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For a Sustainable Planet

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Solar Photovoltaic Systems Time-Series Simulation

Subinterval Distribution vs. Steady-State Assumption

This material is based on work supported by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office Agreement Number 34662.

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Objective:

Replace steady-state assumption of current models with a distribution function that has within each time step a maximum value, a minimum value, and a shape to the distribution.

Accomplishments:

- Derivation of distribution function and scalar integrals
- Comparison to high-resolution time-series data (1-minute data)
- Demonstration on an example 1.1-MW photovoltaic (PV) system in Washington, D.C.
- Commercialization in HOMER software

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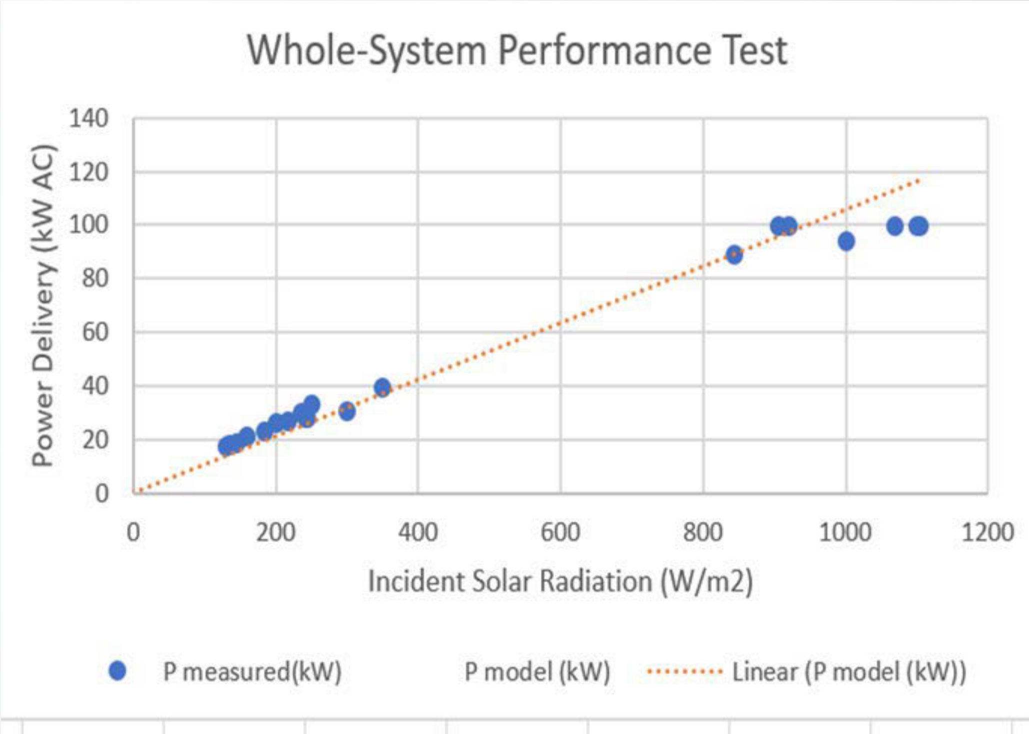
✓ Jal Desai, National Renewable Energy Laboratory

✓ Brian McDonald, HOMER Energy LLC

The Issue: Rapidly Changing Conditions



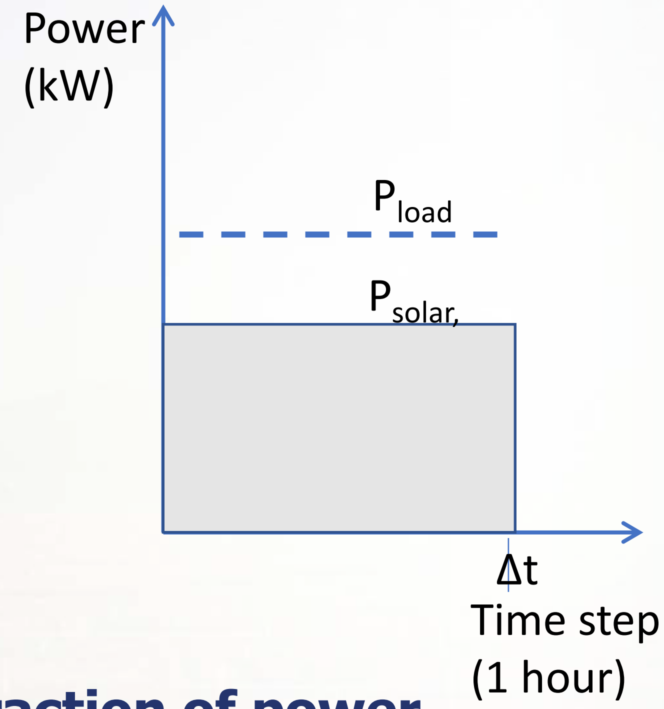
Photos by NREL

Hato Rey, Puerto Rico

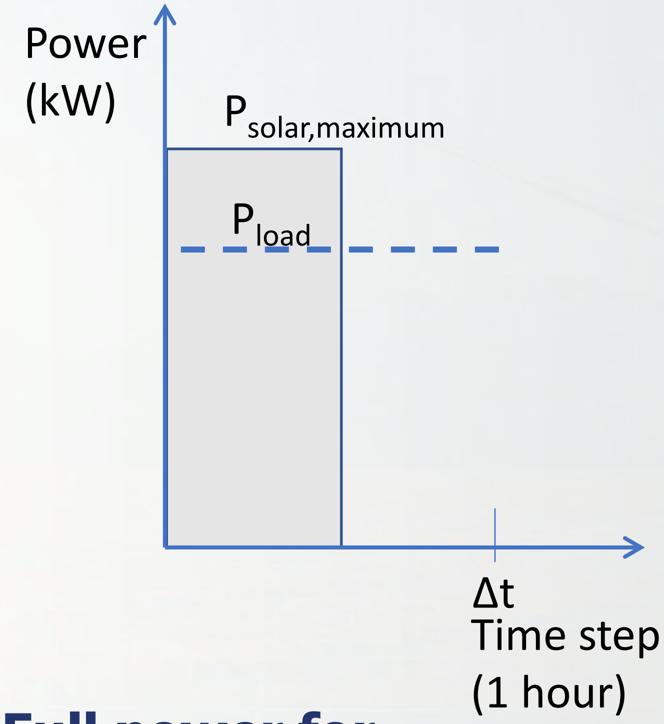
- 125-kW PV array
- 100-kW inverter
- Power recorded manually every 3 minutes for 1 hour
- Hourly average= 50.0 kW
- Maximum=99.5 kW
- Minimum=17.6 kW

Different Interpretations of Capacity Factor (CF)

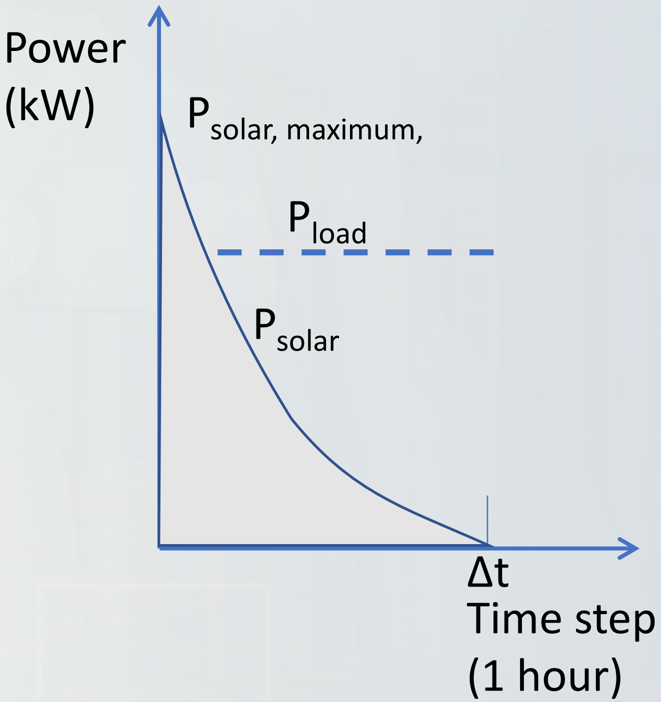
CF = actual energy in time-step/maximum energy in time step



Fraction of power for full time step



Full power for fraction of time step



Distribution of values over time step

Derivation of Distribution Function Form

- Cumulative distribution function:

$$P_{solar} = P_{\mathrm{solar,min}} + (P_{\mathrm{solar,max}} - P_{\mathrm{solar,min}}) * (1 - (t/T)^{n})$$

T is the time step duration; the index t is a percentage of the total time step duration without regard to the time-series order in which the values occur.

Derivation of Distribution Function Form

- **For the purposes of integration-by-parts, redefine the capacity factor to accommodate a nonzero $P_{solar,min}$.**

$$CF = \frac{(P_{solar,average} - P_{solar,min})}{(P_{solar,max} - P_{solar,min})}$$

$$P_{solar,min}T + (P_{solar,max} - P_{solar,min})T\,CF = P_{solar,average}T = \int_0^T P_{solar}\,dt$$

- **Dividing through by the time interval T gives**: $P_{solar,min} + (P_{solar,max} - P_{solar,min})\ CF = \int_0^T P_{solar,AC}\frac{dt}{T}$

- **Substitution of the equation for the distribution function into this equation gives**:

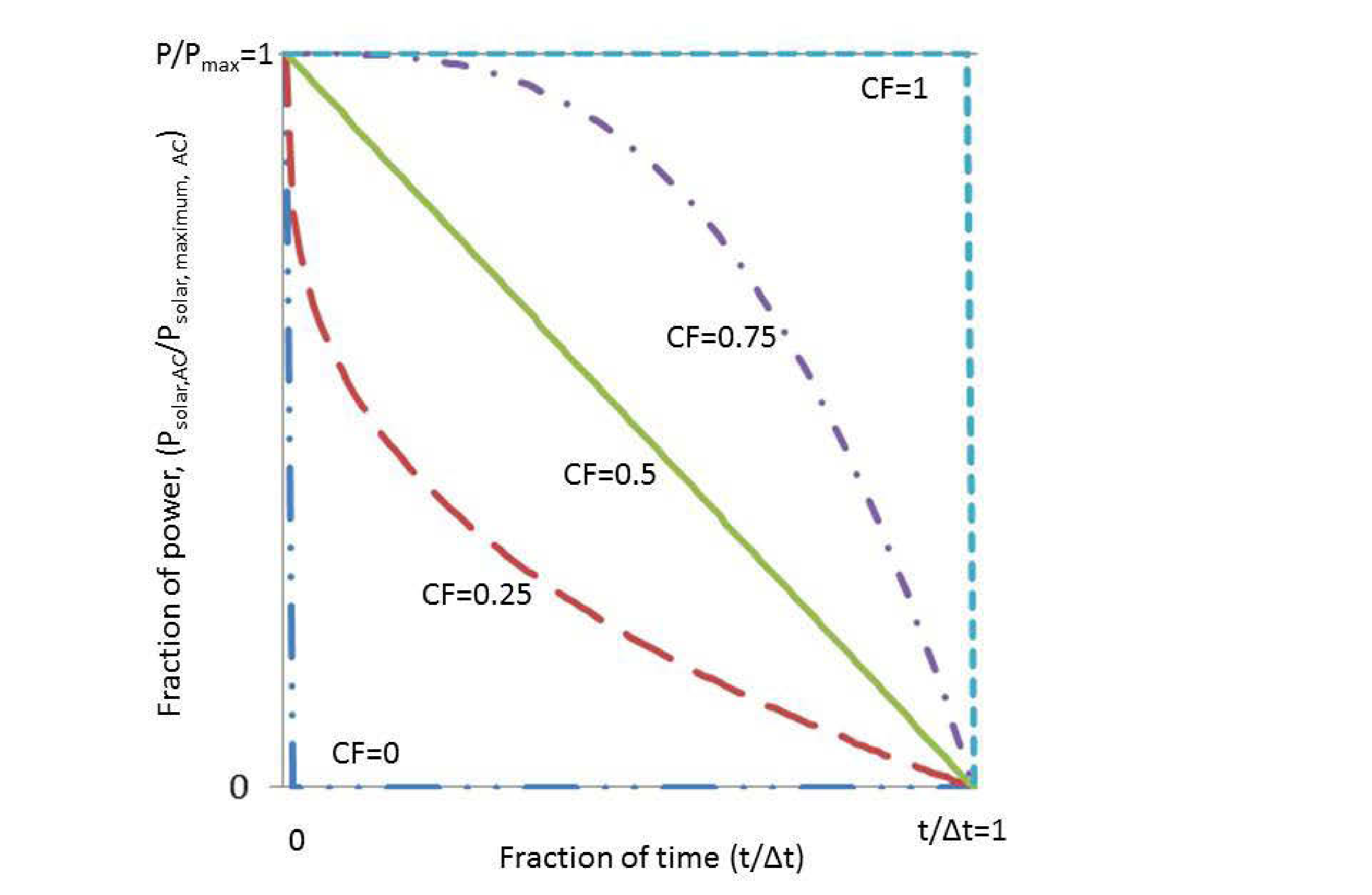
$$(P_{solar,max} - P_{solar,min})\ CF = \int_0^{\frac{t}{T}=1} (P_{solar,max} - P_{solar,min}) * (1 - (t/T)^n)\frac{dt}{T}$$

- **The integral is evaluated between the limits of t/T=0 and t/T=1. Evaluation of the integral gives**: $CF = \left[\frac{t}{T} - \frac{(\frac{t}{T})^{n+1}}{n+1} + \text{constant}\right]$

- **Evaluating the integral at its upper limits**: $CF = 1 - \frac{1}{n+1}$

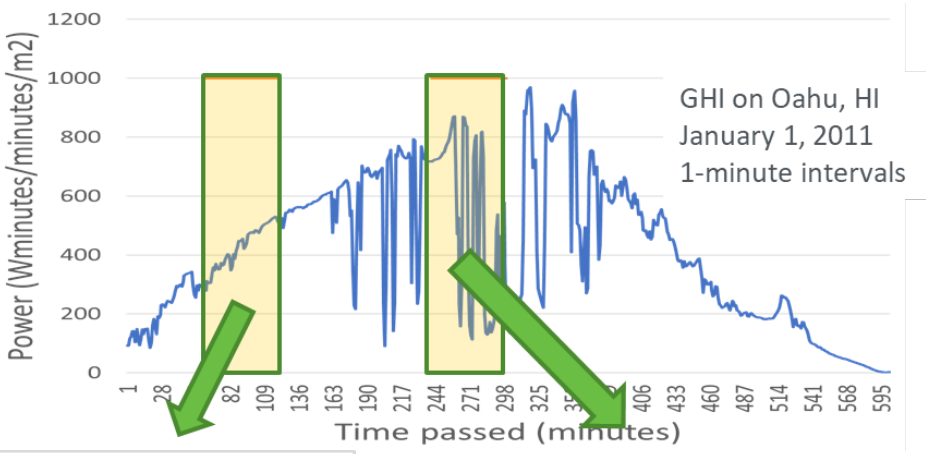
- **Solving for n, we find the expression of the value of n that satisfies the first law of thermodynamics**: $n = \frac{1}{1-CF} - 1 = \frac{CF}{1-CF}$

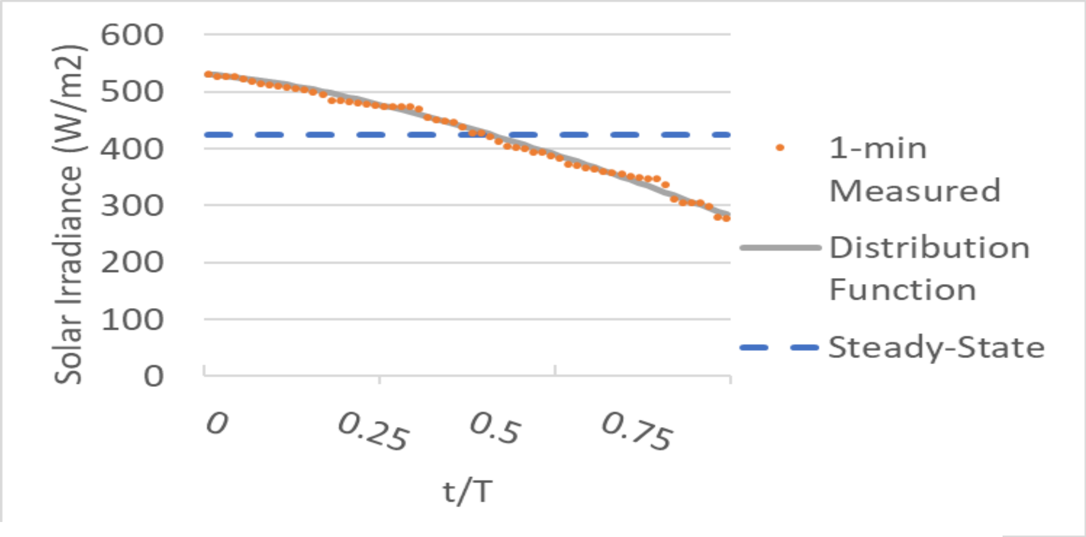
Form of Distribution Function



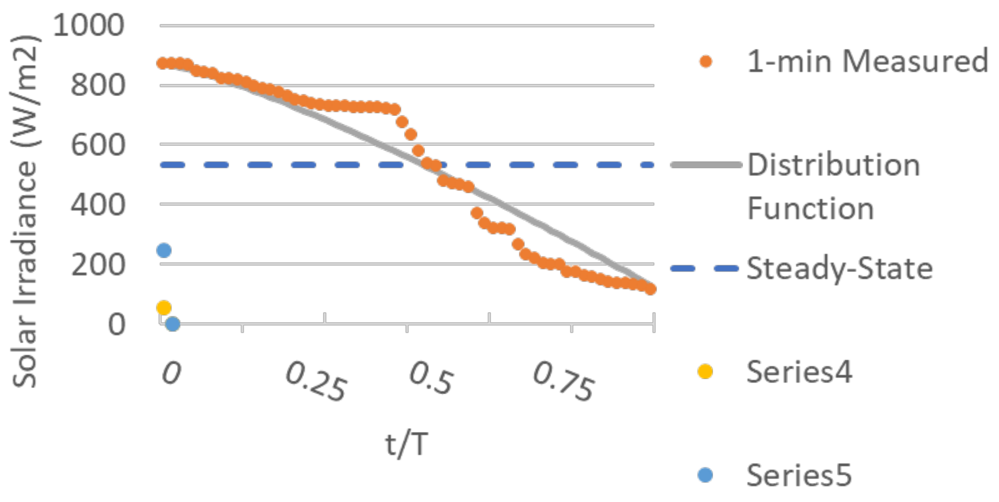
Subinterval distribution function for capacity factor: CF=0, 0.25, 0.5, 0.75, and 1.0.

Comparison to High-Resolution Time-Series Data (1 min)

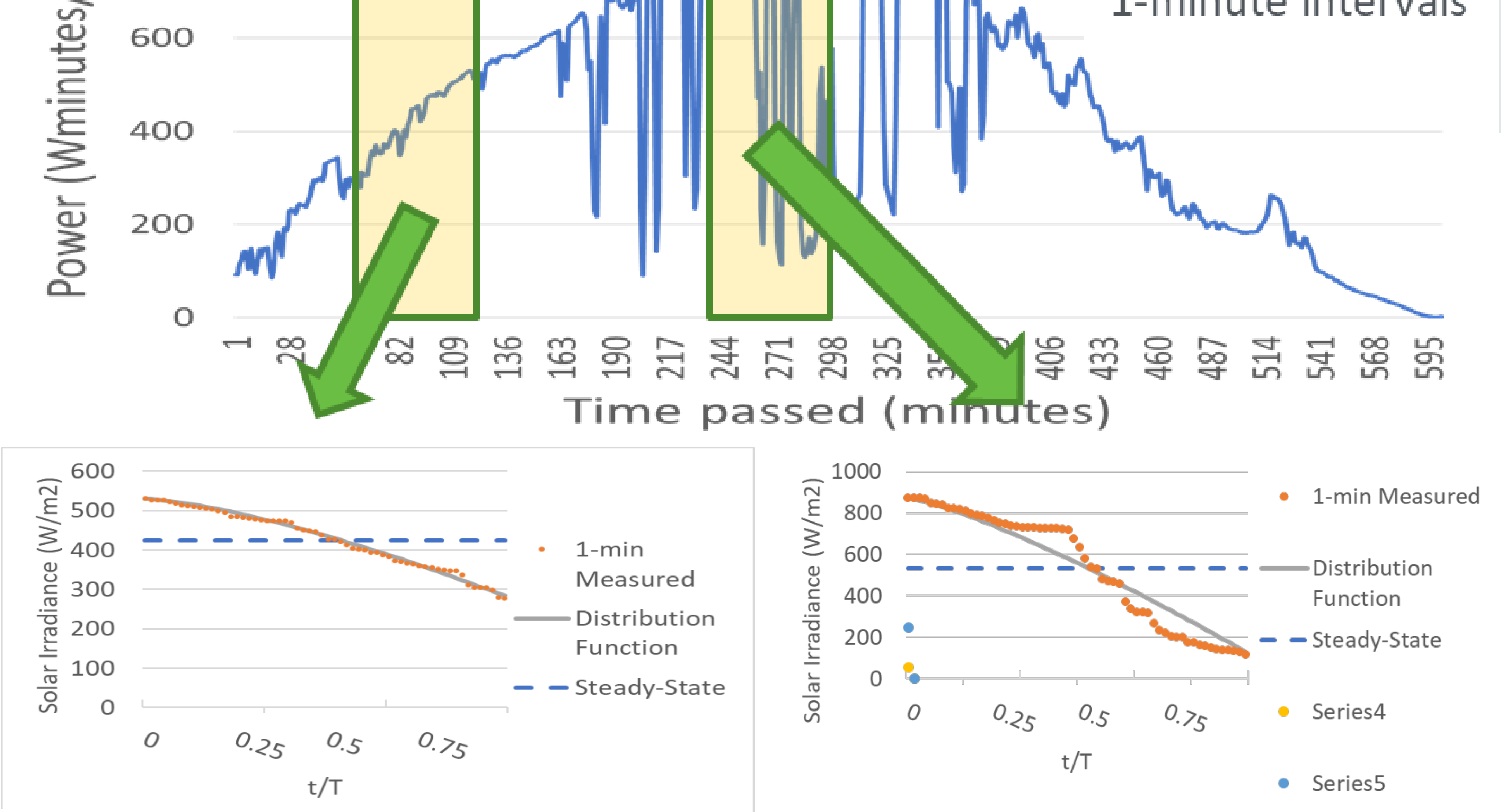




9:00 a.m.–10:00 a.m. 1/1/11
Unimodal distribution
RMSE error distribution = 1.3%; RMSE error steady-state = 15.2%.



11:00 a.m. –12:00 p.m. 1/1/11
Bimodal distribution
RMSE error distribution = 10.2%; RMSE error steady-state = 46.5%



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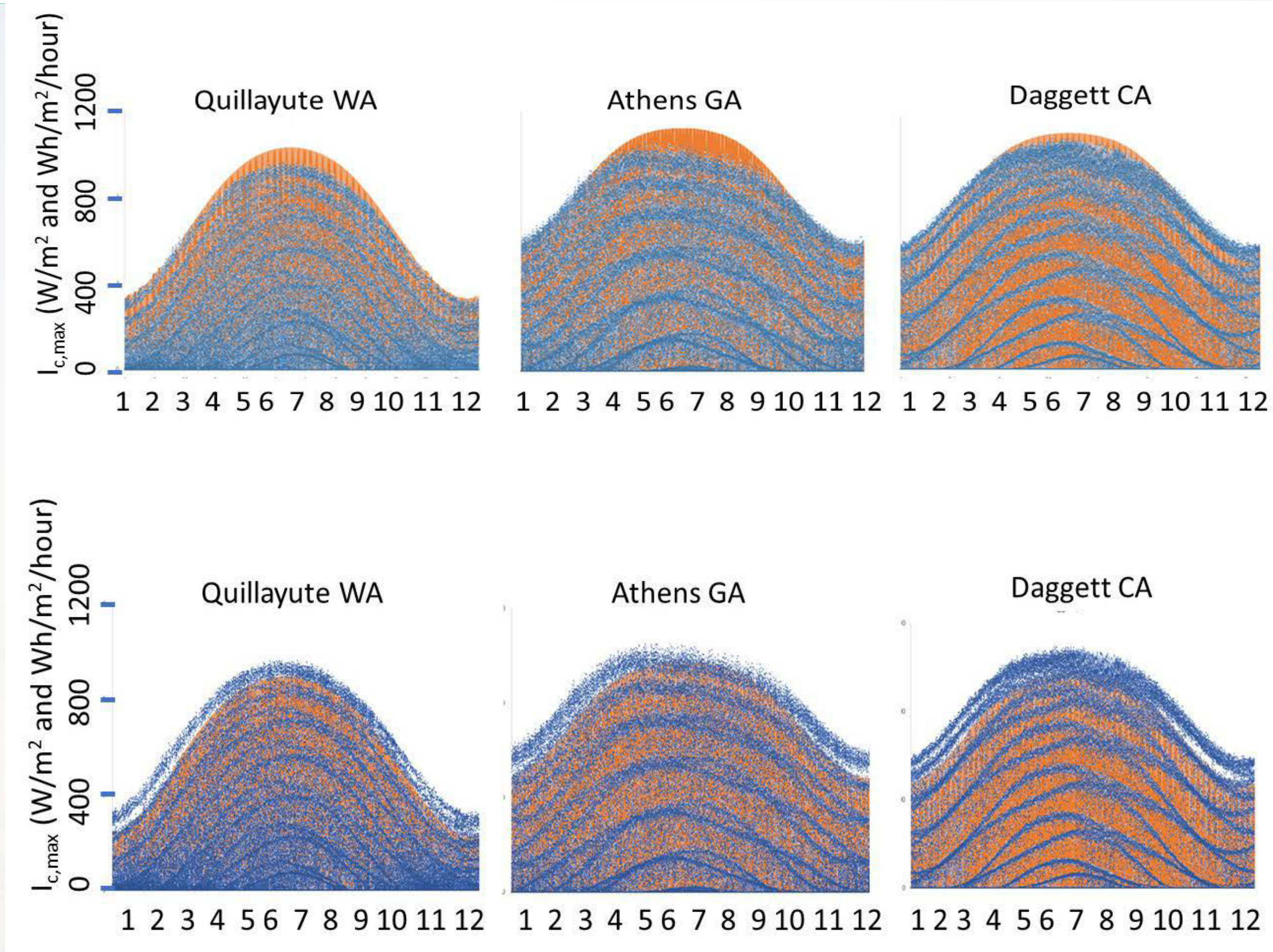
Ic,maximum from “Clear Sky Model” (Reno et al., 2012)



Meinel and Meinel clear-sky model

$I_{c,direct,normal,maximum}$ =1366*(0.76^(AM^0.618))

AM=MIN(38,1/SIN(α))

Daneshyar–Paltridge–Proctor (DPP) clear-sky-model

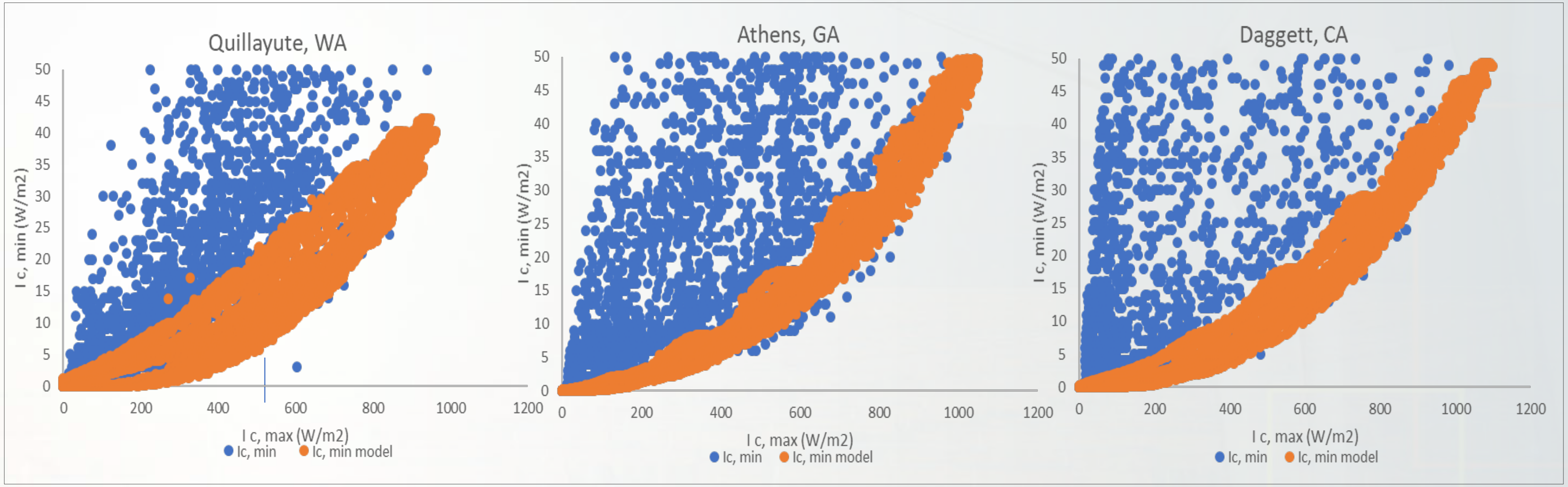
$I_{irect,normal,maximum}$ = 950.2*(1-EXP(-0.075*(α))

and

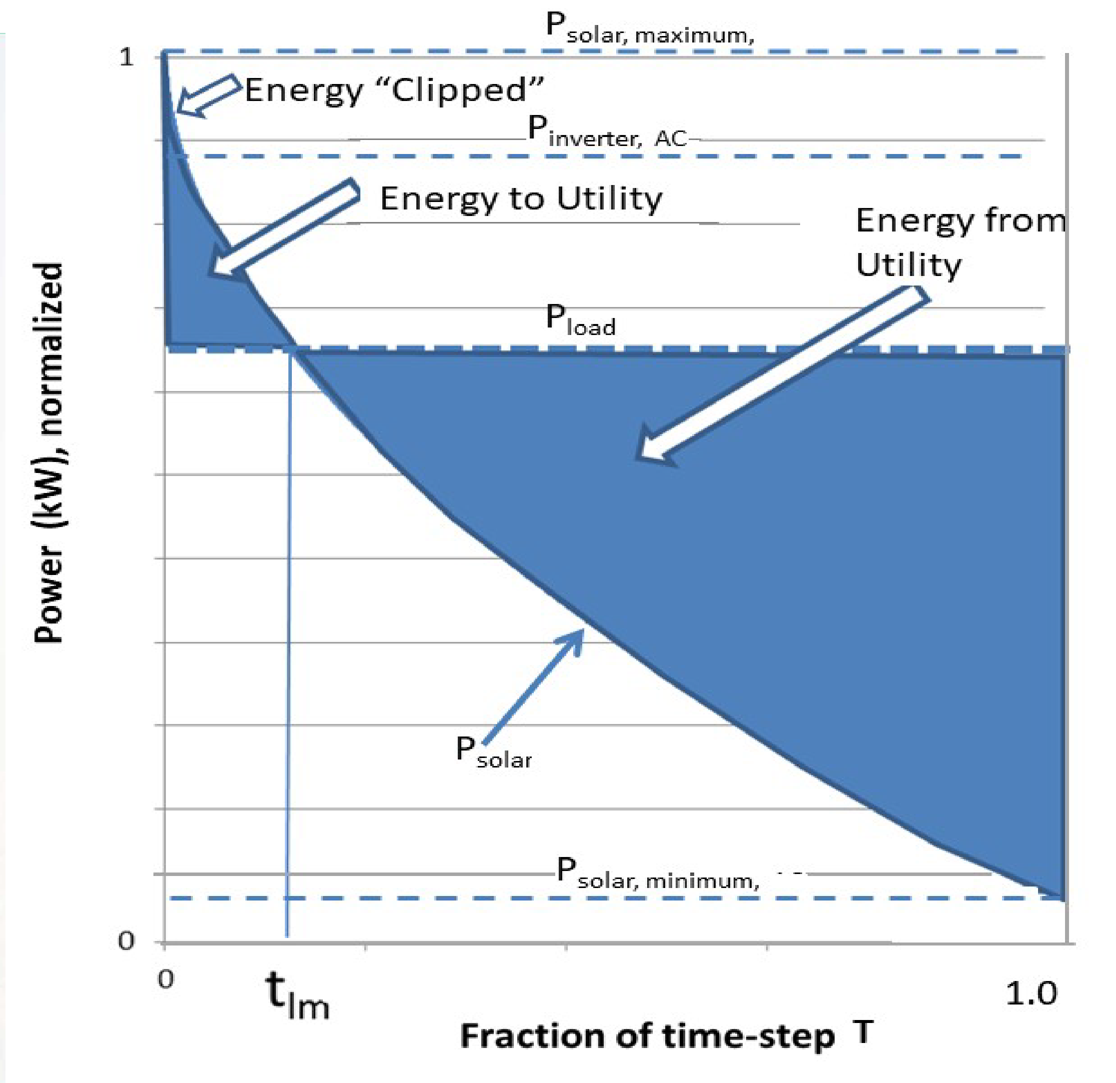
$I_{diffusel,maximum}$ = 14.29+21.04*(π/2-(90-α)*π/180))

Minimum Solar Resource

$$I_{c,minimum} = I_{c,max} * \left(\frac{f}{AM}\right); f = 0.045$$



Scalar Integrals of Energy Quantities within Time Step



Energy in excess of inverter capacity (kW, also called "clipped energy"), energy in excess of load (kW), or in excess of any other threshold, are calculated by integration (as areas under the curve).

The fraction of the time step when the power from the generator exceeds the load is t_{lm}

Integration by Parts for Any Threshold Value, L

Integration is performed by parts, from $0<t< t_{lm}$ and from $t_{lm} <t< 1.0$. The fraction t_{lm} is the fraction of the time step when P_{solar} exceeds the value L (the power load or any threshold to be evaluated).

$$L = P_{solar} = P_{solar,\min} + (P_{solar,max} - P_{solar,\min})\left(1 - \left(\frac{t_{lm}}{T}\right)^{n}\right)$$

$$\left(\frac{t_{lm}}{T}\right)^{n} = 1 - \frac{L - P_{solar,\min}}{(P_{solar,\max} - P_{solar,\min})}$$

$$n \ln \frac{t_{lm}}{T} = \ln\left(1 - \frac{L - P_{solar,\min}}{(P_{solar,\max} - P_{solar,\min})}\right)$$

t_{lm} is the fraction of the time step T when the power level P_{solar} exceeds the threshold value L.

$$t_{lm} = T e^{\left[\frac{\ln\left(1 - \frac{L - P_{solar,\min}}{(P_{solar,\max} - P_{solar,\min})}\right)}{n}\right]}$$

Scalar Integral Above Value of L: Energy to Utility

E_{tu} stands for "energy to utility."

$$E_{tu} = \int_0^{t_{lm}} (P_{solar} - L)dt$$

$$E_{tu} = \int_0^{t_{lm}} \left(\{P_{solar,min} + (P_{solar,max} - P_{solar,min}) \left(1 - \left(\frac{t}{T}\right)^n\right)\} - L \right) dt$$

$$E_{tu} = \int_0^{t_{lm}} \left(\{P_{solar,max} - (P_{solar,max} - P_{solar,min}) \left(\frac{t}{T}\right)^n\} - L \right) dt$$

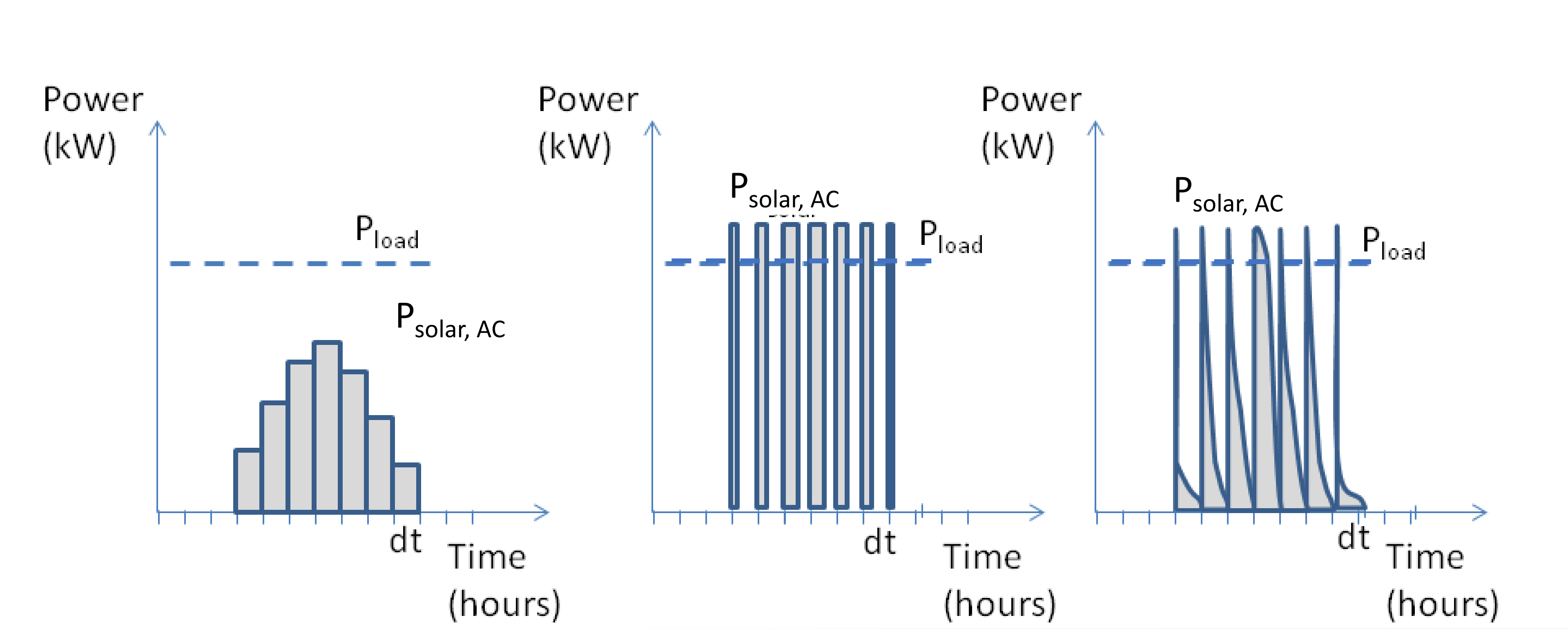
$$E_{tu} = \left[P_{solar,max} t - \frac{(P_{solar,max} - P_{solar,min}) t^{(n+1)}}{(n+1)T^n} - Lt + \text{constant} \right]_0^{t_{lm}}$$

$$E_{tu} = P_{solar,max} t_{lm} - \frac{(P_{solar,max} - P_{solar,min}) {t_{lm}}^{(n+1)}}{(n+1)T^n} - Lt_{lm}$$

Scalar Integral Below Value of L: Energy from Utility

- E_{fu} stands for "energy from utility."
- $E_{fu} = \int_{t_{lm}}^{T} (L - P_{solar})dt$
- $E_{fu} = \int_{t_{lm}}^{T} \left(L - P_{solar,min} - (P_{solar,max} - P_{solar,min})\left(1 - \left(\frac{t}{T}\right)^{n}\right)\right)dt$
- $E_{fu} = \int_{t_{lm}}^{T} \left((L - P_{solar,max}) + (P_{solar,max} - P_{solar,min}) \left(\frac{t}{T}\right)^{n} \right)dt$
- $E_{fu} = \left[(L - P_{solar,max})t + \frac{(P_{solar,max} - P_{solar,min})t^{(n+1)}}{(n+1)T^{n}} + \text{constant}\right]_{t_{lm}}^{T}$
- $E_{fu} = (L - P_{solar,max})T + \frac{(P_{solar,max} - P_{solar,min})T^{(n+1)}}{(n+1)T^{n}} - (L - P_{solar,max})t_{lm} - \frac{(P_{solar,max} - P_{solar,min}){t_{lm}}^{(n+1)}}{(n+1)T^{n}}$

Scalar Integrals Evaluated for Each Time Step in Time-Series Simulation



(a) Power level varies for fixed dt

(b) Fraction of dt varies for fixed power level

(c) Distribution based on kWh for the hour

Demonstration of Prototype Simulation (see MSExcel)

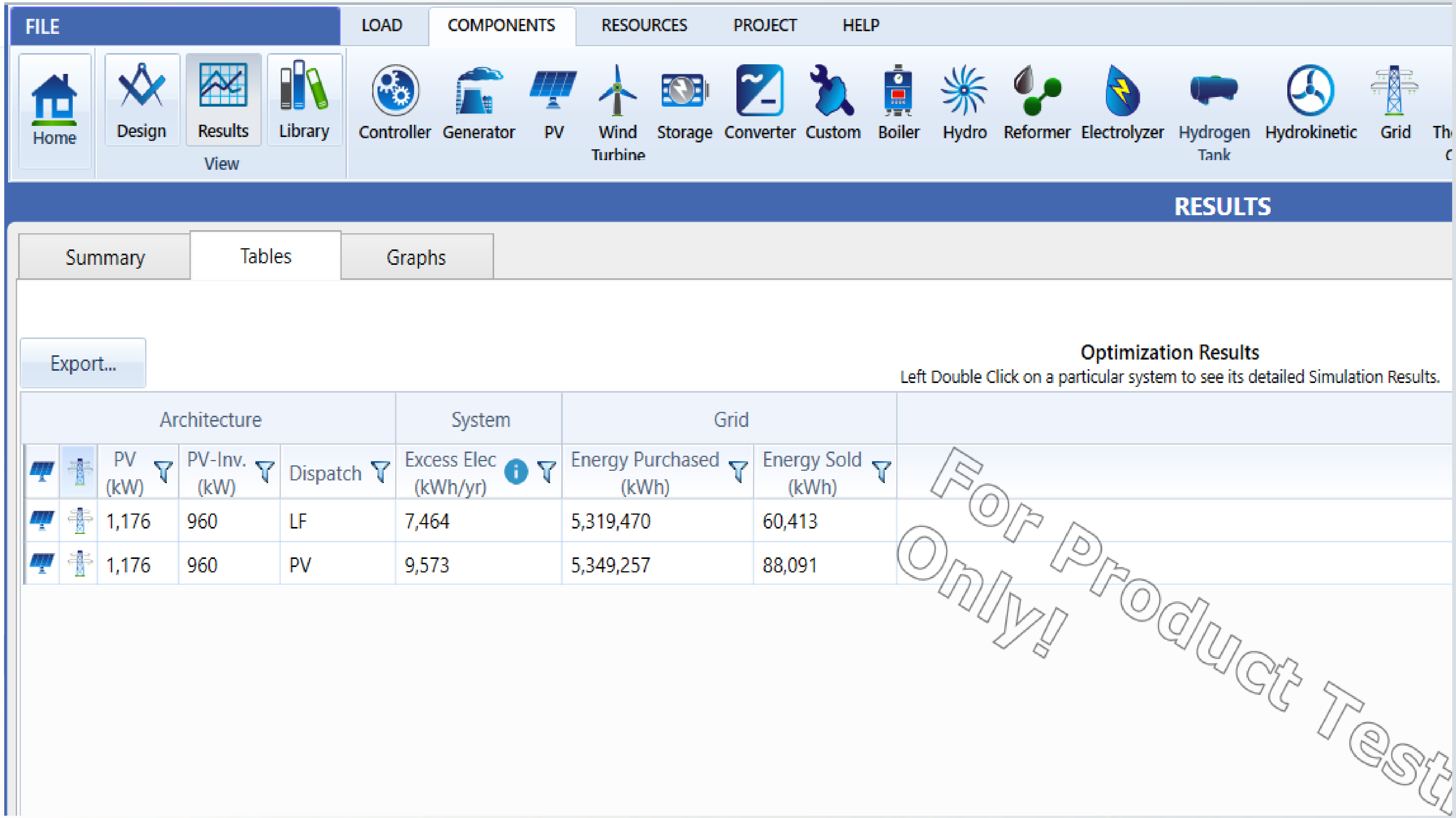
Rooftop PV system in Washington, D.C.:

- 1,176-kW PV
- 960-kW inverter
- 800-kW load.

Results	**OLD WAY: Steady-State**	**NEW WAY: Distribution Function**	**% Difference**
Total PV energy (kWh/year)	1,789,062	1,789,062	0.0%
PV energy “clipped" (kWh/year)	8,888	11,323	27.4%
PV energy to utility (kWh/year)	65,902	87,343	32.5%
PV energy used on-site (kWh/year)	1,714,272	1,690,396	-1.4%
Energy from utility (kWh/year)	5,293,728	5,317,604	0.5%

Commercialization in HOMER

Hybrid Optimization of Multiple Energy Resources (HOMER)



Architecture					System	Grid	
		PV (kW)	PV-Inv. (kW)	Dispatch	Excess Elec (kWh/yr)	Energy Purchased (kWh)	Energy Sold (kWh)
		1,176	960	LF	7,464	5,319,470	60,413
		1,176	960	PV	9,573	5,349,257	88,091

HOMER Results for Sample Problem

Rooftop PV system in Washington, D.C.:

- 1,176-kW PV
- 960-kW inverter
- 800-kW load.

Results	OLD HOMER: Steady-State	NEW HOMER: Distribution Function	% Difference
Total PV energy (kWh/year)	1,756,407	1,756,407	0.0%
PV energy “clipped" (kWh/year)	7,464	9,573	28.3%
PV energy to utility (kWh/year)	60,413	88,091	45.8%
PV energy Used on-site (kWh/year)	1,688,530	1,658,743	-1.8%
Energy from utility (kWh/year)	5,319,470	5,349,257	0.6%

Significance and Impact

- Same estimate of total DC generation potential
- Improved estimates of phenomenon of interest to grid integration:
  - Clipping by:
    - Limited inverter capacity
    - Transformer capacity
    - AC interconnection (line) capacity
    - Contractual/regulatory (curtailment)
  - Sell-back of power exported to utility
  - Battery systems:
    - Maximum charge rate
    - Total throughput (in and out within a time step).

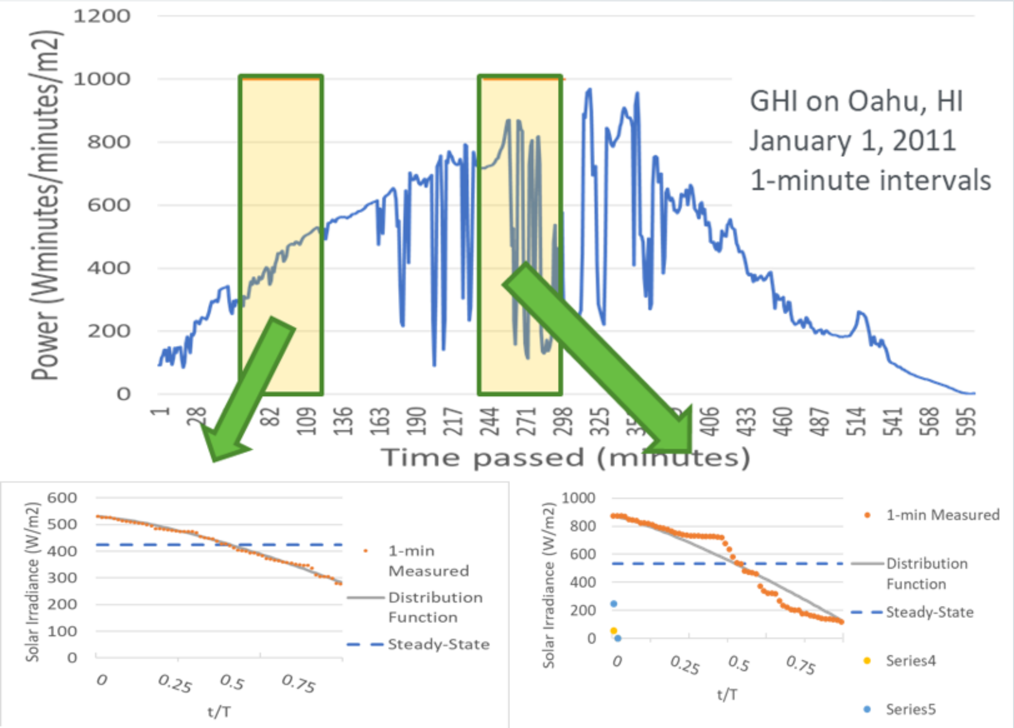
New Distribution Function Replaces Steady-State Assumption in Time-Series Simulation

Objective: Replace steady-state assumption of current models with a distribution function that has within each time step a maximum value, a minimum value, and a shape to the distribution.

Accomplishments include:

- **Derivation** of distribution function and scalar integrals
- **Validation** by comparison to 1-minute data
- **Demonstration** on an example 1.1-MW PV system in Washington, D.C.

1.1 MW PV system	Steady-State Simulation	Distribution Function Simulation	% difference
Total PV Energy (kWh/year)	1,664,249	1,664,249	0.0%
PV Energy "Clipped" (kWh/year)	6,293	30,085	378.1%
PV Energy Sell-back to Utility (kWh/year)	45,790	75,718	65.4%
PV Energy Used On-site (kWh/year)	1,612,167	1,558,446	-3.3%
Energy from Utility (kWh/year)	5,395,833	5,449,554	1.0%



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Bimodal distribution
RMSE error distribution = 10.2%; RMSE error steady-state = 46.5%

Significance and impact:
While providing the same estimate of DC generation, this improved approach improves estimates of phenomenon of interest to grid integration, such as inverter clipping and sell-back to the utility.

Future Work Includes:

- Validation of the method by comparison with actual system performance data
- Investigation of parametric and sensitivity analysis (for example, quantifying inverter clipping over a range of DC/AC ratios and climates; or studying the impacts of the distribution-function approach on optimal component sizing)
- Further investigation into the best selection of inputs such as $I_{\text{maximum direct}}$ and $I_{\text{maximum diffuse}}$
- Also representing other quantities as distributions within the time step, such as the site load, and using the superposition of two distribution functions to calculate energy used on-site versus exported (The current implementation assumes that steady-state load is constant over each time step.)
- Representing the inverter efficiency as a smooth and continuous function and including it in the calculation of the scalar integrals for energy quantities (The current implementation assumes that inverter efficiency is constant over each time step.)
- Commercialization of this distribution-function method in other software products used to model PV system performance.
- Consideration of the distribution-function method for other variable-output generators such as wind turbines.

Solar Photovoltaic Systems Time-Series Simulation

Subinterval Distribution vs. Steady-State Assumption

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