4.401/4.464 Environmental Technologies in Buildings

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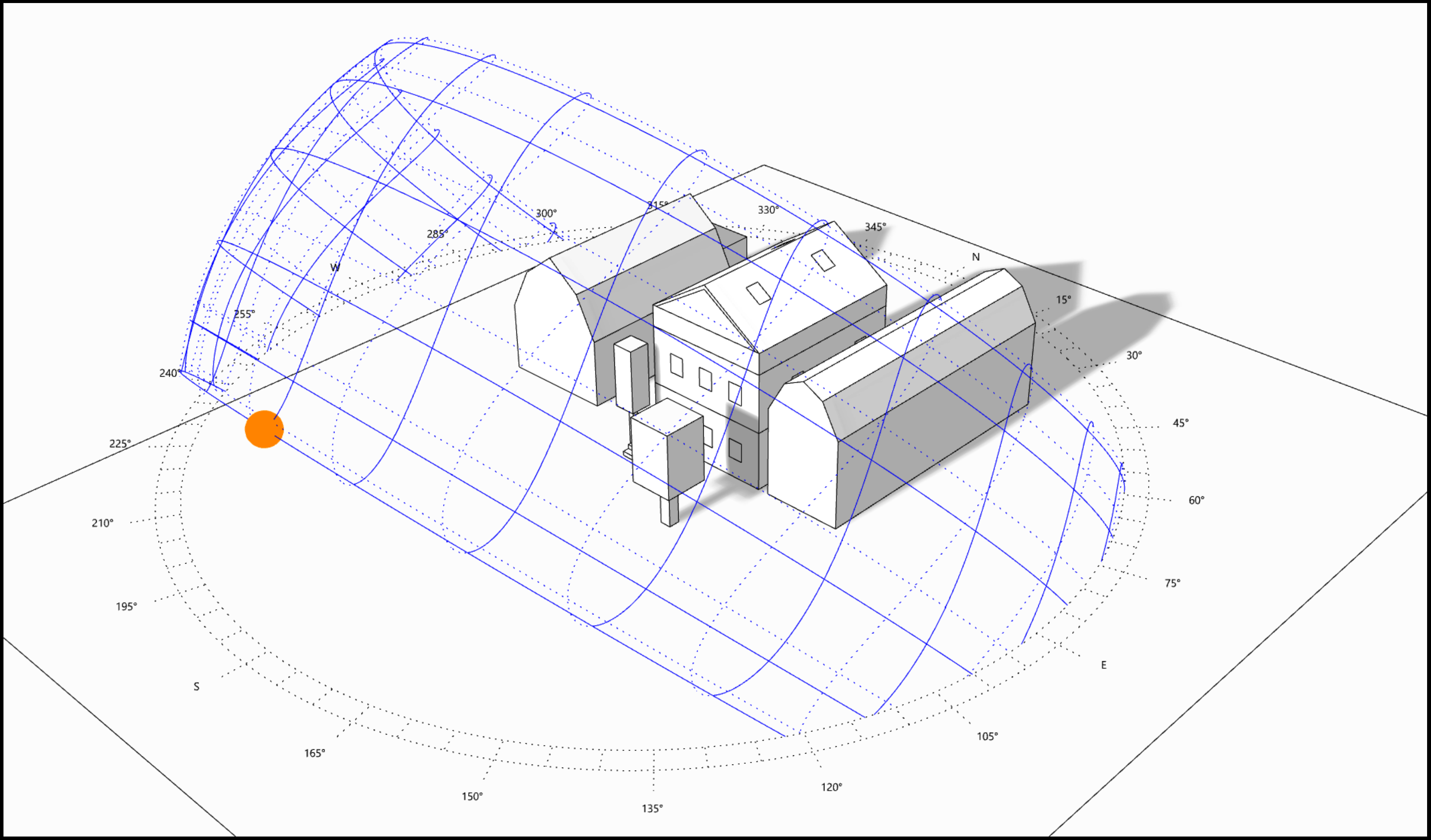
L06 Active Solar

Massachusetts Institute of Technology
Department of Architecture
Building Technology Program

Sky Models

Chapter 9: Radiation Maps

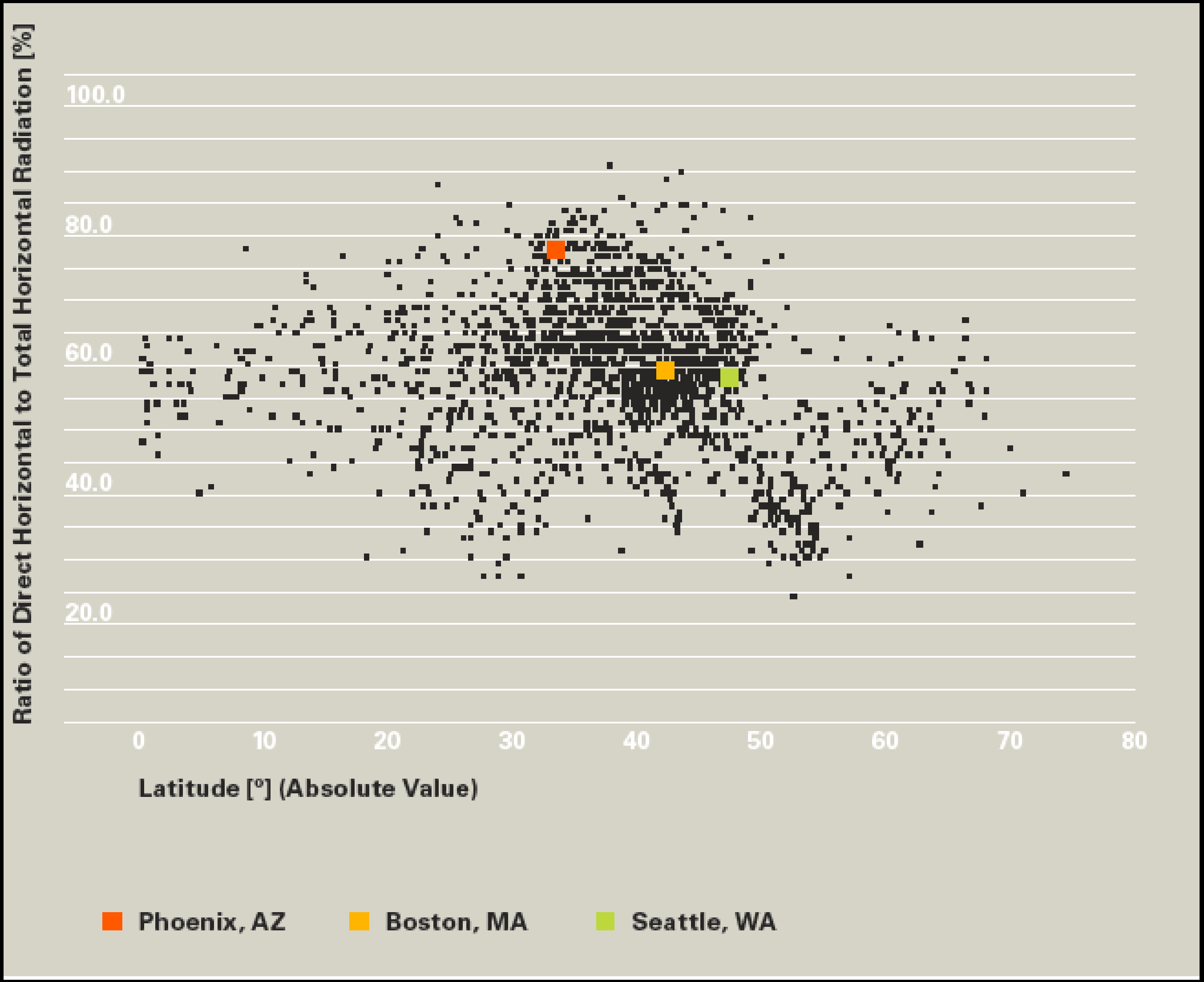
We already know where the sun is.



- ❑ However, total solar radiation is direct + diffuse solar radiation.
- ❑ For surfaces facing away from the equator most solar radiation is diffuse.

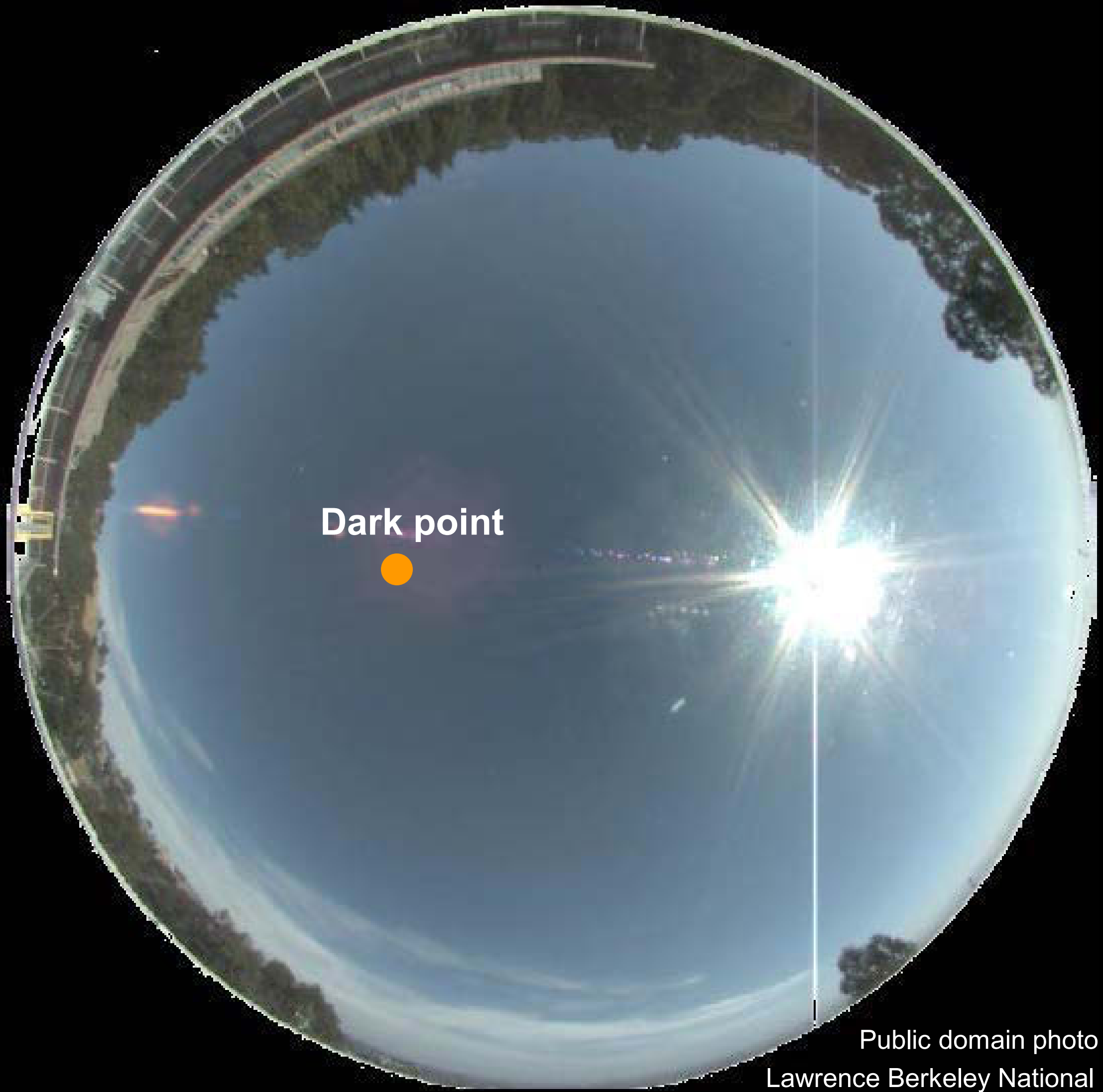
What percentage of total solar radiation does direct sunlight cover?

Ratio of Direct to Total Solar Radiation



- ❑ 50-70% of all solar radiation is direct.
- ❑ I.e. you always should know where the sun is.

Sky Models



Public domain photo courtesy of Lawrence Berkeley National Laboratory.

- Diffuse solar radiation is described through a sky radiance distribution function.

Dark Spot Explained

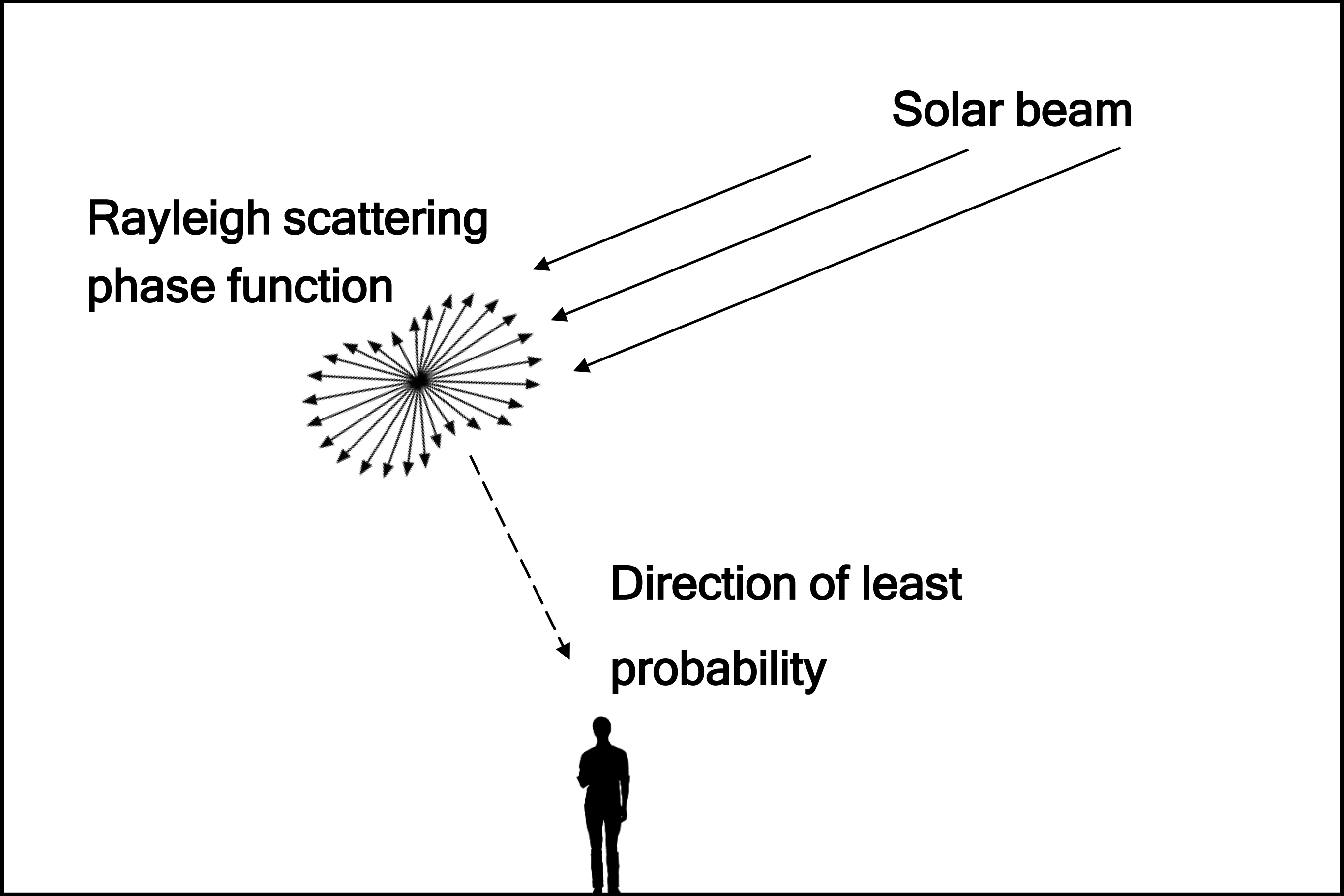
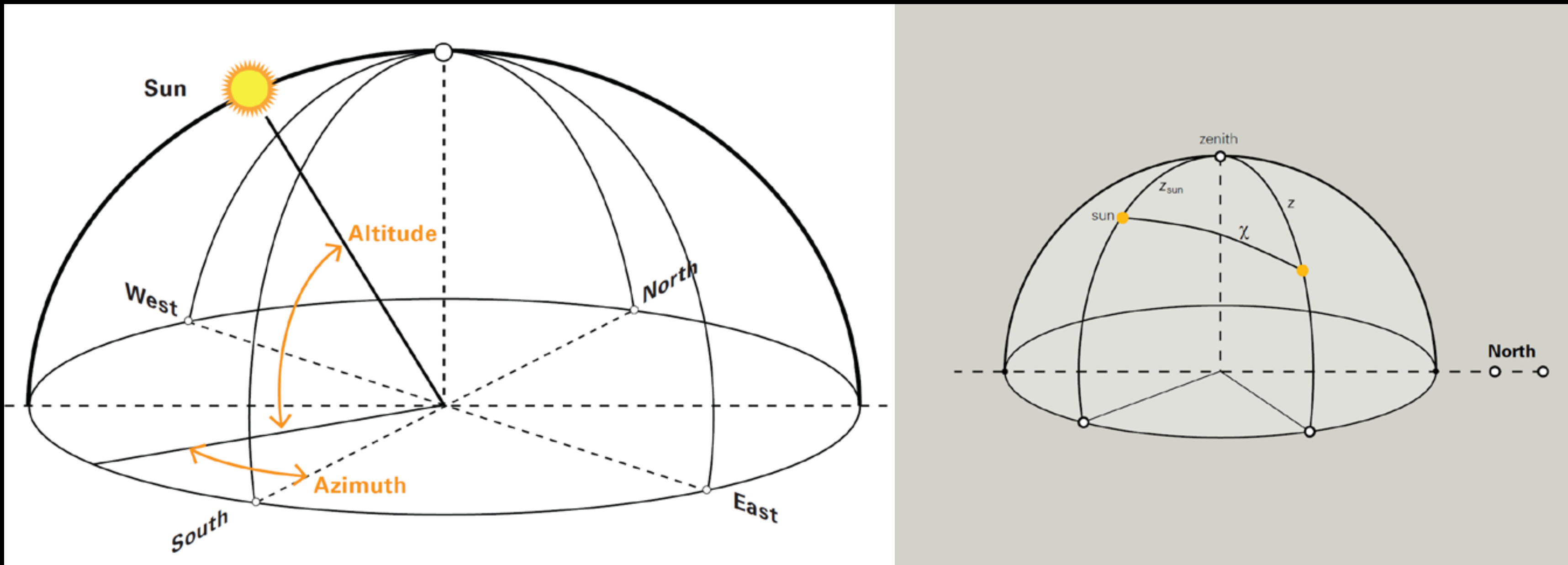


Figure courtesy of J. Sargent, Solemma.
Used by permission.

Sky Models



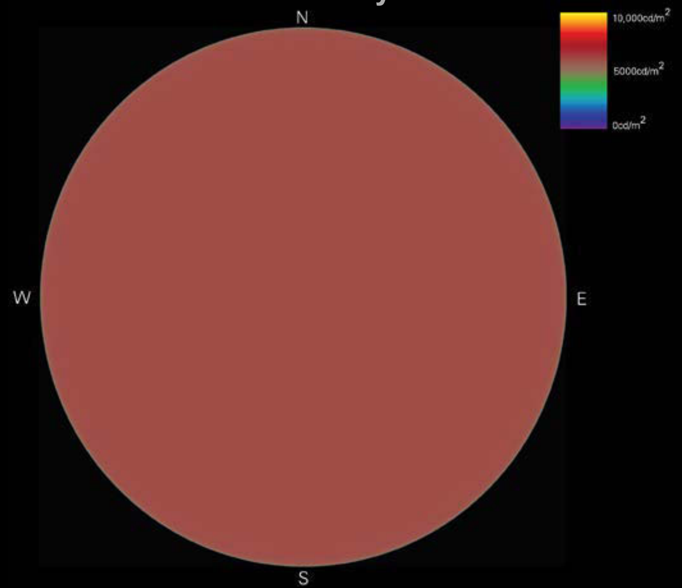
$$\frac{L}{L_{zenith}} = \frac{f(\chi)}{f(Z_{sun})}\,\frac{\varphi(Z)}{\varphi(0)} \text{ with } \varphi(Z) = 1 + a\,e^{b/\cos(Z)};\ f(\chi) = 1 + c[e^{d\chi} - e^{d\pi/2}] + e\cos^2(\chi)$$

Equ 9-2

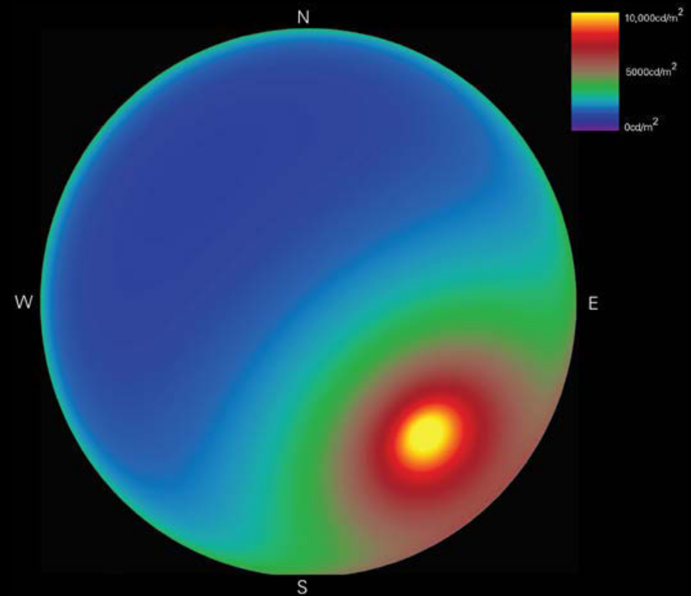
- ❑ Sky radiance distribution functions are defined using a different coordinate system than azimuth and altitude.
- ❑ $\varphi(\chi)$ is called the radiance gradation function. It defines the changes of luminance from horizon to zenith. For a uniform sky this function corresponds to unity (a=0).
- ❑ $f(\chi)$ is called the scattering indicatrix. It relates the changes of luminance of a sky segment to its angular distance from the sun (circumsolar region).

Sky models

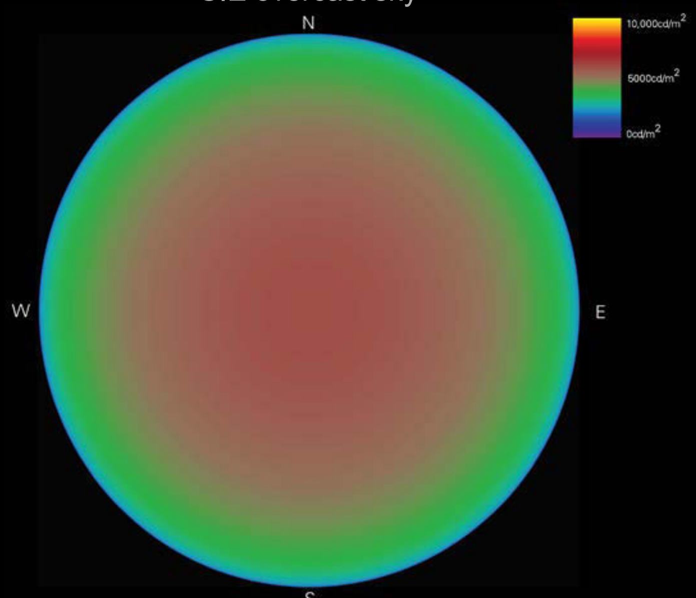
Uniform sky



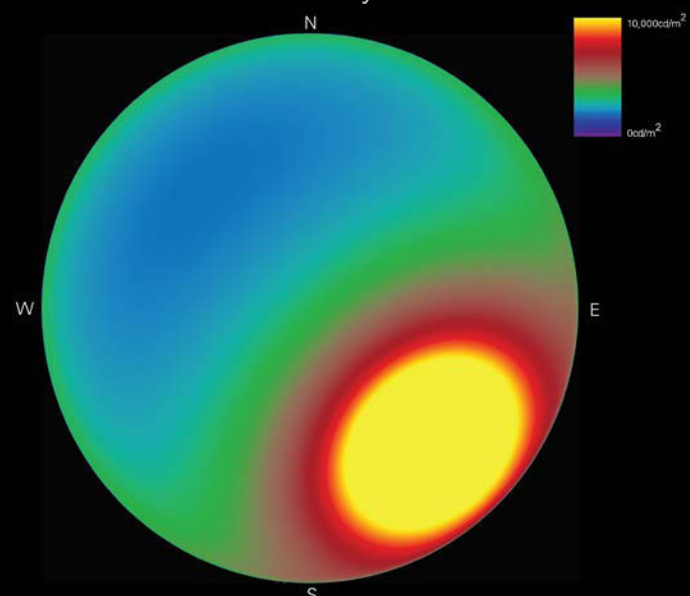
CIE clear sky



CIE overcast sky

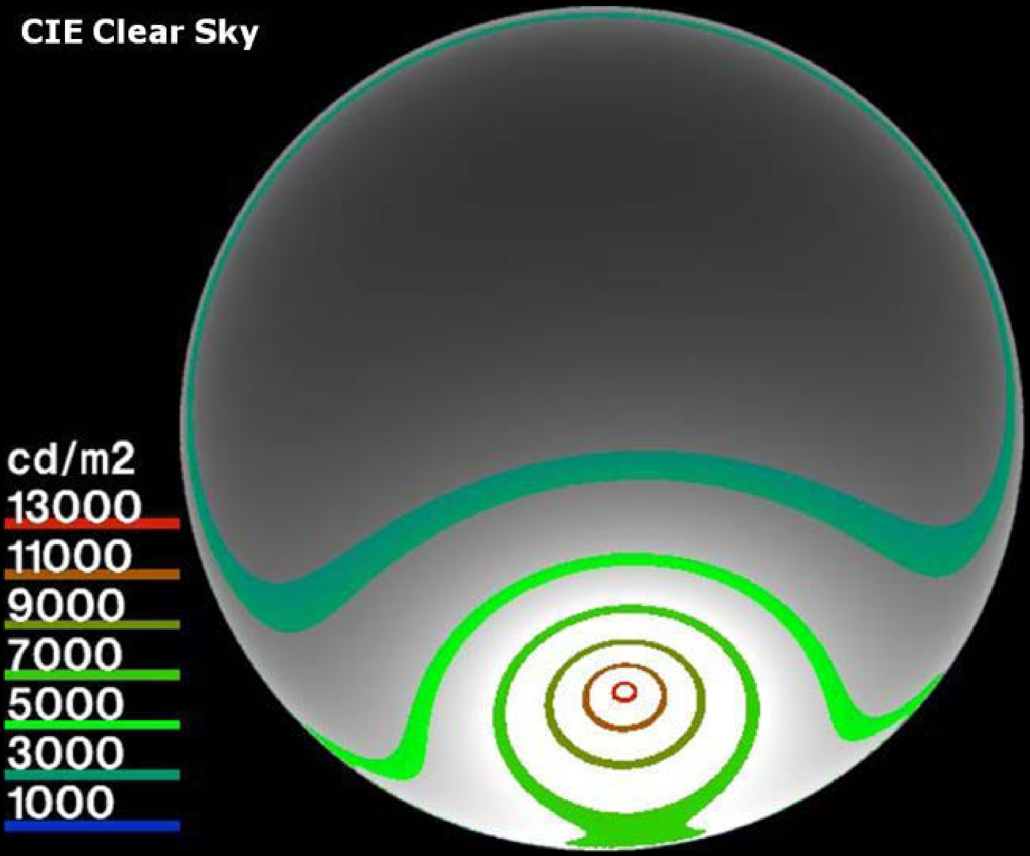


Perez sky

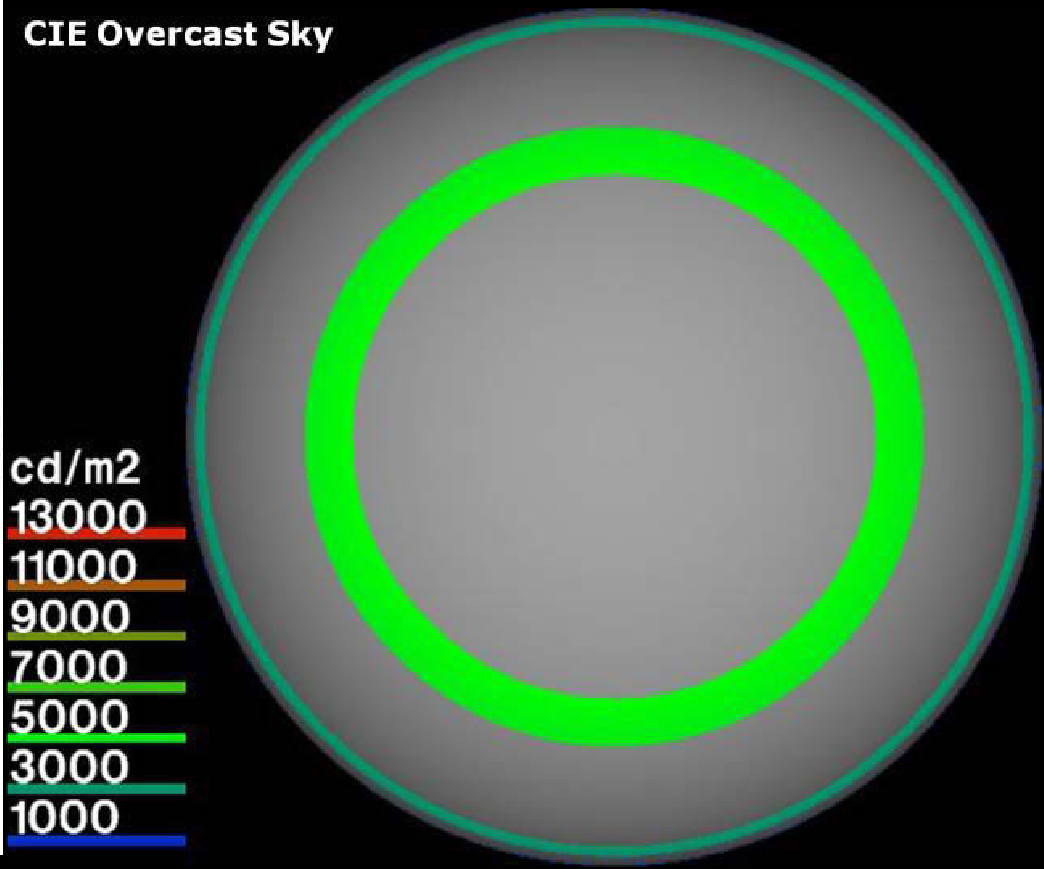


❑ Input for Perez from TMY climate files

Visual Comparison: CIE Clear vs Real Sky

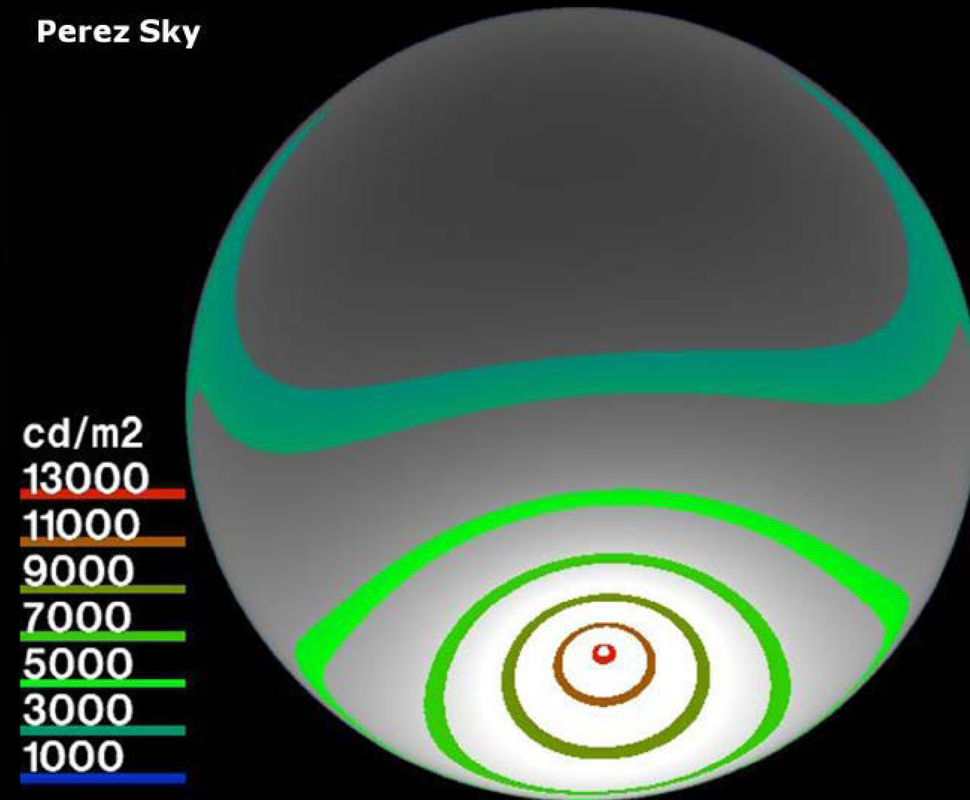


Visual Comparison: CIE Overcast vs Real Sky



MIT SDLAB

Visual Comparison: Perez vs Real Sky

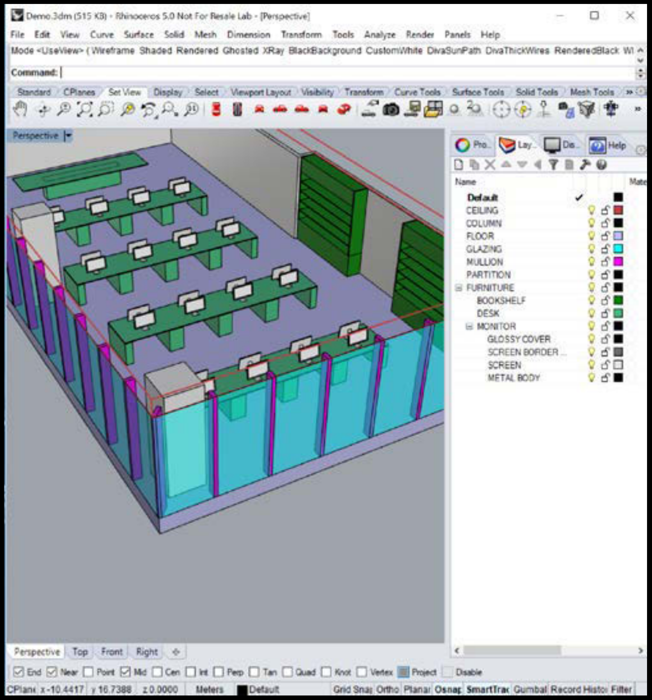


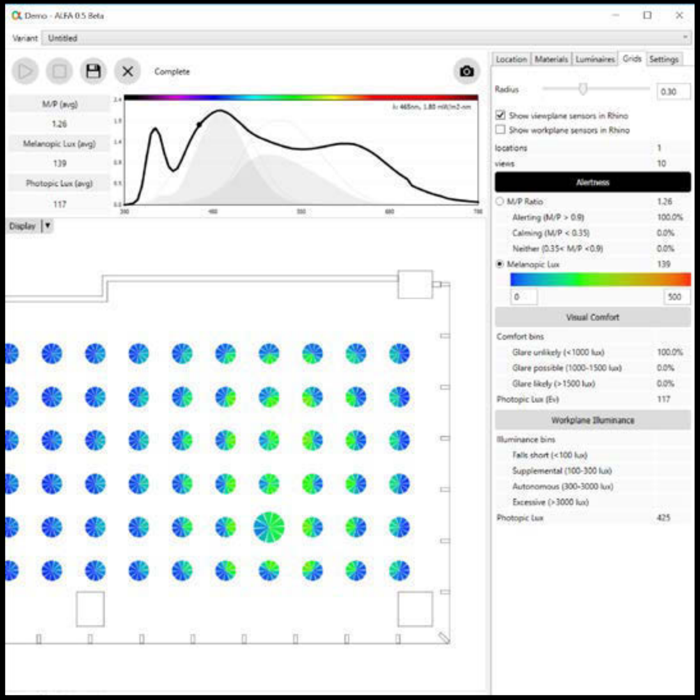
Utah Sky

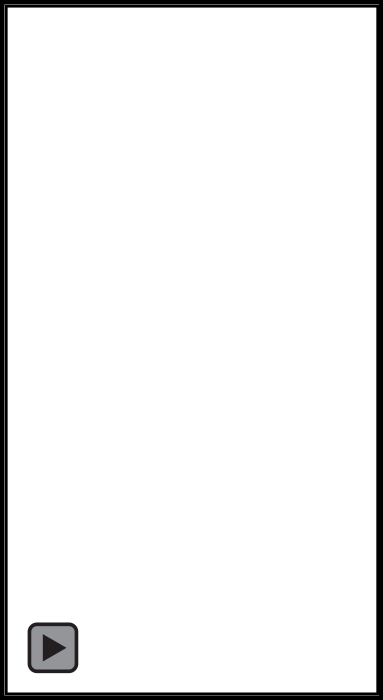
Fig 9.9 Radiance simulation of sunrise at Yavapi Point, Grand Canyon, using the Utah sky model (Simulation: Mark Stock)

Fig 9.10 Radiance simulation of a mirrored sphere under hemispheric HDR photographs of a sky during midday (left) and sunset (right) (Simulation: Mark Stock)

Adaptive Lighting For Alertness)







https://www.solemma.com/Alfa.html

- ❑ ALFA features a spectral sky model, spectral opaque and glazing material descriptions, and a path-tracing-like approach based on Radiance.

ALFA Sky Model Based on libtran

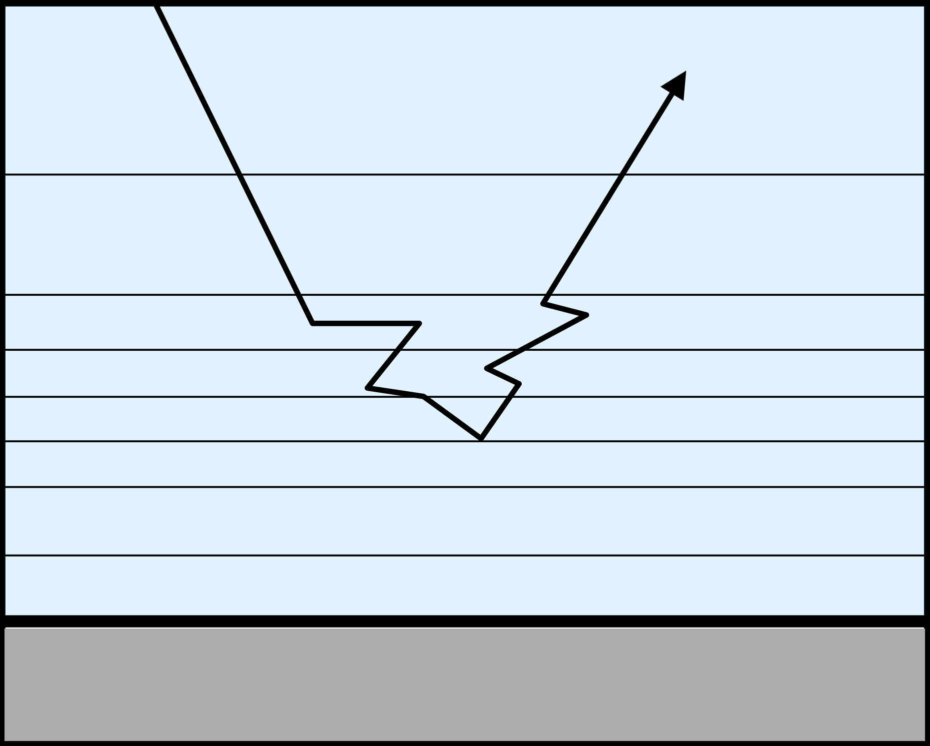


Figure courtesy of J. Sargent, Solemma. Used with permission.

libRadtran (Mayer et al, libradtran.org)

- ❑ **Radiative transfer library used by climate science community**
- ❑ **Comes with discrete ordinate and monte carlo solvers**
- ❑ **1D (plane parallel)**
- ❑ **Accurate calculation of radiance, irradiance, actinic flux**
- ❑ **(Psuedo)spherical**
- ❑ **Library of atmospheric profiles**

❑ ALFA features a spectral sky model, spectral opaque and glazing material descriptions, and a path-tracing-like approach based on Radiance.

ALFA Sky Model Based on libtran

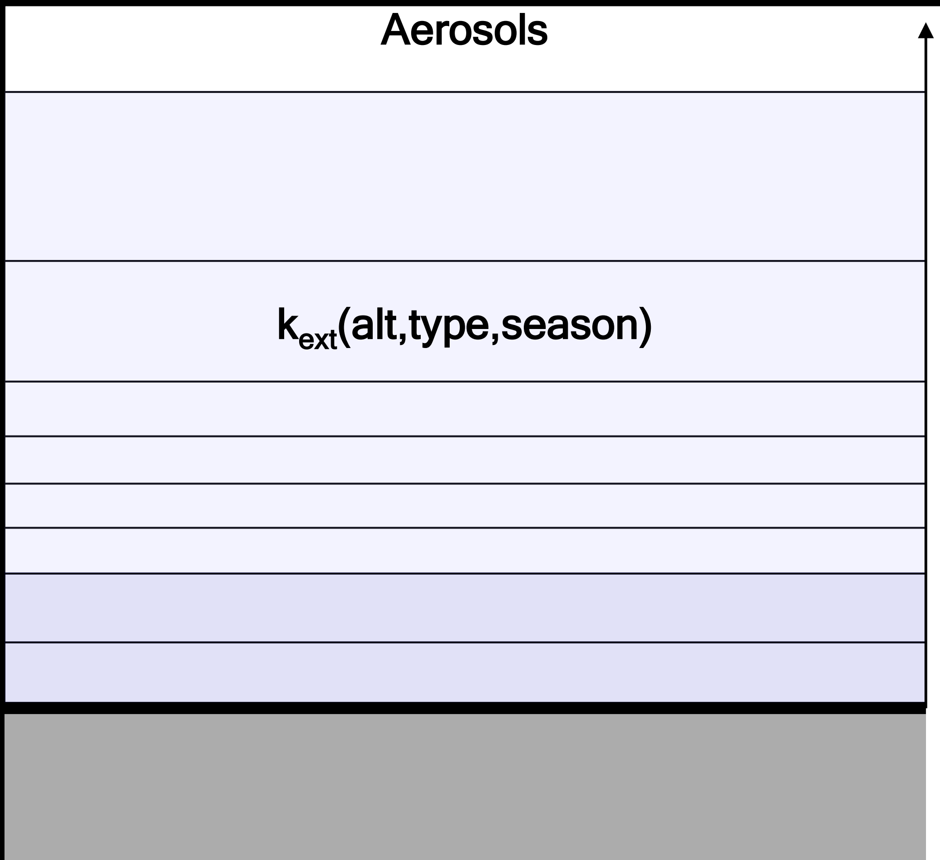
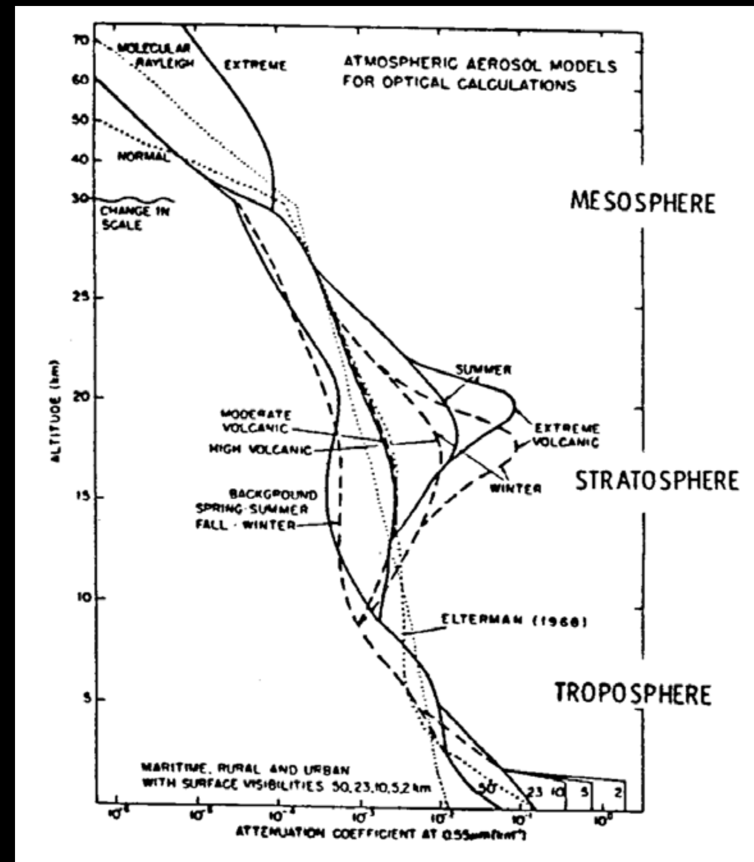
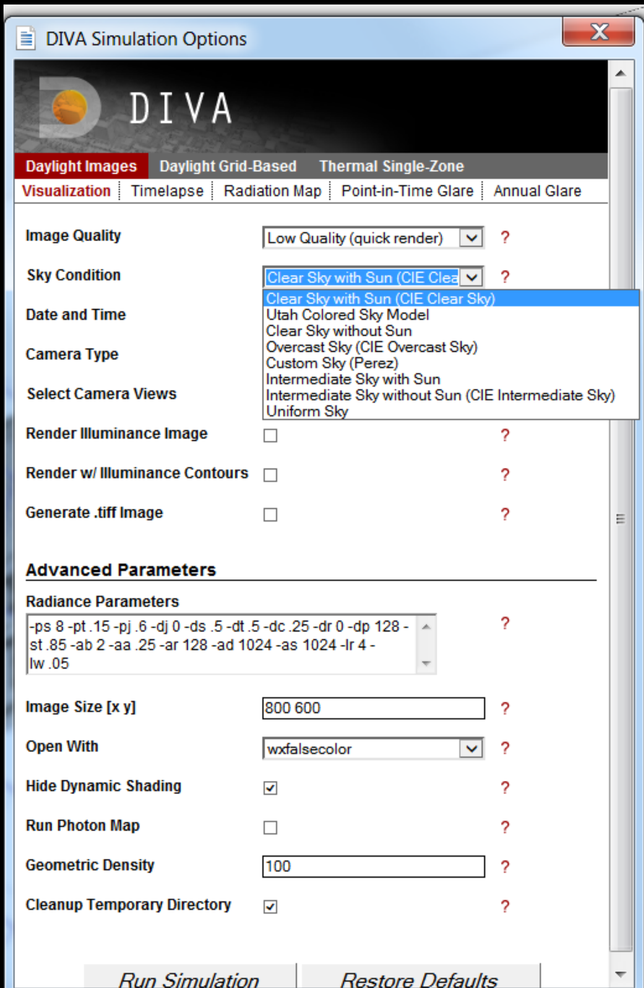


Figure courtesy of J. Sargent, Solemma. Used with permission.

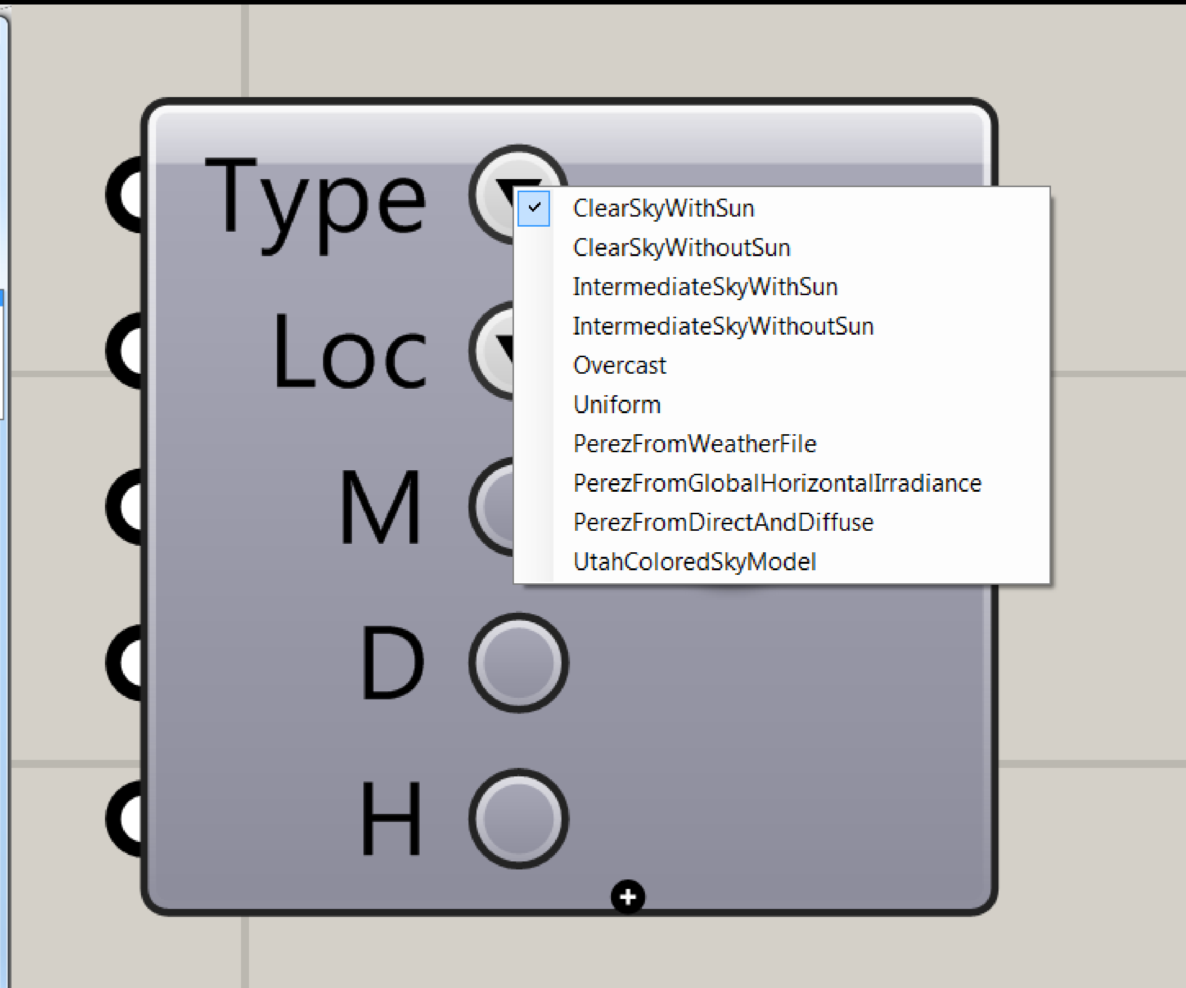


- ❑ The spectral sky model according to libtran

DIVA 4



DIVA-Rhino Visualization

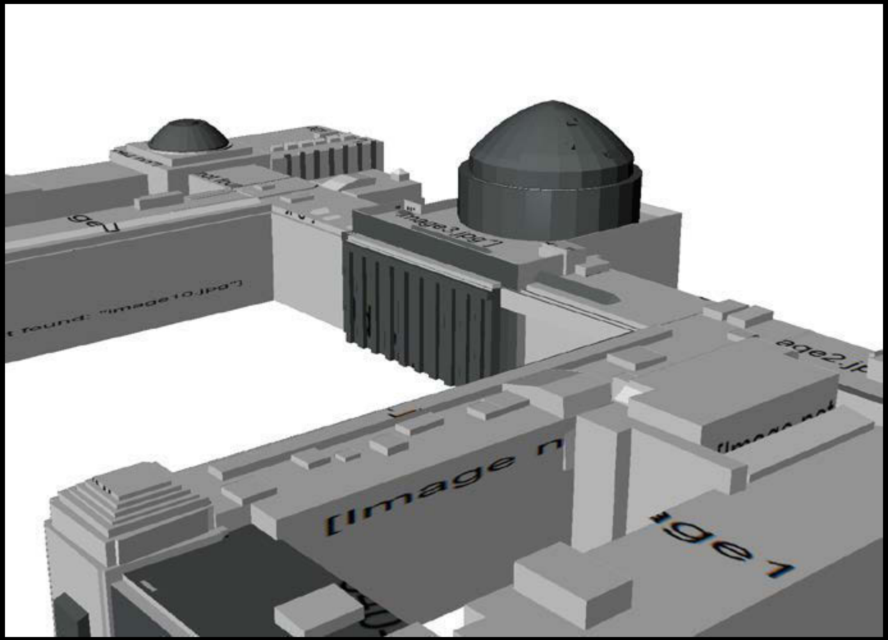


DIVA-GH Sky Definition

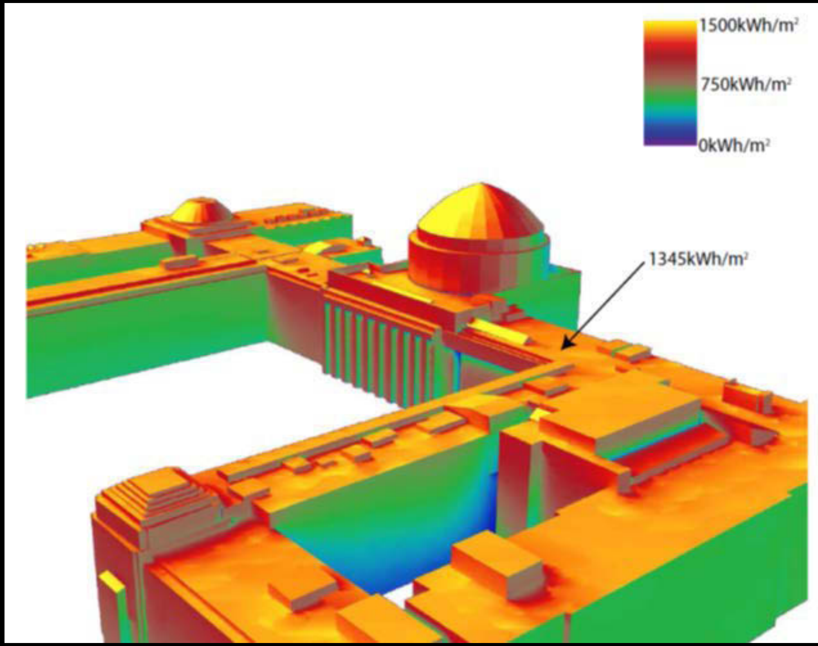
Radiation Maps

How to Calculate Solar Radiation in an Urban Setting?

DIVA for Rhino

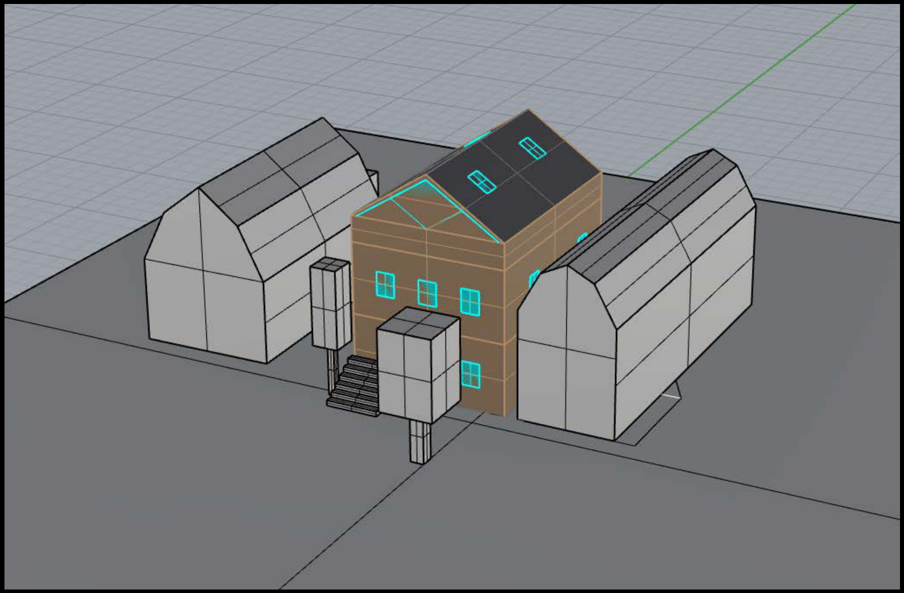


Rhino Model

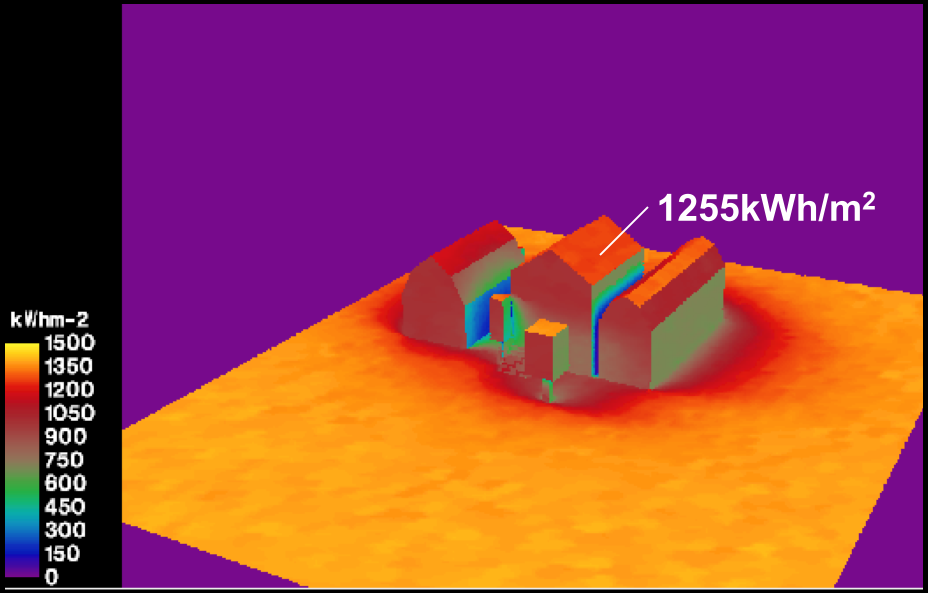


Radiation Map

Assignment 4 – PV Analysis



Rhino Model



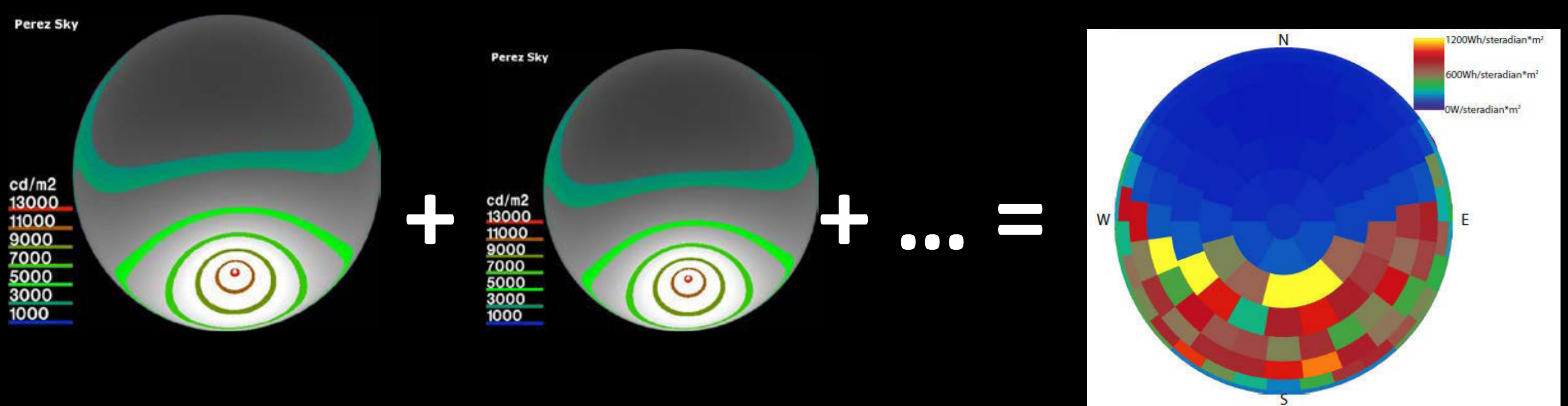
Radiation Map

How does the calculation work?

- ❑ Step (1): Uses EnergyPlus annual climate data.

How does the calculation work?

- ❑ Step (1): Uses EnergyPlus annual climate data.
- ❑ Step (2): Generate Perez sky radiance distribution for each hour of the year/of interest.
- ❑ Step (3): Add up sky conditions for hours of interest and store the values in 145 bins.



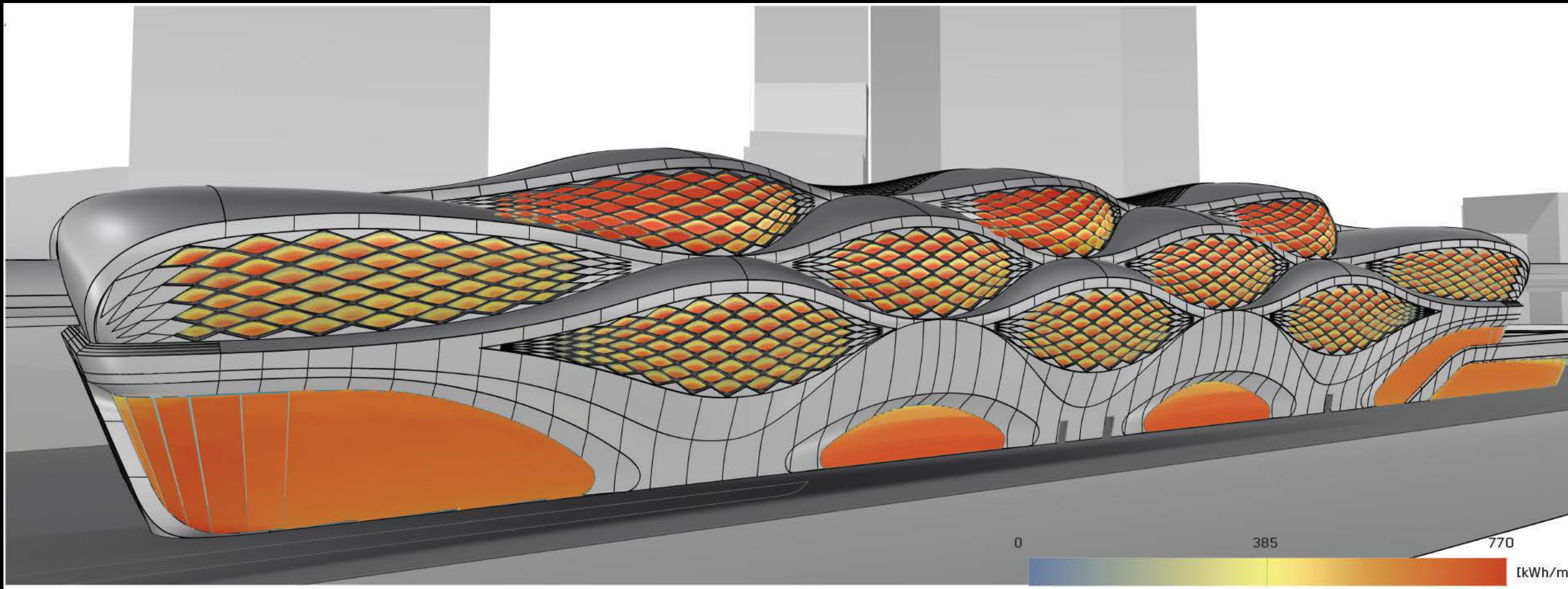
Sky on Jan 1 at 7AM

Sky on Jan 1 at 8AM

Cumulative Sky

Cumulative Sky proposed by several authors including Mardaljevic, Compagnon, Robinson & Stone.
We are using Robinson & Stone's approach.

KAFD Metro Station, Riyadh

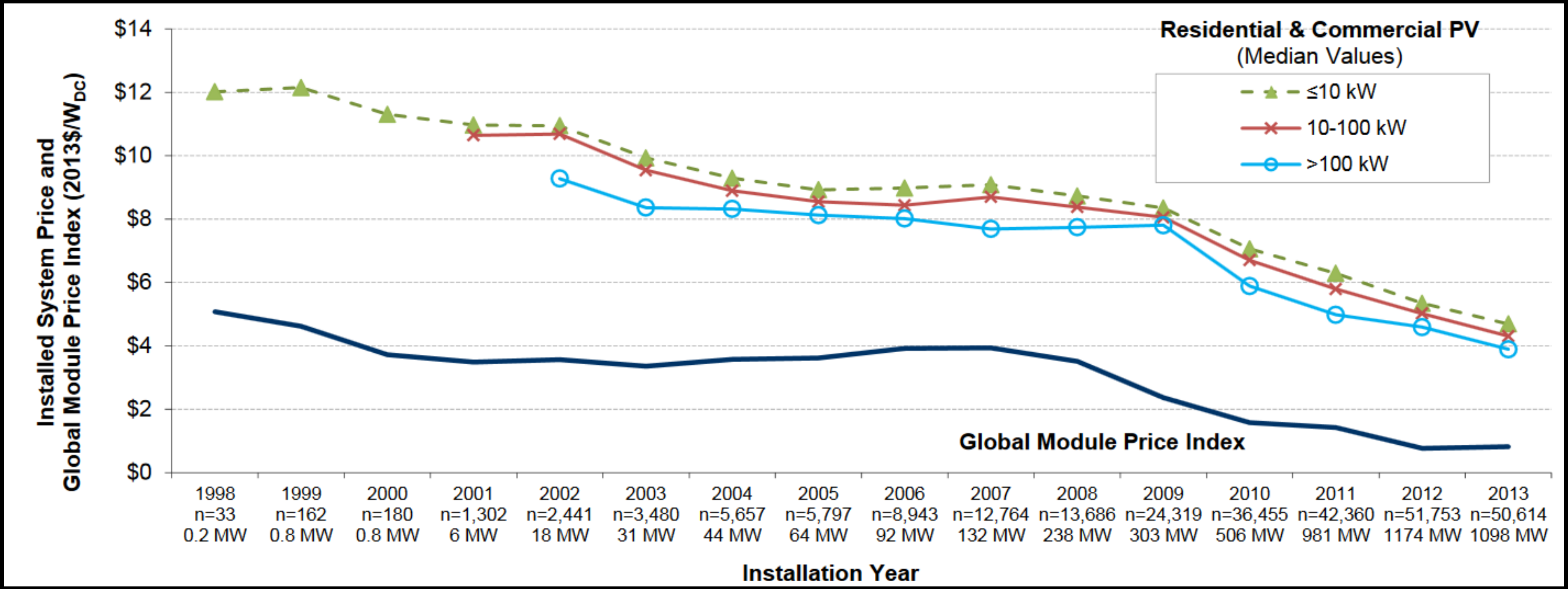


Active Solar

Definition

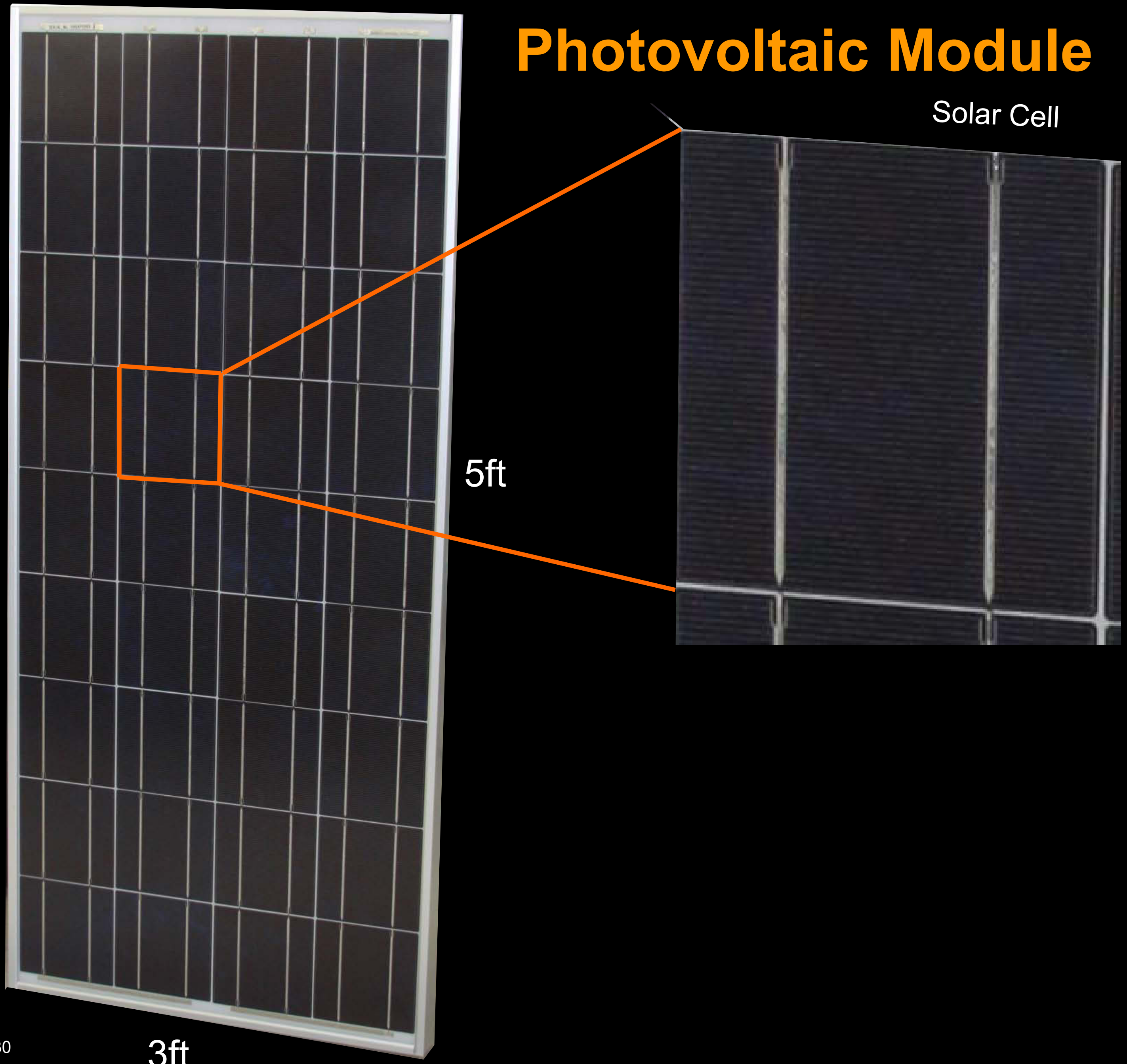
As opposed to “passive,” load-reducing design features, “active” solar design measures use the energy from the sun to generate energy either in the form of heat (solar hot water) or electricity (photovoltaic).

Price Development



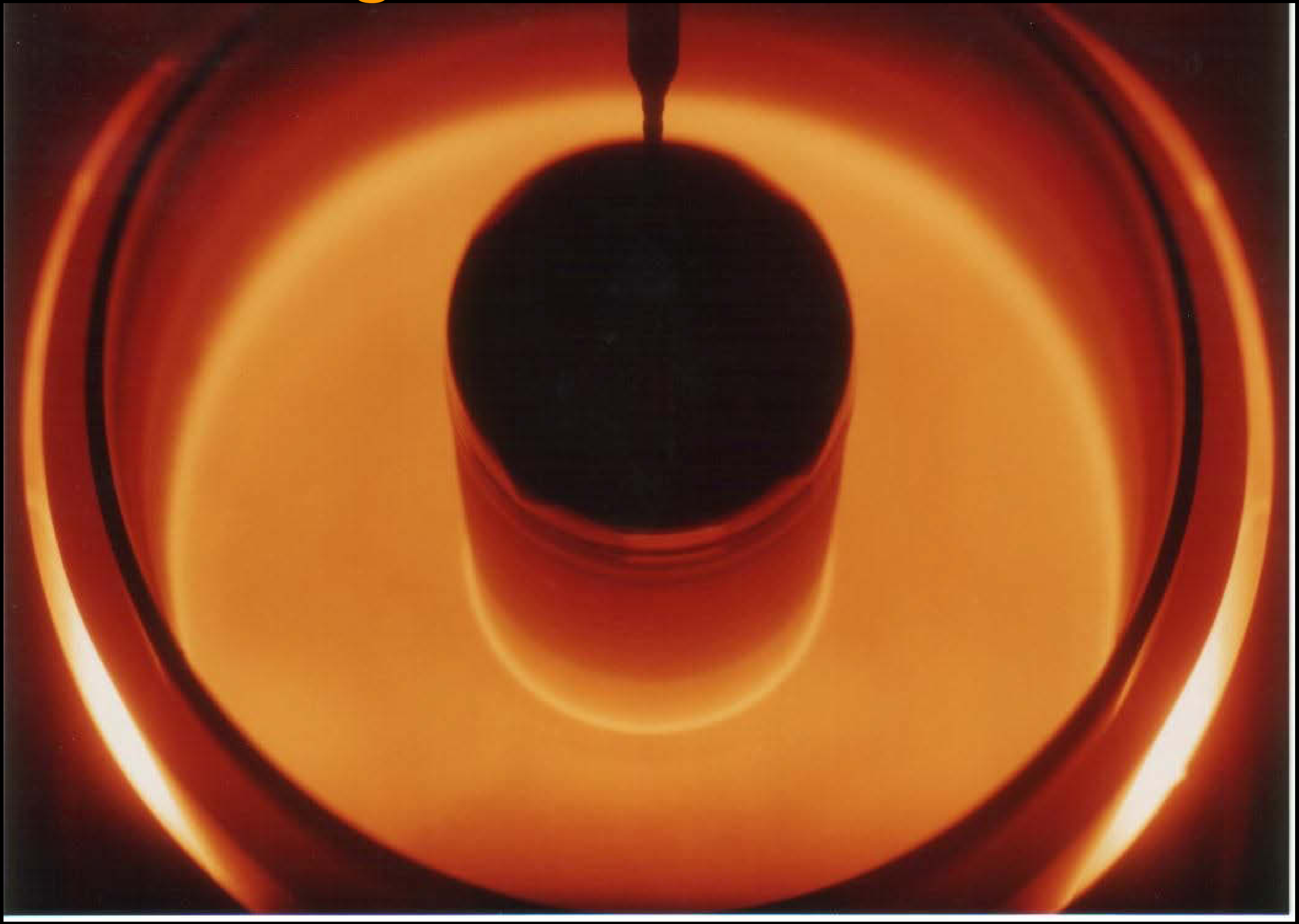
- The current quoted price in Cambridge is 3.50 US /W_{installed}$
- Observe installation versus module costs.

Photovoltaic Module



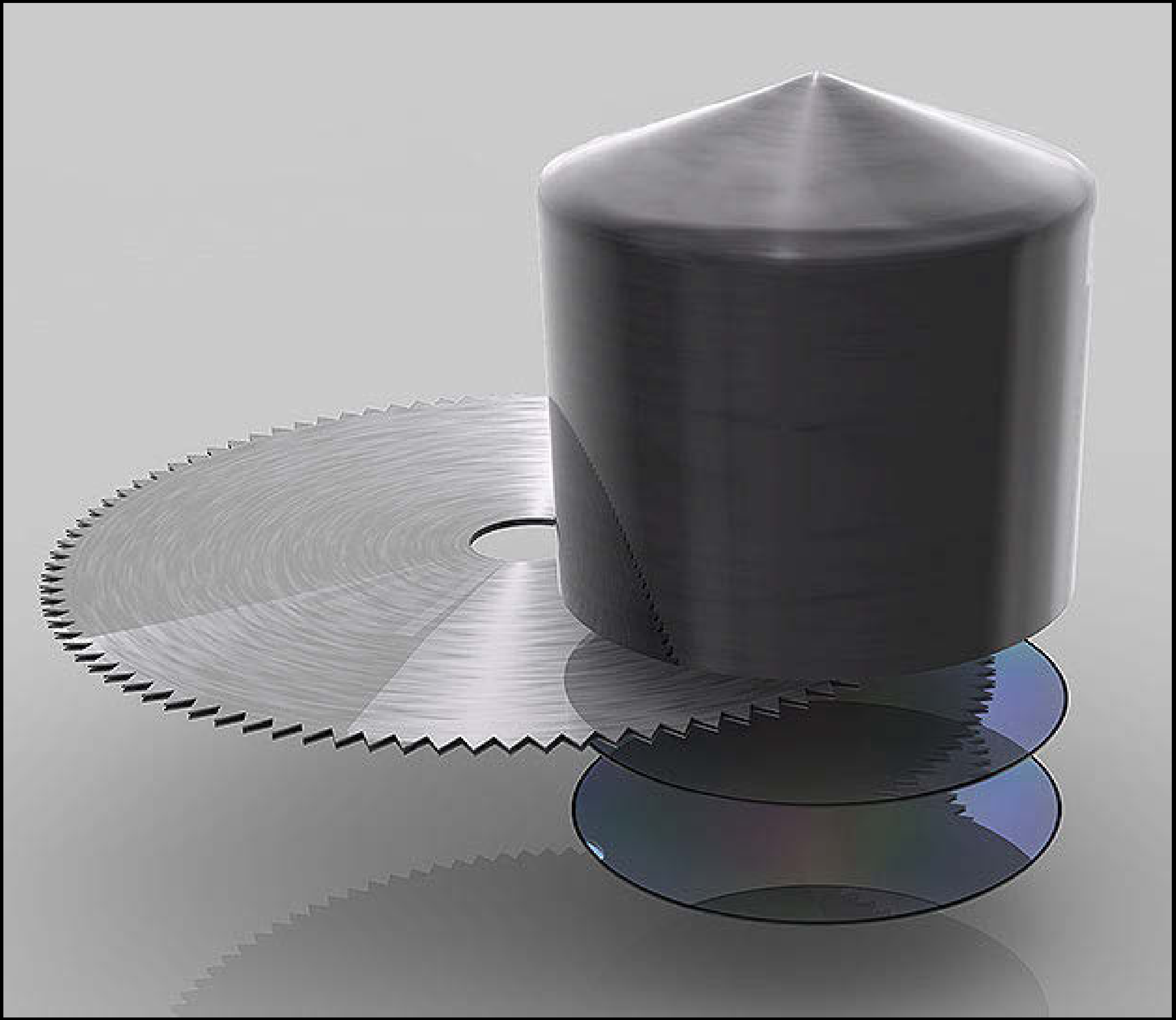
Sand

Silicon Ingot Production

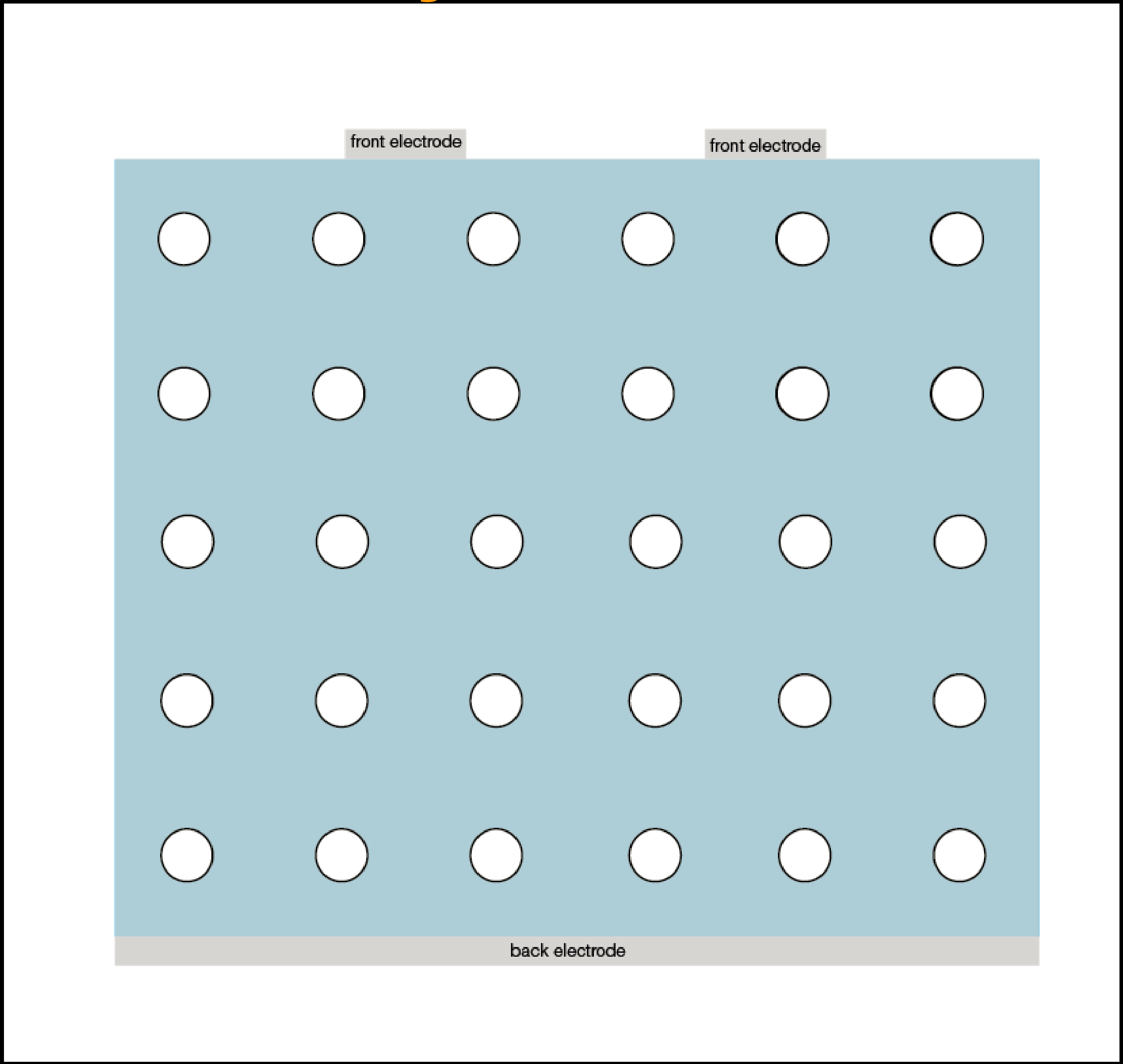


MIT SDLAB

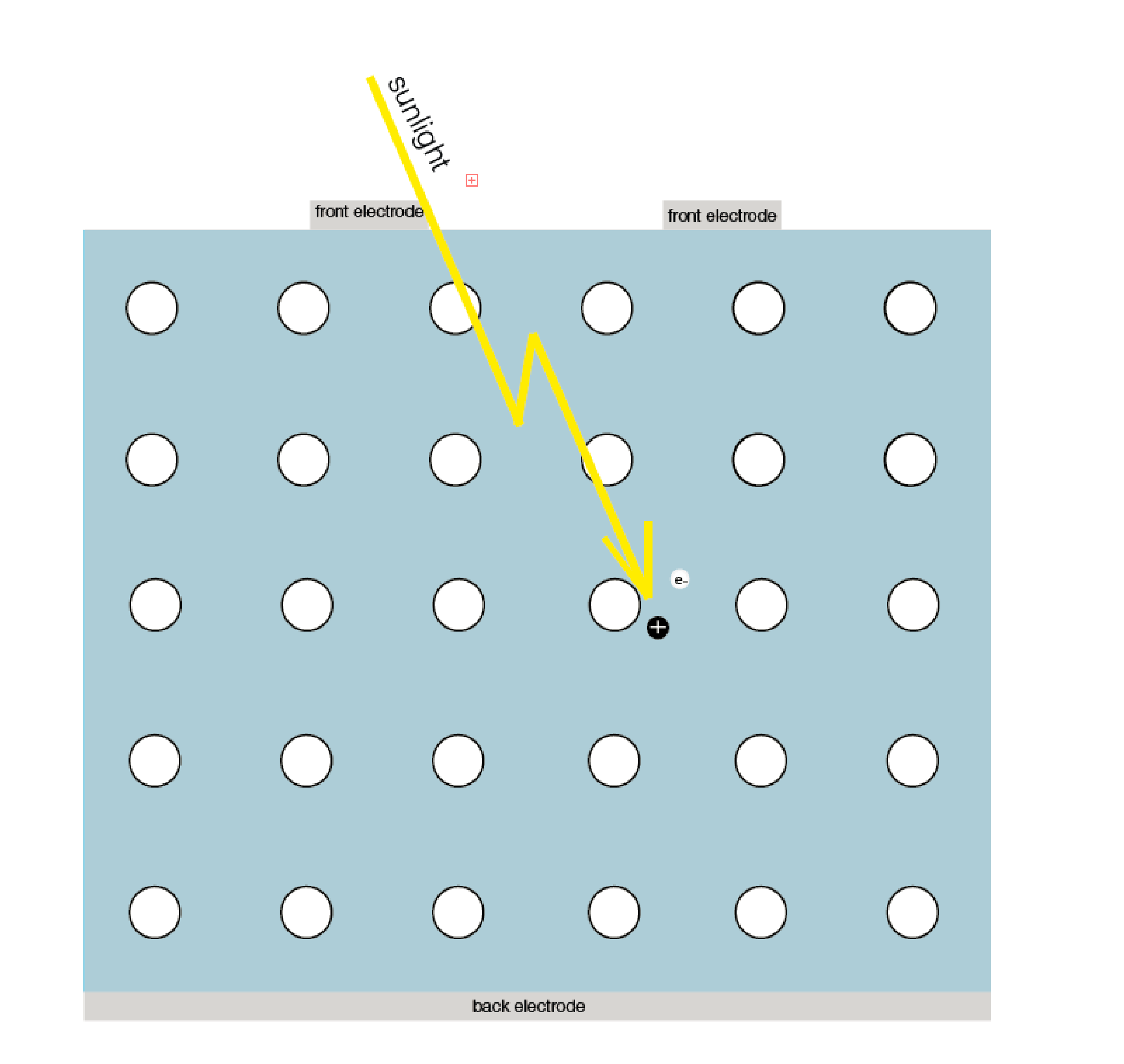
Cutting the Wafers



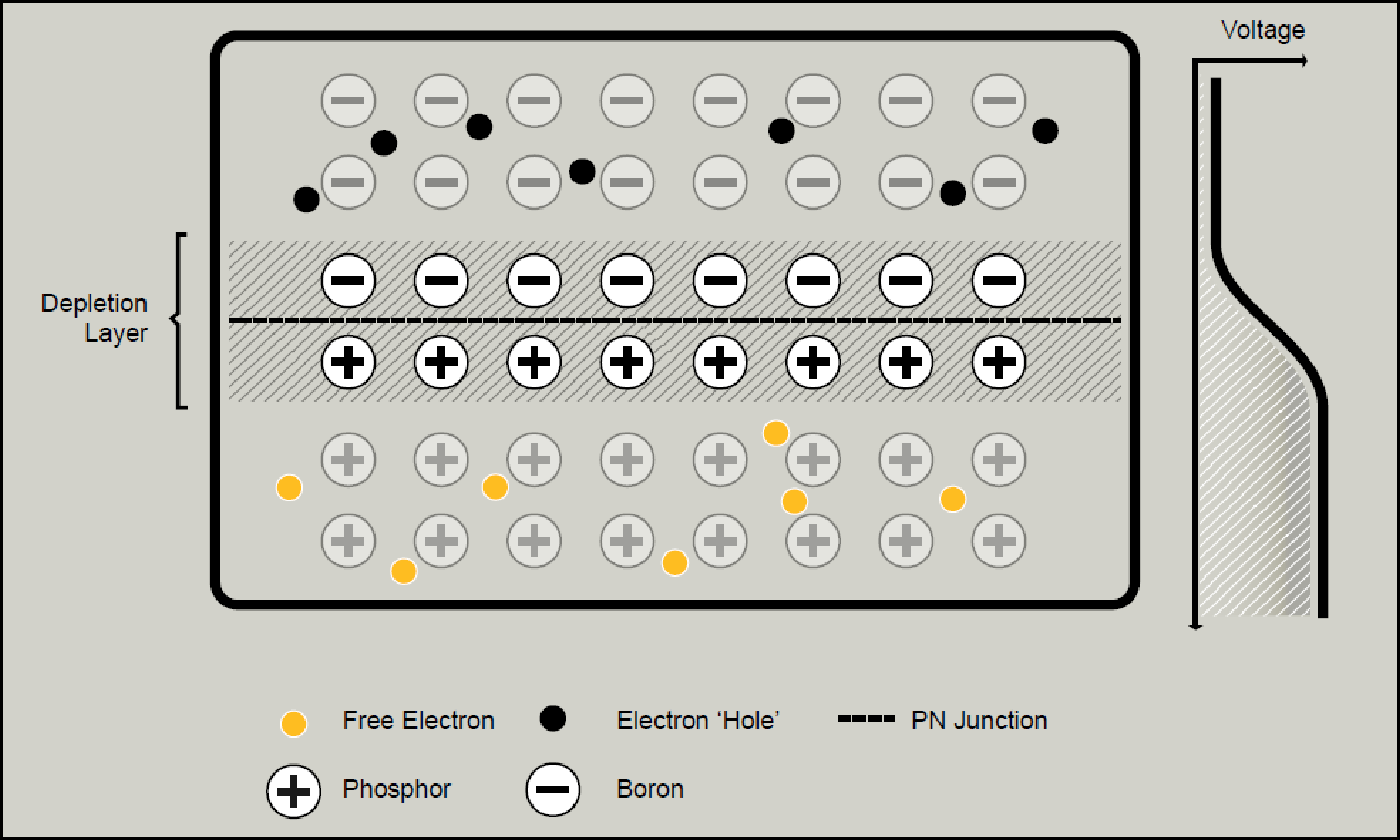
Silicon Crystal



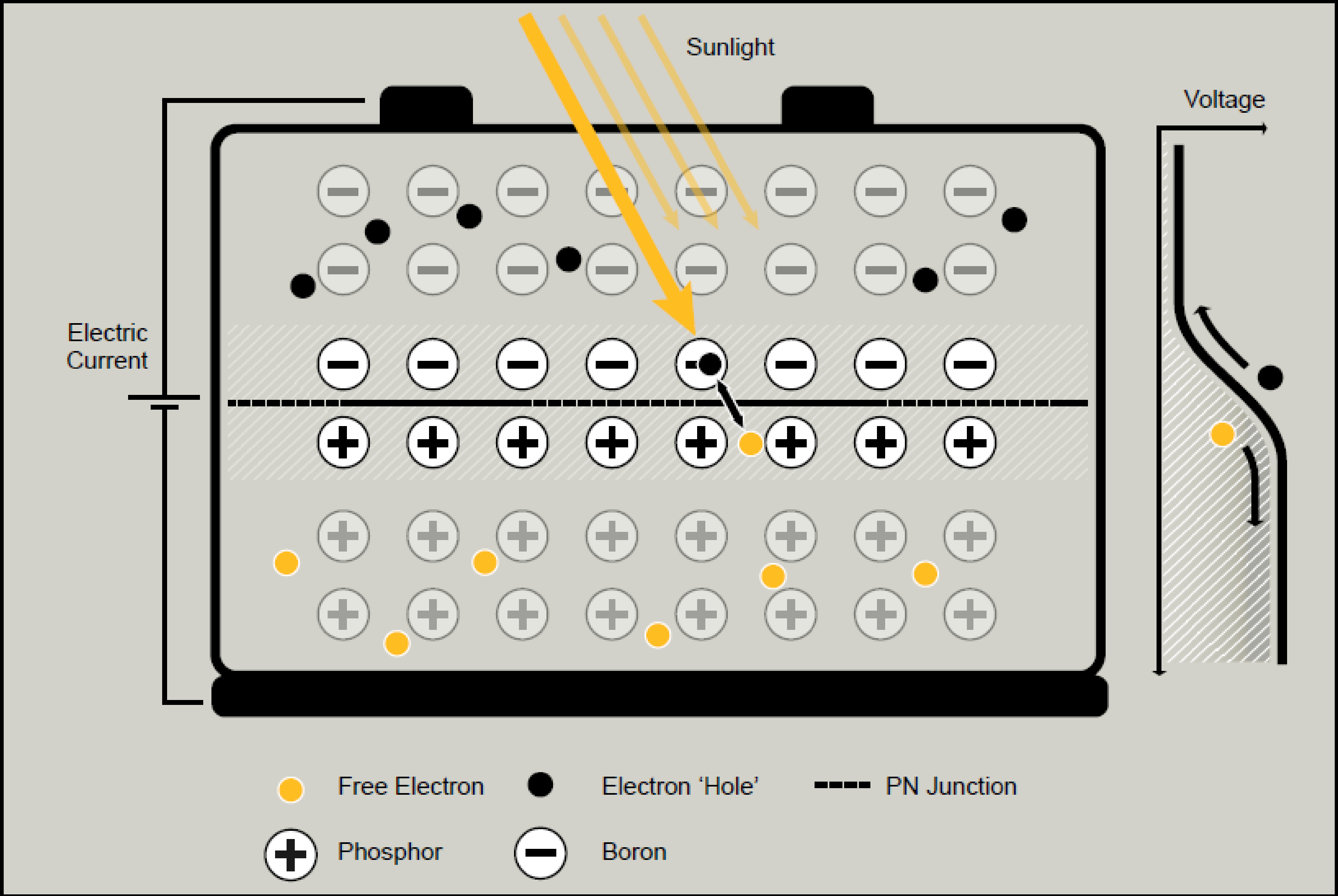
Silicon Crystal (illuminated)



PN-junction

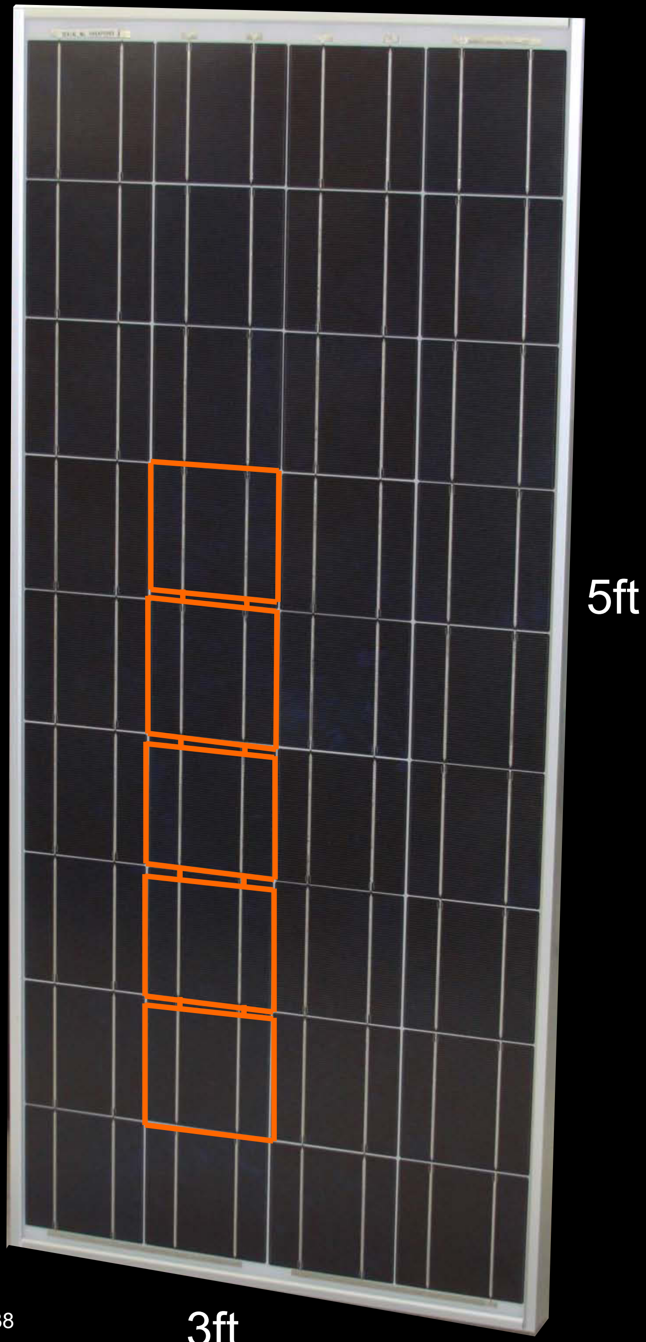

Voltage
Depletion
Layer
Free Electron
Electron 'Hole'
PN Junction
Phosphor
Boron

Solar Cell (illuminated)



- Solar cells generate electricity when the light shines on them.
- More sunlight radiation results in more electricity.
- When solar cells heat up, their efficiency goes down.

Photovoltaic Module

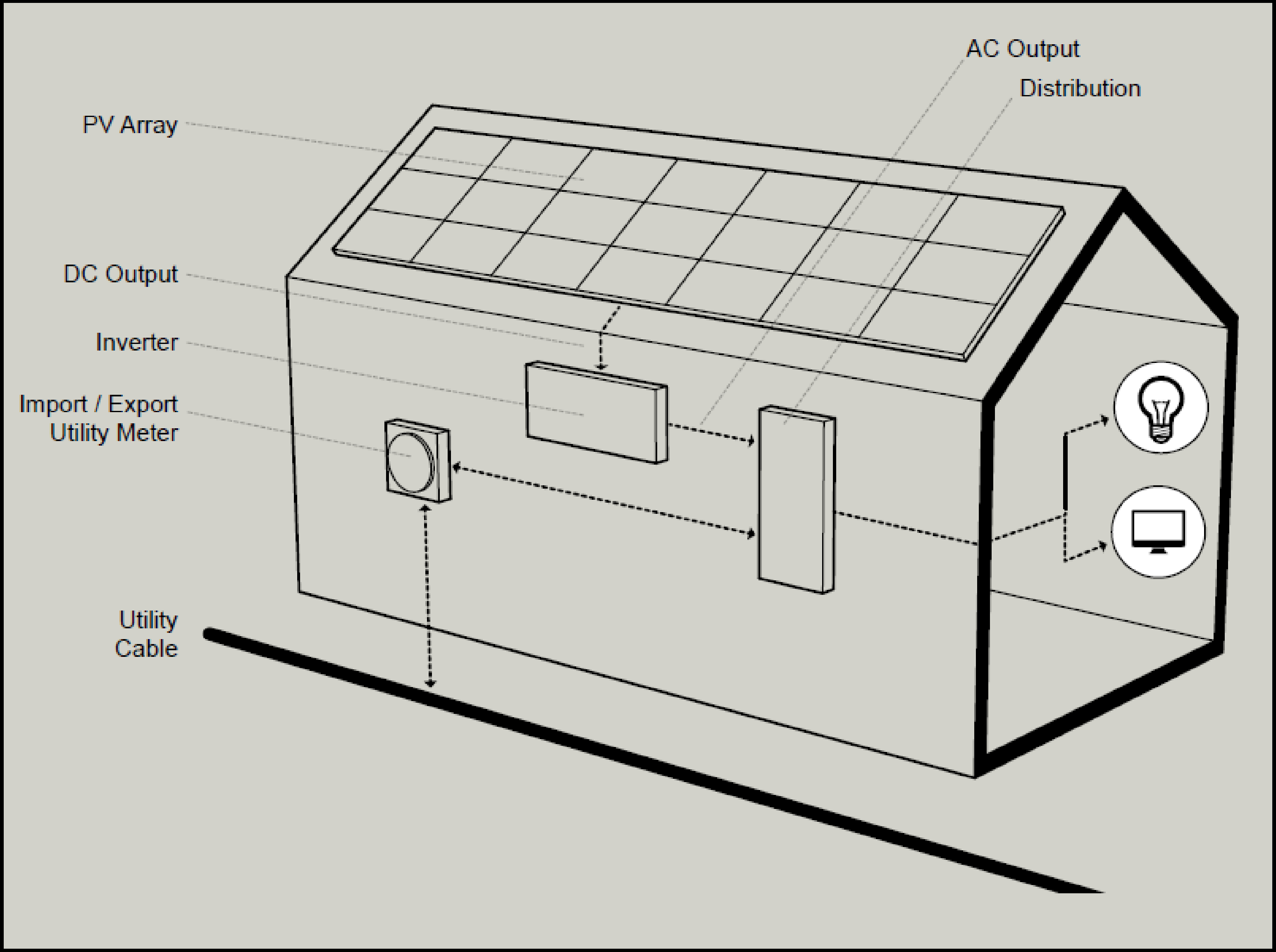


- Maximum Power ~300W under standardized conditions.
- Solar cells are connected in series leading to about 12V output.
- The electric output of a module drops significantly when one or several cells are shaded.

Using the Grid as a Battery

MIT Building W-20, Student Center (Photo courtesy of Alstan Jakubiec. Used by permission.)

Example Residential System



PV Design Guidelines

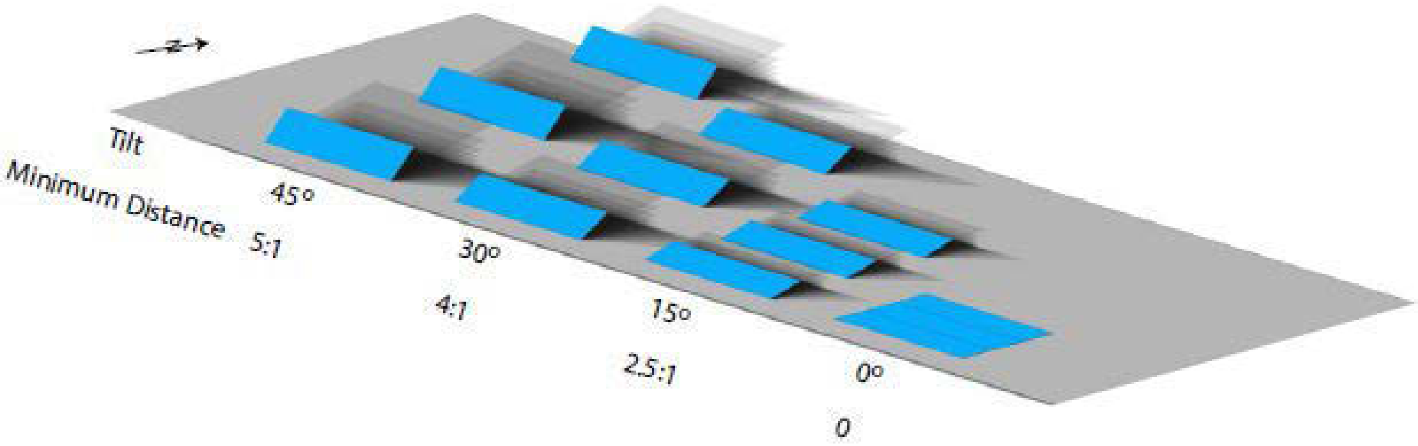
Pick areas of maximum solar exposure: Solar panels generate electricity when solar radiation is incident on them. More solar radiation increases the electricity yield.

Avoid partial shading: Within a PV panel, solar cells are connected in series. If part of a solar panel is temporarily shaded by a nearby chimney or comparable object, the shaded cell becomes a bottleneck for the electric current going through the panel causing the shaded cell to heat up. Beyond a certain temperature a bypass diode will prevent damage to the system by stopping all current from going through, it reducing the electricity yield temporarily to zero even though the sun is shining.

Keep the cells cool: The efficiency of solar cells decreases with increased cell temperature. If possible, rooftops should therefore be kept cool by – for example – increasing the roof's surface albedo. Another technique is to mount the panels off the roof so that they are back-ventilated.

Place HVAC equipment on the side of a roof that is furthest away from the equator: It is advantageous to have solar panels shade rooftop equipment rather than the other way around.

Consider trees and surrounding objects: Remember to include all objects that might shade a potential PV system in your analysis scene, especially deciduous trees which may seem inauspicious during winter months.



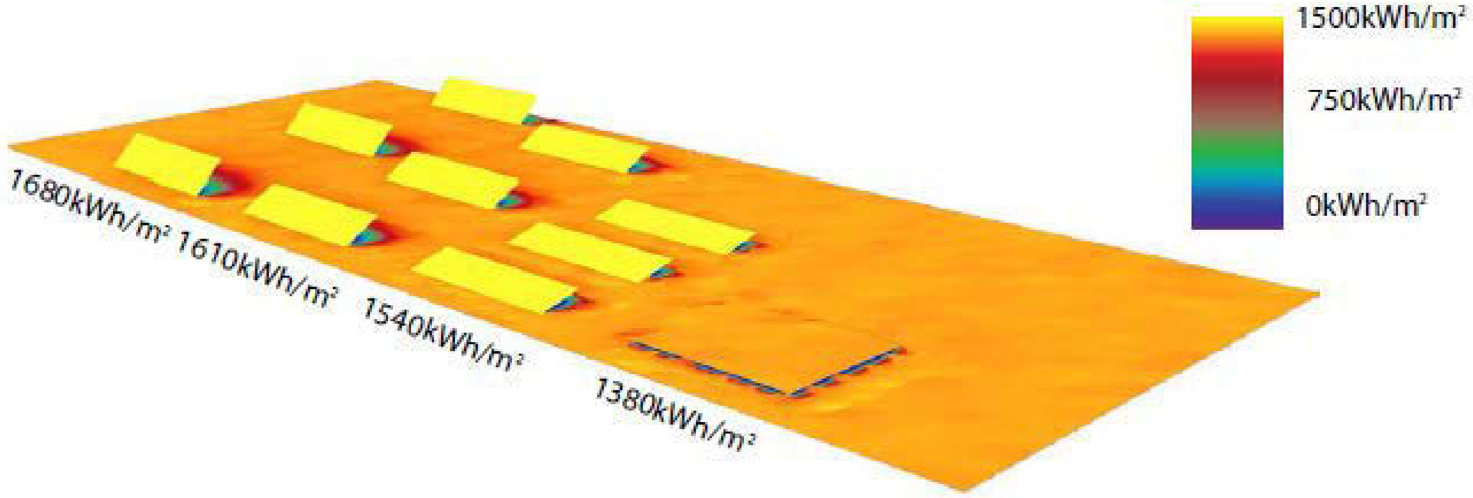


Fig 9.15 Radiation map and shading study of rows of solar panels in Cambridge

Building integrated PV

South North

Integration of Daylighting with Photovoltaics

Calculating PV Electricity yield

Case Study: MIT Dome

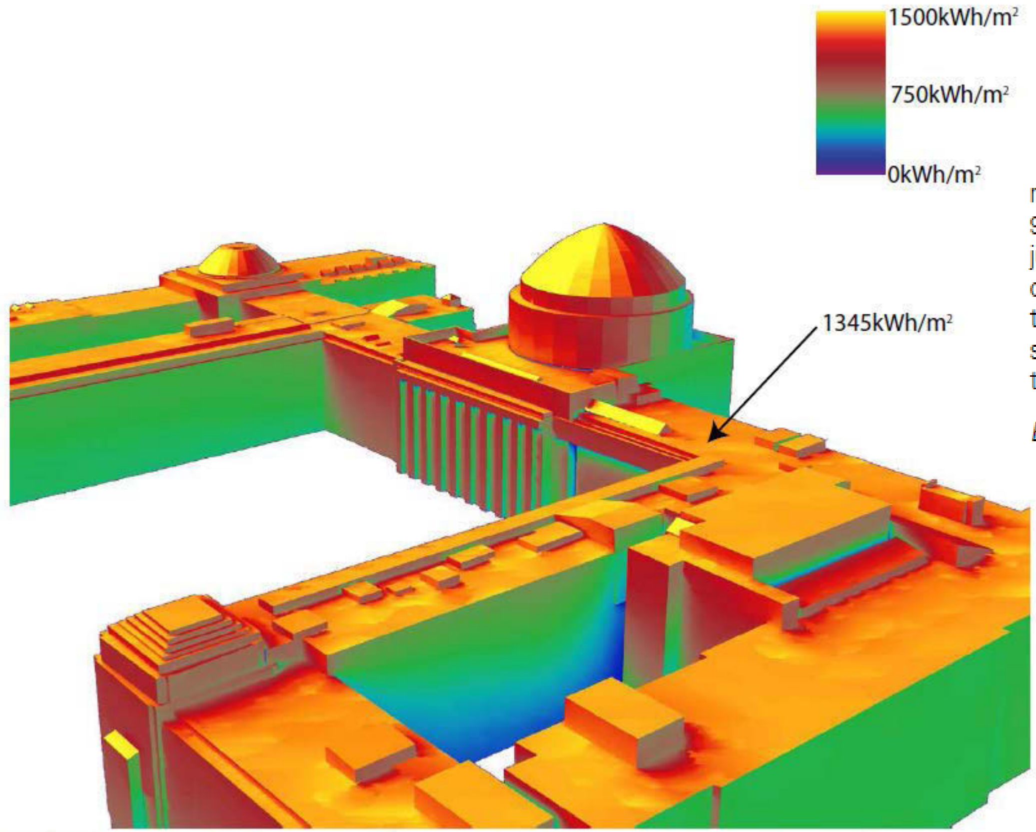


Fig 9.12 Annual radiation map of MIT's main building group using the Boston Logan Airport TM3 weather file

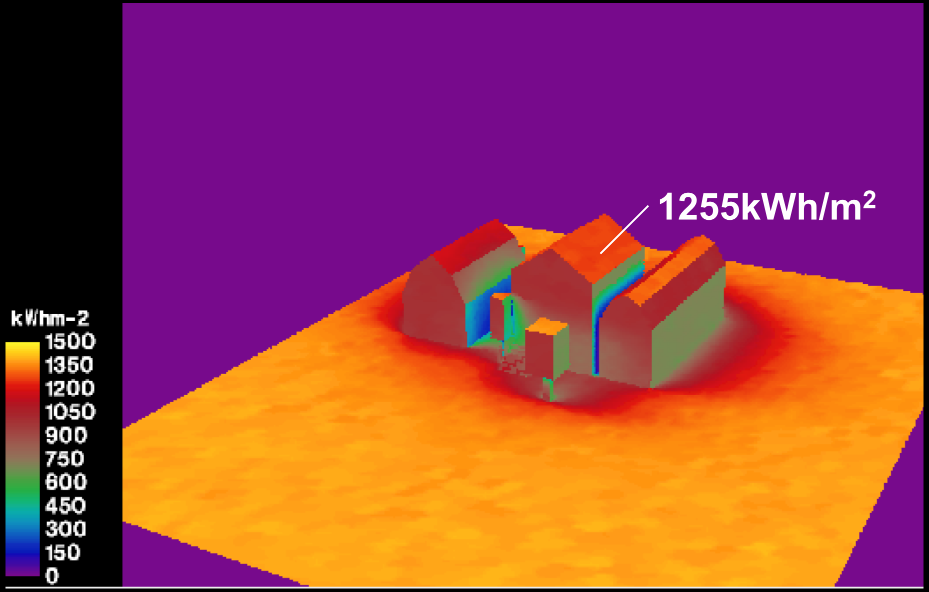
n their simplest version, solar maps can be based on a cumulative sky simulation such as the one in Fig 9.12. For example, if a designer wanted to place a PV panel flat onto the roof just to the east of the MIT Great Dome, the annual solar radiation onto that cell would be 1345kWh/m^2. Assuming a panel efficiency of 16%, meaning that 16% of incident solar radiation is converted into DC electricity, a panel size of 1.6m^2 and an DC to AC inverter efficiency of 96%, this solar radiation translates into an annual electricity yield per panel of

Electricity Yield/Panel = 1345kWh/m^2 x 16% x 1.6m^2 96% =341kWh

Equ 9-3

- Solar Radiation = 1345 kWh/m^2
- Panel Area = 1.6 m^2
- Efficiency = 16%

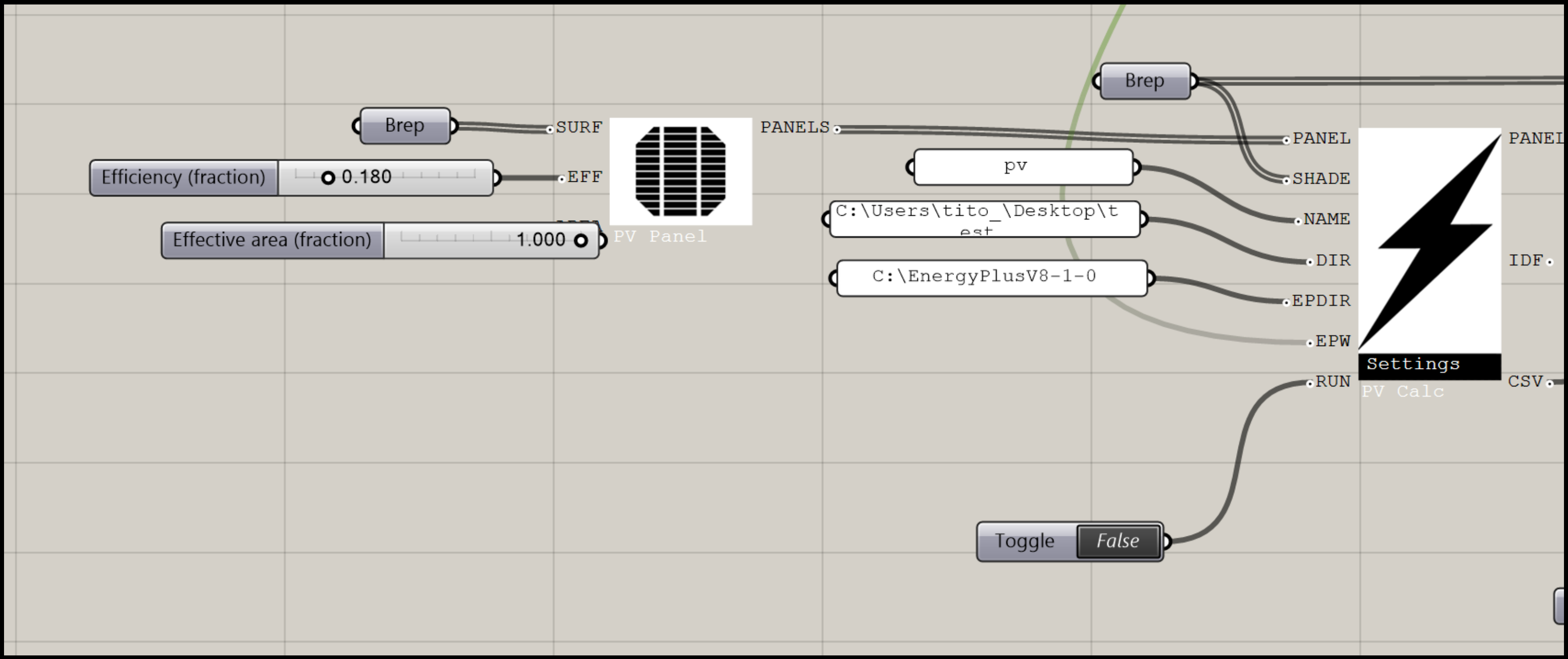
Case Study: Residential Home



Incentives MA
$1000 MA Tax break
30% system cost (federal)
SREC 0.285 $US/kWh

- Solar radiation = 1255 kWh/m^2 yr
- Panel area = 1.5 m^2
- Panel efficiency = 18%
- Converter efficiency 96%
- Panel peak rating 280W_p
- Yield =1255 x 1.5 x 18% x 96% kWh/panel
  = 325 kWh/panel yr
- Initial cost/panel: $US 3.5/$W_p$ x 280 W_p = $US980
- Saved electricity = 325 kWh x $0.18/kWh = $US 58/yr
- Direct payback without incentives: 16.7 years

PV Grasshopper Model



DIVA/Archsim model

Cambridge Solar Map

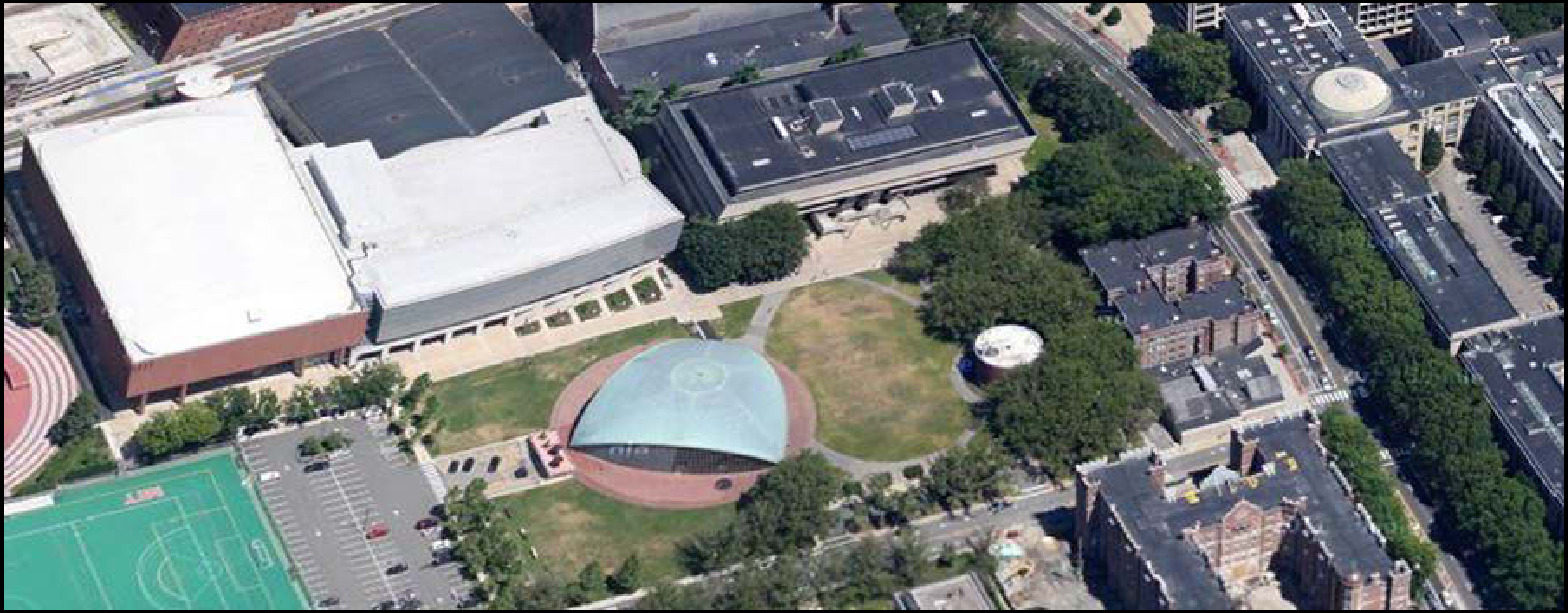
- First large-scale combination of LiDAR data with advanced building simulation modules

https://www.mapdwell.com/en/solar/cambridge

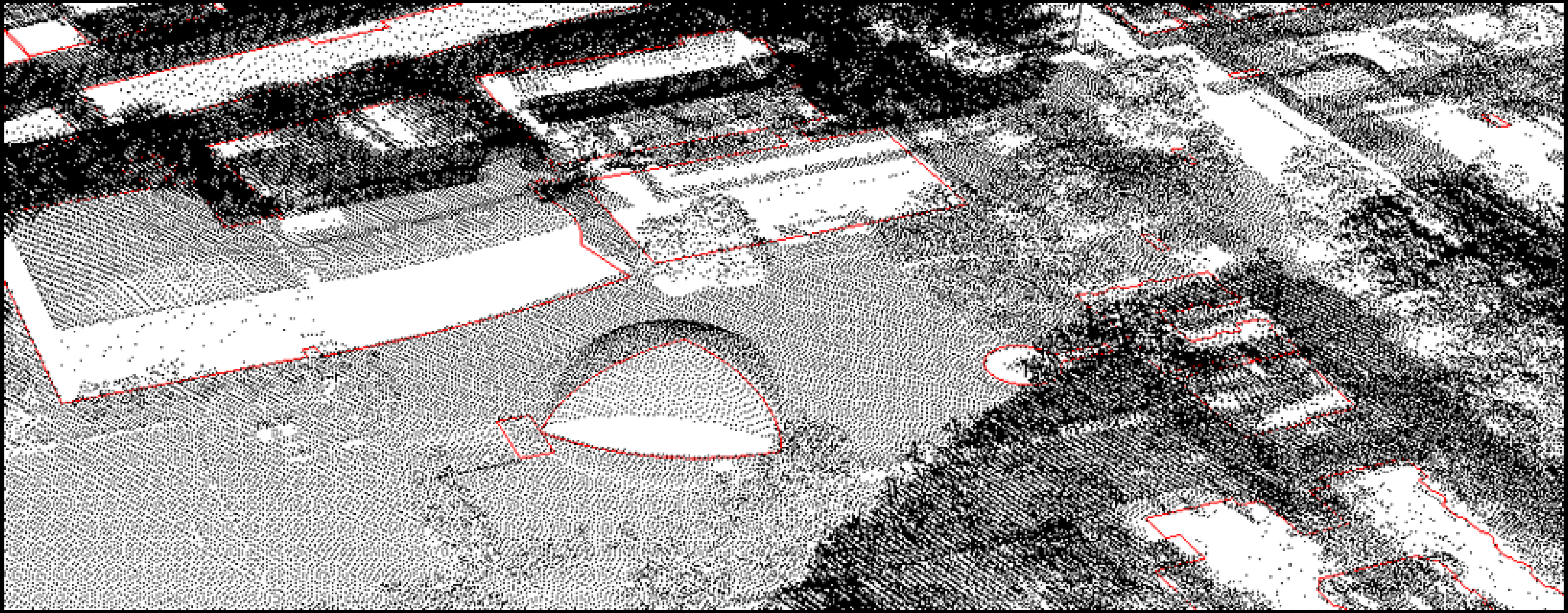
MODERN DEVELOPMENT STUDIO

CAMBRIDGE CDD@344

SDLAB



LiDAR Data of the MIT Campus



3 dimensional point cloud (126 million points).

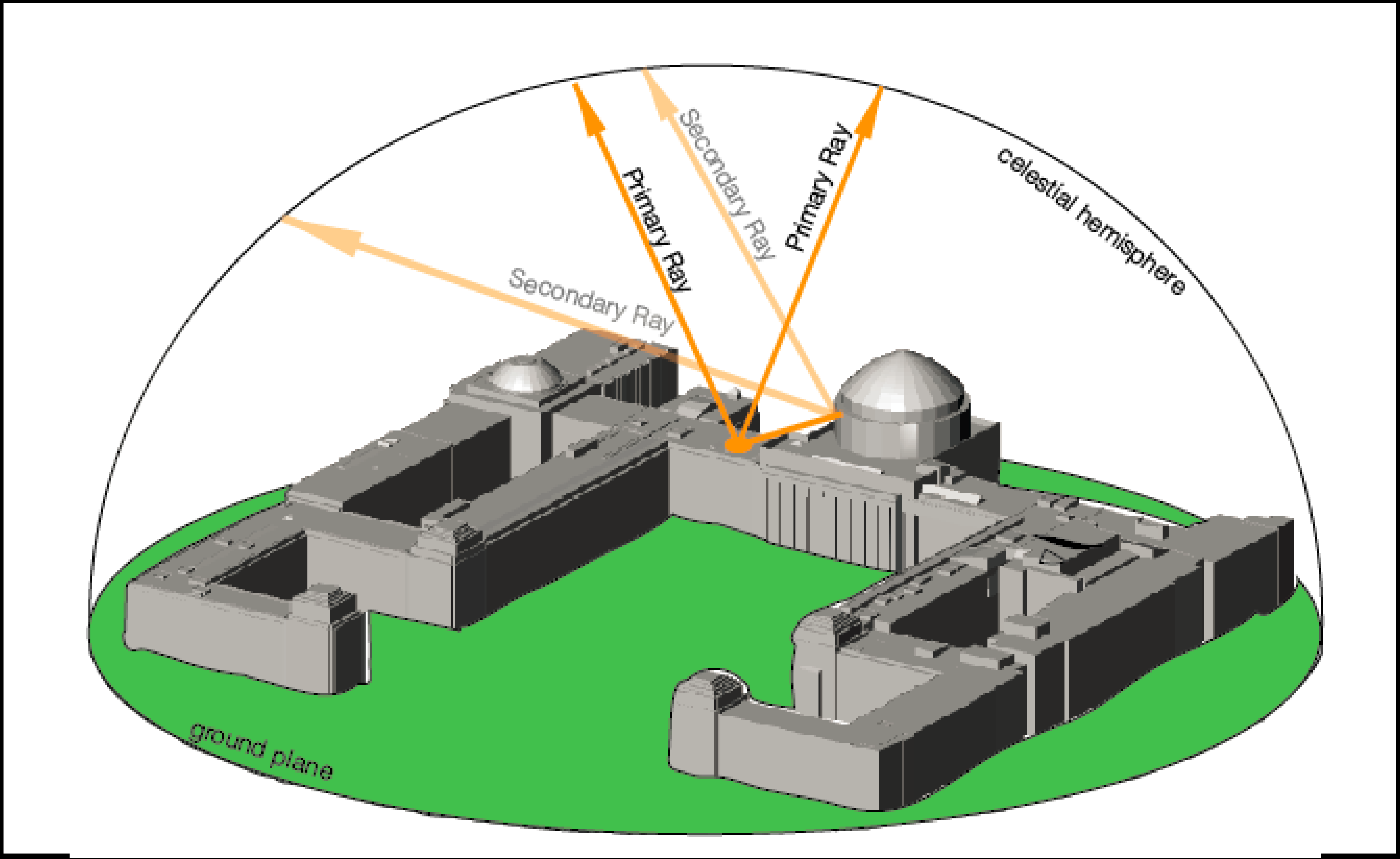
GIS Model of Cambridge

City ArcGIS model: Building Footprints, Exterior Cladding Materials, Ground Composition, Appraised Value and Renovations, Number of Floors, Building Type, Number of Bedrooms, Year of Construction

3D Model of the MIT Campus

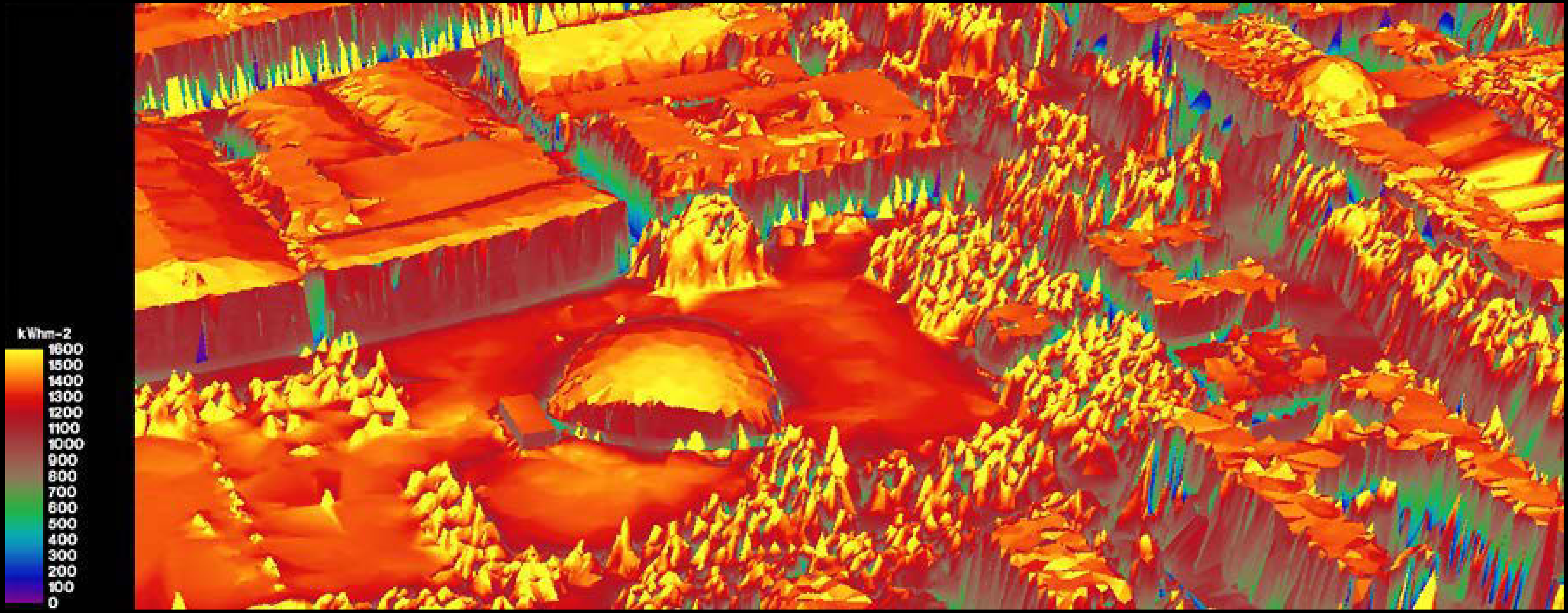
Generation of a 3D model through surface triangulation.

Solar Radiation Calculation



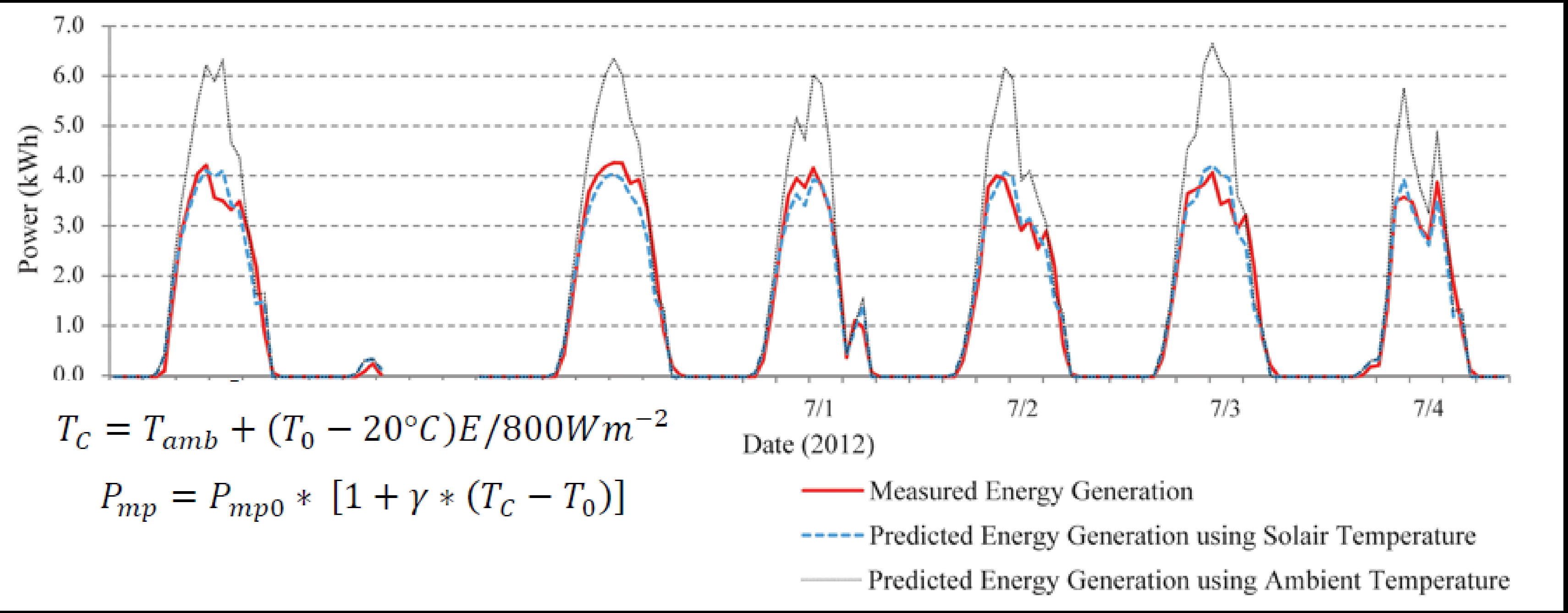
Combination of hourly sky models with Raytracing leads to hourly solar radiation values.

Solar Radiation Map



Cumulative annual solar radiation.

Panel Efficiency is Temperature-Dependent



$$T_C = T_{amb} + (T_0 - 20°C)E/800Wm^{-2}$$

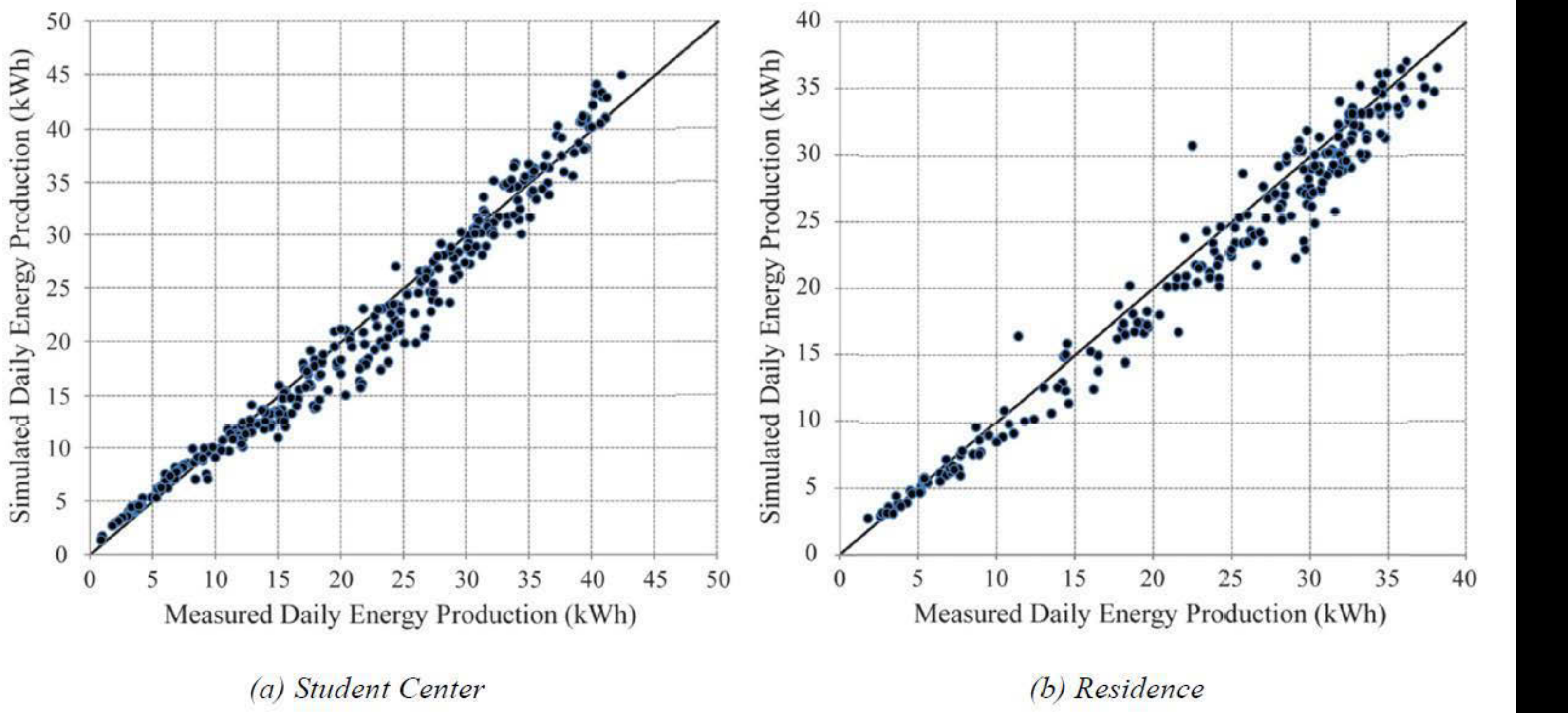
$$P_{mp} = P_{mp0} * [1 + \gamma * (T_C - T_0)]$$

- Predicting electricity yield based on radiation and temperature.
- Accuracy within 4 to 10% annually.

Paper: A Jakubiec and C F Reinhart, 2013, "A Method for Predicting City-Wide Electricity Gains from Photovoltaic Panels Based on LiDAR and GIS Data Combined with Hourly DAYSIM Simulations," *Solar Energy* 93, pp. 127-143.

SDLAB

How accurate are the results?



Annual Error 3.6%

Annual Error 5.3%

Paper: A Jakubiec and C F Reinhart, 2013, "A Method for Predicting City-Wide Electricity Gains from Photovoltaic Panels Based on LiDAR and GIS Data Combined with Hourly DAYSIM Simulations," *Solar Energy 93*, pp. 127-143.

SDLAB

mapdwell LLC

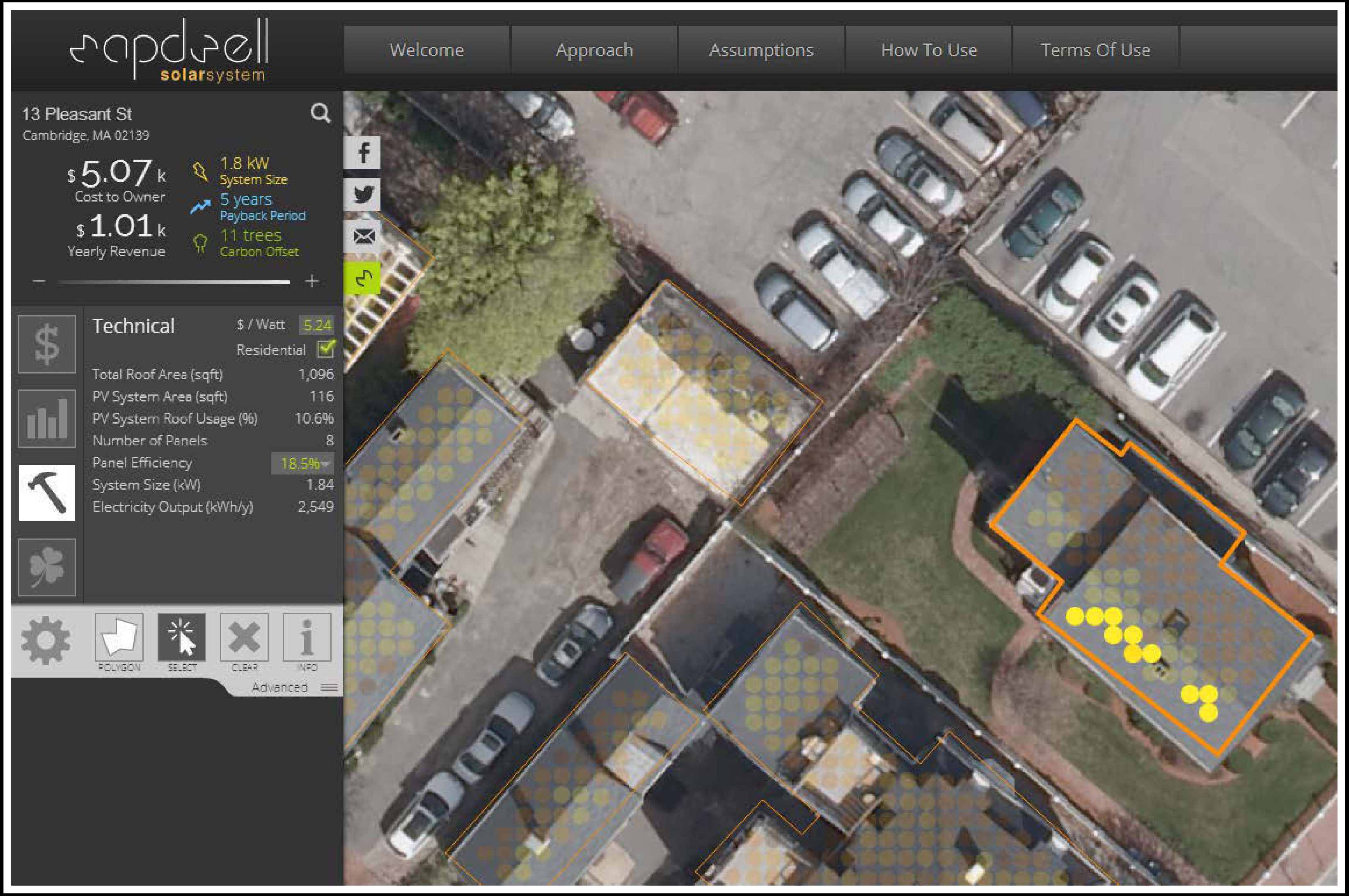
- In 2013 we formed an MIT spinoff that develops interactive maps to predict the potential to install PV on urban rooftops.

http://en.mapdwell.com/

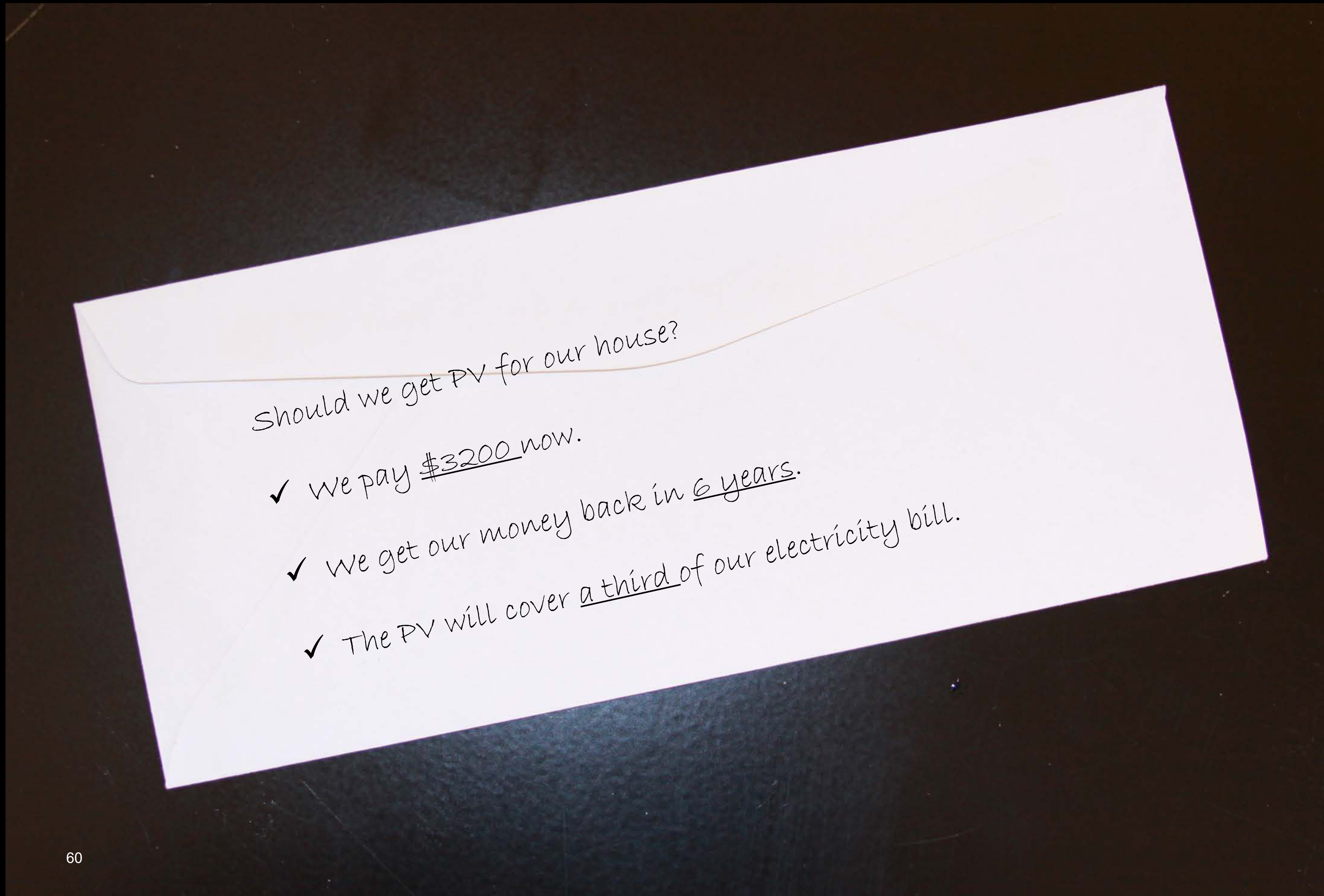
Winner of FastCompany's 2014 Innovation By Design Award for Data Visualization

How can you use the map?

mapdwell LLC



http://en.mapdwell.com/


Should we get PV for our house?
✓ We pay $3200 now.
✓ We get our money back in 6 years.
✓ The PV will cover a third of our electricity bill.

What is Cambridge's collective solar potential?

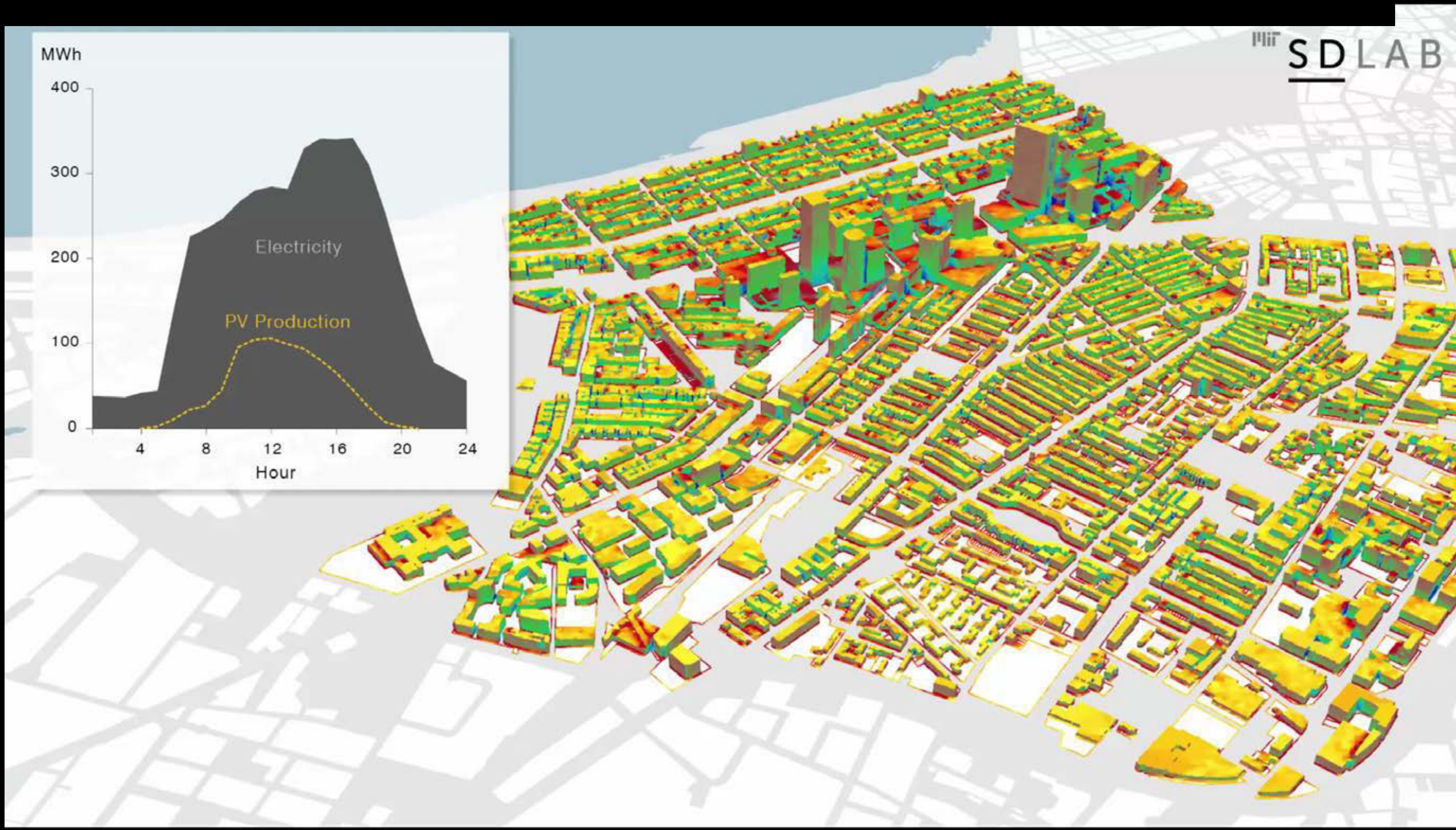
Solar Potential for Cambridge

- If we were up to the challenge we could generate a third of the city's electricity use via PV.
- The cost would be in the order of $US 2.8 billion.

Case Study Wellfleet, MA

- In 2014 the mapdwell map of Wellfleet, MA, successfully supported a community-driven solarize program: Within 4 months 10% of all households went solar.

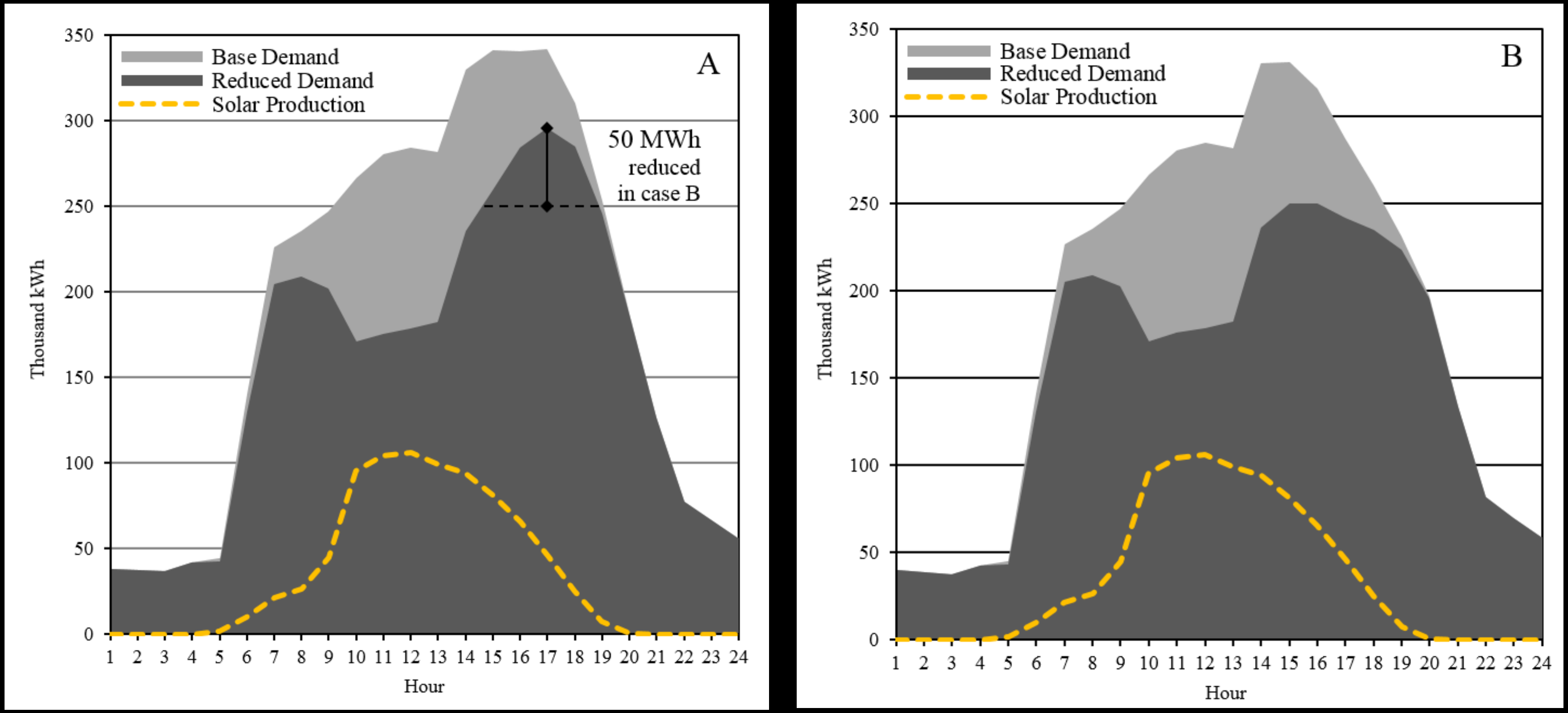
Where are we going…?



- Back Bay with Prudential on July 7 (TMY3) assuming 30% of rooftops filled with PV

Link: www.youtube.com/watch?v=O46GkHSYvYE

Results – Demand – Supply Scenarios



Courtesy of Elsevier, Inc., https://www.sciencedirect.com. Used with permission.

Paper: C Cerezo, C F Reinhart, and J Bemis, "Modeling Boston: A workflow for the efficient generation and maintenance of urban building energy models from existing geospatial datasets," *Energy, 117*, pp. 237-250 (2016).

Challenges

"How to lose half a trillion Euros" **- the *Economist*, October 12th 2013**

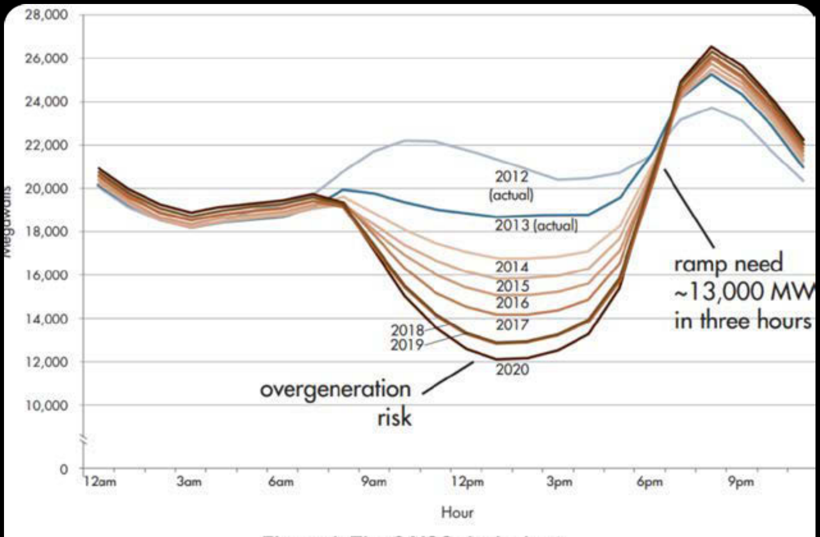
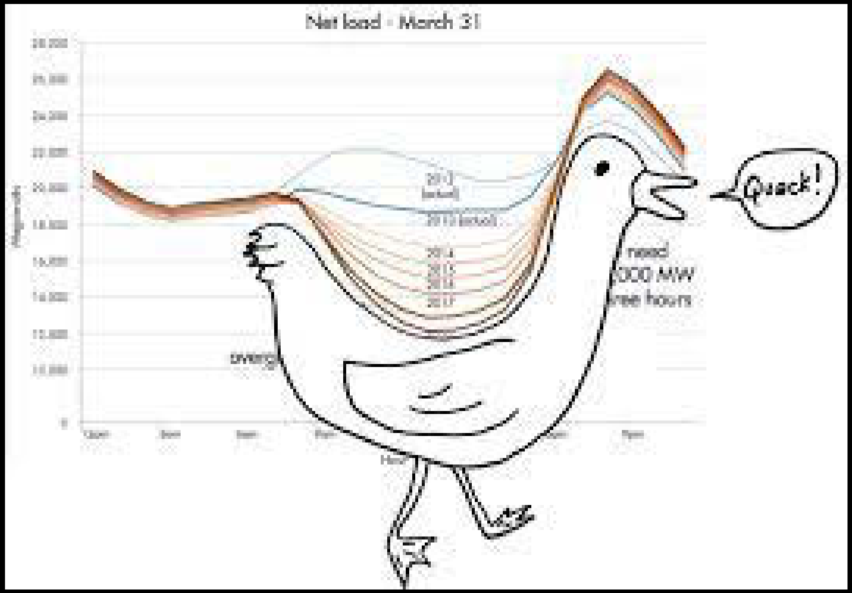


Figure 1. The CAISO duck chart

Source: CAISO 2013



- ❑ **PV does not provide constant electricity**
- ❑ **Increases ramping rates – the infamous 'Duck' curve**
- ❑ **Increases thermal cycling and much greater flexibility of existing plants is required**

How can we reduce the extend of the duck curve?

Energy Storage for Buildings

- ❑ 6.4 kWh capacity at $3000
- ❑ Why should one buy a battery?
  - Solar electricity at night
  - Go net zero
  - Emergency backup

How can Energy Storage reduce an electricity bill?

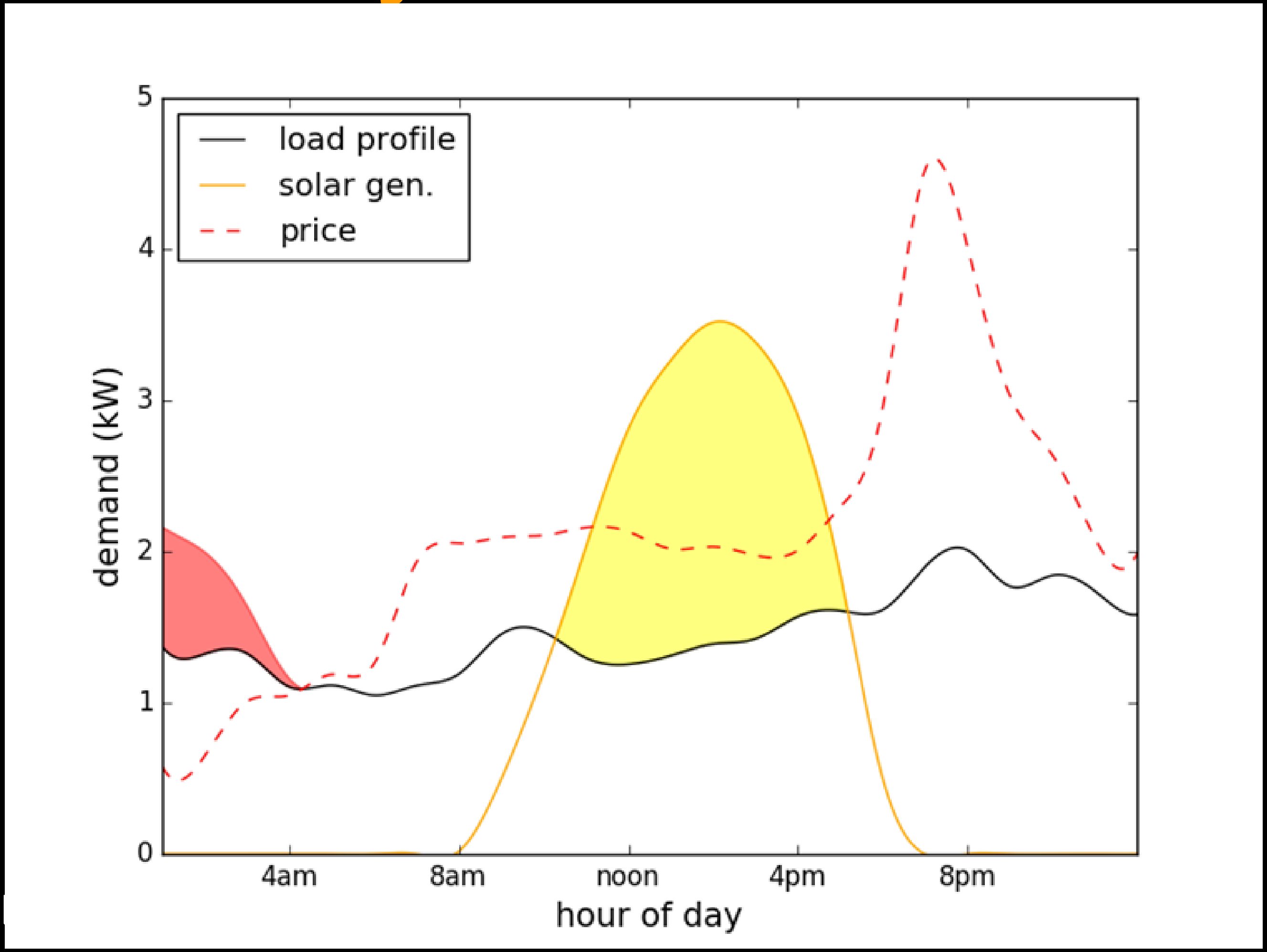
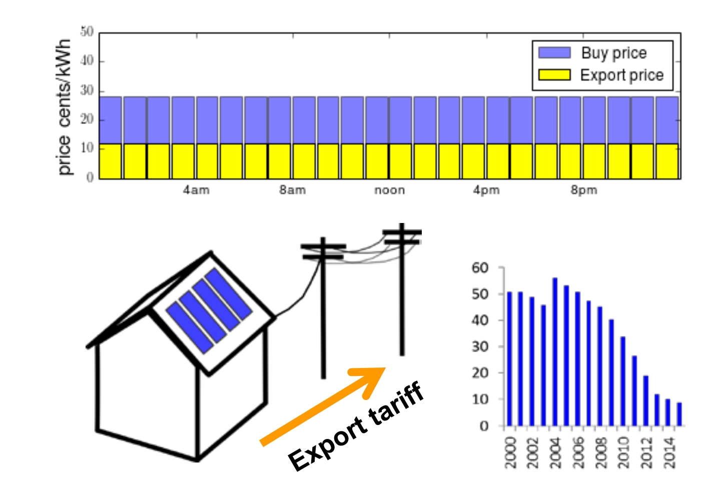


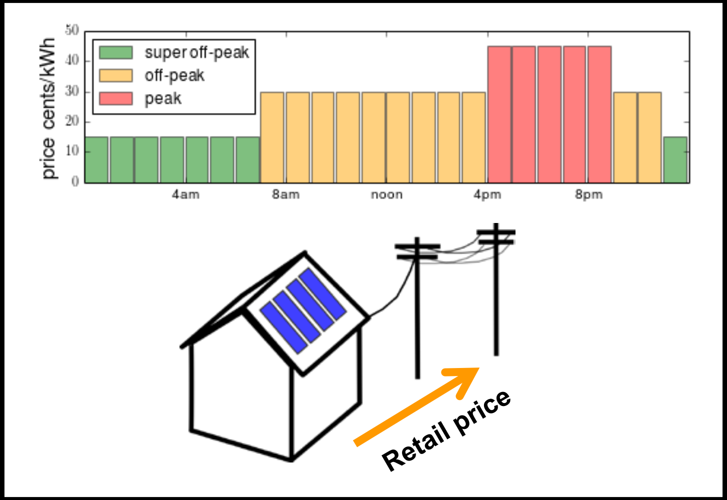
Image courtesy of Edward Barbour and Marta Gonzalez. Used with permission.

- Principle: Replace expensive electricity with cheap electricity

Feed In Tariffs vs. Net Metering

Image courtesy of Edward Barbour and Marta Gonzalez. Used with permission.

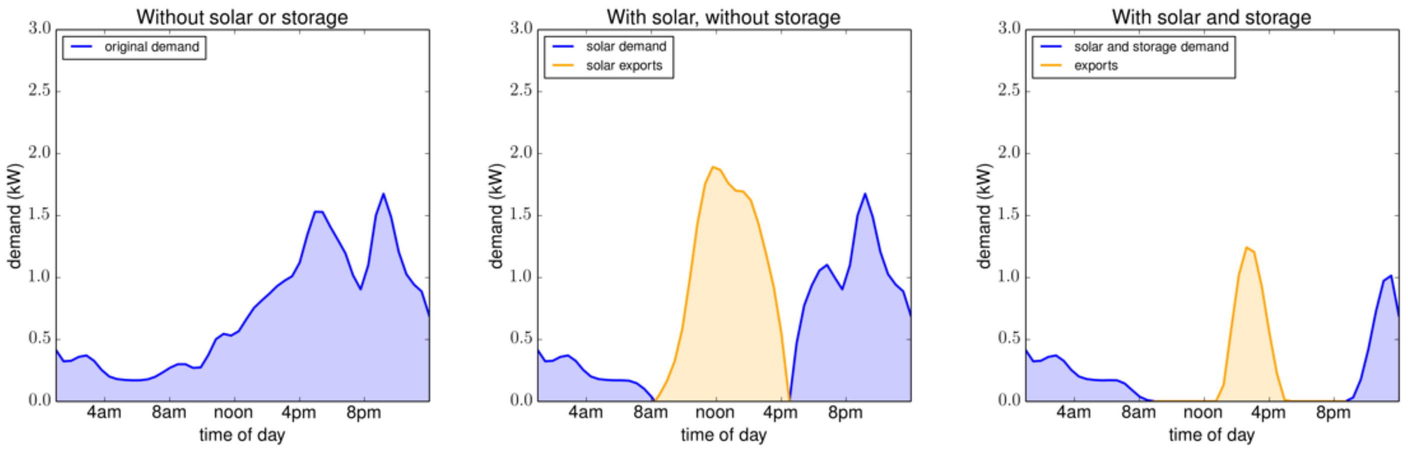




- ❑ Feed In Tariffs (FITs) are predominantly favoured in European electricity markets (i.e. Germany, 12 euro cents/kWh in 2014, UK 5 pence/kWh).
- ❑ Exported electricity is compensated at a fixed export rate (usually lower than retail electricity prices).
- ❑ Money is made by owner by using one's own electricity rather than buying expensive electricity from the grid.

- ❑ Net Energy Metering (NEM) is predominantly favored in the USA.
- ❑ Exported electricity is compensated at the retail price.
- ❑ There will only be an economic incentive to store solar electricity if it occurs at times with low prices.

Example: Feed In Tariffs



- Storage reduces solar exports
- Remaining export is due to the finite capacity of the battery
- The daily electricity cost for this user is reduced from $4.80 to $1.60 with solar and to $0.80 with solar and storage: Saving $4 per day!

Image courtesy of Edward Barbour and Marta Gonzalez. Used with permission.

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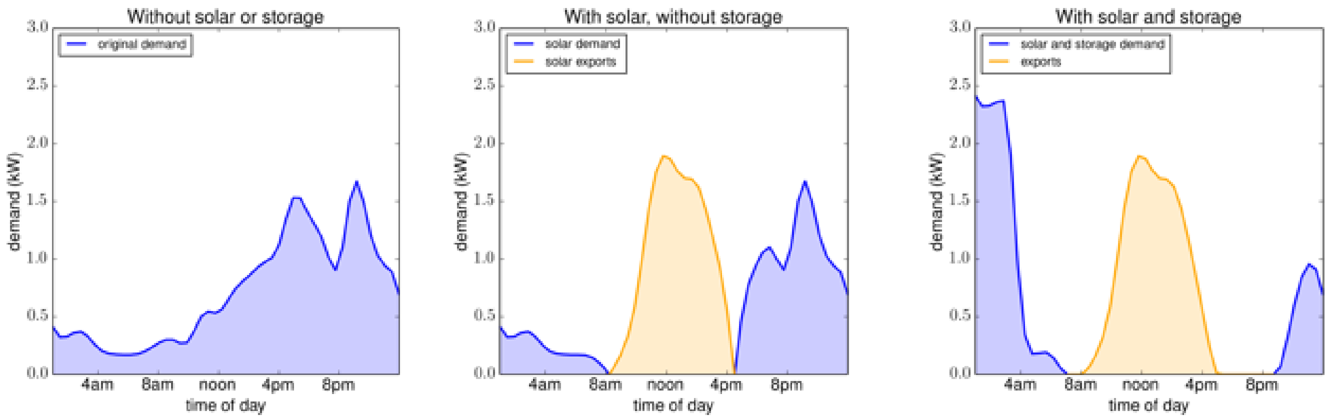
Example: Net Metering



- It is more economic for our users to charge their batteries with early morning electricity than solar, generating a new peak load
- Solar exports are unaffected by storage and Peak-time demand is reduced
- Solar reduces the users daily electricity cost from $4.80 to $0.10 with solar plus with storage the user also earns a net compensation of $1.20!

Image courtesy of Edward Barbour and Marta Gonzalez. Used with permission.

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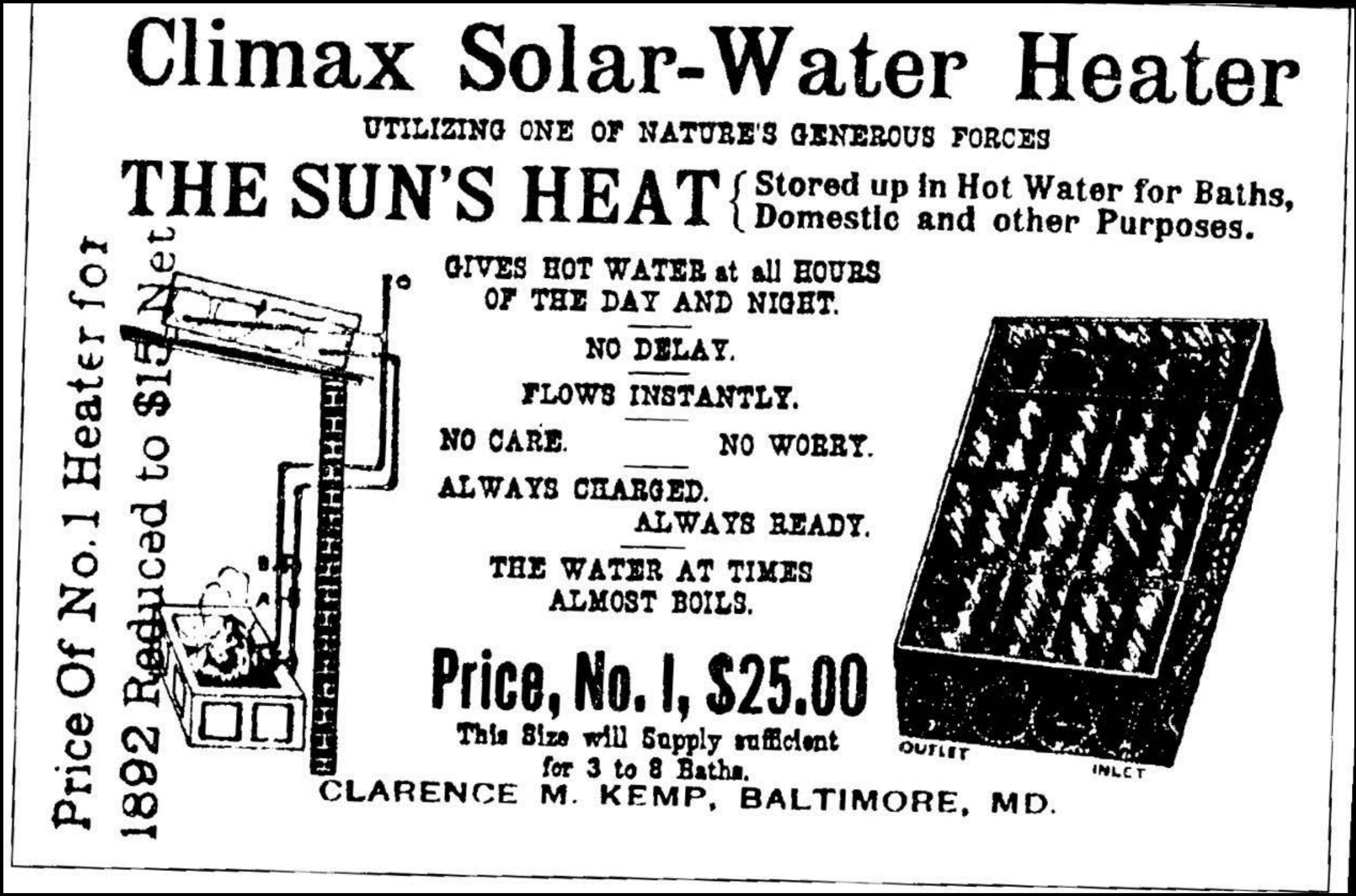
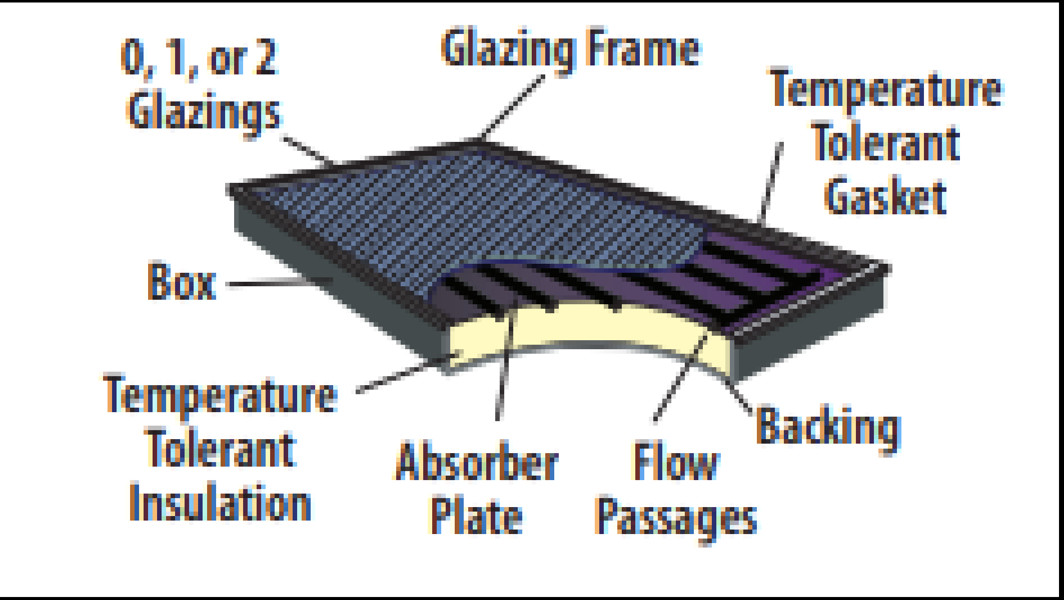
Solar Hot Water

An Old Idea - 1892



Collector Types

Vacuum Tube Collector. Photo courtesy of Greensolarvacuum on Wikipedia.

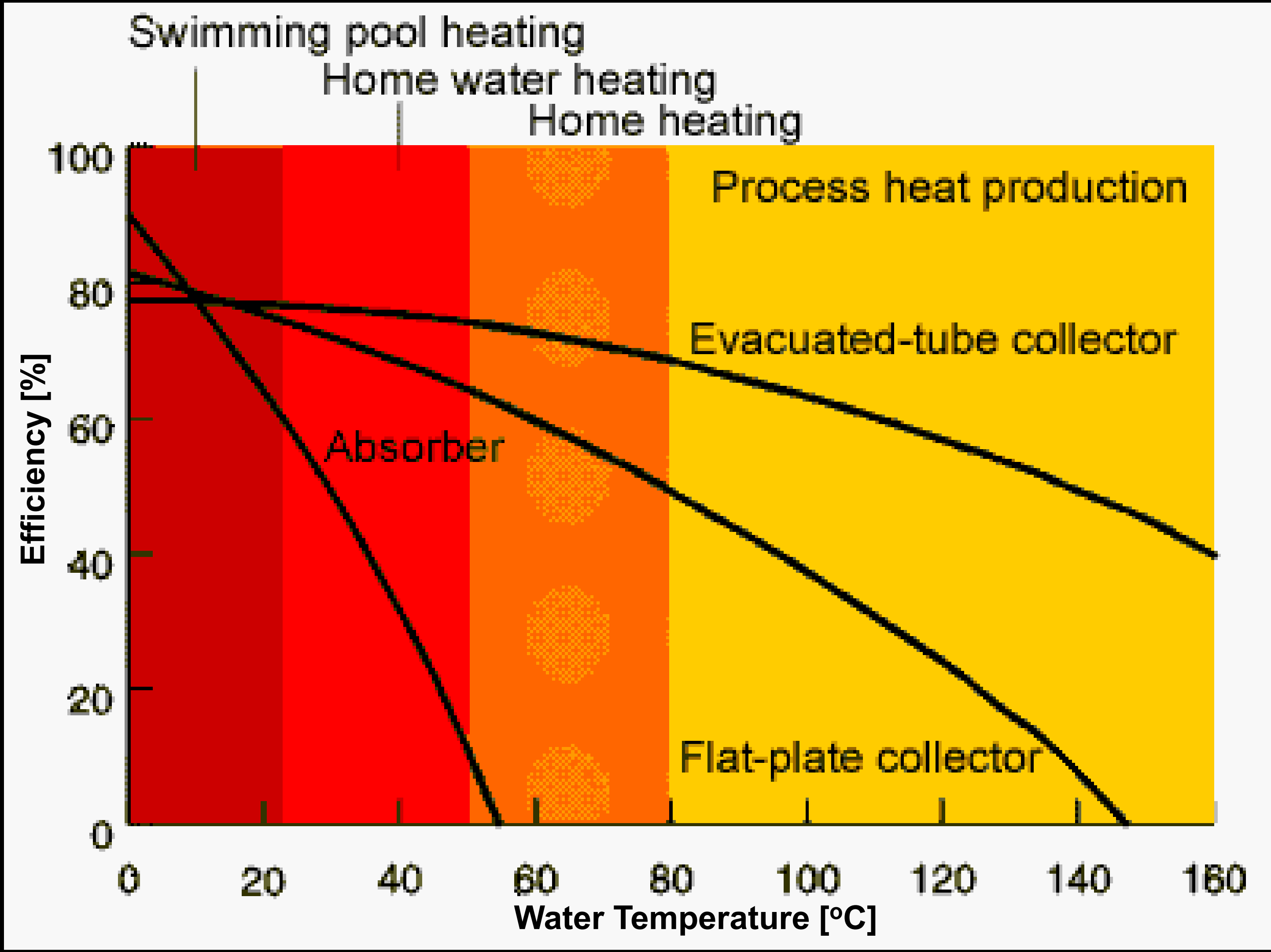


Flat Plate Collector. Public domain image courtesy of US Department of Energy.

Applications include:

- ❑ swimming pools (low tech)
- ❑ seasonal hot water
- ❑ annual hot water
- ❑ annual hot water and heating
- ❑ industrial process heating
- ❑ absorption chiller

Collector Efficiencies and Uses

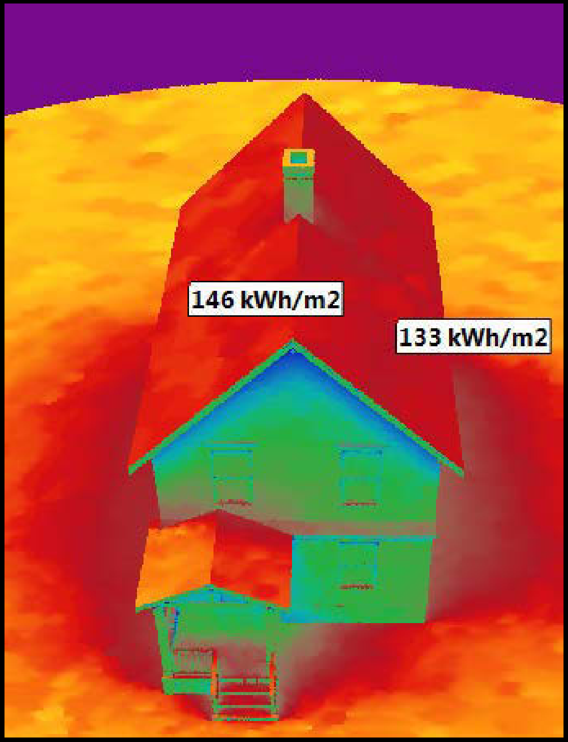


Thermosiphon System

- ❑ The hot water storage tank is located above the solar collector.
- ❑ System does not need a pump, as the water circulates due to natural convection.

Sizing a Solar Collector in Summer

Your household uses 160 l at 65° C of hot water per day (or 40 l/person of which 50% are for showers/baths and 25% for dishwashing and laundry, respectively). The city's main cold water enters the house at 10° C. You want to know how large a solar hot water collector would have to be to cover the hot water energy demand for the family on an average June day. Assume a collector efficiency of 85%.



Solar radiation in June

The thermal heat required to heat 160 l of water from 10° C to 65° C is:

$Q = TM \times \Delta T$ with $TM =$ Volume x SVH x ρ

$TM = 160\ l \times 0.001\ m^3/l \times 4181\ J/kgK \times 997\ kg/m^3$
$= 667\ kJ/K$

$Q = 667\ kJ/K \times 55K = 36682\ kJ =$ 10.2 kWh

The required collector area, $A_{collector}$, is:

$A_{collector} = 10.2\ kWh/(0.85 \times G)$
$= 10.2\ kWh/(0.85 \times 133\ kWh/m^2 \times 1/30)$
2.7 m^2

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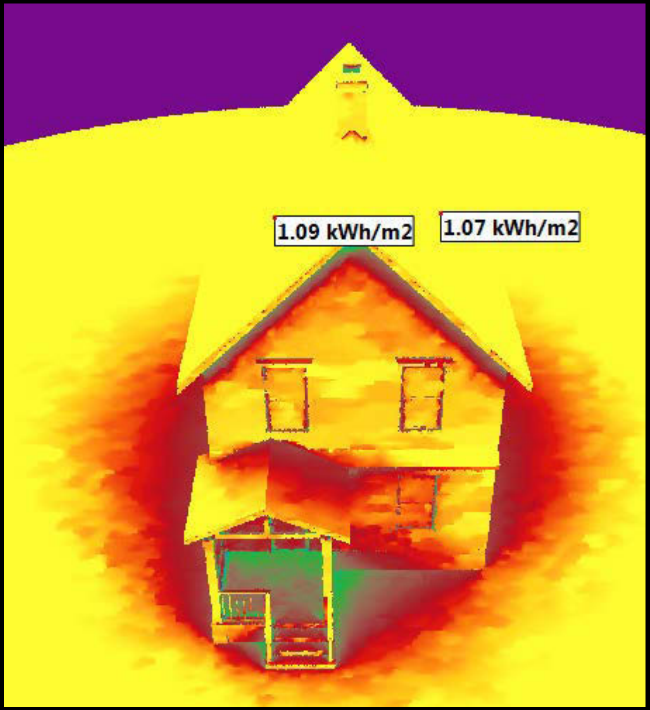
Sizing a Solar Collector in Winter

Your house has a hot water tank that holds 80 gal (~300 l) which roughly corresponds to your domestic hot water (DHW) needs for 2 days. To reach full solar coverage, your system would need to meet your DHW needs during the two consecutive days with the lowest solar radiation in the year. In the Boston TMY3 file those two days are Dec 10 and 11.



Solar radiation on Dec 10 and 11

The total solar radiation on the roof on Dec 10 and 11 is 1.1 kWh/m². On these two days the system has to cover 2x 10.2 kWh = 20.4 kWh of heat.

The required collector area, $A_{collector}$, is:

$A_{collector}$ = 20.4 kWh/(0.85x G)

= 20.4 kWh/(0.85 x 1.1 kWh/m²)

22 m²

- A 100% solar thermal system is not economical.

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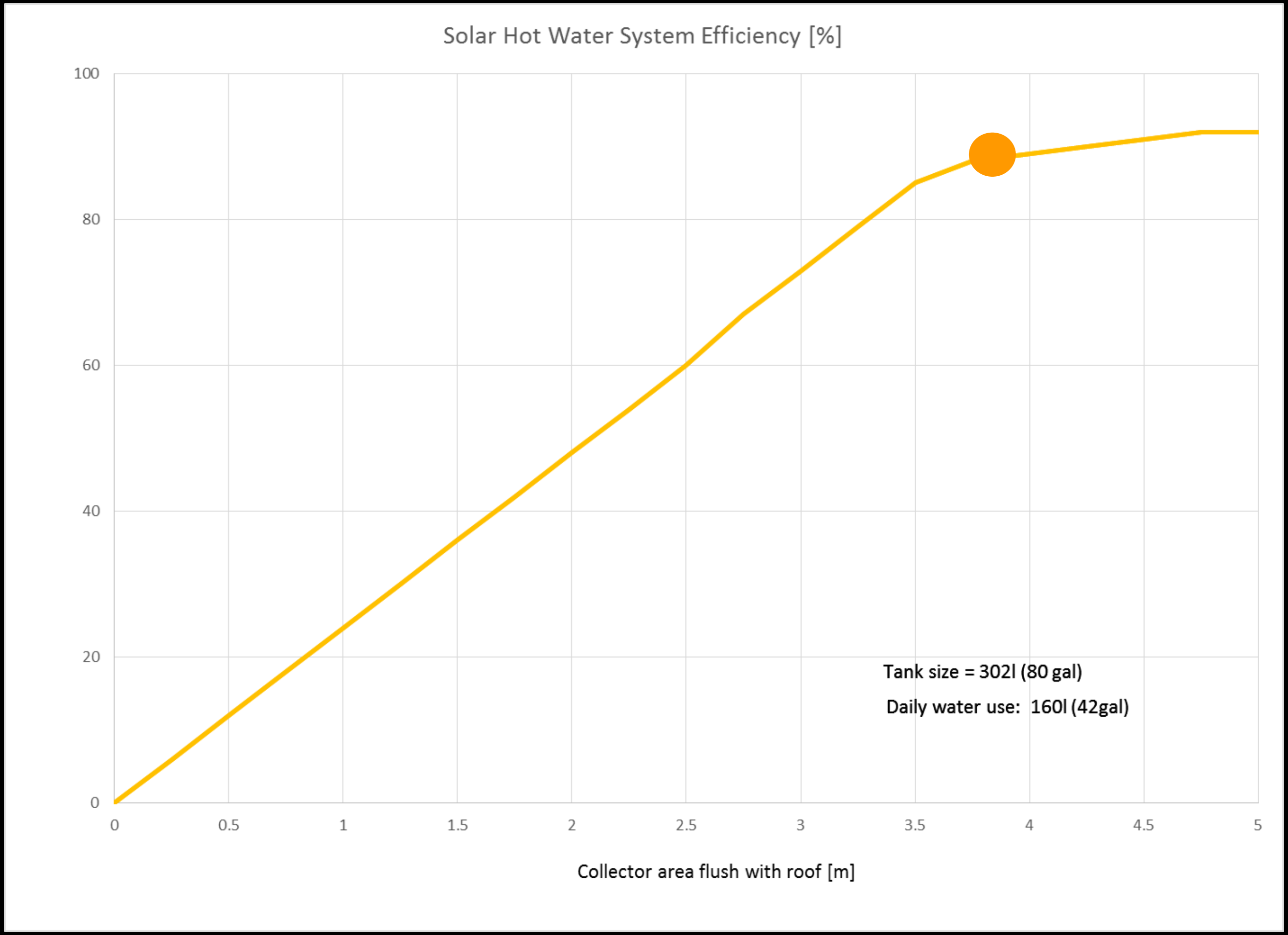
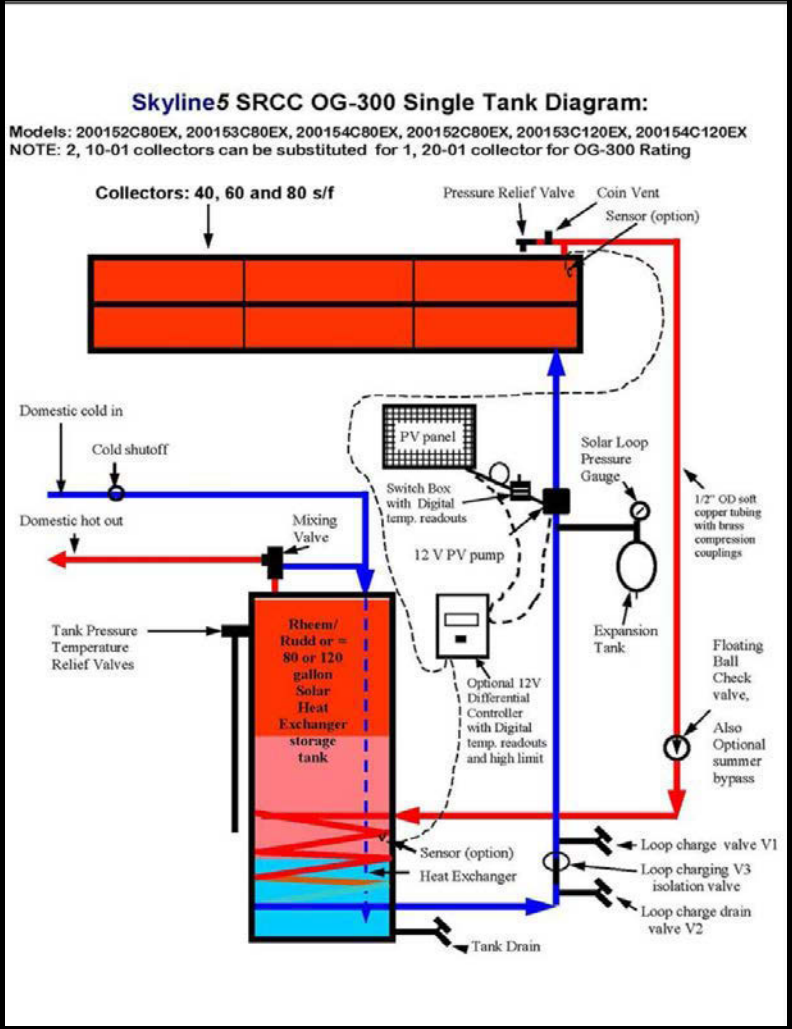
Sizing a Solar Collector



Calculation for the New England House with a collector facing upwards

- ❑ The sweet spot for the system size is at around 3.7 m^2 (40 ft^2). For the New England Home, the system covers around 85% of annual DHW energy needs.

Example System (60ft^2)



Economics

- Over the course of the year, the energy needs for domestic hot water (DHW) are 365 d x 10.2 kWh/d = 3719 kWh.
- For an electric water heater with an efficiency of 90% and an electricity cost of 0.186 $/kWh, the related costs are = $768/yr.
- Assuming that the solar thermal system covers 85% of your domestic hot water energy needs and that you get 30% Federal Government subsidies for the system, the payback time is ($4152 x (1-0.3))/(768$/yr x 0.85) = 4.5yr.

- However, for a gas-fired DHW system at an efficiency of 80% and a cost of 0.035 $/kWh, the related costs are = $163/yr.
- Assuming that the solar thermal system covers 85% of your domestic hot water energy needs, the payback time is ($4152 x (1-0.3))/(163 $/yr x 0.85) = 21 yr

Why do we not see solar thermal systems in New England?

Questions?