Evaluation of Irradiance Decomposition and Transposition Models at Locations Across the United States

Matthew Lave, Cliff Hansen, Andrew Pohl (Sandia)
Billy Hayes (First Solar)

SAND2014-15017 PE
PVSC 40, Denver, CO, 6/9/2014
Summary

• Estimations of POA irradiance are evaluated for tilt angles/orientations that are relevant to fixed tilt PV systems covering different climates in North America.

• Estimating plane of array (POA) irradiance often requires a sequence of models:
  — Decomposition: GHI to direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI)
  — Transposition: GHI, DNI and DHI to total irradiance in POA

• Sandia and First Solar evaluated numerous models, individually and in combination, to develop an understanding of model accuracies and general shortcomings.

http://www.kippzonen.com
The problem

• The number of choices for transposition and decomposition models generates confusion and introduces risk in deployment of PV systems.

• For example, PVsyst provides two options which provide different estimates of POA irradiance (and consequently different estimates of AC energy)
Differences in energy estimates and associated risks

- The modeling options available in PVsyst can produce energy estimates that are upwards of 1% different on an annual basis.
- Depending on which estimate is more accurate the risk can be borne by either stakeholder:

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Risk of underestimate</th>
<th>Risk of overestimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developer and/or EPC</td>
<td>Lose bid or undercapitalize on sale.</td>
<td>Fail performance guarantees.</td>
</tr>
<tr>
<td>Owner and/or Financer</td>
<td>May not be able to capitalize on additional energy generation (contract specific).</td>
<td>Financial return adversely affected. (Bear risk if a PR guarantee)</td>
</tr>
</tbody>
</table>

**Transposition risk is transferred if a PR guarantee**

**Annual difference between PVsyst outputs for different transposition model selections**

- Insolation
- AC Energy

Generic system design applied for all simulations: 1.25 DC/AC; 0.56 GCR; Fixed 25° Tilt; 0° Azimuth
Modeling Process and Models Considered

- Measured GHI
- Is Measured DHI Available?
  - NO
  - YES

**Diffuse Decomposition Models**
- Orgill and Hollands
- Erbs
- Boland
- Reindl 1
- Reindl 2
- Reindl 3
- Reindl 1a
- Reindl 2a
- Reindl 3a
- DISC
- DIRINT
- Posadillo

**Measured GHI + Modeled DHI**

**Transposition Models**
- Isotropic
- Sandia
- Hay/Davies
- Perez

**Modeled POA**

*Models in red denote options in PVSyst.*
All models of either type are:

1. (stationary) empirical (piecewise) correlations;
2. between measured DHI/DNI or POA and input variables;
3. using some historical hourly data set.

Several previous evaluations have found that models perform similarly at shorter time intervals.
Data Used in This Evaluation

- Twelve locations representing a range of climates
- GHI, POA for a southward tilted instrument
  - CMP-11, CM22, Eppley PSP, some Licor-200
  - Multiple instruments at several locations
  - DHI (RSR) at several locations (single instrument)

<table>
<thead>
<tr>
<th>Station</th>
<th>Location</th>
<th>Elevation [m]</th>
<th>Climate Zone</th>
<th>Measured Data</th>
<th>Time Period</th>
<th>SurfTilt</th>
<th>SurfAz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Southeast CA</td>
<td>120</td>
<td>Arid Desert Hot (BWh)</td>
<td>GHI, POA</td>
<td>12/2009 - 8/2013</td>
<td>25°</td>
<td>180°</td>
</tr>
<tr>
<td>2</td>
<td>Northeast NM</td>
<td>100</td>
<td>Arid Steppe Cold (BSk)</td>
<td>GHI, POA</td>
<td>12/2010 - 8/2013</td>
<td>25°</td>
<td>180°</td>
</tr>
<tr>
<td>3</td>
<td>East MI</td>
<td>188</td>
<td>Snow; Fully humid; Warm summer (Dfb)</td>
<td>GHI, DHI, POA</td>
<td>2/2012 - 7/2013</td>
<td>25°</td>
<td>180°</td>
</tr>
<tr>
<td>4</td>
<td>East MI</td>
<td>181</td>
<td>Dfb</td>
<td>GHI, DHI, POA</td>
<td>2/2012 - 7/2013</td>
<td>25°</td>
<td>180°</td>
</tr>
<tr>
<td>5</td>
<td>East MI</td>
<td>193</td>
<td>Dfb</td>
<td>GHI, POA</td>
<td>10/2010 - 9/2013</td>
<td>25°</td>
<td>180°</td>
</tr>
<tr>
<td>6</td>
<td>Southern NV</td>
<td>572</td>
<td>BWh</td>
<td>GHI, POA</td>
<td>1/2011 - 12/2012</td>
<td>25°</td>
<td>180°</td>
</tr>
<tr>
<td>7</td>
<td>Southeast AL</td>
<td>97</td>
<td>Warm temperate; Fully humid; Hot summer (Cfa)</td>
<td>GHI, POA</td>
<td>8/2013 - 11/2013</td>
<td>26°</td>
<td>180°</td>
</tr>
<tr>
<td>8</td>
<td>Central AL</td>
<td>226</td>
<td>Cfa</td>
<td>GHI, POA</td>
<td>7/2013 - 11/2013</td>
<td>40°</td>
<td>180°</td>
</tr>
<tr>
<td>9</td>
<td>Coastal MS</td>
<td>6</td>
<td>Cfa</td>
<td>GHI, POA</td>
<td>2/2013 - 11/2013</td>
<td>15°</td>
<td>180°</td>
</tr>
<tr>
<td>10</td>
<td>Central CO</td>
<td>1829</td>
<td>BSk</td>
<td>GHI, DHI, POA</td>
<td>1/2013 - 12/2013</td>
<td>40°</td>
<td>180°</td>
</tr>
<tr>
<td>11</td>
<td>Central CA</td>
<td>200</td>
<td>Warm temperate; dry, hot summer (CSa)</td>
<td>GHI, DHI</td>
<td>1/2013 - 12/2013</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>12</td>
<td>Central NM</td>
<td>1657</td>
<td>BSk</td>
<td>GHI, GHI, POA</td>
<td>1/2011 – 12/2011</td>
<td>35°</td>
<td>180°</td>
</tr>
</tbody>
</table>

Stations in red allowed for independent testing of diffuse decomposition and transposition models.
Diffuse Decompositions
Decomposition Models: How they work

- **“simple” decomposition models**
  - diffuse fraction a function of clearness index

- **“complex” decomposition models**
  - add other variables attempting to better model variation in diffuse fraction

**GHI -> DHI**

(kt -> DF)

- measured diffuse fraction versus clearness index

Plotted for case when:
- \( \text{SunEl} = 45^\circ \)
- \( \text{AmbT} = 25^\circ \text{C} \)
- \( \text{RH} = 0.5 \)
- \( \text{MF} = 0.2 \)
Findings: Decomposition Models

- Examined hourly data
- Two annual difference metrics (compare modeled vs. measured):
  - RMSD: relates to hourly deviation
  - MBD: relates to annual energy
- DIRINT had lowest RMSD and MBD at all locations, but
- Not significantly less than other models
  - Simple models had similar performance
- Deviation in decomposition model depends on location

Inputs: GHI, kt
        GHI, kt, SunEl
        GHI, kt, SunEl, AmbT, RH
        GHI, kt, SunEl, MF
**Breaking Down the Differences: Decomposition RMSDs**

- For simple models (e.g., Erbs), any point above model curve means DHI was underestimated; any point below means DHI was overestimated.
  - RMSD describes spread of data around the model curve
- DIRINT is a slight improvement over Erbs
  - Lower RMSD, but still shows similar patterns (e.g., gradient from bottom left to top right).
Breaking Down the Differences: Decomposition MBDs

- Climate Plays an important role in annual errors (MBDs)
  - East MI: cloudy days are common
    - more points are above the Erbs model, leading Erbs to have a negative MBD
  - Central NM: clear days are common
    - Clustering of clear-sky values ($kt=0.8$, $DF=0.1$) below Erbs model that contribute to positive MBD
Transposition Models: How they work

GHI +DHI -> POA

- POA has three components:
  \[ POA = POA_{direct} + POA_{diff, refl} + POA_{diff, sky} \]
  - \( POA_{direct} \) a function of GHI, DHI, and angle of incidence
    - Same for each model
  - \( POA_{diff, refl} \) a function of GHI, tilt, and ground albedo
    - All models except for Sandia use albedo = 0.2
    - Sandia model uses empirical albedo derived for central NM
  - \( POA_{diff, sky} \) varies from model to model
    - Isotropic, Sandia: sky diffuse only function of amount of sky seen
    - Hay/Davies, Perez: more diffuse irradiance in circumsolar region
Findings: Transposition Models

• Hay/Davies and Perez show lower RMSD than other models; similar to each other.

• Systematic difference in MAD: Perez > Hay/Davies
  — E.g., Hay/Davies MBD -1% at Stn. 3, while Perez +1%

• Little dependence on location
  Except for Sandia model, which was calibrated at Stn. 12
Isotropic model has large negative errors during clear-sky conditions (kt≈0.7) and low angles of incidence (AOI<40°), since it doesn’t account for additional diffuse in the circumsolar region.

Sandia model has similar behavior, but generally more positive values due to enhanced albedo.

Hay/Davies and Perez also have negative values in clear sky, low AOI conditions, but effect is smaller.

Colors and numbers in plots indicated contribution to MBD; if all boxes were summed, the result would be the rMBD.
Combined Models:
Transposition Models with Diffuse Models
Findings: Combined Models

- Focused combined model evaluation on 2 decomposition and 2 transposition models
  - Decomposition: DIRINT (lowest deviation) and Erbs (default in PVsyst)
  - Transposition: Hay/Davies and Perez (best performing and both options in PVsyst)
- Combined model POA deviation is NOT the sum of deviation from individual models
  - Positive errors in DHI from decomposition models lead to negative errors in DNI
    - This may lead to underestimating POA
    - But this can also be offset by positive errors in the transposition models
- RMSD depends more on location than model combination
Modeled vs. Measured DHI

- Combined models tend to have higher POA estimates than transposition models with measured DHI
  - Large negative errors in decomposition models significantly increased MBD / POA annual energy
  - Small to moderate positive errors in decomposition models had little effect on MBD / POA annual energy

<table>
<thead>
<tr>
<th>rMBE in DHI estimates</th>
<th>Erbs</th>
<th>DIRINT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stn. 3</td>
<td>-4.3%</td>
<td>-4.2%</td>
</tr>
<tr>
<td>Stn. 4</td>
<td>-5.0%</td>
<td>-4.7%</td>
</tr>
<tr>
<td>Stn. 10</td>
<td>0.7%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Stn. 12</td>
<td>2.4%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

**rMBE in POA estimates**

![Graph showing rMBE in POA estimates for different stations.]

© Copyright 2013, First Solar, Inc.
Addressing uncertainty

- Biases can be present in measurements, making it challenging to determine which model had the smallest annual bias error.
- Multiple sensors can be used to reduce the effect of measurement bias.
Distributions of Discrepancies

- Distributions of annual relative mean bias differences (discrepancy) were computed for all combinations of models.
- Results highlight a +/- 1% spread in discrepancy which represents the effect of sensor biases (in both GHI and POA).
- Bias discrepancies suggest that the Hay transposition model has a lower relative error compared to Perez when using modeled DHI as input.
Findings/Summary

• Diffuse decomposition model performance varies based on climate
  — In predominantly clear or cloudy climates, models may over or under estimate the amount of diffuse
  — Annual errors range from rMBD of ~-10% to +10% (of GHI) at locations studied.
  — Hourly errors in DHI are large (>10% rRMSD) at all locations

• Transposition model performance does not seem to vary much with climate
  — Transposition model rMBD ~-4% (isotropic) to ~+1% (Perez)
  — rRMSD (% of POA) <10%; smaller than decomposition model rRMSDs

• Combined models typically overestimated POA
  — Most sever for Perez transposition model where POA was already high
  — Hay/Davies transposition + modeled DHI found to have rMBD closer to zero than Perez transposition
Further Work Needed

- Improve decomposition and transposition models
  - Decomposition models which account for local climate (amount of clear-sky hours)
  - Transposition models which perform better during clear-skies and low AOIs
  - Combined models with low RMSD and MBDs.

- Evaluate transposition models for tracking systems (which experience more instances of low AOI).

- Validation at more locations to further derive the impact of climate, AOI, tilt angle, etc.

- Determine impact of high DC/AC ratios. Do clear-sky errors become less important due to clipping?