 'DESIGN CONDITIONS,0'
    print >>f, 'TYPICAL/EXTREME PERIODS,,'
    print >>f, 'GROUND TEMPERATURES,,,,,,'
    print >>f, 'HOLIDAYS/DAYLIGHT SAVINGS,No,0,0,0'
    print >>f, 'COMMENTS 1,Generated by weather-maker.py from Bureau of
Meteorology solar and weather data (%d)' % opts.year
    print >>f, 'COMMENTS 2,Please report bugs in weather-maker.py to
b.elliston@student.unsw.edu.au'
    print >>f, 'DATA PERIODS,1,1,Data,Sunday,1/ 1,12/31'

def tmy3_record (f, record):
    t = datetime.datetime (opts.year,1,1)
    t += datetime.timedelta (hours=record['hour'])

    line = '%02d/%02d/%d,%02d:50,-9900,-9900,%d,1,5,%d,1,5,-9900,1,0,-
9900,1,0,-9900,1,0,-9900,1,0,-9900,1,0,-9900,?,9,-
9900,?,9,%.1f,A,7,%.1f,A,7,%.1f,A,7,%d,A,7,%d,A,7,%.1f,A,7,-9900,?,9,-
9900,?,9,-9900,?,9,-9900,?,9,-9900,?,9,-9900,-9900,?,9' \
        % (t.month, t.day, t.year, t.hour + 1, record['ghi'],
record['dni'], \
               record['dry-bulb'], record['dew-point'], record['rel-
humidity'], \
               record['atm-pressure'] / 100, record['wind-direction'],
record['wind-speed'])
    print >>f, line

def epw_record (f, record):
    t = datetime.datetime (opts.year,1,1)
    t += datetime.timedelta (hours=record['hour'])

    line =
'%d,%d,%d,%d,50,_______________________________________,%.1f,%.1f,%d,%d,
```

```
9999,9999,9999,%d,%d,%d,999999,999999,999999,999999,%d,%.1f,99,99,9999,9
9999,9,999999999,99999,0.999,999,99,999,0,99' \
        % (t.year, t.month, t.day, t.hour + 1, record['dry-bulb'],
record['dew-point'], \
               record['rel-humidity'], record['atm-pressure'],
record['ghi'], record['dni'], record['dhi'], \
               record['wind-direction'], record['wind-speed'])
    print >>f, line

# Return the GHI and DNI for a given location and time.
def irradiances (locn, hour):
    x, y = locn.xy ()
    # Compute a solar data filename from the hour
    # Use 2010 as the reference year, as it was not a leap year.
    hours = datetime.timedelta (hours=hour)
    tzoffset = datetime.timedelta (hours=opts.tz)
    hr = datetime.datetime (opts.year, 1, 1) + hours - tzoffset
    if hr.month == 2 and hr.day == 29:
        # skip Feb 29 on leap years
        hr += datetime.timedelta (days=1)
    filename = hr.strftime (opts.grids + '/HOURLY_GHI/%d/' % opts.year +
hr.strftime ('solar_ghi_%Y%m%d_%HUT.txt'))
    try:
        f = bz2.BZ2File (filename + '.bz2', 'r')
        line = f.readlines ()[x + 6]
        f.close ()
        ghr = int (line.split()[y])
    except IOError:
        try:
            f = open (filename, 'r')
            line = f.readlines ()[x + 6]
            f.close ()
            ghr = int (line.split()[y])
        except IOError:
            # print 'missing', filename
            ghr = 0

    filename = hr.strftime (opts.grids + '/HOURLY_DNI/%d/' % opts.year +
hr.strftime ('solar_dni_%Y%m%d_%HUT.txt'))
    try:
        f = bz2.BZ2File (filename + '.bz2', 'r')
        line = f.readlines ()[x + 6]
        f.close ()
        dnr = int (line.split()[y])
    except IOError:
        try:
            f = open (filename, 'r')
            line = f.readlines ()[x + 6]
            f.close ()
            dnr = int (line.split()[y])
        except IOError:
```

```
            # print 'missing', filename
            dnr = 0

    if ghr == -999:
        ghr = 0
    if dnr == -999:
        dnr = 0

    # Compute direct horizontal irradiance:
    # DHI = GHI - DNI cos (zenith)
    observer.date = hr + datetime.timedelta (minutes=50)
    sun.compute (observer)
    zenith = (math.pi / 2.) - sun.alt
    dhr = ghr - dnr * math.cos (zenith)
    if dhr < -10:
        # Don't worry about diffuse levels below 10 W/m2.
        warn ('negative diffuse horizontal irradiance: %d' % dhr)
        dhr = 0
    return ghr, dnr, dhr

# Read station details file.

def station_details ():
    global stnumber
    global stname
    global ststate

    line = [line for line in open (opts.hm_details, 'r') if 'st,' +
opts.st in line] [0]
    st = line[0:2]
    stnumber = line[3:9].strip ().lstrip ('0')
    stname = line[15:55].strip ()
    ststate = line[107:110]
    verbose ('Processing station number %s (%s)' % (stnumber, stname))

    latitude = float (line[72:80])
    longitude = float (line[81:90])
    locn = LatLong ((latitude, longitude))
    altitude = int (float (line[111:117]))
    wflags = line[153:156]
    sflags = line[157:160]
    iflags = line[161:164]
    if int (wflags) or int (sflags) or int (iflags):
        warn ('%% wrong = %s, %% suspect = %s, %% inconsistent = %s' \
                  % (wflags, sflags, iflags))

    return (locn, altitude)

parser = optparse.OptionParser (version='1.0', description='Bug reports
to: b.elliston@student.unsw.edu.au')
```

```
parser.add_option("--grids", type='string', help='top of gridded data
tree')
parser.add_option("-y", "--year", type='int', help='year to generate')
parser.add_option("--st", type='string', help='BoM station code
(required)')
parser.add_option("--hm-data", type='string', help='BoM station data
file')
parser.add_option("--hm-details", type='string', help='BoM station
details file')
parser.add_option("--tz", type='float', default=10.0, help='Time zone
[default +10]')
parser.add_option("-o", "--out", type='string', help='output filename')
parser.add_option("--format", "--format", default="epw", help="output
format: EPW [default], TMY3", metavar="FORMAT")
parser.add_option("-v", "--verbose", action="store_true",
dest="verbose", default=False, help="verbose run")
opts,args = parser.parse_args ()

if not opts.grids or not opts.hm_data or \
        not opts.hm_details or \
        not opts.out or not opts.year or not opts.st:
    parser.print_help ()
    print
    sys.exit (1)

infile = open (opts.hm_data, 'r')
outfile = open (opts.out, 'w')

locn, elevation = station_details ()
sun = ephem.Sun ()
observer = ephem.Observer ()
observer.elevation = elevation
observer.lat = str (locn._lat)
observer.long = str (locn._lon)

if opts.format.lower () == 'tmy3':
    verbose ('Generating a TMY3 file')
    tmy3_preamble (outfile)
elif opts.format.lower () == 'epw':
    verbose ('Generating an EPW file')
    epw_preamble (outfile)
else:
    raise ValueError ("unknown format %s" % opts.format)

i = 0
for line in infile:
    if len (line) == 1:
        # Skip weird ^Z lines.
        continue
    data = line.split (',')
    if data[1] == 'Station Number':
```

```
            # Skip this line; it is the header.
            continue
        if data[2] != str (opts.year):
            # Skip years that are not of interest.
            continue
        if data[3] == '02' and data[4] == '29':
            warn ('skipping Feb 29')
            i += 1
            continue

        # Generate pedantic warnings.
        verify (data)

        record = {}
        record['hour'] = i
        try:
            record['dry-bulb'] = float (data[7])
        except ValueError:
            record['dry-bulb'] = 99.9
        try:
            record['wet-bulb'] = float (data[8])
        except ValueError:
            record['wet-bulb'] = 99.9
        try:
            record['dew-point'] = float (data[9])
        except ValueError:
            record['dew-point'] = 99.9
        try:
            record['rel-humidity'] = float (data[10])
        except ValueError:
            record['rel-humidity'] = 999.
        try:
            record['wind-speed'] = float (data[11])
        except ValueError:
            record['wind-speed'] = 999.
        try:
            record['wind-direction'] = int (data[12])
        except ValueError:
            record['wind-direction'] = 999
        try:
            record['atm-pressure'] = int (float (data[15]) * 100)
        except ValueError:
            record['atm-pressure'] = 999999.

        record['ghi'], record['dni'], record['dhi'] = irradiances (locn, i)
        i += 1

        if opts.format.lower () == 'tmy3':
            tmy3_record (outfile, record)
        elif opts.format.lower () == 'epw':
            epw_record (outfile, record)
```

```
infile.close ()
outfile.close ()
```

13.3.3. Latlong.py

```
# latlong.py: latitude and longitude support
# Copyright (C) 2010, 2011 Ben Elliston
#
# Latitude/longitude spherical geodesy formulae & scripts (C) Chris
Veness 2002-2011
# (www.movable-type.co.uk/scripts/latlong.html)
#
# This file is free software; you can redistribute it and/or modify it
# under the terms of the GNU General Public License as published by
# the Free Software Foundation; either version 3 of the License, or
# (at your option) any later version.

cellsize = 0.05
xllcorner = 112.025
yllcorner = -43.925
maxcols = 839
maxrows = 679

import math

class LatLong:
  def __init__ (self, (arg1,arg2)):
    if type (arg1) == type (1.) and type (arg2) == type (1.):
      # Pair of floats
      self._lat = arg1
      self._lon = arg2
    elif type (arg1) == type (1) and type (arg2) == type (1):
      # Pair of ints
      self._lat = yllcorner + cellsize * (maxrows - arg1)
      self._lon = xllcorner + cellsize * arg2
    else:
      raise TypeError

  def xy (self):
    col = int ((self._lon - xllcorner) / cellsize)
    assert col < maxcols
    row = int (maxrows - ((self._lat - yllcorner) / cellsize)) - 1
    assert row >= 0
    return row, col

  def distance (self, another):
    "Compute the distance between this lat/long and another."
    # Code adapted from Chris Veness
    R = 6371 # km
```

```
    dlat = math.radians (another._lat - self._lat)
    dlon = math.radians (another._lon - self._lon)
    lat1 = math.radians (self._lat)
    lat2 = math.radians (another._lat)
    a = math.sin(dlat/2) * math.sin(dlat/2) + \
        math.sin(dlon/2) * math.sin(dlon/2) * math.cos(lat1) *
math.cos(lat2)
    c = 2 * math.atan2 (math.sqrt (a), math.sqrt(1-a))
    return R * c

  def __repr__ (self):
    return self.__str__ ()

  def __str__ (self):
    return '(' + str (self._lat) + ', ' + str (self._lon) + ')'

class BoundingBox:
  def __init__ (self, (ll, ur)):
    self._lowleft = ll
    self._upright = ur
    assert self._lowleft._lon <= self._upright._lon
    assert self._lowleft._lat <= self._upright._lat

  def contains_p (self, coord):
    return (coord._lat >= self._lowleft._lat and \
              coord._lat <= self._upright._lat) and \
              (coord._lon >= self._lowleft._lon and \
                 coord._lon <= self._upright._lon)

  def slice (self):
    ll = _lowleft.xy ()
    ur = _upright.xy ()
    s1 = slice (ur[0], ll[0])
    s2 = slice (ll[1], ur[1])
    return s1, s2

  def __repr__ (self):
    return self.__str__ ()

  def __str__ (self):
    return '(' + str (self._lowleft) + ', ' + str (self._upright) + ')'
```

13.3.4. Fill blanks in TMY3 files

```
Sub LoopThroughFiles()
    Dim strFile As String
    Dim FilePath As String
    Dim i As Integer
    Dim fnamearray As Variant
```

```
    i = 2
    FilePath = "G:\Work\0Projects\A0103 ASI _Austela SAM for
Oz\Work\TMY3\New TMY3\"
    strFile = Dir("G:\Work\0Projects\A0103 ASI _Austela SAM for
Oz\Work\TMY3\New TMY3\")
    Do While Len(strFile) > 0
        Workbooks.Open Filename:=FilePath & strFile
        fnamearray = Split(strFile, ".")
        fname = fnamearray(0)
        ThisWorkbook.Sheets("Sheet1").Cells(i, 1) = fname
        fixDates
        ThisWorkbook.Sheets("Sheet1").Cells(i, 2) = sumDNI(strFile)
        ThisWorkbook.Sheets("Sheet1").Cells(i, 4) = fillBlanks(strFile)
        ThisWorkbook.Sheets("Sheet1").Cells(i, 3) = sumDNI(strFile)
        Application.DisplayAlerts = False
        fpath = "G:\Work\0Projects\A0103 ASI _Austela SAM for
Oz\Work\TMY3\New TMY3\Blanks filled\" & fname
        Workbooks(strFile).SaveAs Filename:=fpath,
FileFormat:=xlWorkbookDefault
        Workbooks(fname).Close
        Application.DisplayAlerts = True
        strFile = Dir
        i = i + 1
    Loop
End Sub

Function fillBlanks(strFile As String) As Integer
Dim startTime As Integer
Dim endTime As Integer
Dim myTime As Integer
Dim myMonth As Integer
Dim findStart As Boolean
Dim startDay As Integer
Dim endDay As Integer
Dim minStartTimes(1 To 12) As Integer
Dim maxEndTimes(1 To 12) As Integer
Dim Blanks As Integer
Dim ws As Worksheet

For Each ws In Workbooks(strFile).Worksheets
    startTime = 25
    endTime = 0
    lastMonth = 1
    myMonth = Month(ws.Cells(3, 1))
    findStart = True
    For i = 3 To 8762
        If myMonth = lastMonth Then
        Else
            minStartTimes(lastMonth) = startTime
            maxEndTimes(lastMonth) = endTime
```

```
            startTime = 25
            endTime = 0
        End If
        If ws.Cells(i, 5) = 0 Then
            If findStart Then
            Else
                If Round(ws.Cells(i - 1, 2).Value * 24, 0) > endTime
Then
                    endTime = Round(ws.Cells(i - 1, 2).Value * 24, 0)
                End If
                findStart = True
            End If
        Else
            If findStart Then
                If Round(ws.Cells(i, 2).Value * 24, 0) < startTime Then
                    startTime = Round(ws.Cells(i, 2).Value * 24, 0)
                End If
                findStart = False
            End If
        End If
        lastMonth = myMonth
        myMonth = Month(ws.Cells(i, 1))
    Next i
    minStartTimes(lastMonth) = startTime
    maxEndTimes(lastMonth) = endTime

    For i = 3 To 8762

        myMonth = Month(ws.Cells(i, 1))
        If ws.Cells(i, 5) = 0 Then
            myTime = Round(ws.Cells(i, 2).Value * 24, 0)
            If myTime > minStartTimes(myMonth) And myTime <
maxEndTimes(myMonth) Then

                myval = ws.Cells(i + 1, 8).Value
                mytime2 = Round(ws.Cells(i + 1, 2).Value * 24, 0)
                consecBlanks = 1
                Do Until myval <> 0 Or mytime2 = maxEndTimes(myMonth)
                    consecBlanks = consecBlanks + 1
                    myval = ws.Cells(i + consecBlanks, 8).Value
                    mytime2 = Round(ws.Cells(i + consecBlanks, 2).Value
* 24, 0)
                Loop

                Blanks = Blanks + consecBlanks
                If consecBlanks < 5 Then
                    For j = 0 To consecBlanks - 1
                        ws.Cells(i + j, 5) = Round((j + 1) * (ws.Cells(i
+ consecBlanks, 5).Value - ws.Cells(i - 1, 5).Value) / (consecBlanks +
1) + ws.Cells(i - 1, 5).Value, 0)
```

```
                        ws.Cells(i + j, 5).Interior.Color = RGB(0, 255, 
0)
                    Next j
                Else
                    For j = -1 To consecBlanks
                        If i + j - 24 < 3 Then
                            ws.Cells(i + j, 5) = ws.Cells(i + j + 24, 
5).Value
                        ElseIf i + j + 24 > 8762 Or ws.Cells(i + j + 24) 
= 0 Then
                            ws.Cells(i + j, 5) = ws.Cells(i + j - 24, 
5).Value
                        Else
                            ws.Cells(i + j, 5) = Round((ws.Cells(i + j + 
24, 5).Value + ws.Cells(i + j - 24, 5).Value) / 2, 0)
                        End If
                        ws.Cells(i + j, 5).Interior.Color = RGB(0, 0, 
255)
                    Next j
                End If
                i = i + consecBlanks - 1
            End If
        End If

    Next i

    For i = 3 To 8762

        myMonth = Month(ws.Cells(i, 1))
        If ws.Cells(i, 8) = 0 Then
            myTime = Round(ws.Cells(i, 2).Value * 24, 0)
            If myTime > minStartTimes(myMonth) And myTime < 
maxEndTimes(myMonth) Then

                myval = ws.Cells(i + 1, 8).Value
                mytime2 = Round(ws.Cells(i + 1, 2).Value * 24, 0)
                consecBlanks = 1
                Do Until myval <> 0 Or mytime2 = maxEndTimes(myMonth)
                    consecBlanks = consecBlanks + 1
                    myval = ws.Cells(i + consecBlanks, 8).Value
                    mytime2 = Round(ws.Cells(i + consecBlanks, 2).Value 
* 24, 0)
                Loop

                Blanks = Blanks + consecBlanks
                If consecBlanks < 5 Then
                    For j = 0 To consecBlanks - 1
                        ws.Cells(i + j, 8) = Round((j + 1) * (ws.Cells(i 
+ consecBlanks, 8).Value - ws.Cells(i - 1, 8).Value) / (consecBlanks + 
1) + ws.Cells(i - 1, 8).Value, 0)
```

```
                        ws.Cells(i + j, 8).Interior.Color = RGB(0, 255,
0)
                    Next j
                Else
                    For j = -1 To consecBlanks
                        If i + j - 24 < 3 Then
                            ws.Cells(i + j, 8) = ws.Cells(i + j + 24,
8).Value
                        ElseIf i + j + 24 > 8762 Or ws.Cells(i + j + 24)
= 0 Then
                            ws.Cells(i + j, 8) = ws.Cells(i + j - 24,
8).Value
                        Else
                            ws.Cells(i + j, 8) = Round((ws.Cells(i + j +
24, 8).Value + ws.Cells(i + j - 24, 8).Value) / 2, 0)
                        End If
                        ws.Cells(i + j, 8).Interior.Color = RGB(0, 0,
255)
                    Next j
                End If
                i = i + consecBlanks - 1
            End If
        End If

    Next i
    fillBlanks = Blanks
Next ws
End Function


Function sumDNI(strFile As String) As Double
Dim ws As Worksheet
Dim tempsum As Double

tempsum = 0
For Each ws In Workbooks(strFile).Worksheets
    For i = 3 To 8762
        tempsum = tempsum + ws.Cells(i, 8).Value
    Next i
Next ws
sumDNI = tempsum / 1000
End Function

Sub fixDates()
Dim myDate As Date

myYear = Year(Cells(3, 1))
myDate = "1/01/" & myYear


For i = 3 To 8762
```

```
    If i = 3 Then
    Else
        If ((i - 3) Mod 24) = 0 Then
            myDate = myDate + 1
        End If
    End If
    Cells(i, 1) = myDate
Next i

End Sub
```

IT Power Renewable Energy Consulting

Southern Cross House, 6/9 McKay St, Turner, ACT
PO Box 6127 O'Connor, ACT 2602
info@itpau.com.au

abn 42 107 351 673
p +61 (0) 2 6257 3511
f +61 (0) 2 6257 3611

itpau.com.au