ENERGY CONVERSION MODEL FOR SOLAR FORECASTING

PREPARED BY: Energy forecasting

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DRAFT

Contents

Version Release History

VERSION	DATE	BY	CHANGES
0.1	20/3/2013	Michael Eastowod	Initial release for internal review
0.2	22/3/2013	Nathan White	Condensed and separated background theory
0.3	08/04/2013	Jiun Siew	Incorporating review comments

1 Introduction

Utility-scale solar generating systems are a relatively new phenomenon, not only in Australia but across the world. It is expected that as more solar generating systems are installed, knowledge about their modes of operation and typical power output will improve. The need to improve solar energy forecasts becomes more acute as solar generation begins to contribute higher proportions of the total generation in a system.

The Australian Solar Energy Forecasting System (ASEFS) is being designed to project expected generation from solar power generators in the short, medium, and long term.

The ASEFS will itself form a component of the existing Australian Wind Energy Forecasting System (AWEFS), sharing many of its administrative functions and interfaces.

A principal component of ASEFS is an Energy Conversion Model (ECM), which produces forecasts of generation based on measurements of ambient conditions and the configuration of solar plant. This paper describes, and invites comment on, the design of the ECM and its associated parameters.

1.1 Scope of consultation

This paper considers solar forecasting for current and future phases of ECM development. Its intention is to present the parameters necessary for producing forecasts for both current solar generation technologies, and future technologies that are not yet commercially-realised.

An Excel workbook accompanies this paper as Schedule A. The workbook concisely describes the ECM model input parameters and provides areas for respondents to comment on each. While the workbook is not final, it does suggest the type, style and content of data that will be gathered as part of the registration process for solar generators.

Comments are invited on the design of the ECM guidelines. In particular:

- The appropriateness of parameters listed in Schedule A, including their value for the current phase of development and for as-yet unrealised solar generation technologies.
- Whether there are additional parameters or considerations that should also be included in the guidelines, and the justification for these.
- Any other issue relevant to the ECM guidelines or development of the ASEFS.

In this paper, items in **bold** are parameters defined in the ECM as listed in Schedule A. Some model parameters may not be required for early phase development, but may provide enhanced forecasting accuracy for subsequent phases. These are marked in the text as “may be required”.

This document provides an overview of the parameters being considered as an input to the ECM and includes a brief explanation as to how and why each parameter is used. The sections below are divided into broad topical categories that are relevant to forecasting solar energy output such as irradiance and energy conversion.

The accompanying workbook contains a list of all the parameters and specifies details such as measurement units, sampling rates and whether or not the parameter is required.

Note that in both this document and the workbook, several parameters have text that is highlighted in red. These parameters are highlighted because, while they are considered by AEMO as an important input to the ECM, there are concerns about its practicality in the deployment of solar systems. As such, AEMO would like to receive specific feedback regarding these parameters.

1.2 Consultation Timelines

The consultation process will follow the timelines outlined below:

Item	Date
Draft consultation papers published	12 April 2013
Consultation feedback closes	3 May 2013

Item	Date
Meet with respondents[1]	13-17 May 2013
Final recommendation	31 May 2013

1.3 Timelines for Solar Forecasting Project

Timeframes for the solar forecasting project is outlined below

Item	Target Completion Date
Design	17 June 2013
Development and testing	30 April 2014
Deployment	29 May 2014

2 Solar generating systems

Each solar generating system is identified by its **Facility ID** and/or **Facility Name**. Each facility has a dynamic parameter, **Facility Online**, which specifies its current state.

To provide a forecast of solar generation, two items of information must be determined for each facility: the forecast irradiance at the generation site, and the energy conversion performed by the generation equipment.

These two components can be determined through analysis of a range of underlying quantities that represent ambient conditions and plant configuration. These quantities and their relationship to the ECM parameters are described in the following sections.

3 Irradiance

The light that falls on a solar generating facility is a combination of the original beam (*direct normal irradiance*), light scattered by the atmosphere (*diffuse irradiance*), and light reflected from nearby objects including the ground, vegetation, buildings and clouds (*reflected irradiance*).

Devices that measure solar energy typically measure either the direct normal irradiance, or the global horizontal irradiance (the sum of direct normal, diffuse, and reflected irradiances)[2].

Global horizontal irradiance is a required dynamic model parameter.

Direct normal irradiance is a required dynamic model parameter.

These two irradiance measurements are useful to confirm the accuracy of estimates of the spectral power distribution, and may also be used when spectral estimates cannot be made due to the lack or failure of other instruments.

Several factors affect irradiance at particular site. The most significant of these are described in the following sections.

3.1 Solar position

Irradiance is highly dependent on the position of the sun in the sky relative to an observer on the Earth's surface, this is itself a function of the latitude of the observer, the solar time (calculated based on the longitude and time zone of the observer), and the declination angle (which is independent of solar facility).

Facility Latitude is a required static model parameter.

Facility Longitude is a required static model parameter.

The **Facility time zone** is calculable from latitude and longitude without further input.

[1] Meetings with respondents will include AEMO's service provider

[2] Diffuse and reflected irradiance can be derived by subtracting DNI from global horizontal irradiance. Diffuse and reflected irradiance are rarely separated into their distinct components, except where one or the other is under specific study.

Solar position calculations must also convert solar time to market time (Australian Eastern Standard Time) in order to forecast for the correct dispatch interval.

A **Facility Map** is a required static model parameter. The map should be a terrain map indicating the position of receivers, strings, and measurement devices in either a PDF or high resolution image.

3.2 Atmosphere

The solar radiation incident on the Earth is attenuated by the atmosphere before striking the ground. The effect of the atmosphere on incident radiation is determined by a range of factors. Each factor attenuates the extra-terrestrial spectrum in a specific way.

3.2.1 Atmospheric thickness

The thickness of the atmosphere affects the power of radiation reaching the surface and can be estimated at the surface by measurement of barometric pressure.

Barometric pressure is a required dynamic model parameter.

Barometric pressure is allows calculation of the thickness of atmosphere directly above a solar facility, however of greater interest is the density of atmosphere along the path between the facility and the sun (the *slant path*).

Slant atmospheric density may be a required dynamic model parameter.

LIDAR instruments (Light Detection and Ranging) are able to measure slant atmospheric density, however they are also more expensive and more challenging to operate than simple barometric devices. LIDAR instruments also have the advantage of being capable of measuring several parameters of interest from a single device.

3.2.2 Altitude

Direct measurement of atmospheric pressure removes the need to calculate the effect of altitude on pressure. Altitude is still required, however, in the event of a failure of the barometer and for any pressure-predictive models that an ECM may contain for times when pressure measurements or projections are not available as an input.

Facility altitude is a required static model parameter.

3.2.3 Ozone absorption

Ozone is responsible for most of the absorption of high-energy *ultraviolet* (UV) radiation incident on the upper atmosphere.

Total ozone abundance is a common dynamic model parameter. It may be expressed, with increasing accuracy, as a column (vertical) value, a slant path value, or as a slant path density function.

Ozone abundance does not change rapidly. It is likely that daily estimates will adequately track its variation with time. Ozone abundance is also likely to be available from numerical weather prediction (NWP) data streams, and no on-site measurement devices are expected to be required.

3.2.4 Water vapour adsorption

The complex nature of water bonding introduces a range of ways in which water can absorb incident radiation.

Water vapour abundance is a required dynamic model parameter. It may be expressed, with increasing accuracy as one of the following dynamic model parameters that may be required by the ECM:

- **Relative humidity**,
- **Column water vapour abundance**,
- **Slant water vapour abundance**, or
- **Slant water vapour density distribution**.

Measurements at five minute intervals are likely to adequately track changing values.

Water vapour abundance may be measured directly or indirectly using a variety of instruments. Many of these instruments are either expensive, require specific scientific expertise to maintain, or are impractical for day to day measurement. A ground-based humidity measurement constitutes the minimum requirement, although a LIDAR may serve multiple functions, including measurement of other atmospheric species and the height of clouds.

3.2.5 Carbon dioxide, oxygen, and trace gas adsorption

Carbon dioxide and oxygen abundance is relatively constant, and is therefore these are not required model parameters. The effect of other trace gas abundance is small, and therefore these are also not required model parameters.

3.2.6 Aerosols

Aerosols are a natural and highly variable component of the atmosphere, and include particles such as dust, smoke, sea spray, biological debris and sulphates from industry.

Aerosol composition varies widely between locations and over different time scales. The varying concentration and size of aerosol particles in the atmosphere can be expressed as a single measurable factor called the *aerosol optical thickness*.

Aerosol optical thickness may be a required dynamic model parameter. It may be expressed, with increasing accuracy, as either:

- **Column aerosol optical thickness**,
- **Slant aerosol optical thickness**; or
- **Aerosol optical thickness density**.

This quantity can be measured or inferred in a variety of ways, but is likely to be available from numerical weather prediction (NWP) data streams, and on-site measurement devices may not be required.

In the absence of aerosol optical thickness measurements, historically-tuned local parameters may be used.

3.3 Cloud

Clouds are a form of localised optical thickening that can result in very fast changes in irradiance and the solar power output. Estimation of the effect of clouds on irradiance requires knowledge of both the distribution and the type of clouds above or approaching a facility.

Cloud coverage is a required dynamic model parameter. The coverage is expressed as a percentage of the total 180º view from the site. The coverage estimation has two roles: to provide a probability that the facility is or will be under cloud shadow, and to allow for adjustment to the diffuse spectrum for light scattered from clouds.

At present, cloud coverage data is available from satellites via NWP data feeds. Such data is useful for forecasts in the range of one hour to one day, but cannot provide a suitable indication of cloud for short-term forecasting. In the short term, a persistence method may be more useful, in which the prevailing cloud cover is extrapolated from recent measurements of power output and other indicators from the site.

Short and medium-term forecasts can be further improved by improved methods of cloud detection using a range of additional measurements.

Cloud type may be a required dynamic model parameter.

Cloud scale may be a required dynamic model parameter.

Cloud height may be a required dynamic model parameter.

Cloud velocity may be a required dynamic model parameter.

Such detection may result in a range of data streams and significant on-site processing capability. It is not expected that such detailed information will be known initially. Estimation of these detailed parameters implies a much higher volume of data to be inserted into the SCADA stream, and it may be adequate to instead transfer a measure of the likelihood of the facility being under shadow from a cloud of defined optical thickness for a specific duration.

3.3.1 Cloud optical thickness

The key property for forecasting the degree of shadowing due to cloud is the cloud's optical thickness

Cloud optical thickness may be a required dynamic model parameter. At its highest resolution, the cloud optical thickness assumes values based on a grid of points describing the 180º visible sky above a facility, taking an average of the values contributed various cloud types present at different vertical levels. Where this resolution is not available, it may be represented by an average thickness value (a grid with a single point). Where no measurement data is available, near-historical data may be used to infer an average value.

3.3.2 Albedo

Albedo is a term commonly used to describe reflectivity. Clouds reflect both upward, when radiation is incident from space, and downward, when radiation is incident from the Earth. Satellite-based systems that interpret images of cloud may need to consider both the albedo of the cloud and the albedo of the underlying ground in order to provide good estimates of cloud optical thickness.

Cloud albedo may be a required dynamic model parameter.

Site albedo distribution may be a required dynamic model parameter.

Site albedo may be a required dynamic model parameter if a site albedo distribution is not supplied.

3.4 Measurement devices

Forecast accuracy depends on the accuracy of the algorithms and devices that estimate specific model parameters. Errors in either direct measurement or derivation of values based on measurement indirectly can interact in unanticipated ways.

Measurement devices that fail may continue to produce measurement data. Devices need to be capable of signalling the forecasting system when erroneous data is being delivered.

List of measurement devices is a required static model parameter

For each measurement device:

- **Device online** is a required dynamic model parameter.
- **Device functioning** is a required dynamic model parameter.

Some devices may not be capable of self-determination of correct function. The forecasting system should incorporate techniques for detecting faulty device output when this is the case. Such devices would have an assumed "device functioning" value of "true", subject to override by the forecasting system.

3.4.1 Calibration

To account for variations in manufacture, instruments are calibrated against known standards. Instruments may be subject to "drift", such that measured values gradually diverge from true values.

The calibration of instruments implies three important points to note for solar forecasting systems:

- The system should not rely on the input of any one instrument being available. The system must incorporate fall-back strategies for when instruments are unavailable.
- Minimum standards for metrology must be developed and applied.
- The system should not rely on the correctness of any particular instrument. Where possible, checks should be undertaken to identify instruments that are subject to unacceptable drift.

Last device calibration date may be a required semi-static model parameter.

3.4.2 Fall-back and override

In some circumstances, certain variables may be unavailable (due to measurement device failure, for example), or may not be relevant to forecasts defined on a particular time scale.

Parameters described in by ECM may be related to other parameters by *fall-back* and *override* relationships.

- A fall-back relationship occurs when a detailed parameter value may fall back to a less-detailed parameter value when the detailed information is not available.

- An override relationship occurs when a less-detailed parameter overrides a more-detailed parameter. For example, availability of the facility as a whole overrides the availability of individual strings. In a solar thermal plant, availability of the turbine-generator pair overrides the number of concentrators available.

4 Energy conversion

Solar generating systems convert irradiance (radiation power) collected at receivers into electrical power through various mechanisms.

The conversion process can be parameterised by several key considerations that are discussed in the following sections.

Each class of receivers can be defined by a specific set of these characteristic parameters, and each receiver class requires its own ECM configuration.

List of receiver classes (defined on the facility) is a required static model parameter.

Receiver type (defined on the receiver class) is a required static model parameter.

Receiver rating (defined on the receiver class) is a required static model parameter.

Each receiver class is identified by its **Receiver ID**.

4.1 Spectral response

Solar generating systems are not 100% efficient, and the critical parameter is the portion of incident energy that can be converted into usable power. The ‘spectral response’ is a more detailed version of the concept of efficiency that is capable of responding to changes in ambient conditions.

Normalised spectral response is a required static model parameter. The response is given as a series of values between 0 and 1 for the wavelength range 200 nm to 4,000 nm. The spectral response is given for each type of receiving system.

Future development of ASEFS is expected to enable forecasting of distributed generating systems that may comprise a range of energy-receiving and power conversion products. For example, a collection of homes that incorporate rooftop photovoltaic generation may incorporate modules and inverters from different manufacturers, and supply a different amount of power. In this case, the spectral response of the system is the weighted sum of the responses of the individual rooftop systems.

4.2 Surface reflectivity

The reflectivity of a solar collector may change depending on the angle of incident light, and the presence of any anti-reflective coatings.

Surface reflectivity as a function of angle of incidence is a required static model parameter.

For solar thermal systems, reflectivity of the absorbing surface may or may not have a functional relationship to the angle of incidence of light on that surface. Where there is no relationship, the reflectivity function is expressed by a constant value of 0 (as any constant surface reflectivity is captured by the spectral response curve).

Rooftop photovoltaic systems are expected to be non-uniform, not only in the type of modules employed, but in the angle and orientation at which they are installed. It is not considered practical to maintain a list of individual systems and the angle and orientation of the modules in each one. In this case it may be suitable to make assumptions common for housing in the area. Such assumptions would allow the development of an approximate reflectivity function.

4.3 Temperature response

Both photovoltaic and solar thermal generating systems respond differently depending on their operating temperature. Depending on the solar technology installed, both the receiver surface temperature and ambient temperature measurements may be important.

Ambient temperature is a required dynamic model parameter.

Receiver surface temperature is a required dynamic model parameter.

When receiver surface temperature measurements are not available, the receiving surface temperature can be inferred from a combination of ambient temperature, wind speed, and wind direction.

Wind speed is a required dynamic model parameter.

Wind direction is a required dynamic model parameter.

In some cases, wind speed and direction measurements may also be used to infer cloud velocity vectors.

Temperature response is a required static model parameter. For photovoltaic systems, the response is a function of the cell temperature. For solar thermal systems, the response is a function of the difference in temperature between the receiving surface and the ambient environment.

In photovoltaic systems, when the temperature response is linear, the slope of the curve is referred to as the *panel* ***derating coefficient***. It may be a suitable proxy if a temperature response curve is not supplied.

4.4 Area

The power of a solar generating facility increases with the area of its energy-absorbing surface. This is a function of the receiver surface area, and the number of receivers online.

Number of receivers is a required static model parameter, defined for each receiver class.

Receiver surface area is a required static model parameter, defined for each receiver class.

Receivers online is a required dynamic model parameter, defined for each receiver class.

4.5 Concentration

Solar generating facilities that incorporate reflective elements, may concentrate the solar energy of a larger area onto a smaller receiving surface. The ECM includes parameters associated with concentration.

Number of concentrators as a function of receiver ID is a required static model parameter. It is defined relative to a single receiving surface as systems with more than one receiver may have a different number of concentrators assigned to each one.

Concentrator efficiency is a required static model parameter.

Concentrator area is a required static model parameter. For central receiver systems, this would be the area of a single reflector.

Concentrators online is a required dynamic model parameter. A reflector, for example, may not be directed at the receiver for one reason or another. In such instances the contribution of that reflector should not be counted.

Some photovoltaic systems incorporate lenses to focus sunlight onto smaller solar cells. In these cases it is reasonable to describe the total cell surface area as the absorber surface area, and the ratio of the total lens surface area to the total absorber surface area as the number of concentrators.

4.6 Orientation

A radiation beam that strikes a surface at an angle imparts less energy than the same beam striking perpendicular to the surface. It is common for solar energy systems to actively orient their absorbing surfaces as perpendicular as possible to incident radiation, referred to as *tracking*.

Solar thermal systems, though they employ sun-tracking reflectors, are not classified as tracking systems because the tracking is required to focus the concentrating beam, not change the beam angle of incidence at the receiver. Orientation parameters discussed in this section apply to photovoltaic systems only.

Tracking systems may orient themselves to the position of the sun over the course of a day and/or the change in position at solar noon throughout the year.

Tracking strategy is a required static model parameter. To accommodate non-homogeneous systems, this is a dual-value variable incorporating the type of tracking (none, single-axis altitude, single-axis azimuth, dual-axis) and the portion of total receivers that employ that strategy.

Number of trackers is a required static model parameter.

Tracking minimum altitude angle and **Tracking maximum altitude angle** is a required model parameter

Tracking minimum azimuth angle and **Tracking maximum azimuth angle** is a required model parameter

Trackers online is a required dynamic model parameter, to determine the number of modules that are oriented at the sun and the number of modules that are in their default (parked) position.

Systems that do not employ tracking are commonly oriented in a direction that reduces angle-of-incidence losses. This is also the orientation that tracking systems are expected to default to when active tracking systems are off-line (the *parked* orientation).

Parked altitude angle is a required static model parameter

Parked azimuth angle is a required static model parameter

A parameter that is relatively simple to measure is the global inclined irradiance, which can be used to confirm the accuracy of modelled inclined irradiance values based on horizontal irradiance values, and develop a reflectivity (global albedo) coefficient for a site that may be used in other model calculations.

Global inclined irradiance may be a required dynamic model parameter.

Actual tracking inclination is a required dynamic model parameter.

Actual tracking orientation is a required dynamic model parameter.

Tracking share of panels as a percentage is a required dynamic model parameter.

4.7 Degradation

Solar generation systems degrade with age resulting in changed efficiency over time that must be considered as part of an accurate solar forecasting system.

Degradation curve may be a required static model parameter.

Annual degradation rate is a required static model parameter. It may act as a suitable proxy if the more detailed degradation curve is not supplied.

The nameplate capacity of solar components may be specified according to the expected capacity after a module has been in the field for some length of time. Such specification conventions may require forecasts to be adjusted upwards during the early stages of operation of a solar plant.

4.8 Inversion

Inverters are used to convert direct current into alternating current (AC) in preparation for injection into the AC grid. Inverters are not 100% efficient, with efficiency changing depending on power output. Inverters may also introduce a ‘dead zone’ at low power levels where no AC electricity is produced despite some DC electricity being available.

Inverter types are identified by **Inverter ID**. Each inverter type has its own power-efficiency response.

Inverter response may be a required static model parameter for systems that employ inverters.

Inverter efficiency may be a required static model parameter for systems that employ inverters. It may act as a suitable proxy for occasions when a more detailed inverter response is not supplied.

Inverter rating is a required static model parameter for systems that employ inverters. The inverter response is defined in terms of a percentage output of the rating.

Number of inverters is a required static model parameter for systems that employ inverters. For photovoltaic system forecasting purposes, the number of inverters is synonymous with the number of strings (see Section 7).

4.9 Alternative energy sources

In some cases, the output of a solar plant can be decoupled from real time solar irradiance through the use of storage technologies or backup generation sources.

Auxiliary supply capacity is a required static model parameter for systems that incorporate energy storage or backup systems.

Auxiliary supply contribution is a required dynamic model parameter for systems that incorporate energy storage or backup systems. This value may be negative when systems with storage are actively injecting energy into their storage matrices.

5 Network control

As semi-scheduled generators, solar generating facilities may be subject to down-regulation by AEMO, to protect the power system from unsafe or potentially insecure power flows. A control set point limits the active or reactive power that may be delivered by the generator.

Active power control set point is a required dynamic model parameter.

Reactive power control set point is a required dynamic model parameter.

To confirm the correct operation of controls, the active and reactive power output of the plant is required.

Active power generation is a required dynamic model parameter.

Reactive power generation is a required dynamic model parameter.

Plant Availability is a required dynamic model parameter that specifies in MW, the amount of available power from the facility.

6 Lifecycle

Facilities go through a life cycle, from the proposal and design stages, through the construction and commissioning stages, a long operational stage and then decommissioning. Measurements may be taken at each stage, and for analysis of historical data it is important to track the status of the facility, so that non-operational data may be filtered from operational data.

Facility status is a required semi-static model parameter. Although its value is expected to change, such changes occur infrequently only.

7 Arrangement

In the Australian Wind Energy Forecasting System, AEMO developed the concept of “turbines” and *clusters* to estimate the availability of a wind farm in the absence of SCADA measurements (by counting turbines available). The forecasting system uses the concept of a cluster to identify models of wind turbine that may require different treatment by the ECM.

The same interfaces are intended to be used for ASEFS.

In ASEFS, the concept of a “turbine” is replaced by a *string*. The system counts the number of strings available and multiplies by the string capacity to estimate station availability. While a string can define any arrangement of receiving surfaces, it is convenient to apply the concept of a string to an identifiable unit of generation.

For photovoltaic systems, a “string” refers to all of the modules connected to the DC side of a single inverter. The number of inverters in the total system defines the number of strings. For solar thermal systems, a “string” refers to a single turbine-generator couple. The number of concentrators online parameter may be used to determine plant availability for pre-dispatch.

Clusters define non-homogeneous parts of the generating system that may require the application of distinct response curves or other parameters. All static model parameters are defined with reference to the cluster to which the receiver belongs.

A utility-scale photovoltaic system in which all of the modules and inverters originate from a single manufacturer may belong to a single cluster. A distributed system consisting of many individual rooftop systems may define each system as a distinct cluster, or employ some aggregation of those systems into clusters based on similar characteristics.

Central receiver solar thermal systems may define a cluster for each generating unit, as the heat-exchange, turbine and generator components may be custom-built for each reflector field. Where there are multiple receivers all of identical construction, a single cluster may be suitable.

Number of clusters is a required static model parameter.

String centre latitude is a required static model parameter.

String centre longitude is a required static model parameter.