The Impact of Solar Radiation on the Heating and Cooling of Buildings

Lucas Witmer
June 25, 2014
LWitmer@psu.edu

Reference: Brownson 2013
Acknowledgements

• Dr. Jeffrey R.S. Brownson – Dissertation Advisor
• Dissertation Committee including Dr. Seth Blumsack, Dr. Mort Webster, and Dr. Stephen Treado
• Research collaborators on projects that have led to this work including Mr. Donghun Kim and Mr. Vivek Srikrishnan
• The Pennsylvania State University, the College of Earth and Mineral Sciences, and the John and Willie Leone Department of Energy and Mineral Engineering.
• The Earth and Mineral Sciences Energy Institute
• This research has been supported by the Consortium for Building Energy Innovation (formerly the Energy Efficient Buildings Hub), an energy innovation hub sponsored by the U.S. Department of Energy under Award Number DE-EE0004261.
This presentation discusses the use of solar energy data for buildings.

Modeling Shade on Building Surfaces

Quality of Data: impact on Real-time controls

Conditional Probability Distributions and Calculating DNI
Buildings comprise a significant portion of total energy use, of which the largest portion is HVAC.

- Buildings: 40%
- Industrial: 32%
- Transportation: 28%
- Residential: 22%
- Commercial minus HVAC: 9.0%
- Commercial Heat: 6.7%
- Commercial Cooling: 1.5%
- Commercial Ventilation: 1.2%

The Sun, a primary driver of HVAC loads, has a geometric relationship with any surface.
Solar irradiance is comprised of beam and diffuse components.
Paths to Enlightenment: Ways to calculate irradiation on a tilted surface

\[
k_t = \frac{I_{\text{meas}}}{I_0(\text{calc'd})} \quad \frac{I_d}{I} = f(k_t) \quad I_b = I - I_d
\]

Integrate data.
Check instrument error.

Error = ±5% → ±50 W/m²

Variable Error: Long Tail Distr. (Non-Gaussian)

Calculate AM0 Irradiation and clearness index

HDKR, Perez model

Error = ±14 W/m²

Apply Anisotropic Diffuse Sky/Ground Model and Sum

calculated POA irradiation

calculated horizontal components

e.g. \( k_T \)

empirical correlations for DHI/GHI

\[
I_b, I_d, I_{b,t}, I_{d,t}, I_{g,t}
\]

\[
I_b, I_d
\]

measured horizontal components

\[
I_{b,n}, I_{d,n}
\]

measured DNI irradiation

Error = ±5% → ±50 W/m² vs. Observed(top) = ±61 W/m²

Compared to satellite derived vertical surface estimation error of ±20% → ±200 W/m²


References: Zelenka 1999
The empirical correlation models for separating beam and diffuse from total were never intended for sub-hourly data.
Large fractions of opaque wall surfaces on buildings encounter shade.

**Building 661 - Roof Shading - Hours of Daily Direct Solar Irradiation**

Jun 21 May/Jul Apr/Aug Mar/Sep Feb/Oct Jan/Nov Dec 21

![Diagram of Building 661 with shading analysis](image)

**Hours of Direct Irradiation**

- 7+
- 6
- 5
- 4
- 3
- 2
- 1
- 0

Building 101 Shading
Vertical Surface Analysis - December 21

![Diagram of Building 101 with shading analysis](image)
Contributions

1. Accurate shade information has value in building energy modeling and management.
2. Thermal comfort ranges can be violated when advanced controls are informed by poor quality irradiation data.
3. The usefulness of on-site irradiance data is increased with analyses of probability distributions on multiple surfaces.
Methods

• Transient System Simulation Tool (TRNSYS) with TRNSHD and TRNSYS3D plugin for SketchUp
• Data analysis in MATLAB and R
• Irradiance measurements in Philadelphia, PA
• Simulation of building energy controls
• Exploratory data analysis with irradiance measurements in Golden, CO
Validating the shade tracking method of TRNSHD in TRNSYS requires five cases:

- **Case 1**: Opaque Wall Full Sun
- **Case 2**: Opaque Wall Shaded
- **Case 3**: Opaque Wall Shaded Manually
- **Case 4**: Wall with Window Full Sun
- **Case 5**: Wall with Window Shaded
Implementation of a shade fraction for opaque building surfaces in TRNSYS requires manual modification.

1. Intercepts surface irradiation
2. Scales as specified
3. Passes to Building
Results for Philadelphia show that TRNSHD in TRNSYS does not handle shade fractions for opaque surfaces.
Sensitivity of energy load to shade fraction for two typical wall types in Philadelphia shows considerable impact of shade (#1)

Light-weight wall construction

Heavy-weight wall construction
Methods

• Transient System Simulation Tool (TRNSYS) with TRNSHD and TRNSYS3D plugin for SketchUp
• Data analysis in MATLAB and R
• Irradiance measurements in Philadelphia, PA
• Simulation of building energy controls
• Exploratory data analysis with irradiance measurements in Golden, CO
A case study building in Philadelphia is instrumented with three Pyranometers on exterior walls to measure incident irradiation. The building is oriented six degrees West of North.
The impact of exterior shading objects is observed
Modeled vs Measured Irradiance using Hourly Weather Analytics GHI for Philadelphia
Exterior shading objects are modeled, creating a filter to match the onsite vertical surface measurements.

3 “Sensors” with Aperture of 0.01m²
No Shade Filter
Shade Filtered

Winter Modeled Irrad [W/m²] vs. Measured Irrad [W/m²]
North 90° Tilt

Winter Modeled Irrad [W/m²] vs. Measured Irrad [W/m²]
East 90° Tilt

Winter Modeled Irrad [W/m²] vs. Measured Irrad [W/m²]
West 90° Tilt

Spring Modeled Irrad [W/m²] vs. Measured Irrad [W/m²]
North 90° Tilt

Spring Modeled Irrad [W/m²] vs. Measured Irrad [W/m²]
East 90° Tilt

Spring Modeled Irrad [W/m²] vs. Measured Irrad [W/m²]
West 90° Tilt

Summer Modeled Irrad [W/m²] vs. Measured Irrad [W/m²]
North 90° Tilt

Summer Modeled Irrad [W/m²] vs. Measured Irrad [W/m²]
East 90° Tilt

Summer Modeled Irrad [W/m²] vs. Measured Irrad [W/m²]
West 90° Tilt

Fall Modeled Irrad [W/m²] vs. Measured Irrad [W/m²]
North 90° Tilt

Fall Modeled Irrad [W/m²] vs. Measured Irrad [W/m²]
East 90° Tilt

Fall Modeled Irrad [W/m²] vs. Measured Irrad [W/m²]
West 90° Tilt
The shade filter reduces the RMSE of the data set by an average of 23 W/m².

<table>
<thead>
<tr>
<th>Surface</th>
<th>West</th>
<th>North</th>
<th>East</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Before Shade Filter</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td>102</td>
<td>22</td>
<td>120</td>
</tr>
<tr>
<td>Spring</td>
<td>140</td>
<td>51</td>
<td>135</td>
</tr>
<tr>
<td>Summer</td>
<td>135</td>
<td>68</td>
<td>108</td>
</tr>
<tr>
<td>Fall</td>
<td>113</td>
<td>31</td>
<td>105</td>
</tr>
<tr>
<td><strong>After Shade Filter</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td>88</td>
<td>18</td>
<td>47</td>
</tr>
<tr>
<td>Spring</td>
<td>116</td>
<td>28</td>
<td>81</td>
</tr>
<tr>
<td>Summer</td>
<td>131</td>
<td>40</td>
<td>101</td>
</tr>
<tr>
<td>Fall</td>
<td>103</td>
<td>26</td>
<td>74</td>
</tr>
</tbody>
</table>
Methods

• Transient System Simulation Tool (TRNSYS) with TRNSHD and TRNSYS3D plugin for SketchUp
• Data analysis in MATLAB and R
• Irradiance measurements in Philadelphia, PA
• Simulation of building energy controls
• Exploratory data analysis with irradiance measurements in Golden, CO
With the filtered data, we now have an “apples to apples” comparison for an HVAC Controls Experiment.
The solar overestimation case of July 8, 2013 shows increased energy consumption with no comfort violation.
The solar underestimation case of July 11, 2013 shows reduced energy consumption with a comfort violation.
Total comfort violations for the month of July amount to 39 Kh while the differences in energy consumption and peak power are negligible (#2)

<table>
<thead>
<tr>
<th></th>
<th>Energy consumption [kWh/day]</th>
<th>Peak Power [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>rMPC</td>
<td>628.63</td>
<td>59.96</td>
</tr>
<tr>
<td>mMPC</td>
<td>627.05</td>
<td>59.62</td>
</tr>
</tbody>
</table>

Histogram of the Maximum Comfort Violation for each Day in July

Histogram of the Cumulative Comfort Violation for each Day in July
Methods

• Transient System Simulation Tool (TRNSYS) with TRNSHD and TRNSYS3D plugin for SketchUp
• Data analysis in MATLAB and R
• Irradiance measurements in Philadelphia, PA
• Simulation of building energy controls
• Exploratory data analysis with irradiance measurements in Golden, CO
Multi-pyranometer array: a low cost method for capturing local irradiance at high fidelity

Maxwell et al., 1986

Maxwell et al., 1999

$1k - $5k for an MPA

$10k - $50k for pyrheliometer
The conditional probability of some irradiance level given the time of day and year is useful information for a control system and for the estimation of DNI.
Hour of the Day:

4  8  12  16  20

Spring East 90°

Conditional Probability

0.0  0.2  0.4  0.6

Irradiance [W/m²]

50  250  450  650  850  1100
The probability distributions enable the estimation of DNI with a multi-pyranometer array and an ANN (#3)
Future Work

• Application of shade mapping on opaque surfaces to building energy modeling software tools
• Comparison of onsite solar irradiance measurements and offsite satellite derived estimates in an actual building with implemented MPC controller
• Implementation of probability distribution of irradiance levels in MPC formulation for weighted decision making
• Fully quantify the minimum data set necessary for accurately estimating DNI with an MPA and ANN
• Assess the computational effort of estimating DNI with an ANN compared against iteratively solving an inverted sky problem.
In conclusion, on-site solar data from multiple pyranometers coupled with comprehensive shade mapping provides useful information:

1. Accurate shade information has value in building energy modeling and management.
2. Thermal comfort ranges can be violated when advanced controls are informed by poor quality irradiation data.
3. The usefulness of on-site irradiance data is increased with analyses of probability distributions on multiple surfaces.
References


