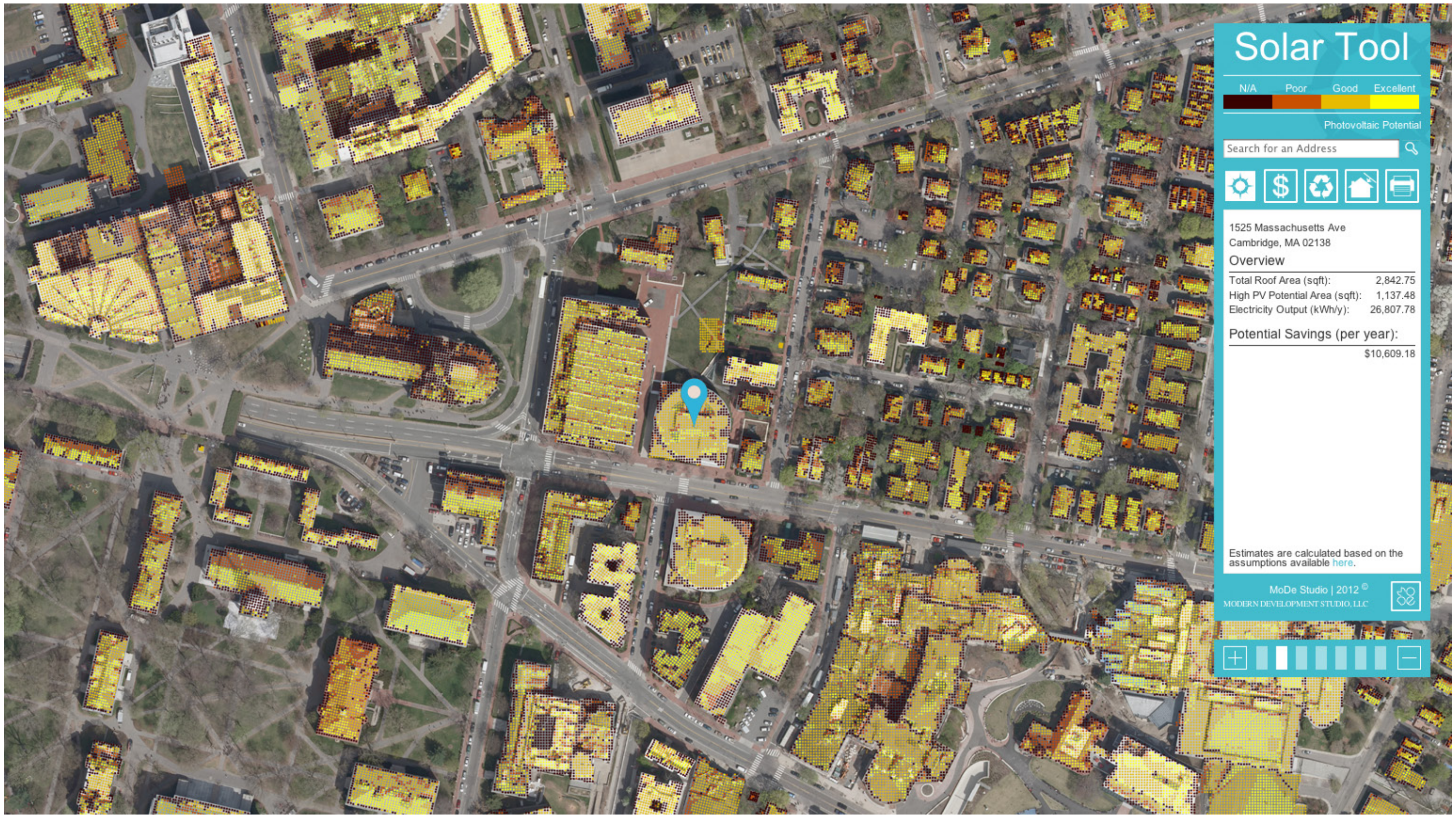
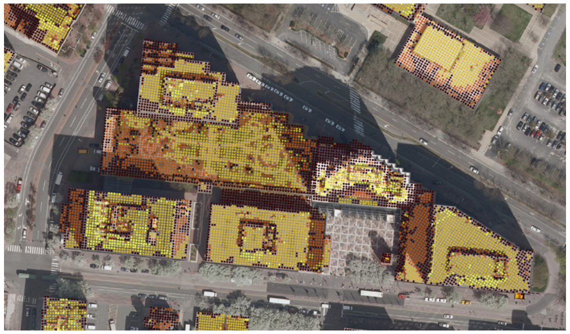


J. Alstan Jakubiec
alstan@jakubiec.net

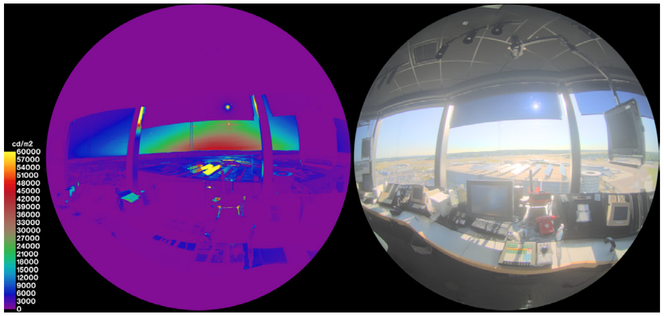
Christoph F. Reinhart

Massachusetts Institute of Technology, Building Technology Program

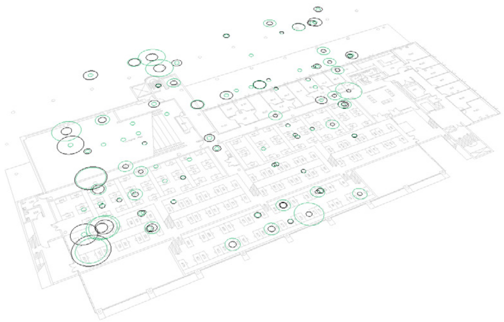
Three Projects



Towards Validated Urban Photovoltaic Potential Maps

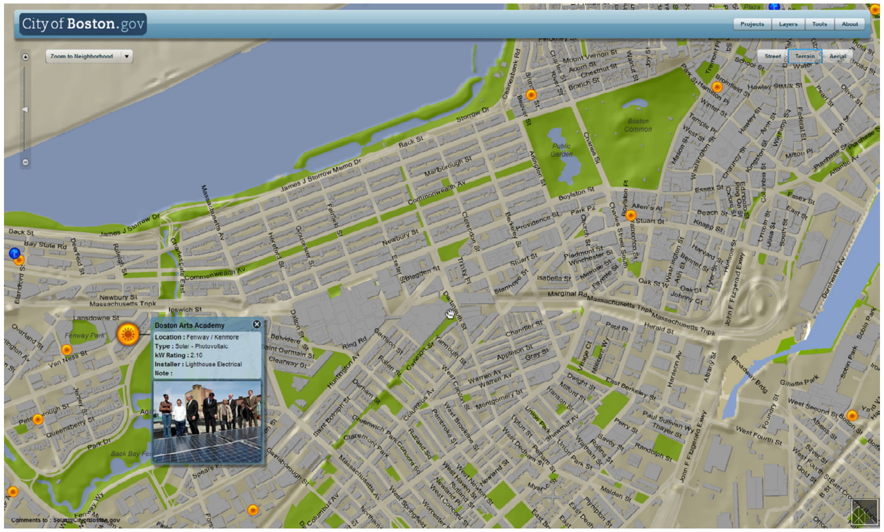


Causes of Glare in the Urban Environment



Validation of Annual Glare Predictions in a Large Daylit Space

Towards Validated Urban Photovoltaic Potential Maps



Renew Boston Solar
http://gis.cityofboston.gov/SolarBoston/

LA county Solar Map
http://solarmap.lacounty.gov/

Goals of PV potential maps

- promote renewable energy generation
- reduce summer time peak loads
- increase environmental awareness of residents
- improve the sustainable image of a city

Outputs

- electric production from a PV system (kWh)
- energy savings from a SHW system (Therms)
- resulting annual electricity savings (dollars)
- carbon savings (lbs)
- useful roof area (sq. ft.)
- system payback period (years)
- system costs (dollars)
- local rebates and incentive programs

Questions

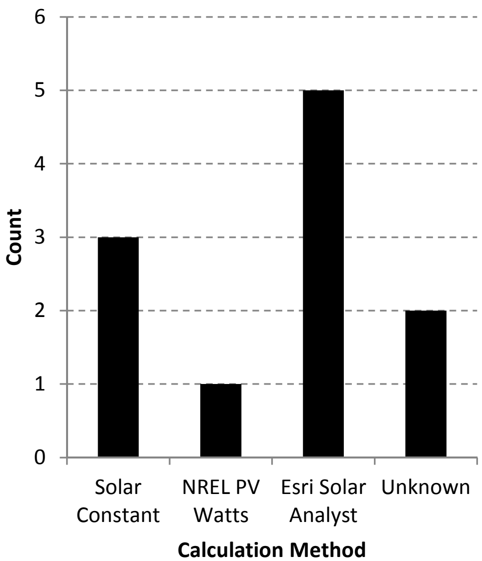
- Which assumptions are employed by existing maps?
  - ◊ geometry
  - ◊ simulation algorithm
  - ◊ representation of climate

- How accurate are the methods employed?

- Can we do better?
  - ◊ urban-scale best practice daylighting model
  - ◊ validation of model against real PV yields

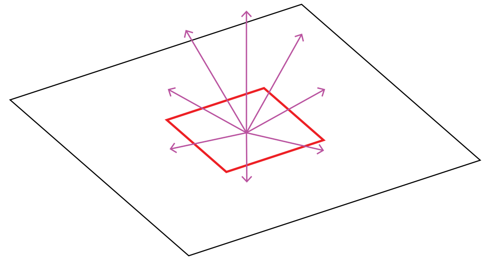
Surveyed Existing Maps	
Anaheim	http://anaheim.solarmap.org/
Berkeley	http://berkeley.solarmap.org/
Boston	http://gis.cityofboston.gov/SolarBoston/
Denver	http://solarmap.drcog.org/
Los Angeles County	http://solarmap.lacounty.gov/
Madison	http://solarmap.cityofmadison.com/madisun/
New York City	http://nycsolarmap.com/
Portland	http://oregon.cleanenergymap.com/
Salt Lake City	http://www.slcgovsolar.com/
San Diego	http://sd.solarmap.org/solar/index.php
San Francisco	http://sf.solarmap.org/

Methods of Calculating Solar Irradiation



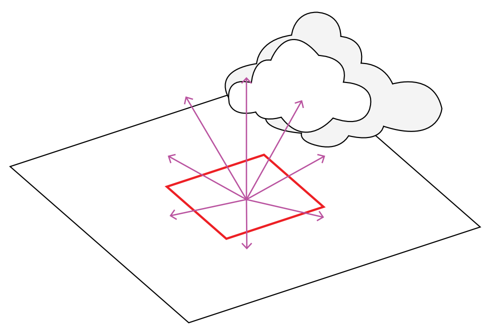
Histogram of Calculation Methods Used in Public PV Potential Maps

- Solar Constant Method



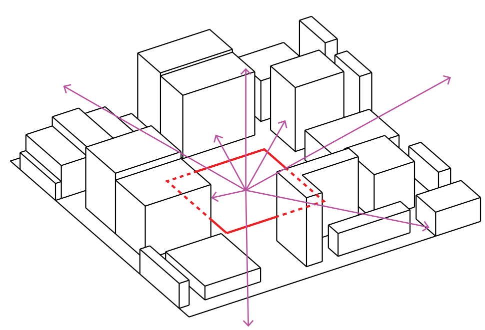
◊ Uses a constant irradiation value applied to all roof surfaces.
◊ Cannot account for urban context, roof orientation or reflections.

- NREL PV Watts



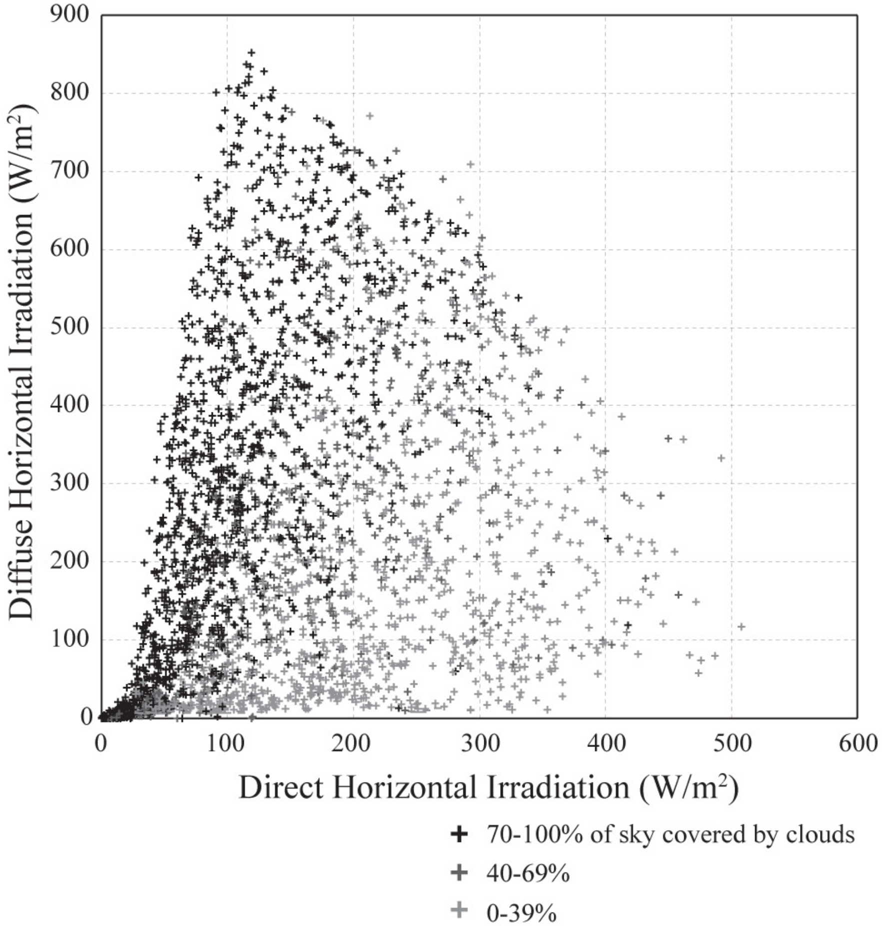
◊ Uses local TMY2 weather data to generate sky models.
◊ Cannot account for urban context or reflections.

- Esri Solar Analyst



◊ Generates a sky mask based on measured height at surrounding locations.
◊ Cannot account for reflections.

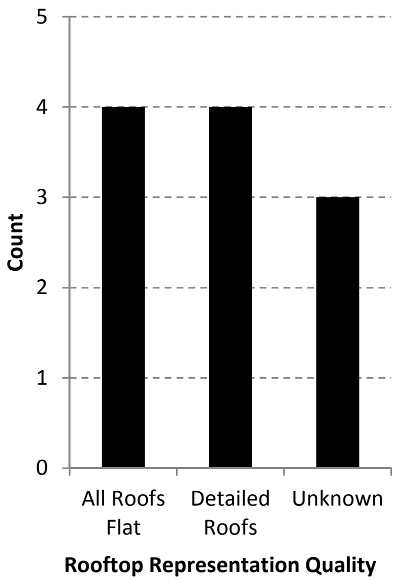
Representation of Climate in Solar Analyst



Hourly Direct and Diffuse Radiation and Cloud Cover from Boston Logan TMY3 Weather Data

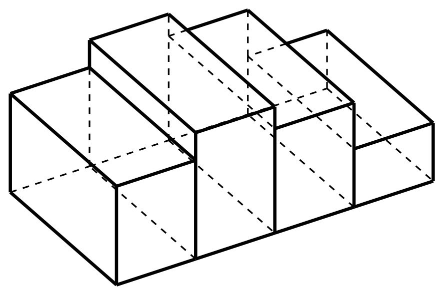
- Solar Analyst's algorithm fixes the ratio between direct and diffuse solar radiation.
- In reality, climate and the ratio between direct and diffuse radiation varies widely throughout the year.
- Choosing a value for the direct/diffuse ratio in the Solar Analyst algorithm is very difficult.

Methods of Geometric Representation

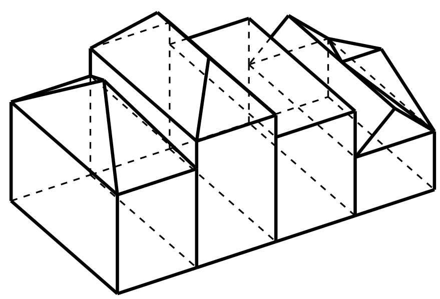


Histogram of Rooftop Geometric Quality in Public PV Potential Maps

- Flat Roofs
  - ◊ Models where all buildings are modeled with flat roofs.
  - ◊ Sometimes "useful" roof area is determined through image analysis.

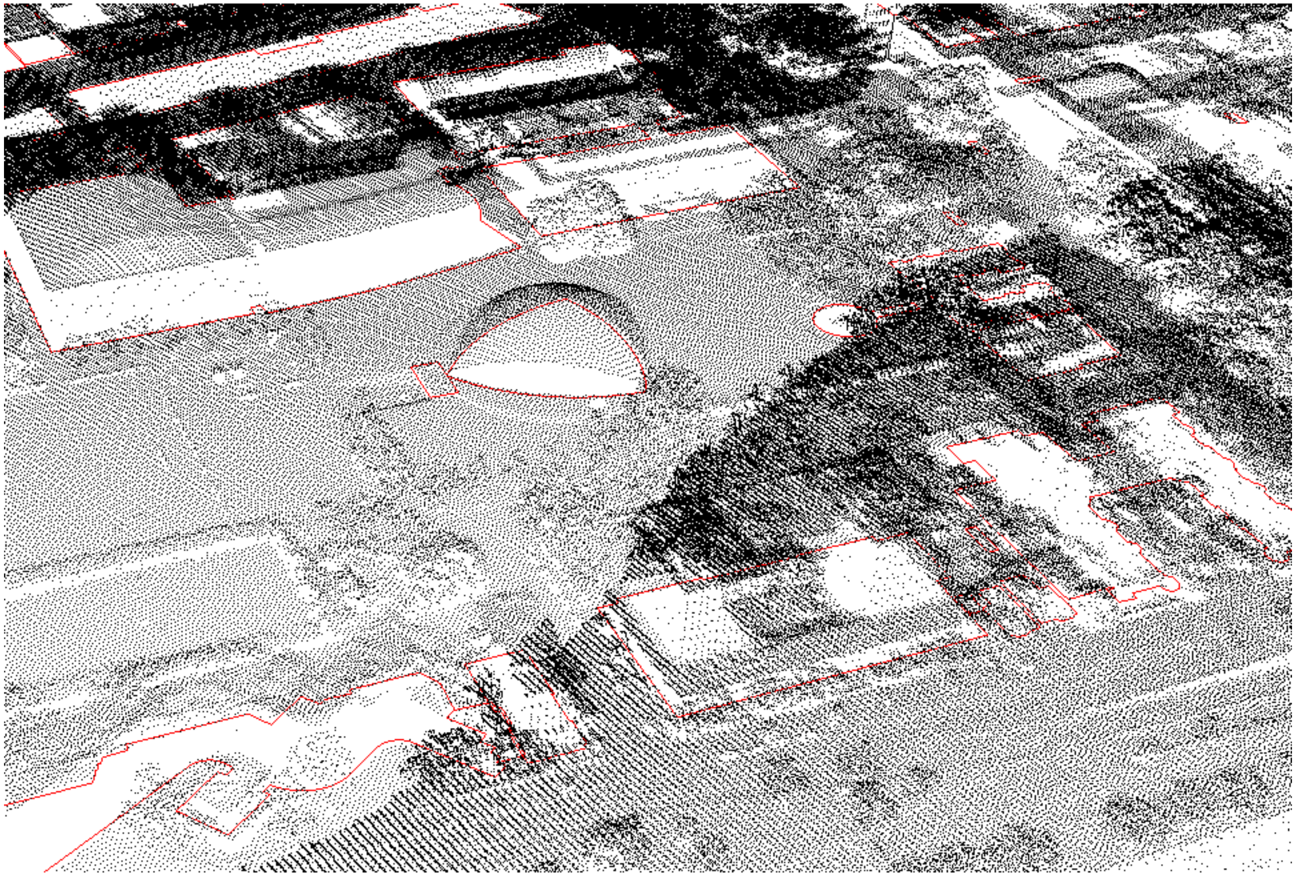


- Detailed Roofs
  - ◊ Models where roof form is represented in detail, including rooftop elements such as HVAC equipment.

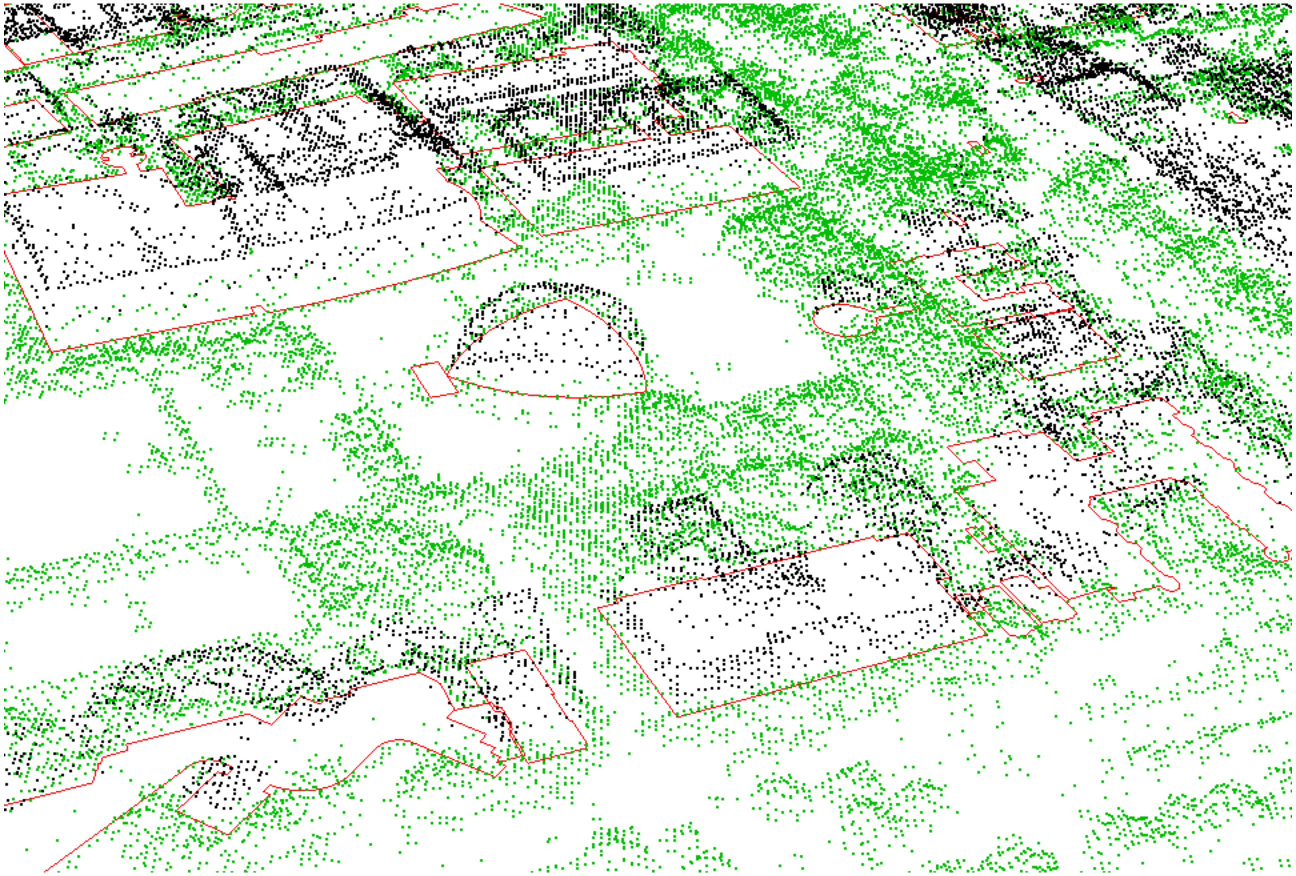


3D Model Generation

Example location, Kresge Oval at MIT. Different types of building forms and landscape exist on site.

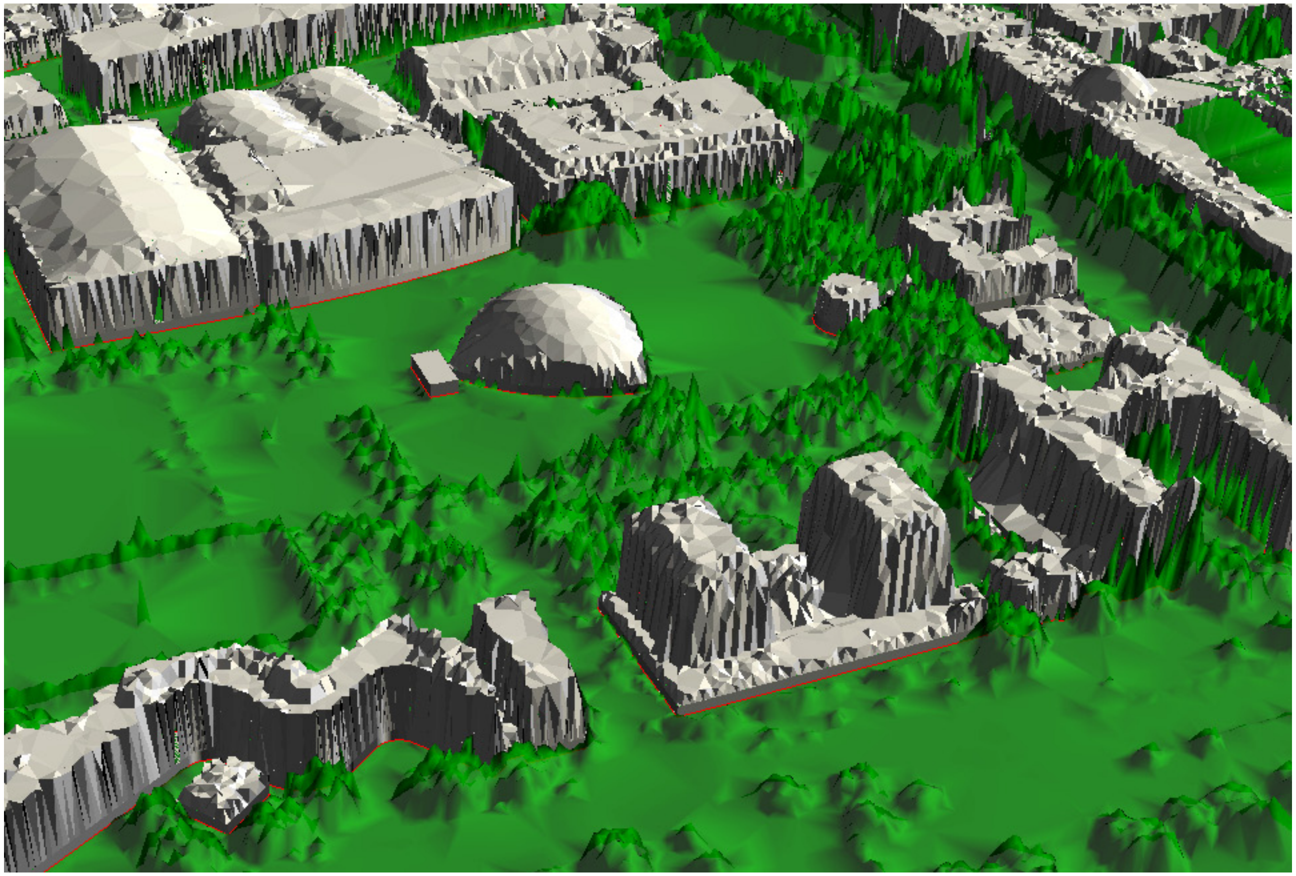


Raw LiDAR data: 126,600,000 points.



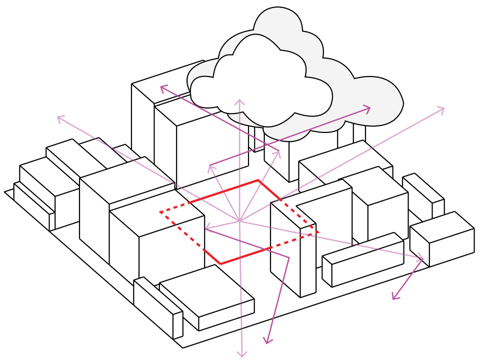
Most relevant, reclassified points (9,400,000) divided between building area and landscape.

3D Model Generation



3D model constructed by Delaunay triangulation. 16,500,000 triangles for Cambridge.

Radiance / DAYSIM Climate-Based Simulations

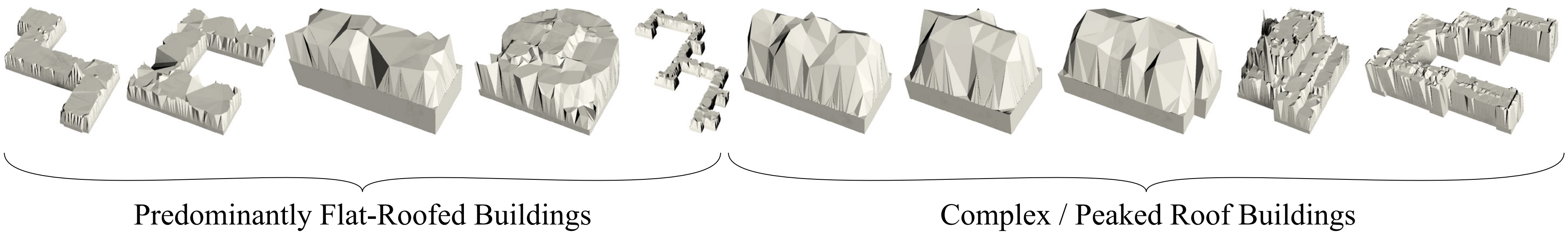


◊ Reverse raytrace engine considers shading from surrounding buildings and trees.
◊ Reflections from surrounding context considered.
◊ Simulations based on TMY3 typical climate data.
◊ Hourly results available for detailed analysis.

Parameter	Value
(ab) ambient bounces	2
(ad) ambient divisions	2048
(as) ambient supersamples	16
(ar) ambient resolution	6750
(aa) ambient accuracy	0.1

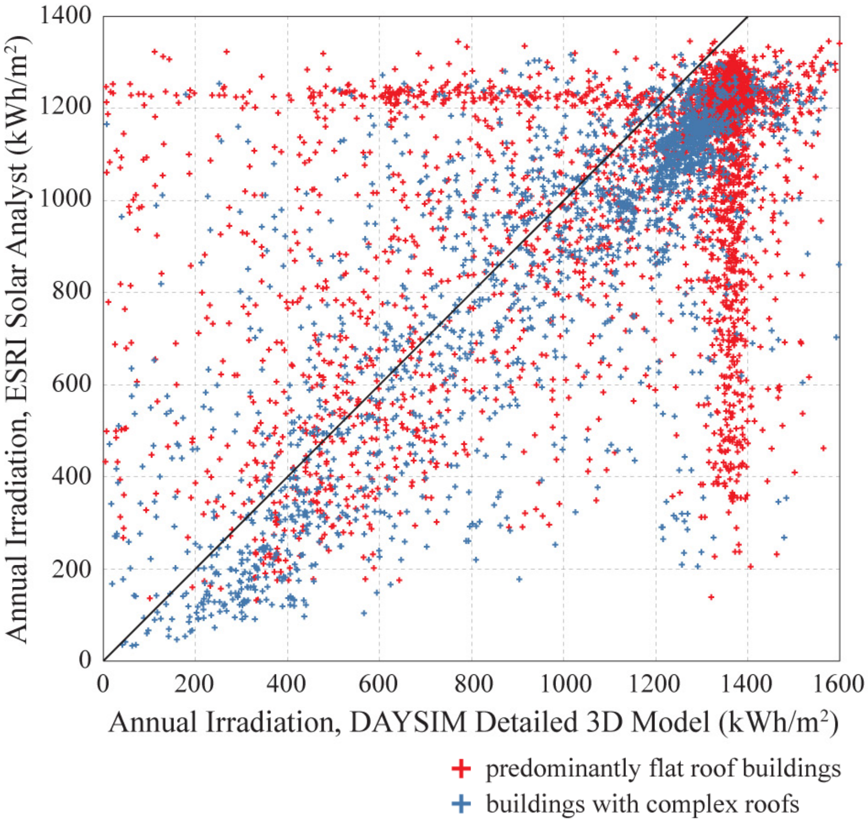
Radiance simulation parameters

Ten Typical Buildings Used for Comparison



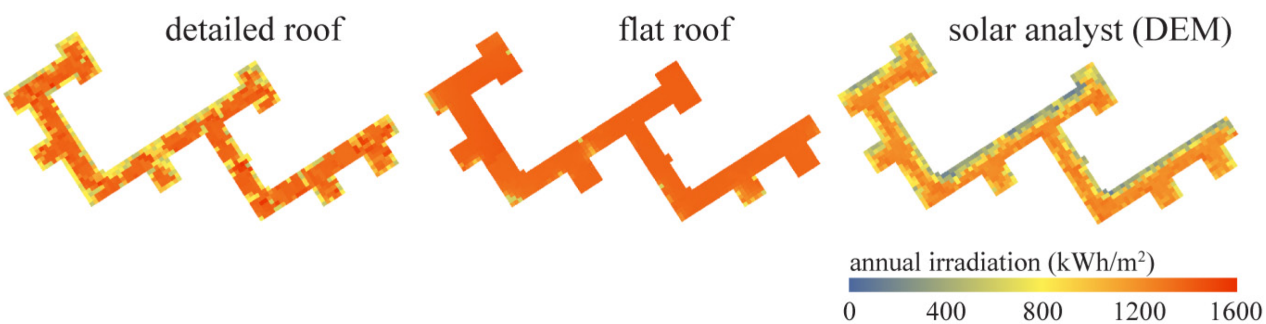
Compare irradiation using Radiance/DAYSIM and other calculation and geometric methods.

Comparison with Esri Solar Analyst (Annual Results)



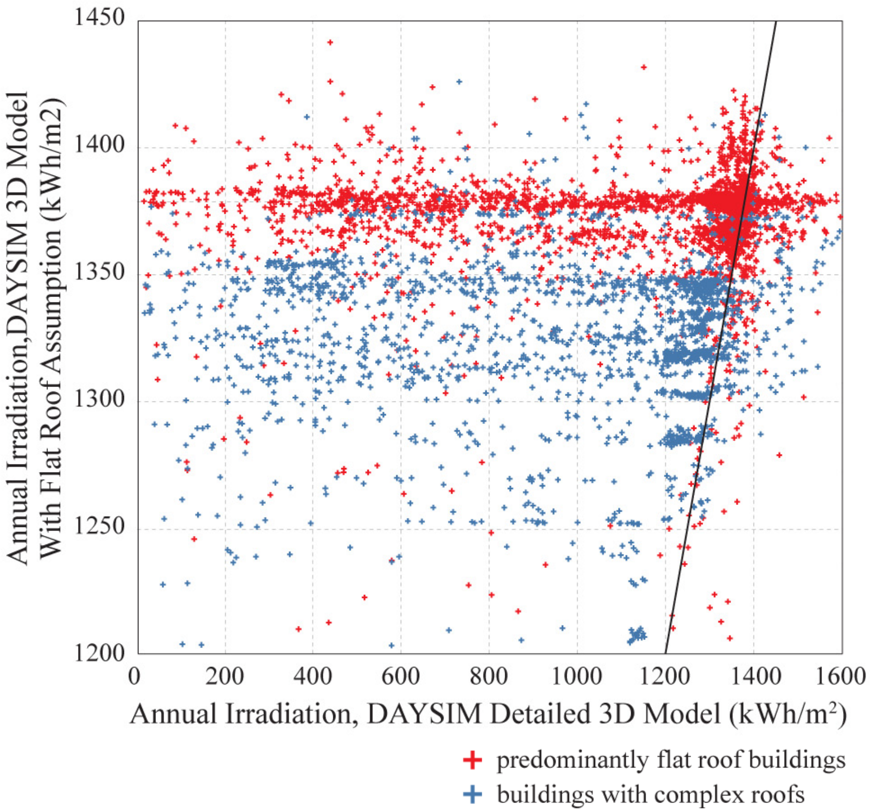
- Detailed DAYSIM calculations predict more irradiation in general. Expected as reflections are taken into account.

- Notice stratified trends. Can be explained by geometric interpolation issues at building edges.



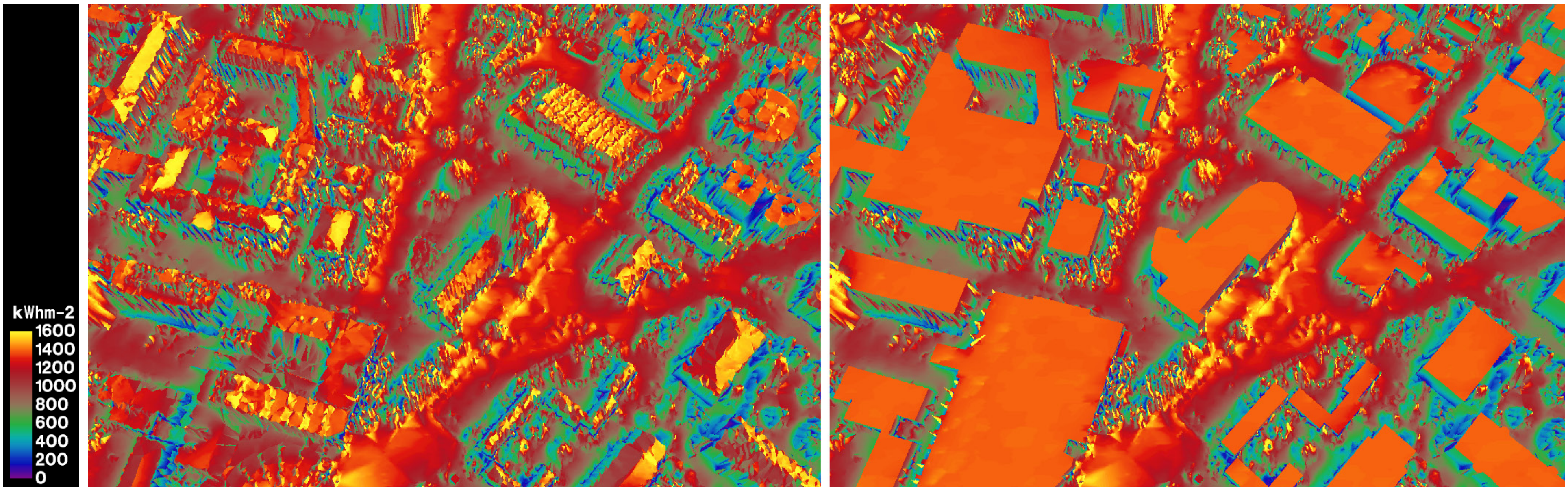
Annual cumulative radiation on one building predicted using three methods.

Comparison with Flat Roof Assumption (Annual Results)



- Detailed DAYSIM calculations used in both simulations; flat building information displayed on vertical axis.
- Flat roof assumption, in general overestimates irradiation; however, underestimates for South-facing roof surfaces.
- Suggests that roof form and orientation is more important than shading between buildings in Cambridge.

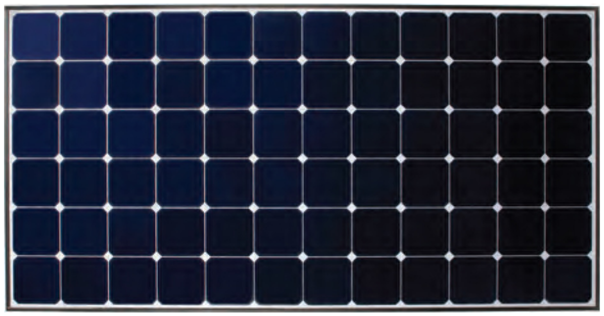
Comparison with Flat Roof Assumption



Annual irradiation map comparison of a model with detailed roof forms (left) with flat roofs (right).

Energy = f(Panel Efficiency, Inverter Efficiency, Panel Temperature, Solar Insolation, Age of System)

- Panel efficiency and temperature coefficients considered based on a standard panel (Sunpower E-18/230W).



- Hourly panel temperature predicted based on Luque and Hegedus 2011.

$$T_C = \frac{T_{amb} + (T_0 - 20C)E}{800\, Wm^{-2}}$$

- Inverter efficiency is 1.0 and systems considered to be new.

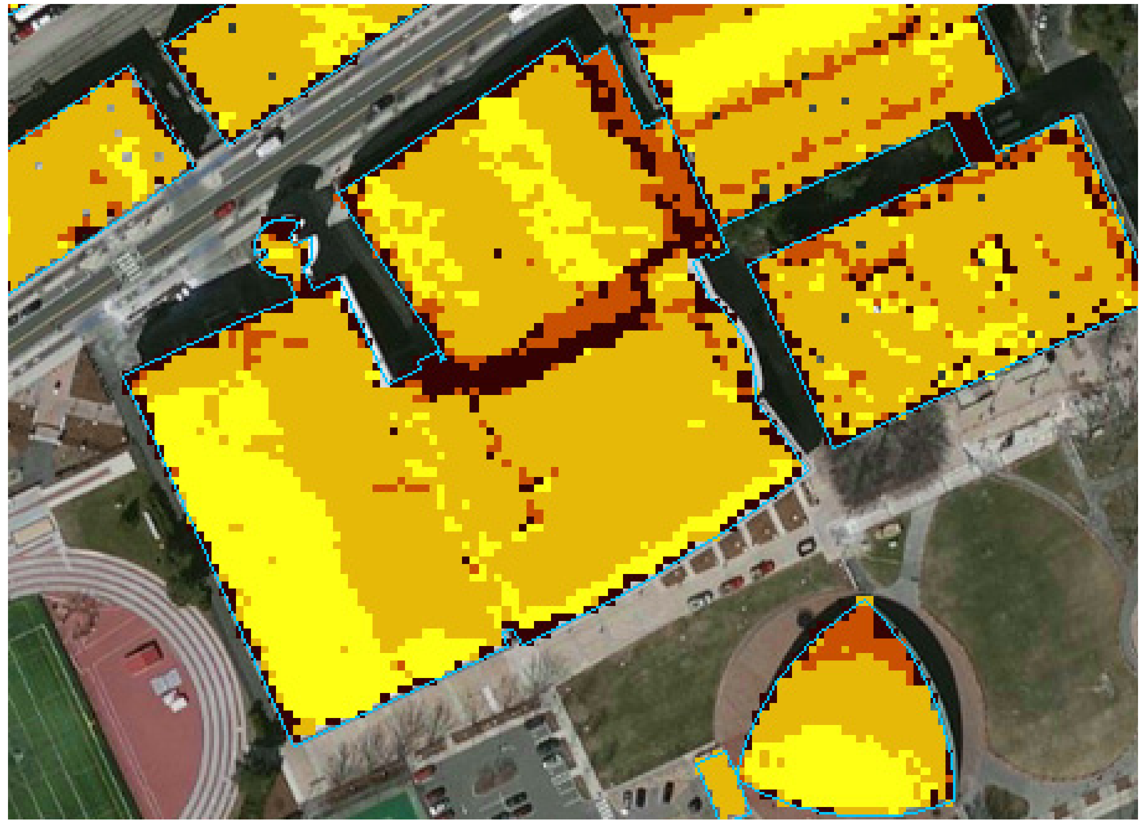
Excellent
> 259.0 kWh/m²

Good
185.0 - 259.0 kWh/m²

Poor
111.0 - 185.0 kWh/m²

Not advisable
< 111.0 kWh/m²

Scale based on PV yields.



Spatial display of photovoltaic potential .

Validation Procedure

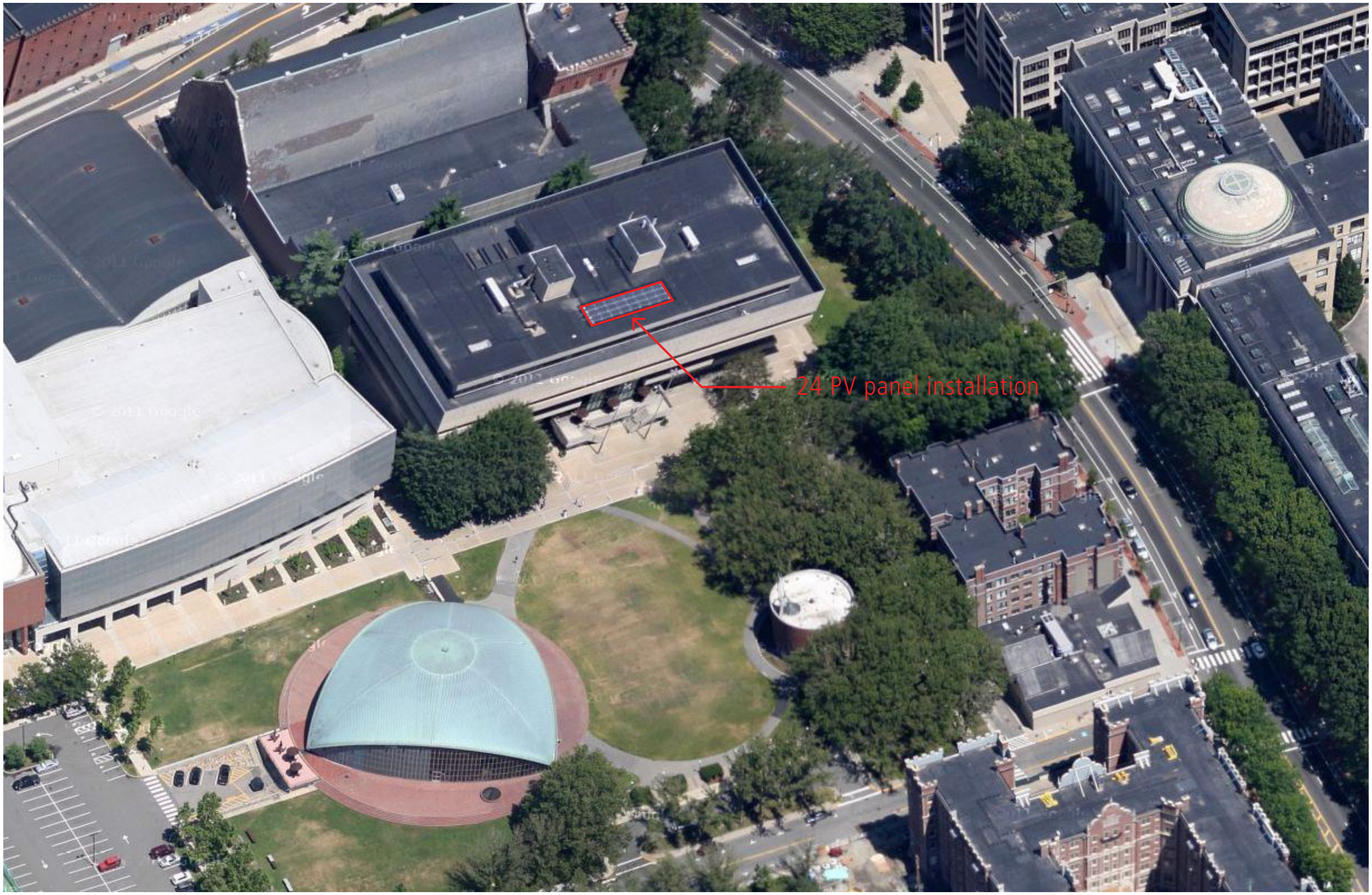
- Compare simulation model to measured photovoltaic installation production.

- Acquire measured weather data for the same period from local weather station.
  - ◊ Global Horizontal Solar Radiation (W/m^2) – Split using Reindl method.
  - ◊ Ambient Temperature (^oC)

Central Square weather station, approximately 1km from site.

- Run simulation model using measured weather and evaluate based on detailed information from the actual PV system.

Array Location



Aerial photograph of W-20, student center photovoltaic panel installation.

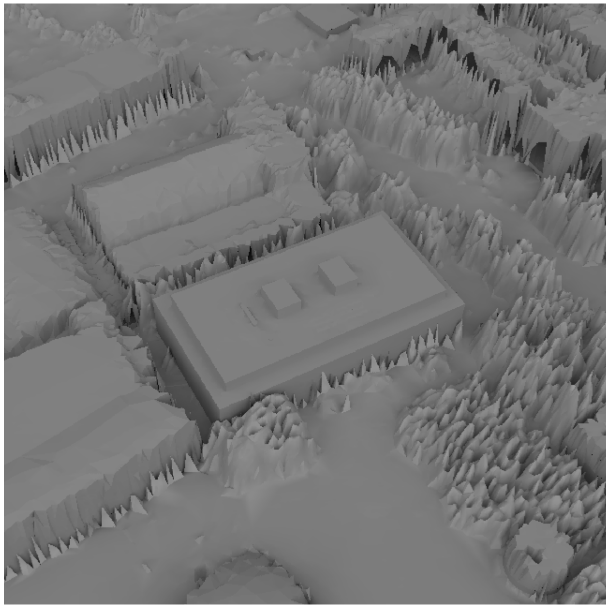
Compare Model to Measured PV Production on the Roof of the MIT Student Center

Photographs taken on a site visit to the panel installation on the roof of building W-20, the MIT student center.

Validation Model Parameters and Detailed 3D Model

Parameter	Value
Panel Count	24
Type	Schott ASE-300-DGF/50
Efficiency	12.3 %
Power at 1,000 W/m^2, 25°C (P_{mp0})	300 W
Temperature Correction Factor (γ)	0.47 % / °C
Panel Tilt	5.0 degrees
Panel Azimuth	22.0 degrees East of South
Inverter Efficiency	94.0 %
Panel Degradation	0.5 % / year (9 years)

Detailed model parameters



3D model used in validation study

Temperature Correction

- The roof is composed of black tar.

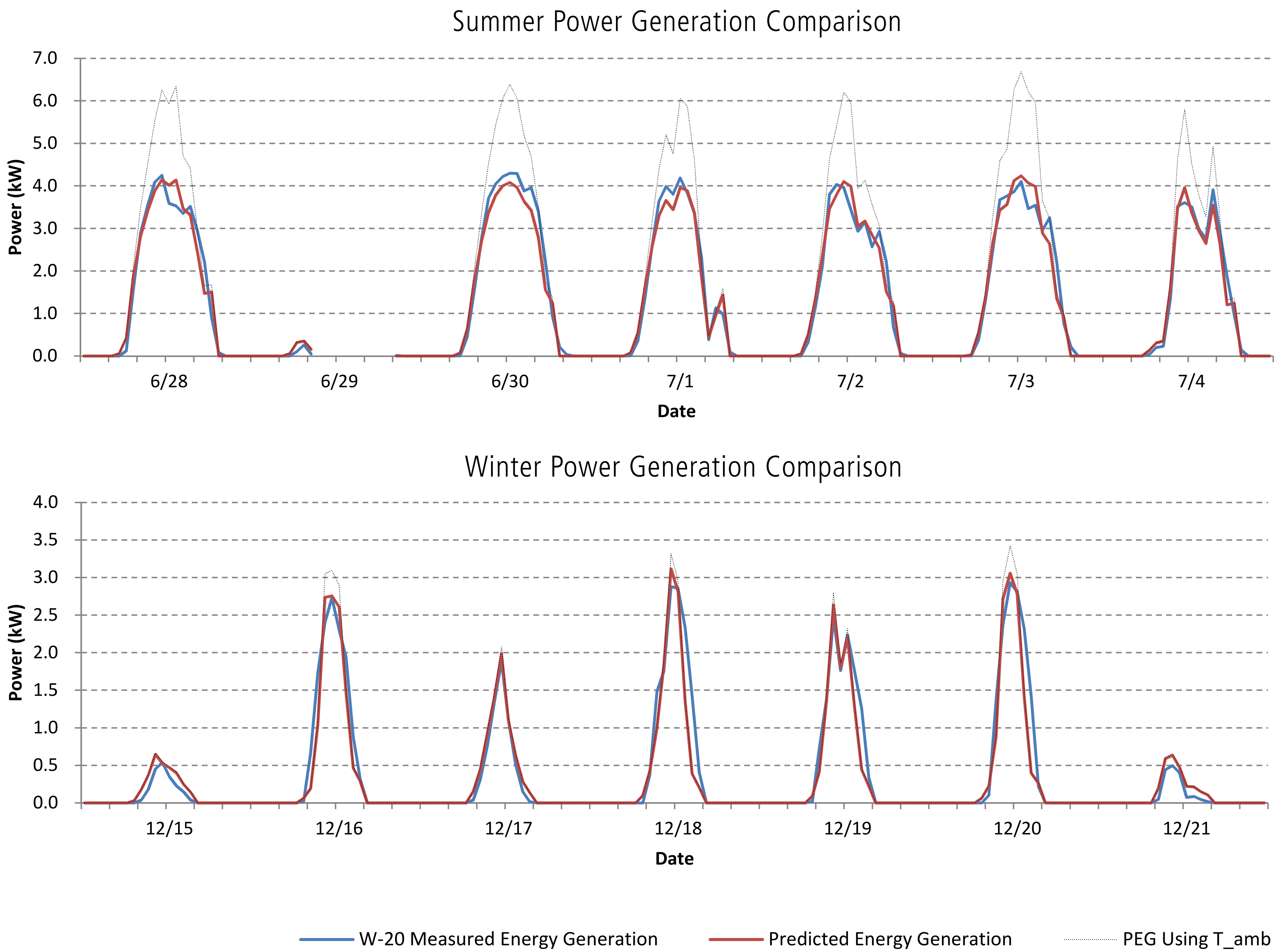
- Ambient air temperature alone is not appropriate to use when determining panel temperature.

- Use sol-air temperature to determine the base ambient temperature on roof.

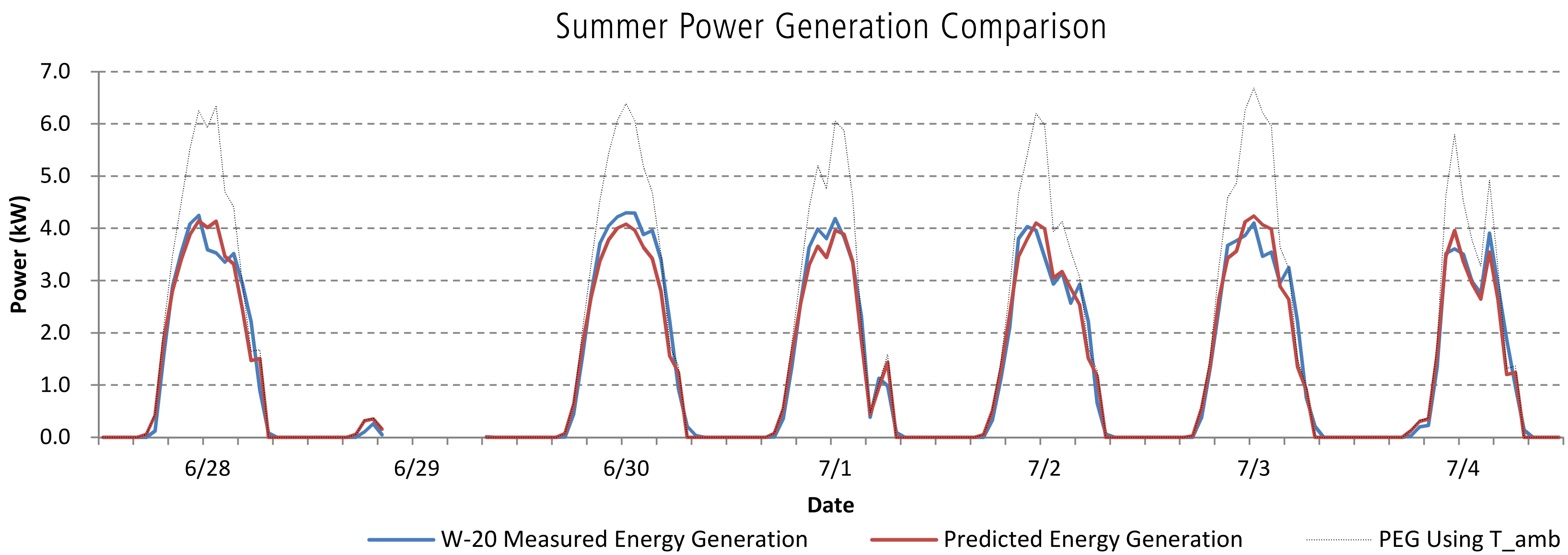
$$T_{solair} = T_{amb} + \frac{(\alpha \cdot E)}{h_c}$$

α, absorptivity (%)
h_c, convective and radiation heat loss coefficient (assumed 15 W/m^2°K)
E, solar insolation (W/m^2)

Predicted vs Measured Results for Two Weeks



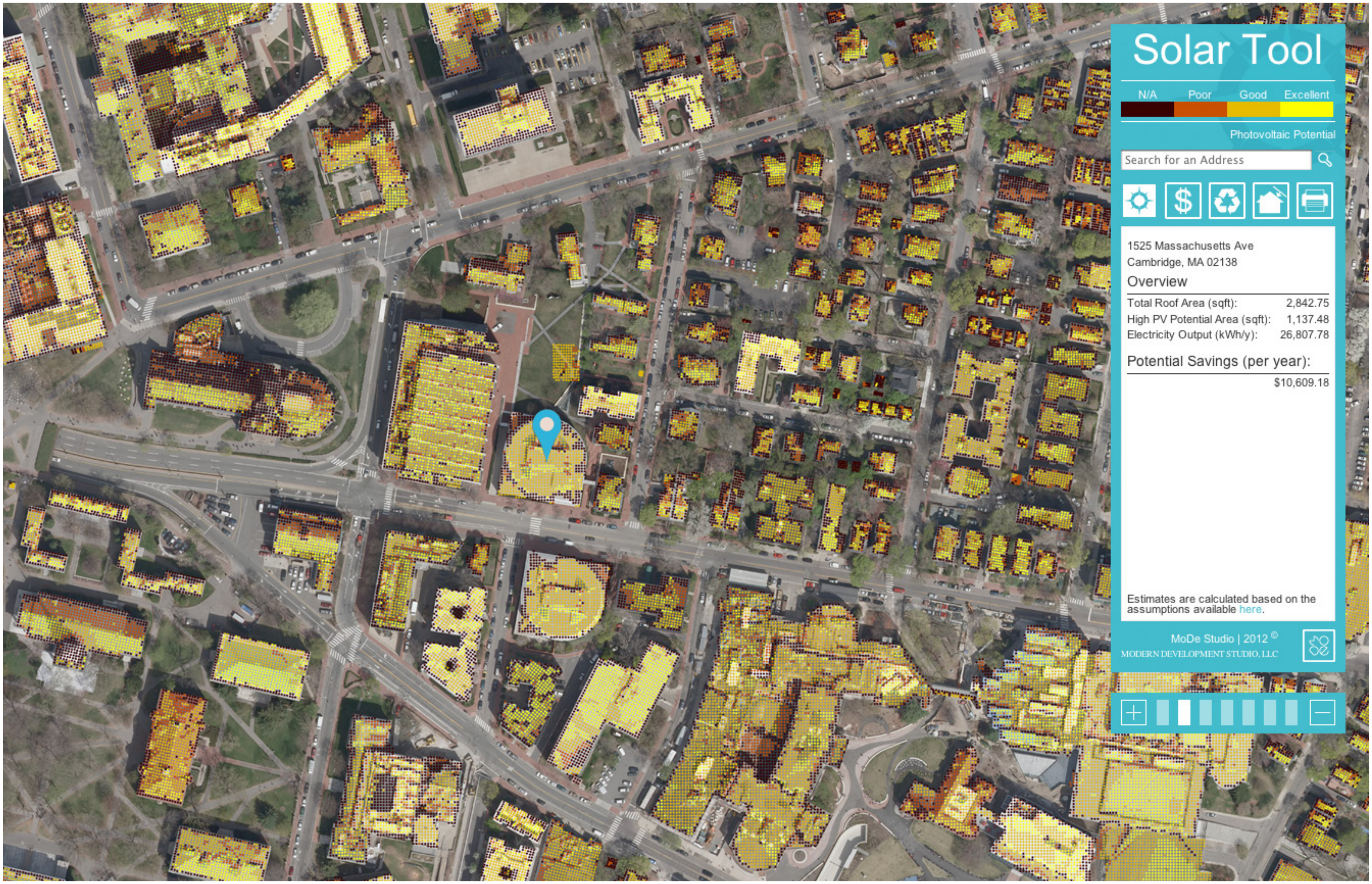
Predicted vs Measured Results for Two Weeks



- Using T_{amb} instead of T_{solair} (neglecting estimation of panel temperature), power generation is strongly overestimated.

- Correct prediction of hourly panel temperature is important for predicting accurate PV yields in hot weather!

Public Photovoltaic Potential Map of Cambridge, MA



Screen Capture of Interactive Photovoltaic Potential Map for Cambridge, MA

Causes of Glare in the Urban Environment

The (Specific) Problem: Air Traffic Controllers Can’t See Planes on the Runway

> 250,000 cd/m^2!
PV panels greater than three orders of magnitude brighter than the computer monitor.

Current Solution: PV Panels Covered by Tarps

Tarps cover hundreds of PV panels which cause glare to air traffic controllers.

View of the air traffic control tower.

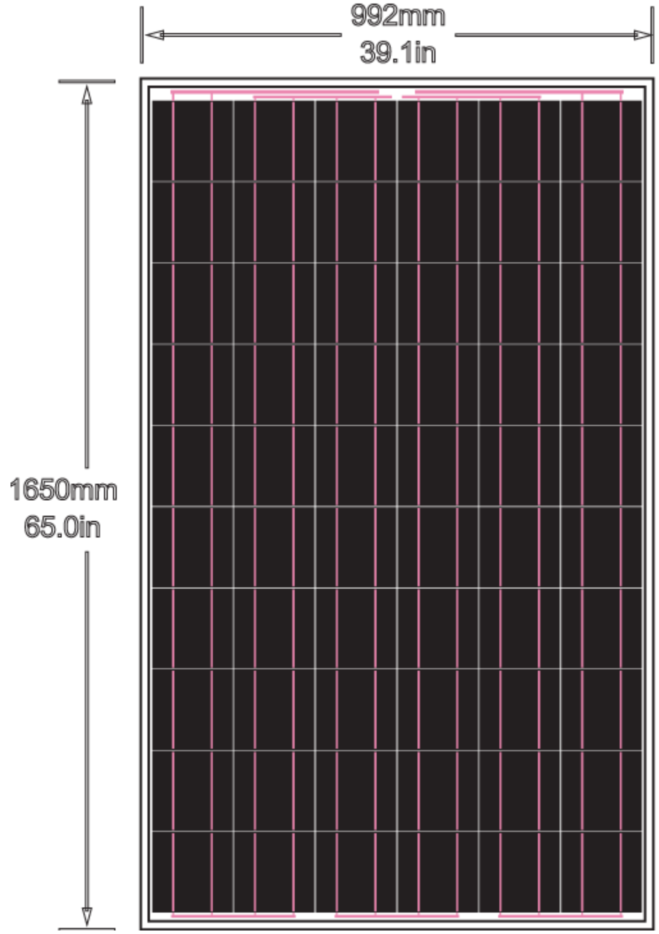
Work in Progress

- Characterize the reflective properties of the installed PV panels and proposed alternative panels.

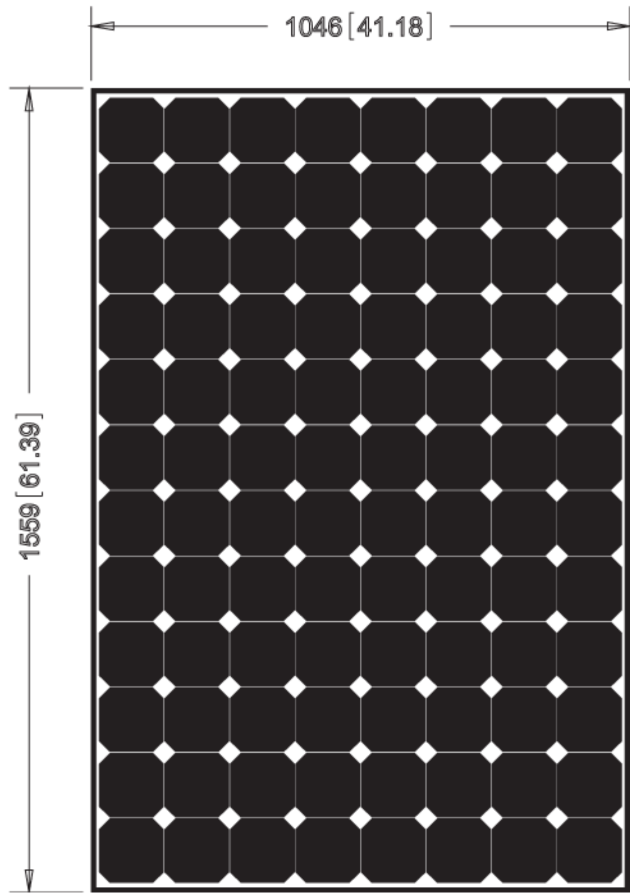
- Model the current conditions using Radiance and DAYSIM and validate against HDR photographs.

- Help the airport propose design alternatives. Simulate PV energy production and visual comfort simultaneously.

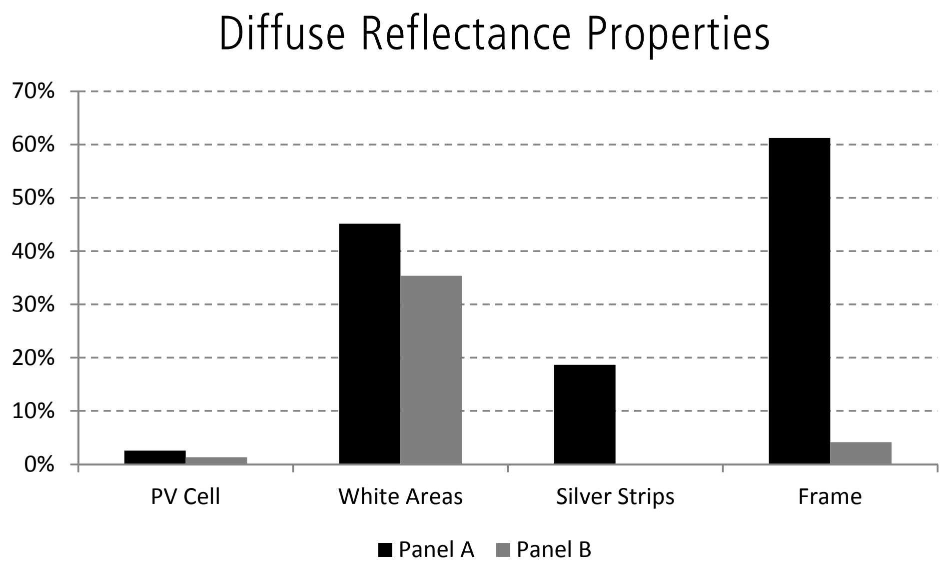
Portable Spectrophotometer

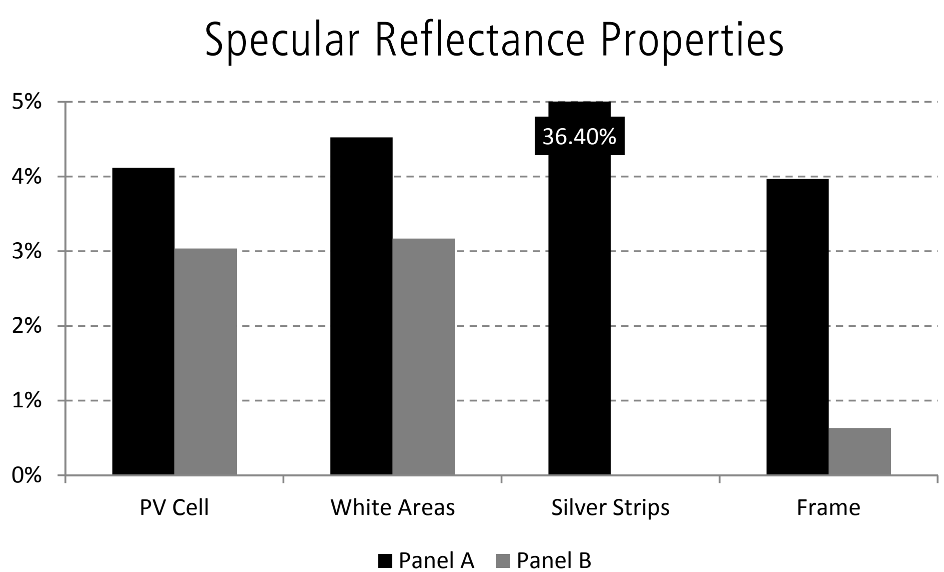


Panel A
Currently Installed



Panel B
Proposed Alternative





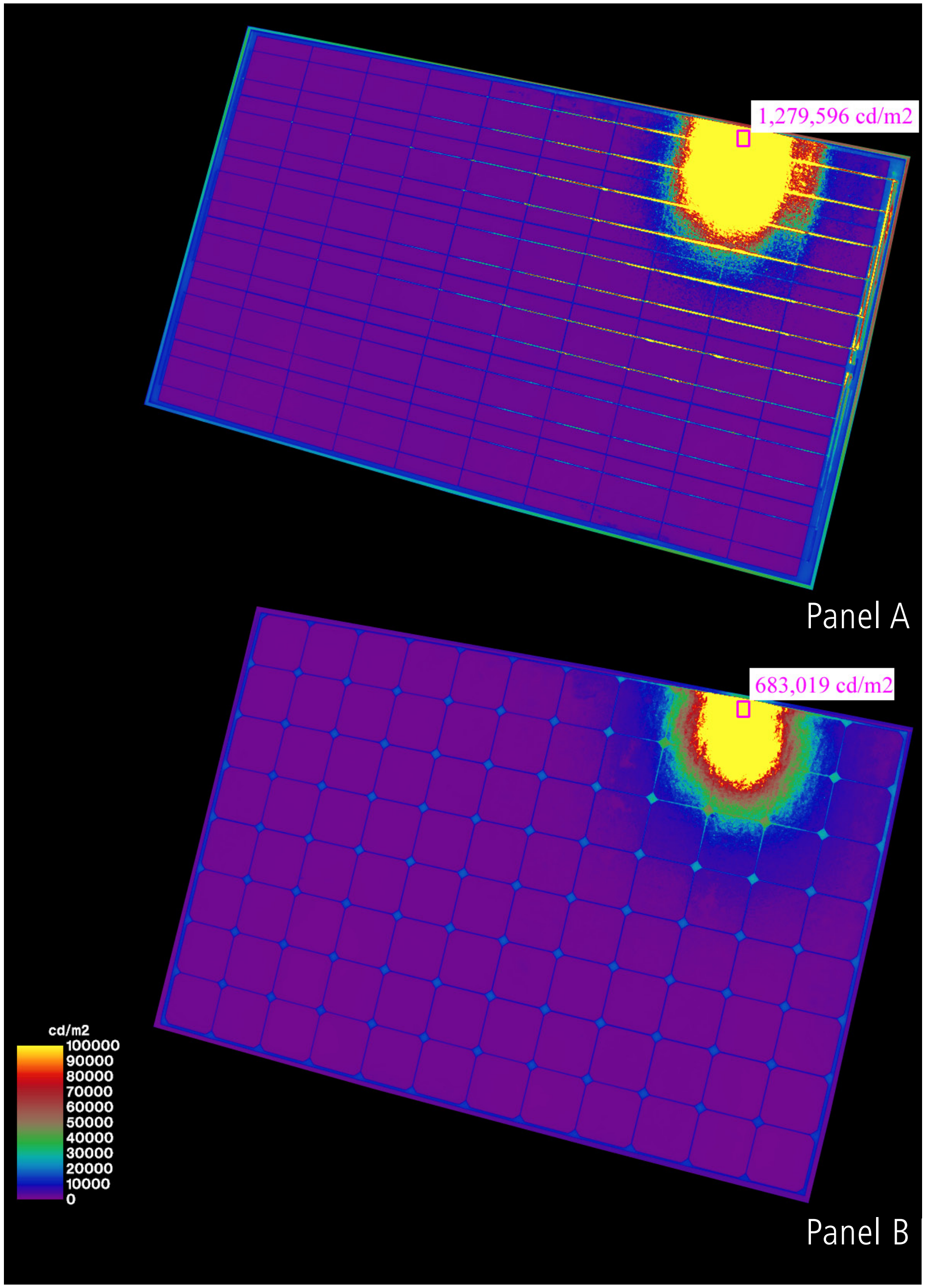
- Surprisingly, panels differ quite a bit in reflective properties.

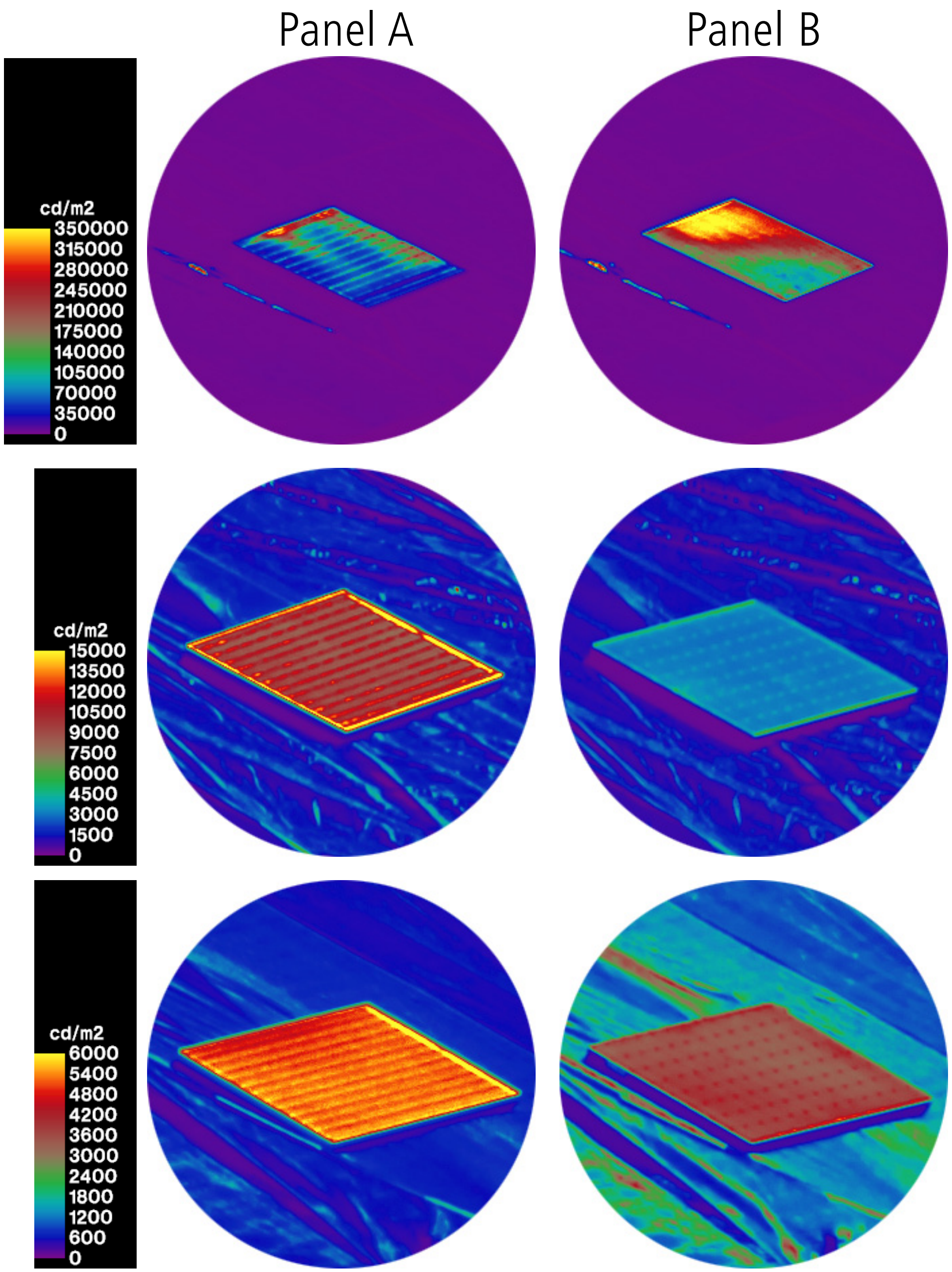
- Area weighted average
Panel A: 8.67% diffuse / 5.58% specular
Panel B: 4.73% diffuse / 2.97% specular

- Roughly panel B reflects half of the amount of light as panel A.

- Ideally we'd use a goniophotometer for this.

HDR Photographic Comparisons

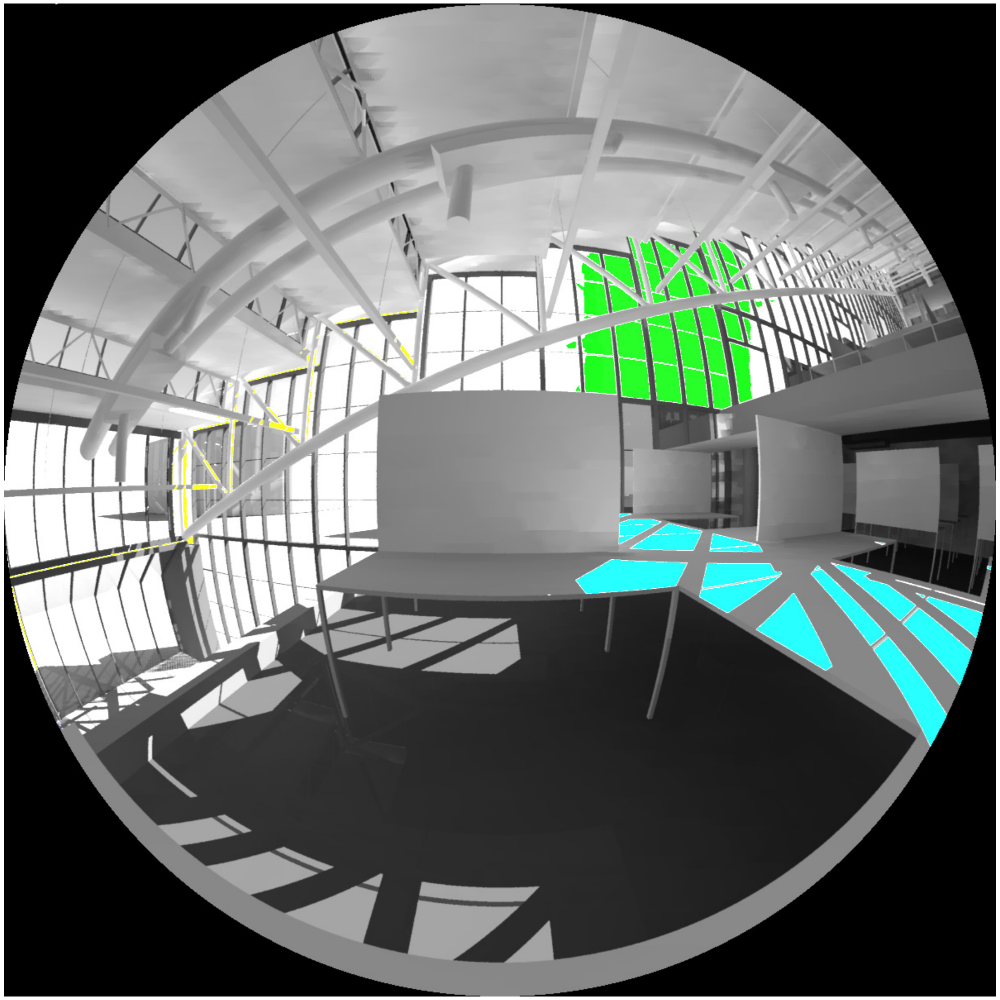




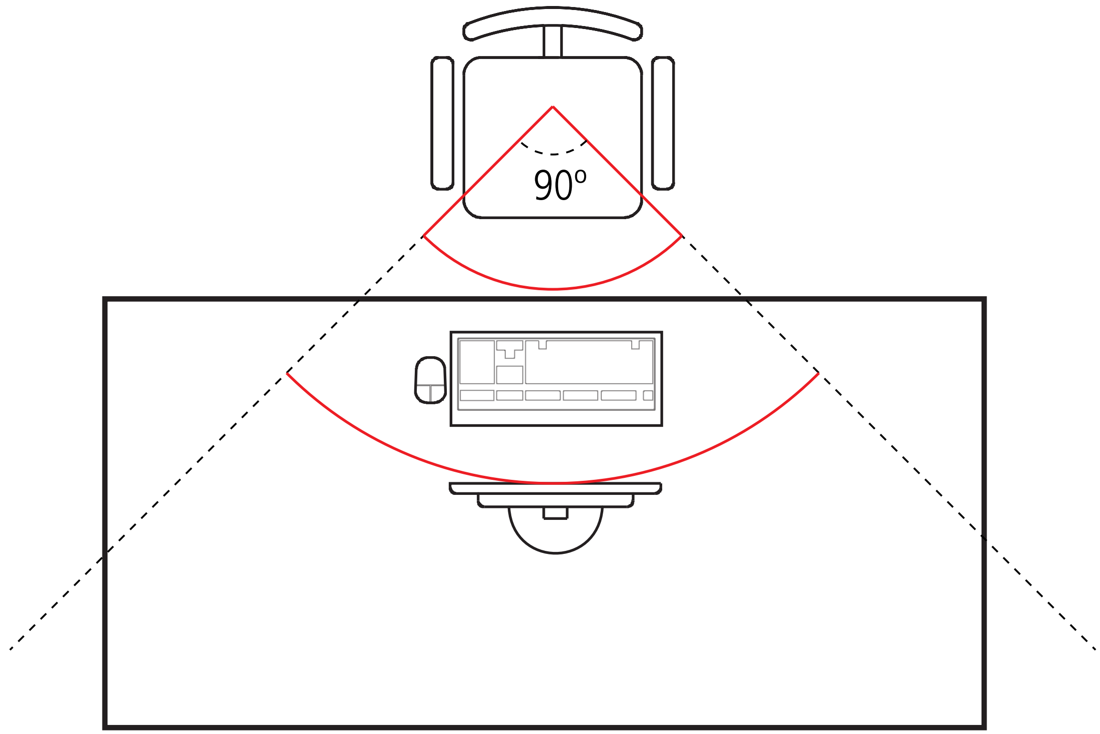
- Photographed panels at different known positions from the control tower under same solar conditions (requested by airport).
- Suggests that Panel A creates a 'larger' glare source do to forward scattering and more intense reflections.
- Panel B seems to create more intense specular region with a 'quicker' falloff to pure diffuse reflection.

Validation of Annual Glare Predictions in a Large Daylit Space

Detailed Radiance Model and Furniture Layout

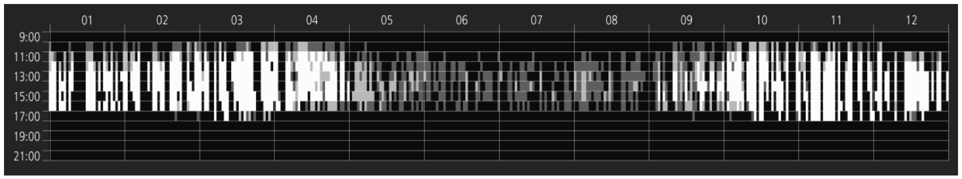


Adaptive Zone

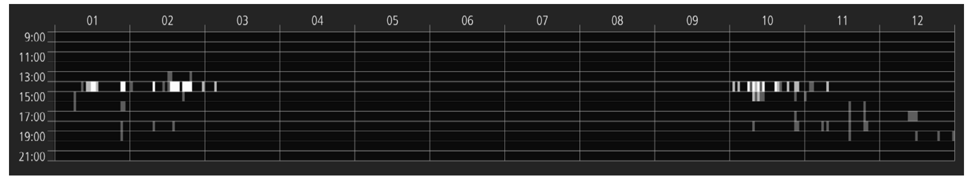


Range of Possible Seating Positions for a Single Occupant

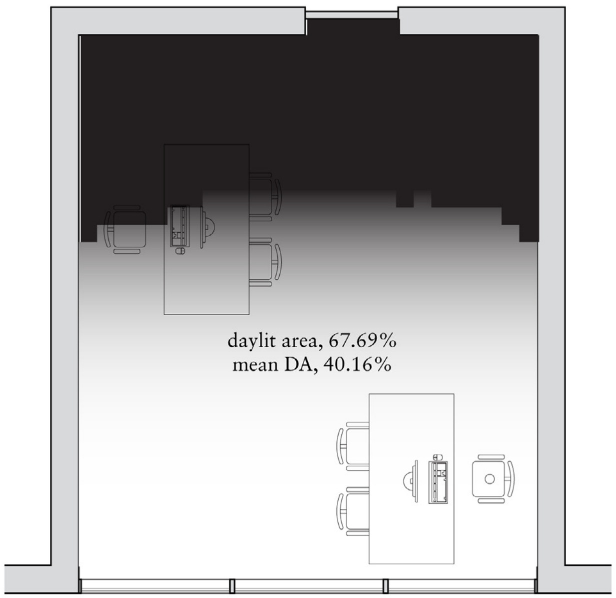
Adaptive Zone

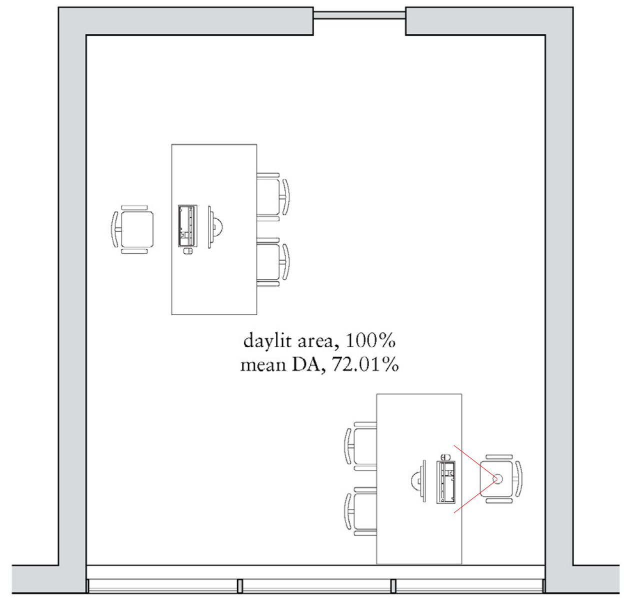


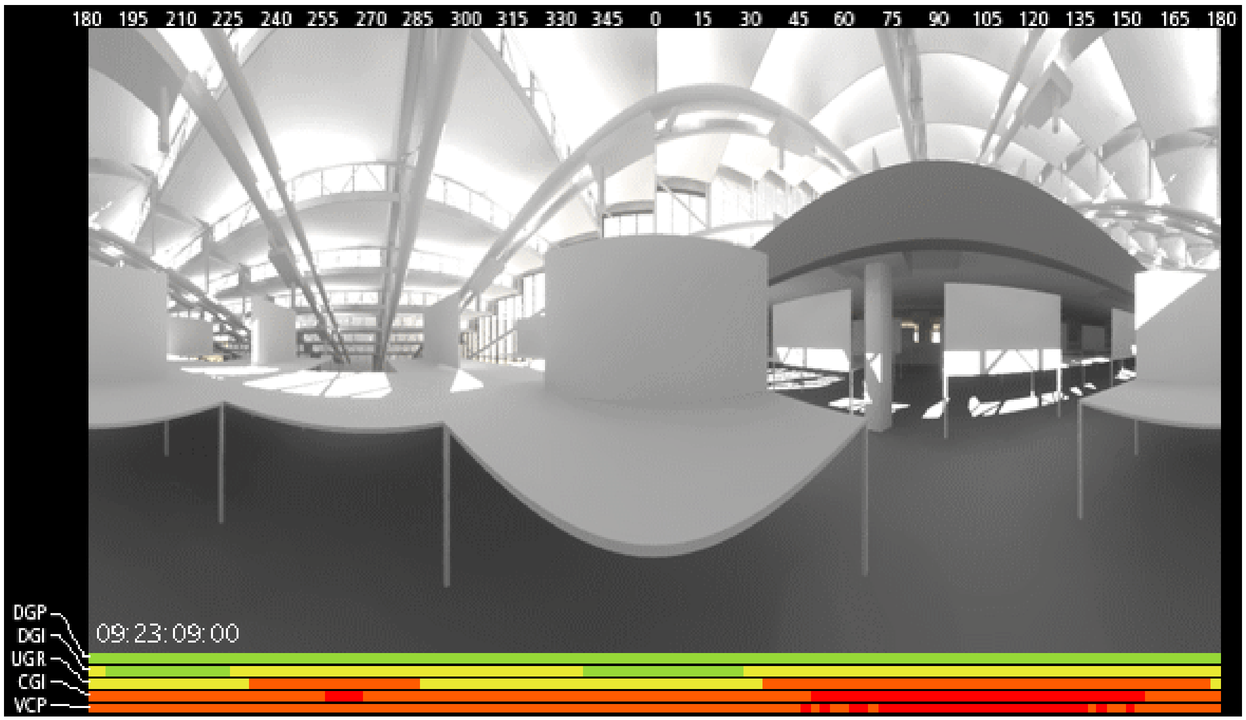
Annual Visual Discomfort from a Single Viewpoint



Annual Visual Discomfort of an Occupant who Can Adapt







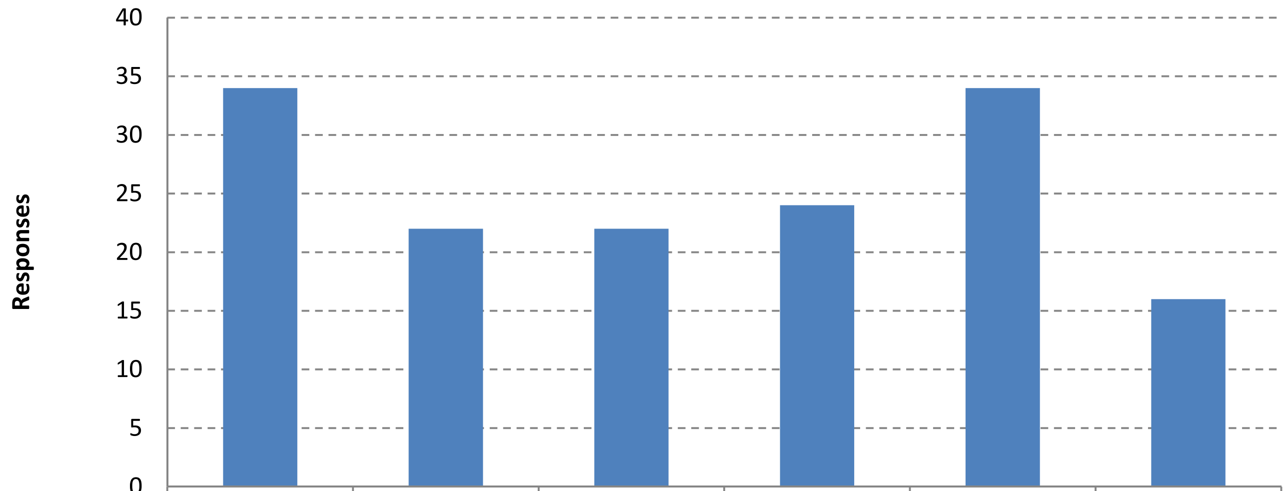
- Imperceptible glare.
- Perceptible glare.
- Disturbing glare.
- Intolerable glare.

Large Occupant Survey and Calibrated Simulation about Visual Comfort

Spatial Discomfort Glare Map of Gund Hall, Harvard University

- Survey data from 100 Harvard students and simulations for 19 different viewing positions at 500 desks in a real daylit space.
- Goal: Validate occupant behavior assumptions and algorithms, make recommendations for glare assessment of large daylit spaces, improve design workflows.

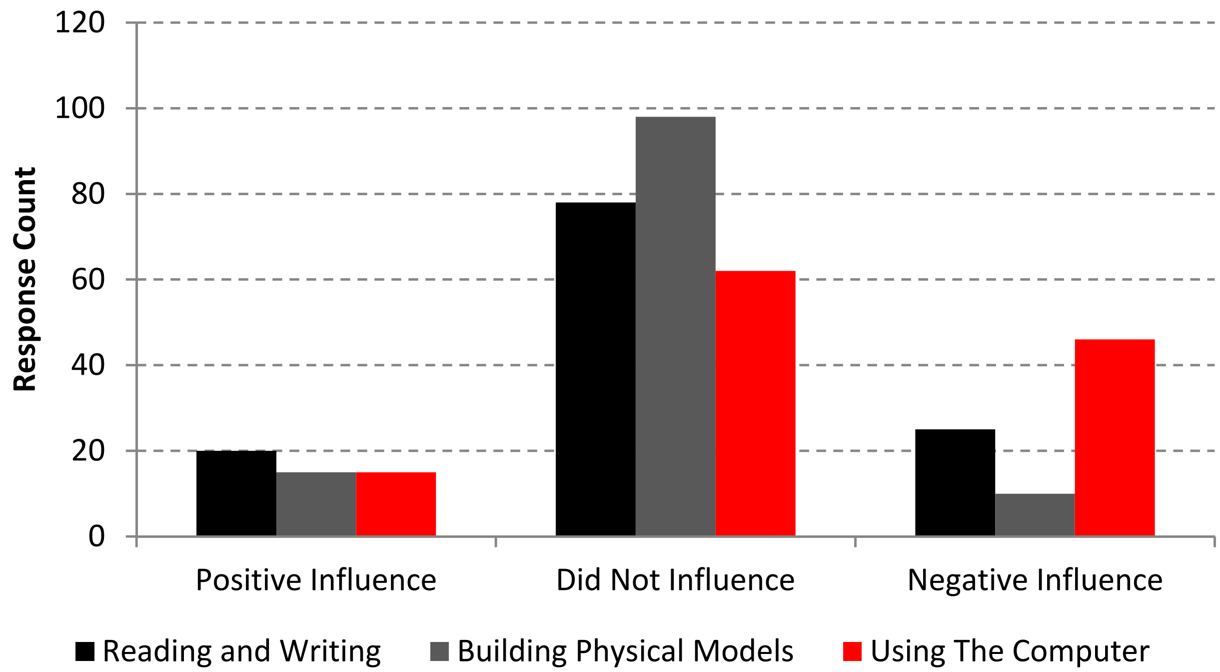
If you experienced visual discomfort over the course of the semester, which strategies did you employ to increase your comfort?



	Nothing. Discomfort was NOT experienced.	Nothing. Discomfort was experienced.	Moved to another position in front of the desk.	Built a shading device not originally a part of the workspace.	Temporarily rotated my chair to avoid bright light or contrast.	Temporarily moved to a completely different location in the building.
Responses	34	22	22	24	34	16

Initial Survey Results

Did the lighting conditions this semester influence your productivity for the following tasks?



Thank you.