Energy consumption in controlled environments: supplemental lighting and CO_2 systems

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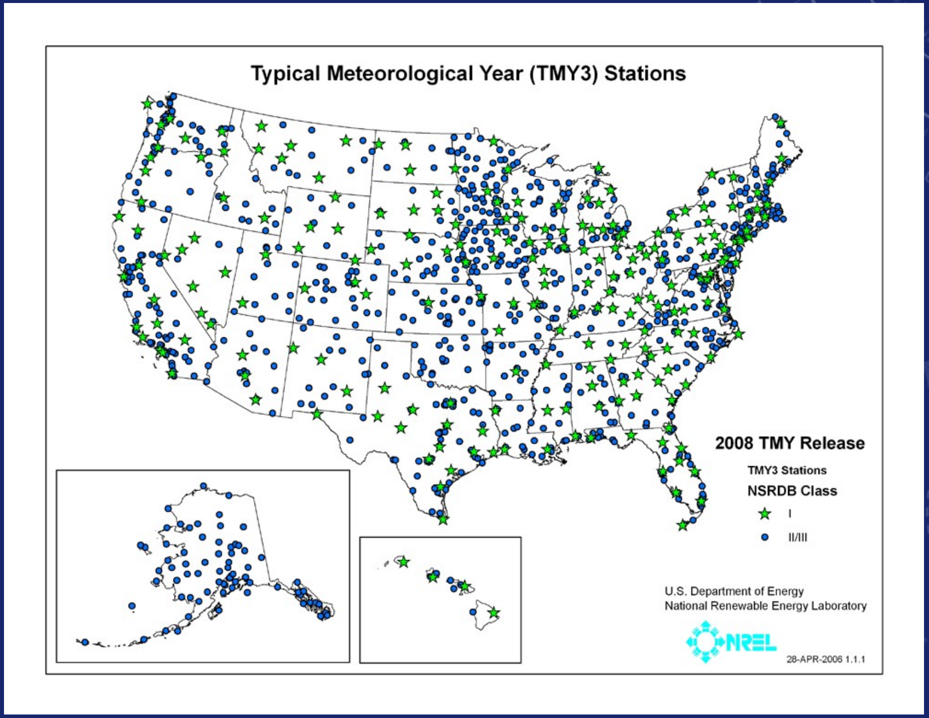
CEA research at Cornell

- Energy modeling
  - Lighting
  - HVAC
  - Carbon footprint
  - Cost
- Control systems
  - Lighting
  - Shade
  - HVAC
  - CO_2
- Plant experiments
  - LED vs HPS
  - CO_2 / DLI
  - Deep pond hydroponics
  - Spinach disease mitigation (*Pythium*)

Cornell CEA Team	
Plant Science	**Engineering**
Neil Mattson (director)	
David de Villiers	Kale Harbick
Jonathan Allred	Tim Shelford
Erica Hernandez	Lou Albright (emeritus)
Bob Langhans (emeritus)	

Building energy modeling

- Decades of research
  - ASHRAE
  - US DoE
  - NREL
- Simulate building energy consumption
  - Calculate loads and system response
  - TMY3 data sets for weather
- Benefits
  - Can be used for existing buildings or proposed designs
  - Model interactions (e.g. lighting and cooling)
  - Simulate performance and estimate cost of upgrades
  - Compare control systems



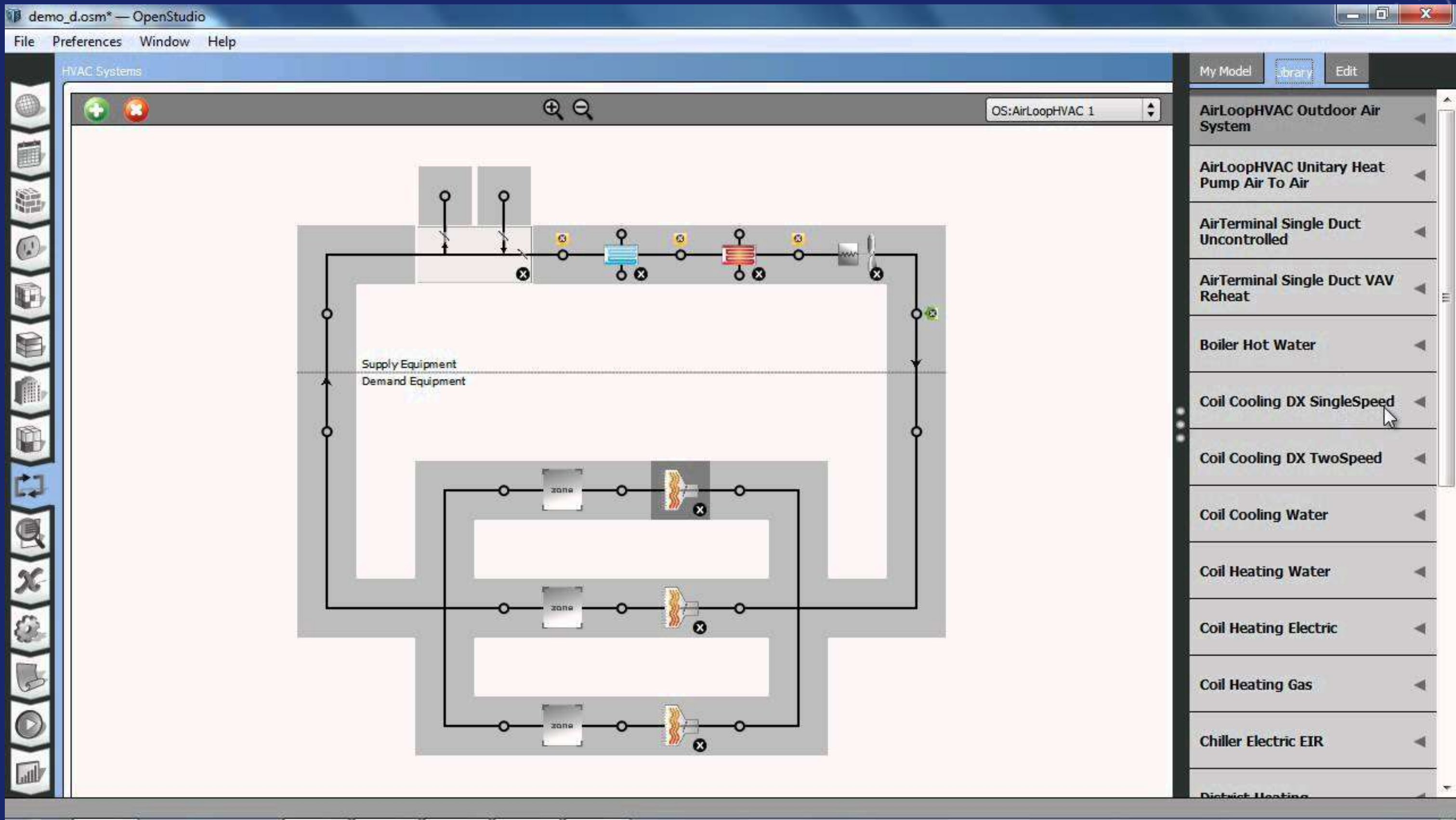
Energy balance in CEA buildings

- Internal loads
  - Lights
  - Evapotranspiration
    - Latent cooling load
    - Sensible heating load
  - In plant factories/vertical farms, internal loads dominate

- External loads
  - Solar
  - Conduction
  - Infiltration
  - Ventilation
  - In greenhouses, external loads often dominate

Loads and set point errors determine HVAC system response

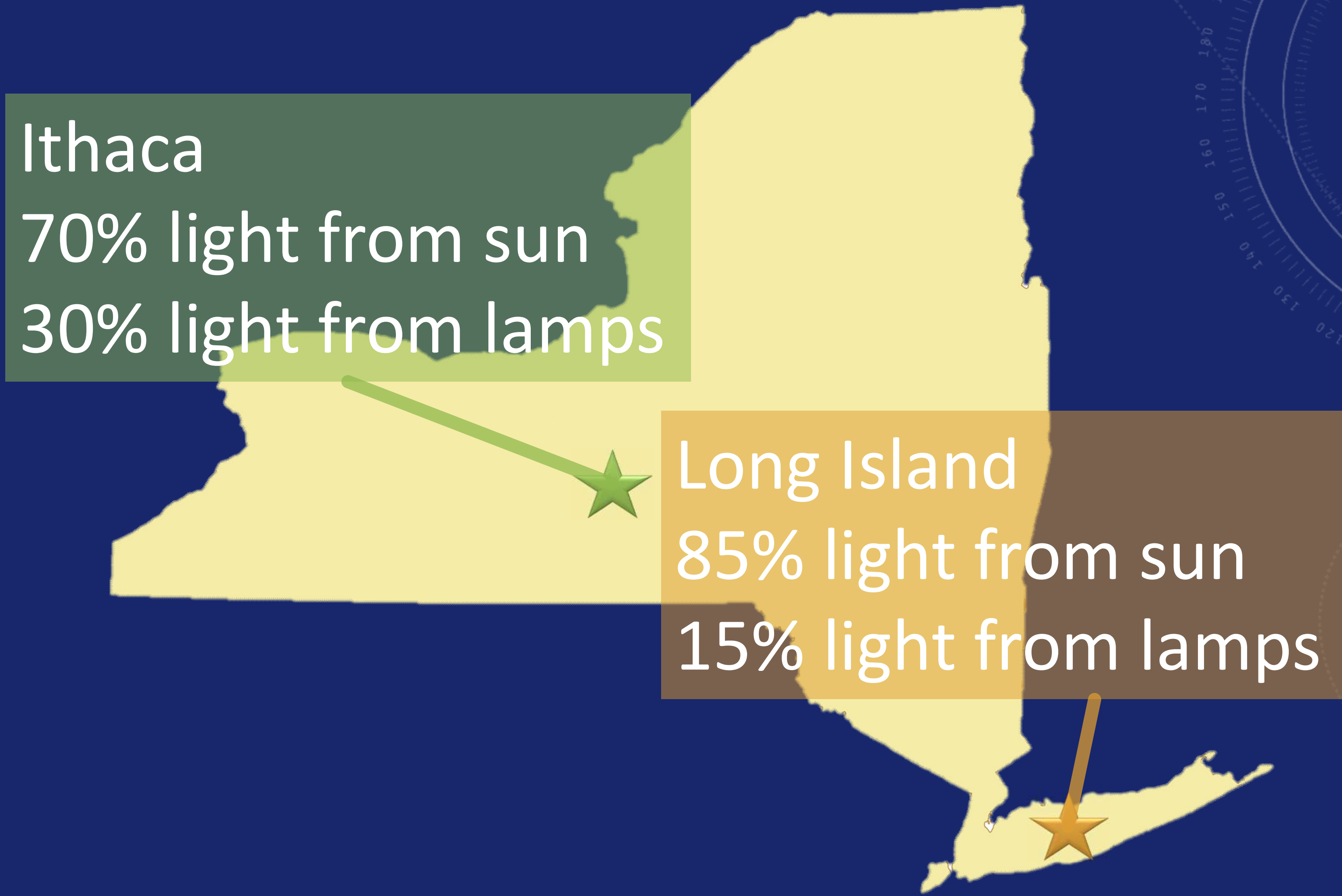
Modified EnergyPlus/OpenStudio



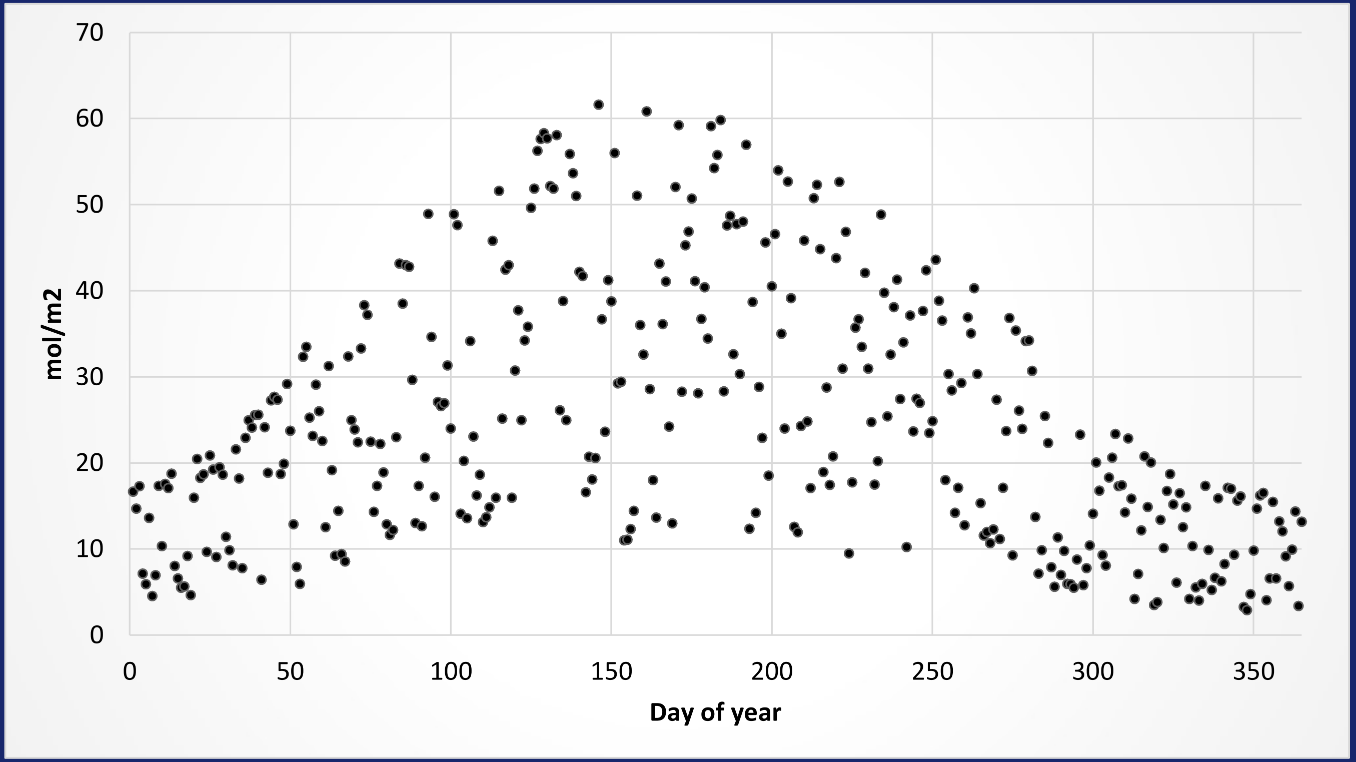
Greenhouse lettuce (Butterhead)

- PAR DLI target: 17 mol/m^2/day
  - Tipburn over 17
  - Needs extra air circulation
- 70 – 85% of light is natural (i.e. free)
- Evaporative cooling
- > 20,000 head/day/ha (5 oz / 140 g)

CEA Greenhouse (lettuce)



Importance of light control

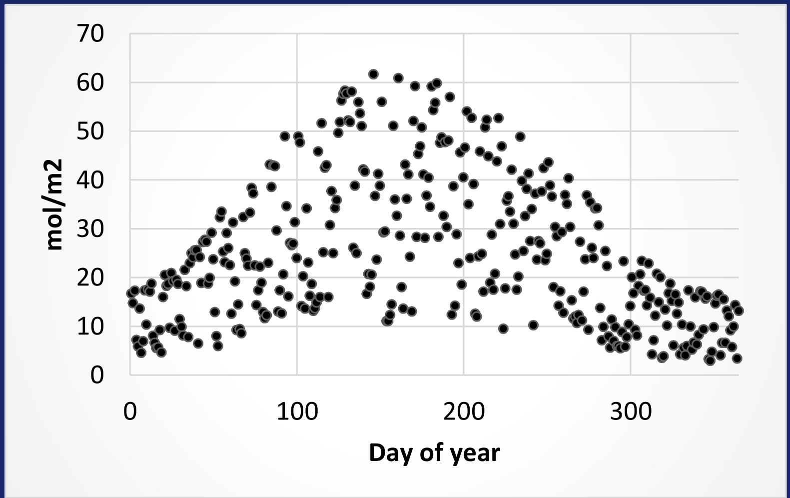


Typical outdoor light per day (Ithaca, NY)

LASSI control

- “Light and shade system implementation”
  - Lou Albright et al
- Predicts natural light accumulation based on first few hours after sunrise
  - Prediction based on set of heuristics that are tunable for different climates
  - Lights on if predicted sunlight is insufficient
  - Deploys shades if predicted sunlight is too much
- Schedules artificial light in off-peak hours as much as possible

LASSI control



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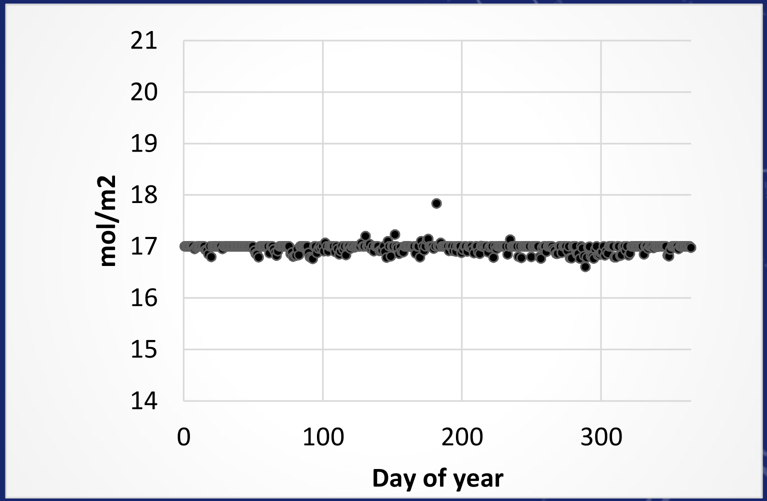

Inside greenhouse with LASSI

Savings: LASSI vs threshold

	Elmira, NY	Minn., MN	Phoenix, AZ
Lighting Electricity	24%	28%	56%
Energy costs	10%	12%	23%
	$80K/ha/y *		

* Assumes $0.056/kWh off-peak (10pm – 7am), $0.088/kWh on-peak, $34/MWh gas

LASSI CO_2 Control

- Virtual light integral

$$\text{PAR}_{\text{virtual}} = \text{PAR}_{\text{actual}} \frac{\ln(2.66\text{E}4) - \ln(400)}{\ln(2.66\text{E}4) - \ln(\text{CO}_2)}$$

- Model uptake and loss through ventilation/infiltration
- At each control step, determine lowest cost combination of light/CO2
- Predict ventilation based on outdoor temperature
- Recent improvement (~10% more savings):
  - Also supplement CO2 when conditions met:
    - Low light month
    - DLI is behind target for current hour
    - Sun is out

Savings: CO_2 vs basic LASSI

	Elmira, NY	Minneapolis, MN
Lighting Electricity	58%	64%
Energy + CO_2 costs	10% (19%)	8% (19%)
	$40-50K/ha/y ($130-140K/ha/y)*	

( ) indicates savings over threshold control

* Assumes $0.056/kWh off-peak (10pm – 7am), $0.088/kWh on-peak, $34/MWh gas, $0.25/kg CO_2

Plant factory

- Warehouse
    - 100% supplemental light
    - Multiple layers possible
        - But just one layer in results presented here
    - Mechanical cooling system

Sensible applications

- Research
- Space
- South pole
- Heating costs >>> elec. cost
- But vegetable plant factories in contiguous U.S. don’t fall in these categories!

Humidity implications

- Lights add sensible heat
- ET removes sensible heat
- ET adds latent heat

- Heat entering a space represents a "cooling load"
- Heat leaving a space represents a "heating load"
- **Impossible to remove moisture using a cooling coil without also reducing temperature (sensible cooling)**

Case 1: sensible > latent

- Common coil capacity
  - 75% sensible cooling
  - 25% latent cooling

- Can result in a plant factory if:
  - Suboptimal plant spacing
  - Suboptimal light efficacy
  - Poor airflow
- Light power > 2x ET power

Case 2: sensible < latent

- Coils remove the excess moisture
- But overcooling results!
- Reheat: heat must be added back somehow

- Can result in a plant factory if:
  - Optimal plant spacing
  - High light efficacy
  - Good airflow
- Light power < 2x ET power
- Example:
  - 1.7 μmol/J @ 17 mol/m^2/d -> 117 W/m^2
  - ET = 67 W/m^2
  - net sensible heat: 50 W/m^2
  - net latent heat: 67 W/m^2

Previous work *

- 3 to 12x lighting energy used in plant factory vs greenhouse, depending on location
- With HVAC energy also included:
  - 1.5 to 5x total energy used in plant factory vs greenhouse (contiguous U.S.)
  - Location
  - HVAC system details (i.e. heat exchanger, reheat system, economizer)
  - ET model
- Moving away from equator favors plant factory
  - Crossover somewhere in Alaska/Canada

* Harbick et al (LightSym 2016)

Savings: with CO_2 vs without

	Minneapolis, MN
Lighting Electricity	53%
Energy + CO_2 costs	26%
	$283K/ha/y *

* Assumes $0.056/kWh off-peak (10pm – 7am), $0.088/kWh on-peak, $34/MWh gas, $0.25/kg CO_2

Conclusions

- Greenhouses consume much less energy for equivalent yield in most climates
  - CO_2 supplementation helps both environments
- Any technology improvements (e.g. lighting efficacy) will help both building types
- CO_2 savings potential is sensitive to:
  - Cost of electricity
  - Cost of CO_2
  - Infiltration rate
  - Ventilation control strategy

Future work

- Improve ventilation prediction for CO_2 controller
- Model additional HVAC system designs for plant factories
- Explore “floating” control options, e.g.:
  - Acceptable humidity range: 50 - 70%
  - Acceptable temperature range: 19 - 24 C
  - Before supplemental light is to be used, drive air humidity and temperature to lowest acceptable values
  - Close greenhouse
  - Supplement CO_2 until temp/humidity exceed upper thresholds
- Model semi-closed greenhouse systems
  - Small mechanical cooling system for shoulder months to minimize ventilation requirements

Thank You

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