

Denowatts Methodology

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1. Introduction

This document describes the methods and standards utilized by the Denowatts service. This document is divided into three general sections:

- Sensors and Measurement
- Benchmarking and Reporting
- Performance Testing

The intent of this document is to describe the methodology in adequate detail for a technical review of the Denowatts service by independent review. The methodology, terminology, and metrology are modeled after IEC 61724-2017/18 standards with several supporting standards described in the relevant section.

If the reader would like further clarification on any item in this document, please email support@denowatts.com or call 978.309.6688.

2. Sensors and Measurement

2.1 Sensors

2.1.1 Irradiance

2.1.1.1 Plane of Array Pyranometers

The Deno sensor consists of two a-Si photodiode pyranometers operated in transimpedance mode. The photodiodes have a spectral response of 400-1100 nm with peak at ~900 nm and a response/sampling time of under 10 ms. The pyranometers are mounted with a 180-degree rotation to each other and samples of the two pyranometers are averaged together to reduce directional error. Irradiance readings have a measurement resolution of 0.1 w/m² and a range from 0 to 1500 w/m².

Pyranometers are calibrated using a solar simulator with an Air Mass 1.5 filter. The secondary standard used for calibration is measured against a spectrally flat Class A pyranometer under clear sky conditions.

2.1.1.2 Reference Channel

User may connect a 0-20 mV 3rd party pyranometer to the Deno sensor. This reference channel may be especially useful for measuring Global Horizontal Irradiance (GHI) or adding a Class A spectrally flat thermopile POA pyranometer. Measurements and logging are the same as the onboard Deno sensors.

2.1.2 Temperature

2.1.2.1 Cell Temperature

2.1.2.1.1 Deno Integrated Temperature Sensor

The Deno integrated temperature sensor is mounted on the underside of the unit. This sensor is a precision CMOS sensor with typical accuracies of 0.4 °C and is measured in an analog circuit. This sensor generates measured temperature (T_m) which is utilized to calculate cell temperature (T_c) as defined below.

2.1.2.1.2 Denowatts Model

Cell temperature is calculated as a function of plane of array irradiance (I) and the measured temperature (T_m). Temperature is measured on the back of the Deno sensor. This equation is a modified version of the IEC model of converting the back of module temperature to the cell temperature. Constants a and b have been determined through experimentation and are dependent on the mount type of the system.

$$T_c = a * I + b + T_m$$

2.1.2.1.3 Other Models

2.1.2.1.3.1 IEC 61724-2:

The IEC standard provides the following heat transfer model to be used to calculate the cell temperature of solar modules. It calculates a back of module temperature, and then uses that and a conductive model to calculate the cell temperature.

$$T_{BOM} = G e^{a+bw} + T_a$$

$$T_c = T_{BOM} + \frac{G}{1000} dT_{cond}$$

Where T_{BOM} is the back of module temperature, T_a is the ambient temperature, T_c is the cell temperature, w is the wind speed, and G is the plane of array irradiance. Constants a , b , and dT_{cond} have values that depend on the type of module (open rack, roof mount, etc.).

Denowatts utilizes the IEC model due to its simplicity, replicability, and traceability back to a common standard.

2.1.2.1.3.2 NREL (Fuentes model)

NREL uses the Fuentes energy balance model when computing cell temperature. This method uses a heat transfer energy balance that requires iterations to reach the final solution. The energy balance accounts for convection and radiation between the module and both the sky and ground.

Denowatts opted not to use it because of concerns of complication and repeatability.

2.1.2.1.3.3 PVsyst

The PVsyst method uses an energy balance equation that has been simplified. Energy incident on the module that is not turned into power is assumed to become heat. The only other form of heat transfer considered is the convection between the module and the ambient air.

$$T_c = T_a + \frac{1}{U}(\alpha G * (1 - \eta))$$

$$U = U_c + U_v w$$

Where T_a is the ambient temperature, T_c is the cell temperature, w is the wind speed, and G is the plane of array irradiance. α and η are the absorption and PV efficiency (with default values of 0.9 and 0.1 respectively). U_c and U_v are constants that depend on the type of module (open rack, roof mount, etc.). The

default values for U_c and U_v are such that wind speed is considered constant at around 3 m/s.

Denowatts opted not to use it because of the high likelihood of the client's possibly using the default settings for wind (i.e. wind speed is not a variable in measured results).

2.1.2.2 Back of Module Temperature

2.1.2.2.1 External Sensor

The Deno external temperature sensor is attached to the Deno sensor utilizing an IP67 connector and a 3' cable. This sensor is a precision CMOS sensor with typical accuracies of 0.4 °C that is mounted within a sealed cannister and is digitally measured. This sensor generates back of module temperature (T_{bom}) when required for the user's application.

2.2 Measurement

2.2.1 Sensor Position and Attachment

The Deno sensor must be installed in accordance with instruction in the User's Guide.

Sensors shall be mounted at the top of the module in the sunniest part of the array in the "center mass" orientation of the array. Sensors are mounted between solar modules or may alternatively be attached to standard 1 5/8" strut in a similar location.

If multiple orientations exist, utilize one Deno sensor for each unique Plane of Array.

2.2.2 IEC 61724-1 Table Matrix (Summarized)

The Denowatts service utilizes a standard Deno sensor, optional 3rd party sensor, and remote weather services to meet Class B (Medium Accuracy).

Parameter	Units	Deno Standard	Table 3 Class	Notes
Sampling Interval	Seconds	5 (day) 60 (twilight) 900 (night)	B	End Timestamp
Record/Transmit Interval	Seconds	60 (day) 300 (twilight) 900 (night)	B	End Timestamp
Plane of Array Irradiance (POA)	W/m ²	Ground Based	A	2 rotationally opposing pyranometers average readings per Deno sensor
Global Horizontal Irradiance (GHI)	W/m ²	Ground Based	A	Optional Sensor
PV Module Temperature	°C	Ground Based	A	Optional Sensor (1 per Deno sensor)
Cell Temperature (Derived)	°C	Ground Based	N/A	Derived value not contemplated in 61724-1 (1 per Deno sensor)
Ambient Air Temperature	°C	Remote Weather Services	B	TWC Enhanced
Wind Speed	m/s ²	Remote Weather Services	B	TWC Enhanced
Wind Direction	Degrees	Remote Weather Service	N/A	Not considered for Class B
Rainfall	cm	Remote Weather Service	B	TWC Enhanced

3. Benchmarking and Accounting

3.1 Benchmarking

3.1.1 Expected Energy

Expected energy can be used to calculate a variety of useful performance metrics.

Symbol	Parameter
E_e	Expected Energy
$E_{e,in-service}$	In-service Expected Energy
E_p	Predicted Energy
E_m	Measured Energy
E_d	Denowatts
EPI	Energy Performance Index (All-in)
$EPI_{in-service}$	In-Service Energy Performance Index
$BEPI$	Baseline Energy Performance Index
DI	Deno Index
DI_c	Commissioned Deno Index
EA	Energy Availability

The IEC 61724 standard provides a few standard performance indices for describing the status of a site. The energy performance index is the ratio between the measured energy and the expected energy, while the baseline energy performance index is the ratio between the measured energy and the predicted energy. Predicted energy and expected energy are calculated using the same model, but with different inputs. Expected energy uses actual measured irradiance and weather data, while predicted uses average weather data such as the typical mean year datasets.

$$EPI = E_m/E_e$$

$$BEPI = E_m/E_p$$

3.1.2 Comparative Energy

In addition to standard performance metrics, Denowatts offers comparative analytics features. The Denowatt value and Deno Index is calculated in a similar fashion to the expected energy and energy performance index. Denowatts are designed to be a comparative expected energy value. This is calculated using identical system parameters, apart from AC and DC properties, regardless of the systems actual setup. The Deno Index is then calculated from these values.

$$DI = E_m/E_d$$

The Deno Index can be used to compare a site to other sites, or to an earlier version of itself. The comparative value indicates what percentile a site falls into when compared with all sites outfitted with Denowatts. When a site is first outfitted with Denowatts an initial Deno Index is taken from a representative sample of days. The benchmarked performance is then calculated as a ratio of the current Deno Index to the initial Deno Index.

$$\text{Benchmarked Performance} = DI/DI_c$$

Site outages can have a significant effect on the above metrics. For this reason, “in-service” metrics exist to allow for analysis of the functioning part of the system. Energy availability represents how much of the system is in operational condition. This value should be specified when creating outage reports and is used to determine the in-service expected energy.

$$EA = E_{e,in-service}/E_e$$

$$EPI_{in-service} = E_m/E_{e,in-service}$$

3.2 Accounting (In progress)

4. Performance Testing

4.1 Capacity Test

4.1.1 IEC 61724-2 Capacity Evaluation Method

Unconstrained Operation	Times at which the system’s output is not limited by inverter capacity or curtailment
Constrained Operation	Times at which the system’s output is limited by inverter capacity or curtailment
Target Reference Conditions (TRC)	A set of weather conditions (irradiance, temperature, and wind speed) where the system is unconstrained
Target Power	The expected power to be generated at TRC

The source of irradiance and temperature data can be selected. The expected power is calculated on the Deno from five-second samples by default. If non-default settings are chosen, the expected power will be recalculated for those settings based on 15-minute data. The same model is used for both calculations.

For irradiance data, the default source is the integrated dual photodiodes of the Deno sensor. If an external plane of array irradiance sensor is plugged into the Deno pyranometer port, this may be used by selecting the “External” option.

Temperature data has three possible sources, “Cell”, “BOM”, and “Ambient”. Cell temperature is the default setting which uses the integrated temperature sensor and simulation of the Deno. If a back of module (BOM) temperature sensor is installed on the array and plugged into the Deno temperature port, the “BOM” option may be selected to use this sensor. The “Ambient” setting will use local ambient temperature and wind speed data from Weather Underground.

Cell temperature is calculated from ambient temperature, wind speed, and irradiance using the below equation. In this equation a, b, and dT are constants with values of -3.56, -0.075 s/m, and 3 C respectively. These values are representative of a glass/cell/polymer sheet of an open rack system and should be changed for other system types. The table below lists common system types and their coefficients (IEC 61724-2).

$$T_c = T_a + Ie^{a+bW} + \frac{I}{1000} dT$$

Module Type	Mount	A	B	dT
Glass/cell/glass	Open rack	-3.47	-0.0594	3
Glass/cell/glass	Closed roof	-2.98	-0.0471	1
Glass/cell/polymer sheet	Open rack	-3.56	-0.075	3
Glass/cell/polymer sheet	Insulated back	-2.81	-0.0455	0
Polymer/thin-film/steel	Open rack	-3.58	-0.113	3

4.1.1.1 Unconstrained Operation

Target reference conditions (TRC) are used to calculate the unconstrained target power. The TRC should be chosen so that the target power is under unconstrained conditions. It is preferable for the TRC to represent the normal ambient weather conditions of the site.

Data is filtered based on value range and derivative range. This prevents values outside of a suitable range, dead values, and abrupt changes from interfering with the test results. The range values should be chosen so that constrained operation is excluded. Default values for filtering criteria are shown in the table below. The derivative is calculated based on 15-minute time intervals.

	Min Value	Max Value	Min Derivative	Max Derivative
Irradiance (w/m ²)	$0.1 * I_{TRC}$	$1.2 * I_{TRC}$	1	I_{TRC}
Cell Temperature (C)	-10	50	0	4
Wind Speed (m/s)	0	15	0	10
Measured Power (kW)	$-0.01 * AC_{Max}$	$1.02 * AC_{Max}$	1	$\frac{I_{TRC}}{1000} * DC_{Cap}$

Measured power is adjusted to match the TRC so it can be compared with the target power. This is done with the use of a correction factor that is the ratio between the target power and the expected power at the measured conditions. The measured power is then scaled to the corrected power according to the correction factor. The expected power (P_e) is calculated for each data point using the power model of the array (see expected energy documentation for more information).

$$CF = \frac{P_t}{P_e}$$

$$P_c = P_m CF$$

The average corrected power is then taken for all data points that are within acceptable limits. Any data points that deviate from this average by more than 5% are flagged so the cause can be investigated.

4.1.1.2 Constrained Operation

Constrained operation occurs when the production of the array is limited by another factor, such as inverter clipping or curtailment. The target power for time of constrained operation is the AC clipping limit of the inverters.

Data points are chosen for this based on the expected power. If the expected power has reached the AC clipping limit, that data point is flagged as constrained operation. If no data points are flagged, it is assumed that there was no constrained operation during that time period. If a constrained operation test is desired, choose a time interval that contains inverter clipping.

4.1.1.3 Comparison

To determine the results of the test a comparison is made between the target power and the average corrected power (or average power in the

case of constrained operation). The difference, percent difference, and ratio (as both a decimal and a percent) between the target power and average corrected power for both unconstrained and constrained operation. The following equations demonstrate the calculation of these metrics.

$$\text{Difference} = P_c - P_t$$

$$\text{Percent Difference} = \frac{P_c - P_t}{P_t} * 100$$

$$\text{Ratio} = \frac{P_c}{P_t}$$

$$\text{Ratio (percent)} = \frac{P_c}{P_t} * 100$$

4.1.2 E2848-13 Standard Test Method for Reporting Photovoltaic Non-Concentrator System Performance

E2848-13 is an alternate method for creating a power report for an array. Denowatts utilizes the plane of array irradiance, ambient temperature, and ambient wind speed. Data is filtered in the same manner as IEC 61724-2, with the ability to change constraints and manually exclude data points as necessary.

Coefficients are calculated by solving the following equation for the filtered data points collected during the test. A residual analysis is performed as an indication of the regression quality. The power at reference conditions is calculated using the same equation and the determined coefficients.

$$P = I(a_1 + a_2 * I + a_3 * T_a + a_4 * v)$$

4.2 Energy Test

4.2.1 IEC 61724-3 Energy Evaluation Method

Expected energy is used to evaluate the performance of solar PV systems. It is calculated using the measured weather data, specifically irradiance and cell temperature. The models used to calculate the expected energy should be the same as the ones used to calculate predicted energy (energy calculation using historical data). The PV module model and inverter module model are based on the models used by PVWatts.

4.2.1.1 Inputs

Each system requires a handful of array specific user defined parameters in order to calculate the expected energy. These values can be edited in the array edit window. These parameters are used in conjunction with the irradiance and temperature data gathered by the Deno sensor(s). All parameters must be specified in the array information section for expected energy to be calculated.

4.2.1.1.1 Parameters

- COD (commercially operational date)
- DC Capacity
- AC Capacity
- Inverter Efficiency
- Temperature Coefficient
- Static Losses
- Age Derate Factor

4.2.1.1.2 Measured Data

- Irradiance
- Cell Temperature
- Back of Module Temperature
- Age

4.2.1.2 Outages

Outage periods may be specified using the outage reporting feature. Non-environmental outages have an energy availability associated with them which is used when calculating the final expected energy. Environmental outages such as snow assume the array is working at its benchmark performance. In this case the expected energy is calculated from the actual site generation and the Denowatts benchmark.

4.2.1.3 Losses

4.2.1.3.1 Static Losses

Static losses are applied as a percentage to the DC power calculation. Loss factors that should be included are irradiance

level, light induced degradation, mismatch, and ohmic wiring. Total losses should be calculated using the following equation.

$$L_s = 100 \left(1 - \prod_i \left(1 - \frac{L_i}{100} \right) \right)$$

Where L_s is the total static losses in percent and L_i is the loss due to a specific mechanism.

4.2.1.3.2 Thermal Losses

The thermal losses L_t are calculated using the temperature coefficient γ of the solar modules that is supplied by the manufacturer. The temperature coefficient γ should be in units of % per degree Celsius and should be input as a negative.

$$L_t = \gamma(T_c - 25)$$

Cell temperature T_c is calculated on the Deno sensor as a function of the measured temperature and the plane of array irradiance.

$$T_c = a * I + b + T_m$$

4.2.1.3.3 Age Losses

The age derate factor should be given with units of percent per year old. The system age is calculated using the commercially operational day COD and the timestamp of the record, rounded to the lowest year.

$$L_a = Age * Age_{df}$$

Where L_a is the loss due to aging, Age is the age of the PV system, and Age_{df} is the age derate factor.

4.2.1.3.4 Other Losses

Energy models often contain other loss factors that have not yet been mentioned. These factors include shading, incident angle/reflection, soiling, and snow. Shading is not currently considered for the expected energy calculation. Shading is not static and therefore should not be included as a static loss.

Incident angle (IAM) losses are assumed to be identical for the array and the Deno as both are in plane of array and the Deno has similar reflective characteristics. It is assumed that the Deno and the array suffer from the same soiling and snow coverage. Times where the snow coverage of the array is different than that of the Deno can be reported as an environmental outage and handled accordingly.

4.2.1.4 PV Model

The DC power generated P_{dc} (kW) is calculated using the DC capacity P_{dc0} (kW) and the plane of array irradiance I (W/m²) that is recorded by the Deno sensor(s).

$$P_{dc} = \frac{I}{1000} P_{dc0} (1 - L)$$

The total losses L are calculated from the thermal, age, and static losses described in the previous section using the equation below.

$$L = 1 - \left(1 + \frac{L_t}{100}\right) \left(1 - \frac{L_a}{100}\right) \left(1 - \frac{L_s}{100}\right)$$

4.2.1.5 Inverter Model

The inverter efficiency curve is modeled with the following equation.

$$\eta = \frac{\eta_{nom}}{0.9637} \left(-0.0162 * \zeta - \frac{0.0059}{\zeta} + 0.9858 \right)$$

$$\zeta = \frac{P_{dc} * \eta_{nom}}{P_{ac0}}$$

Where η_{nom} is the nominal efficiency of the inverter and P_{ac0} is the AC nameplate of the inverter, both taken from the product literature. The inverter efficiency curve is then applied to the estimated DC power from the modules to determine the AC output power. Values are capped at the AC nameplate value of the system to simulate inverter clipping.

$$P_{ac} = \min (P_{dc}\eta, P_{ac0})$$

5. References

Dobos, A.; PVWatts Version 5 Manual. NREL/TP-6A20-62641. 2014.
IEC 61724:2017, Photovoltaic System Performance

PVSyst Physical Models Used

<http://files.pvsyst.com/help/index.html?models.htm>