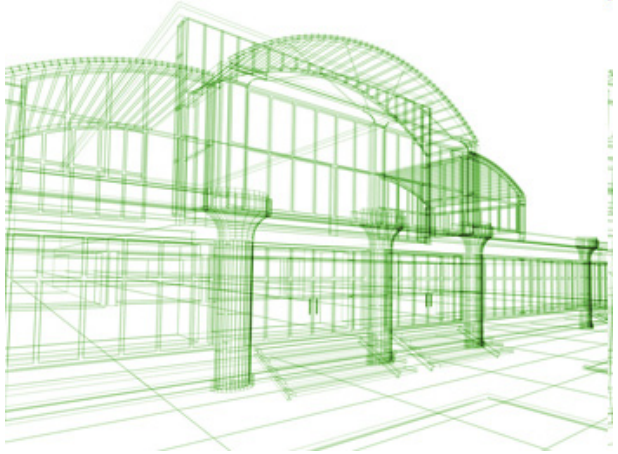
Communication and Modeling for Green Buildings



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ICARES Annual Research Presentations, March 24, 2012

These slides and audio/video recordings of this talk are available at:

http://www.cse.wustl.edu/~jain/talks/icares.htm

The Team

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Overview

Buildings are responsible for around 38% of the total carbon dioxide emissions; 71% of the total electrical energy consumption; 39% of the total energy usage;

1. Large Office Green Building
2. Electric Consumption vs. Temperature and Humidity
3. Heating and Cooling Energy vs. Temp and Humidity
4. Energy Proportional Buildings
5. Publications

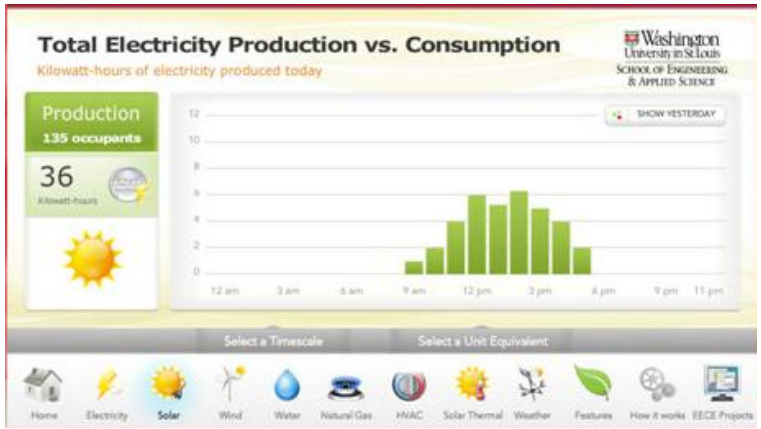
Best Site?
http://www.cse.wustl.edu/~jain/talks/icares.htm

Large Office Green Building

- Energy Environment and Chemical Engineering Dept
- Gold certificate for Leadership in Environment and Energy Design (LEED) by US Green Building Council

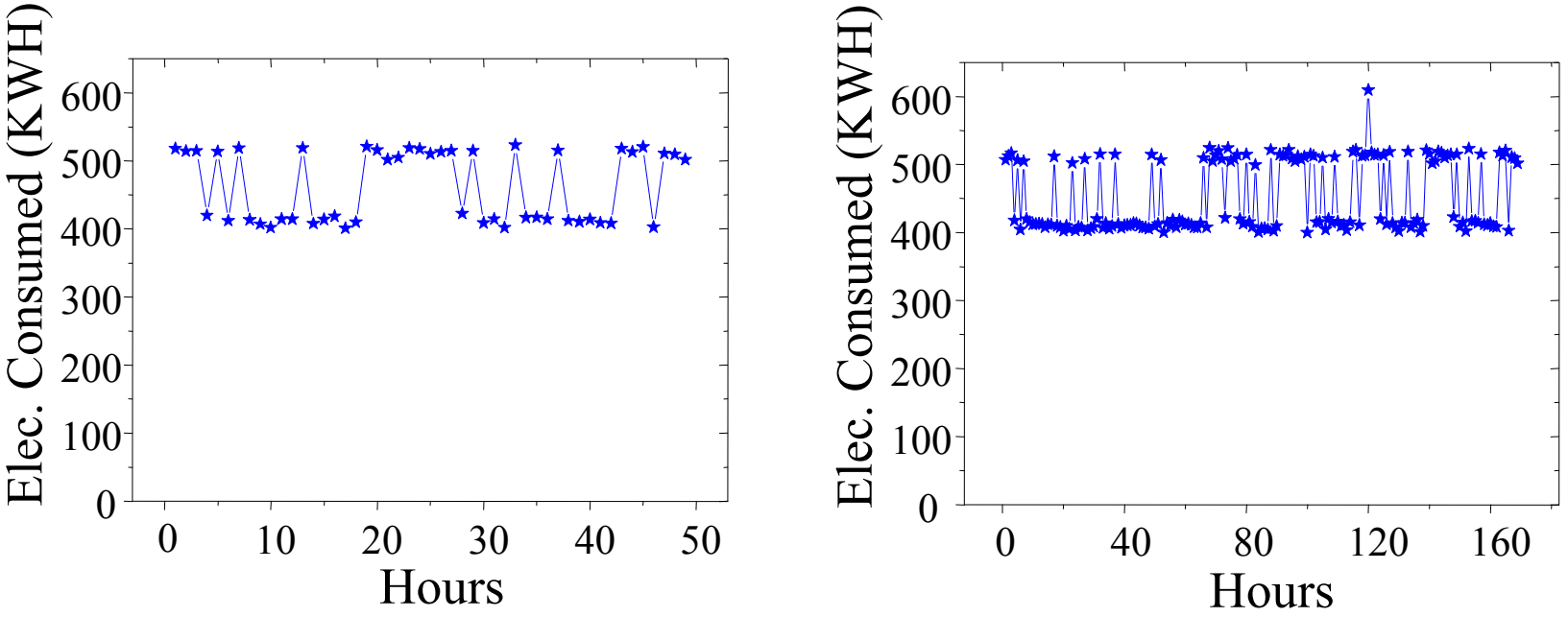
Brauer Hall Features

- High Albedo Roof: Reduce solar radiation heating
- Rainwater collected in cistern
- 8 Solar panels with power of 9.8kw
- A vertical axis wind turbine
- Solar water heater
- Centralized Meters
- Real-time energy data display by online webpage



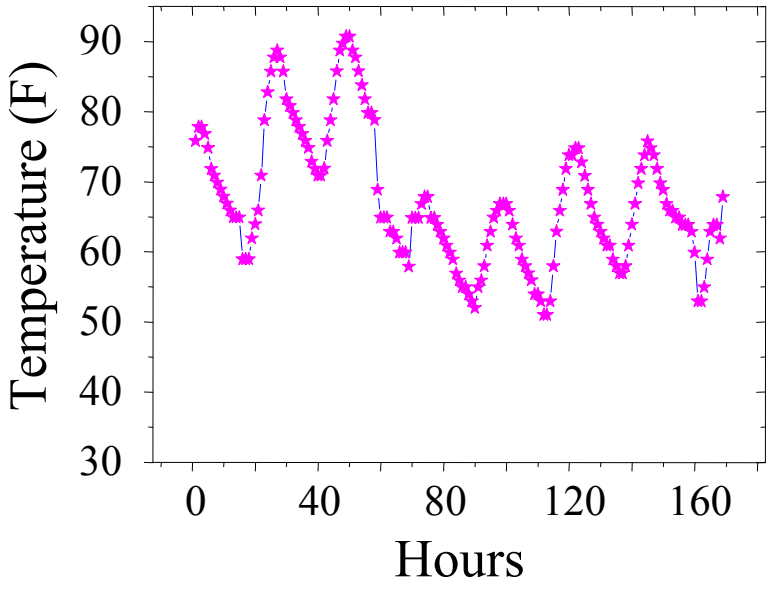
- Goal: Analyze the energy consumption data

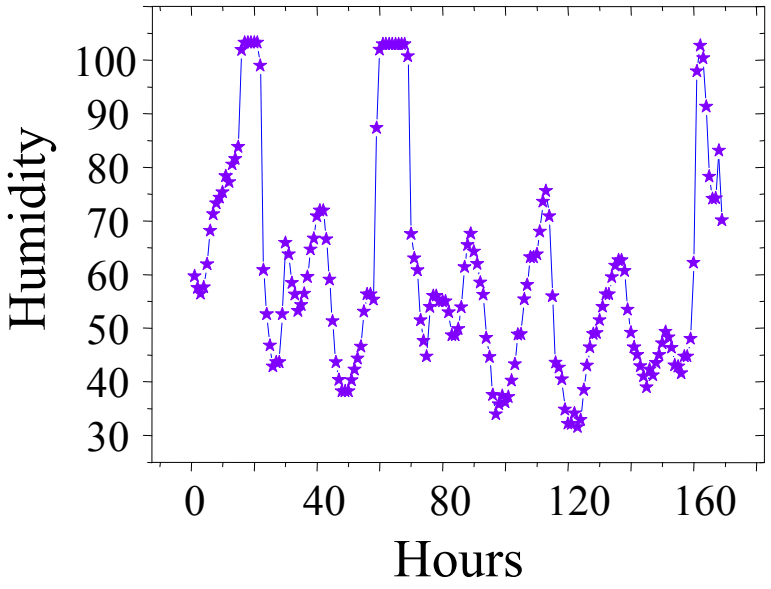
Electricity



- Total hourly electricity consumption traces for 2 days (from 4/14/2010 to 4/15/2010) and 7 days
- Pattern shows very little variation between the busiest hours and the idlest hour ⇒ ***the total electricity consumption possibly has low connection with occupancy***.

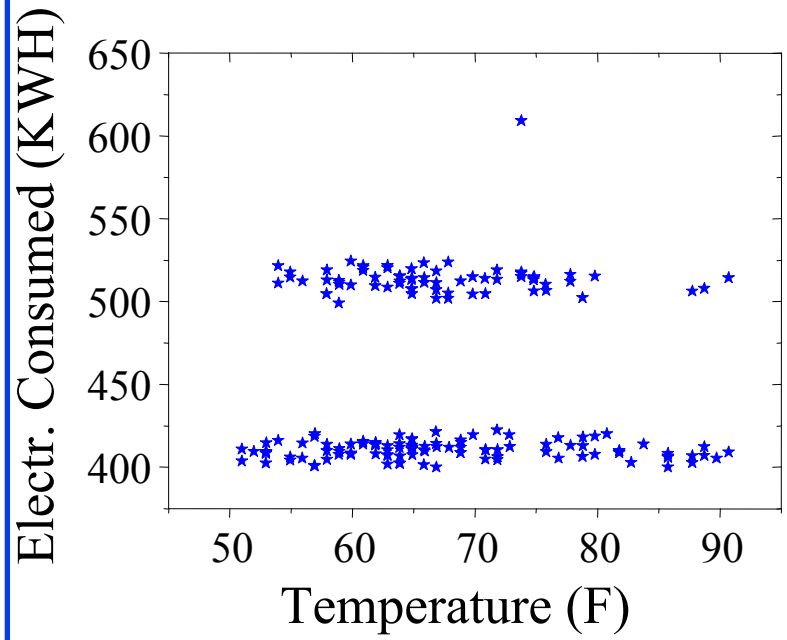
Temperature and Humidity

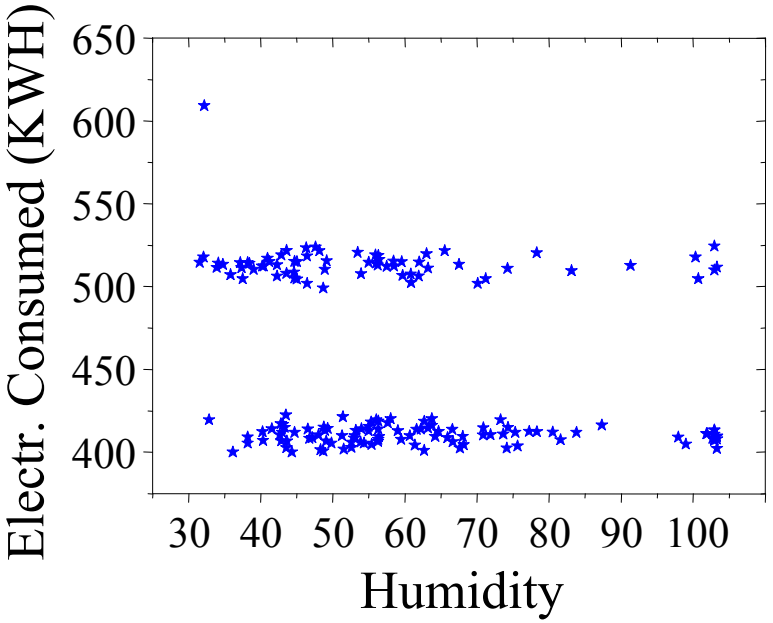




- Temperature and humidity trace for 1 week between 4/8/2010 and 4/15/2010.
- Both fluctuate during days and nights but not see any direct correlation between them

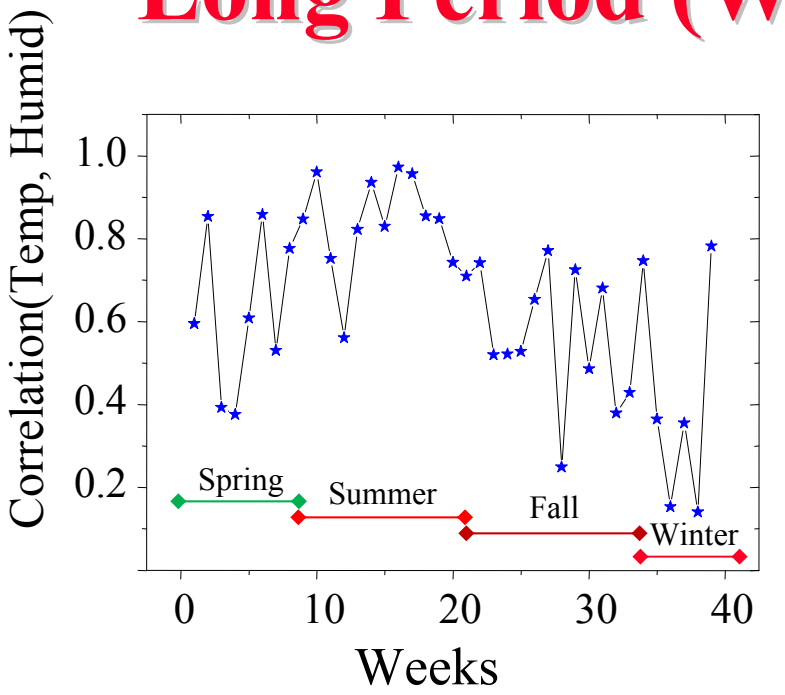
Electricity vs. Temp. and Hum.

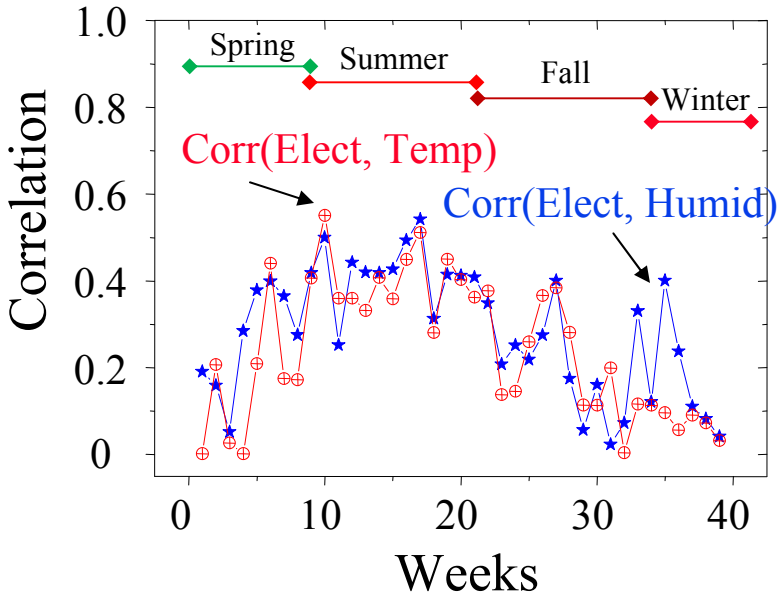




- Conclusion: Electric consumption is not related to temperature or humidity

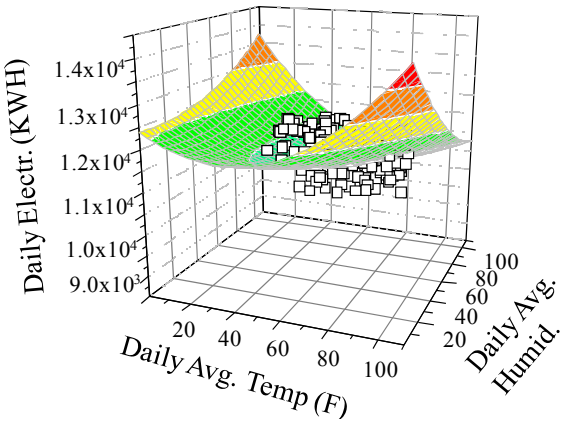
Long Period (Weekly) Correlation



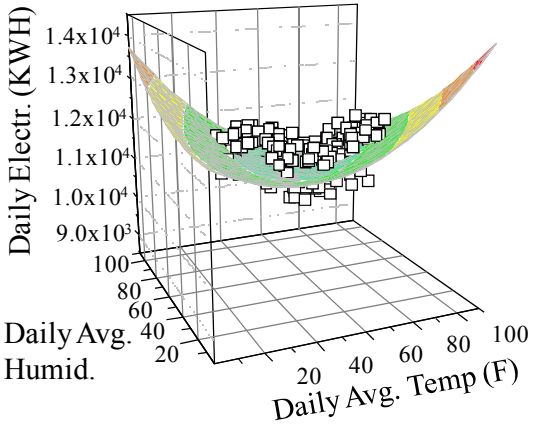


- Temperature (X), Humidity (Y), Electricity (Z)
- A continuous dataset for about 10 months (39 weeks) from 3/18/2011 to 12/31/2011
- Corr(temp, humid) from 0.2 to 0.9; Corr(elect, temp) and Corr(elect, humid) mostly below 0.5
- Conclusion: Electric consumption has low correlation with outside temperature or humidity

3D Regression Graph



(a) Front view

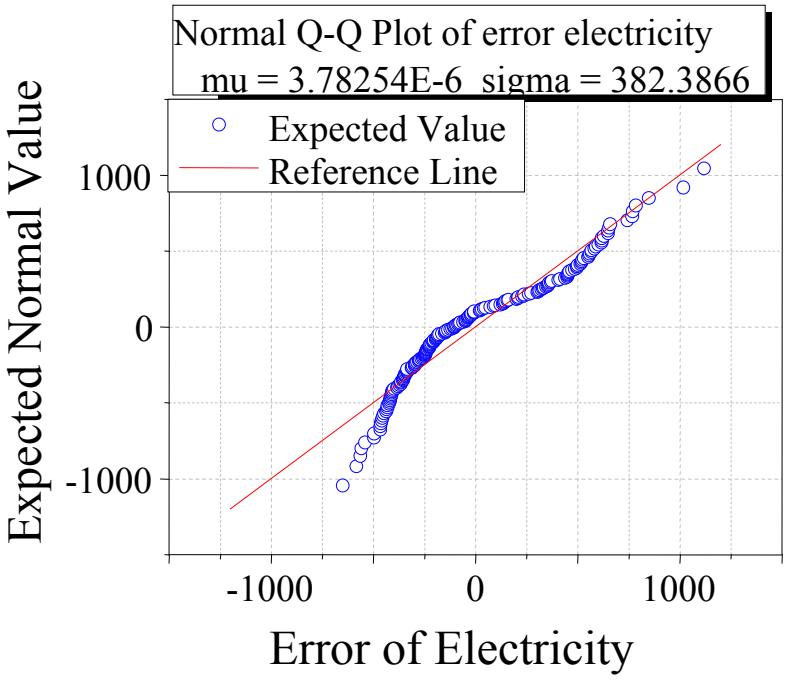


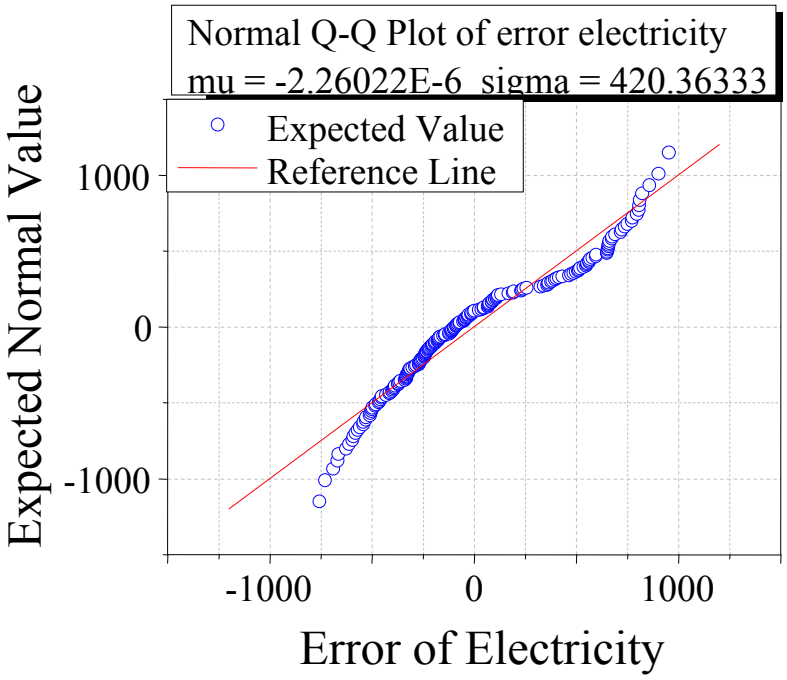
(b) Side view

- Multiple Polynomial Regression (X=Temperature, Y=Humidity)
- $E = a_{00} + a_{01}X + a_{10}Y + a_{11}XY + a_{02}X^2 + a_{20}Y^2 + \varepsilon$
- Coefficient of Mulitple Correlation $R^2 = 0.19$
  => 81% of variation is not related to temperature or humidity

Regression Model Assumption Validation

- The model assumes exponential distribution of errors
- Quantile-quantile Plots show that the assumption is mostly valid

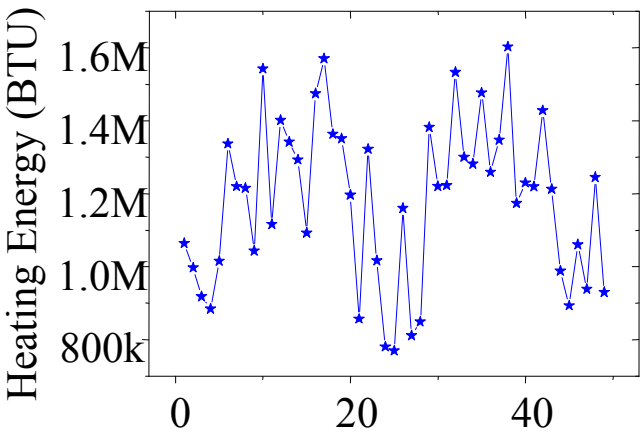


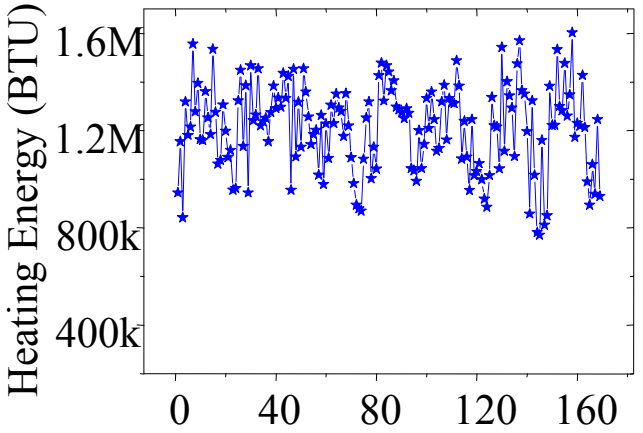


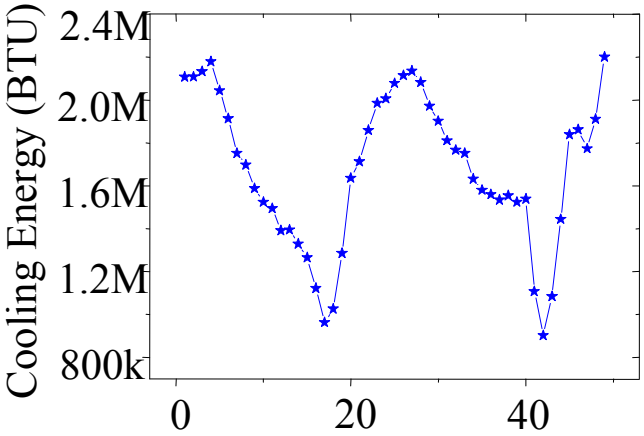
Analysis Phase II

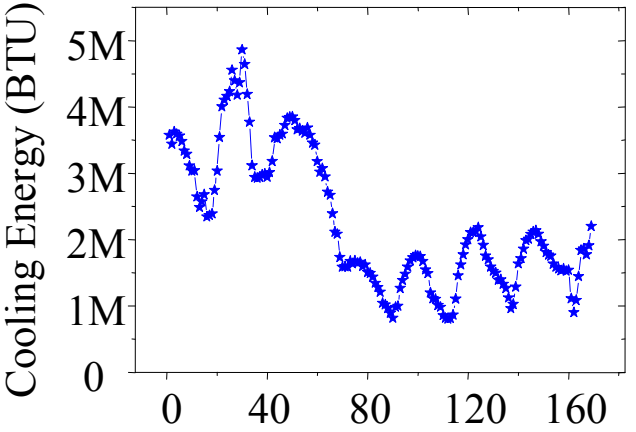
- Central heating and cooling systems
- The building's heating and cooling system is shared with five or six other building
- The same air is circulated to different buildings and is locally cooled or heated as needed
  $\Rightarrow$ Study heating energy and cooling energy separately

Heating and Cooling Energy



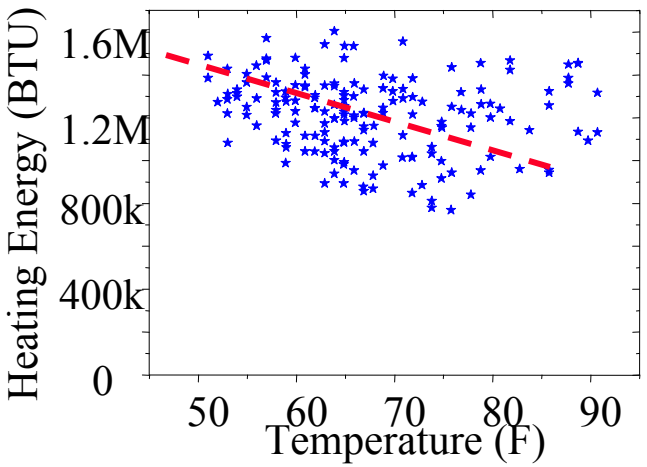


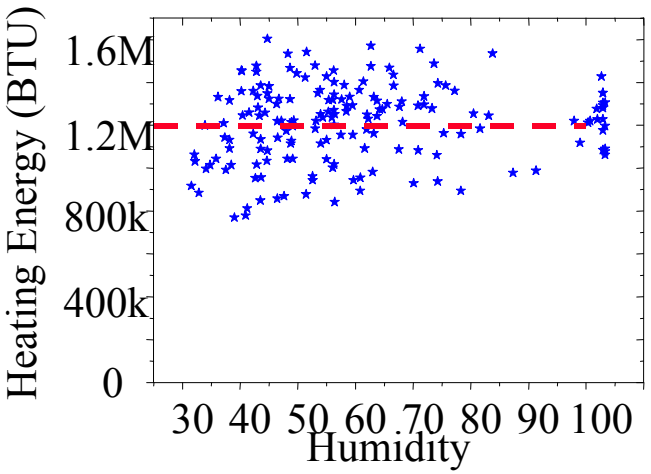


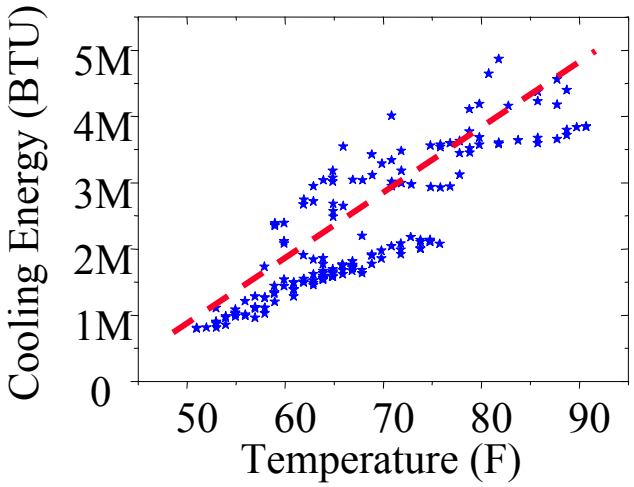


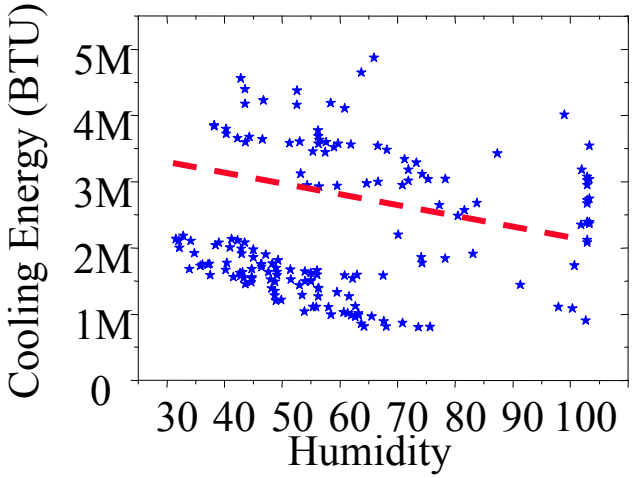
- Traces for 48 hours (2 days) and 168 hours (7 days)
- Heating peak approximately comes with cooling trough.

Heating vs. Temperature and Humidity



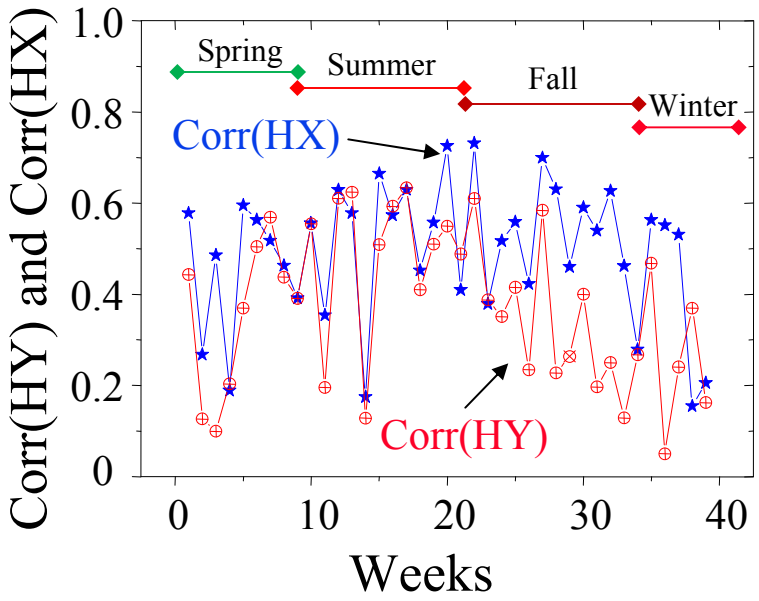


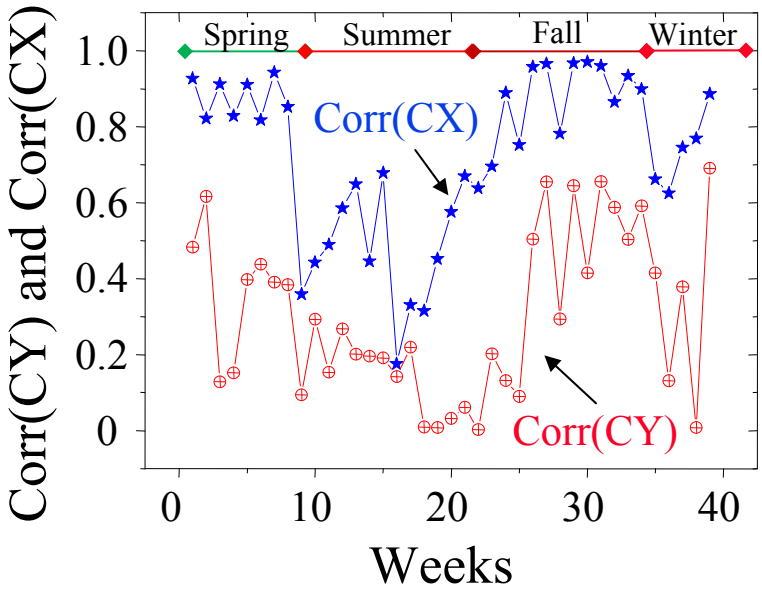




- Cooling highly correlated with temperature

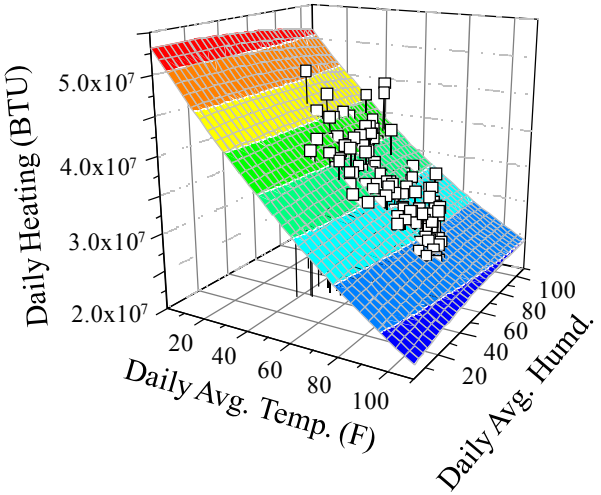
Long Period Correlation Analysis

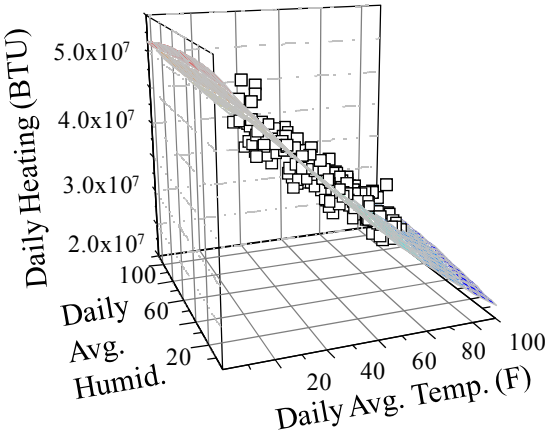




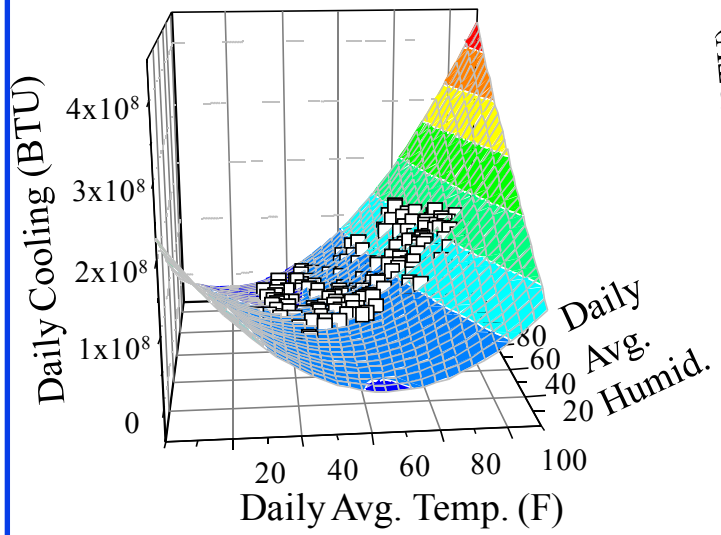
- H=Heating Energy, C=Cooling Energy, X=Temperature, Y=Humidity
- Heating energy correlations are mostly below 0.6.
- Cooling energy correlations are around 0.8 and 0.9 in spring, fall, and winter seasons, while struggling around 0.5 for summer

3D Regression Graph

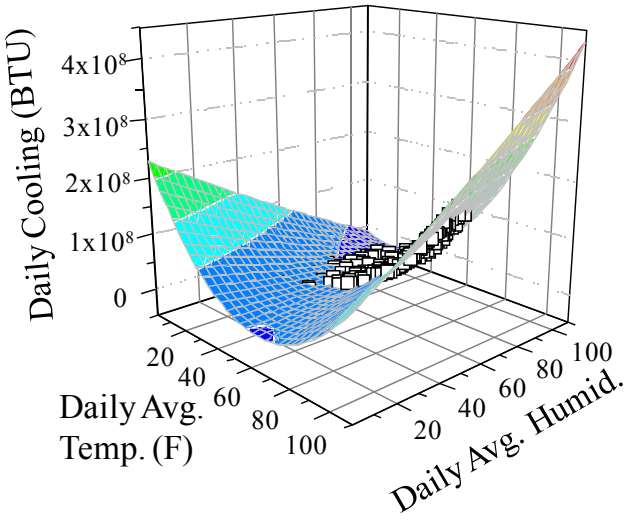




R^2=0.86



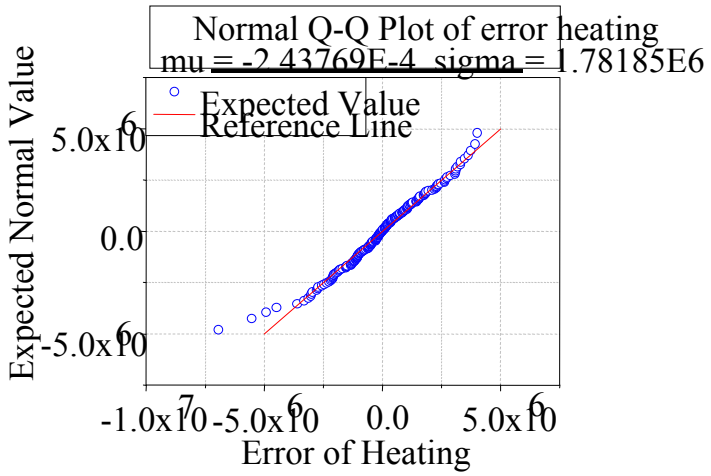
(a) Front view

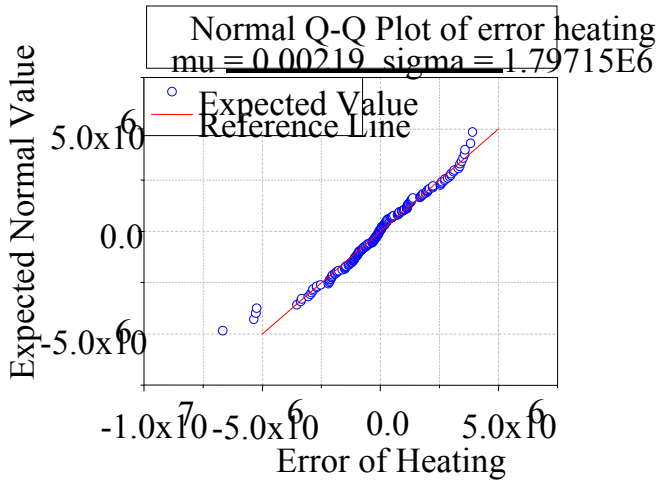


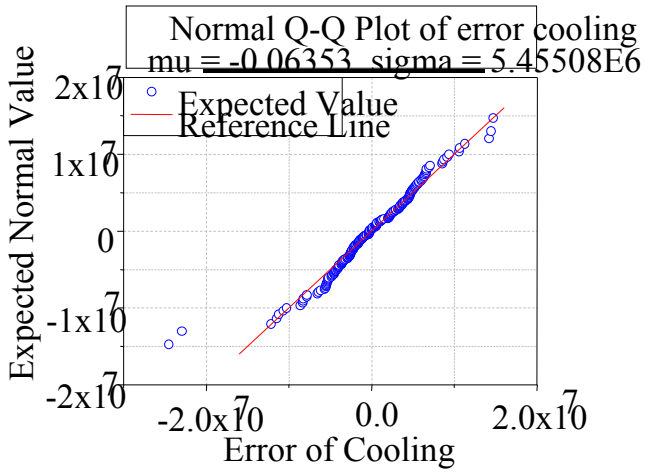
R^2=0.98

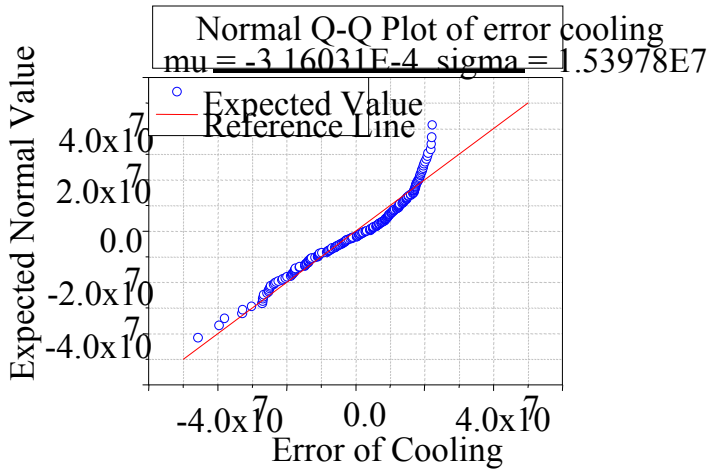
(b) Side view

Model Assumption Validation









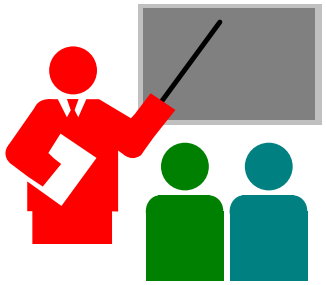
- Errors are approximately normally distributed.

Energy Proportional Buildings

- Similar to Energy Proportional Computing
- Old Computing and communication:
  - Same power for idle or busy state
    idle = execute null instructions
    or send zeros on wire to keep the clocks synchronized
  - Energy consumption was independent of load
- New CPUs and network devices are designed to be energy proportional $\Rightarrow$ Energy $\propto$ Load
- We coined the term "Energy Proportional Building" for buildings that consume less energy when unoccupied or when the outside weather is good

Energy Proportional Buildings

- Energy proportionality can be obtained by occupancy sensors, and sensor controlled energy consumption
  - Much cheaper than Solar Panels, wind turbines, …
  - Easily done for residential buildings and small office buildings.
  - Can be done for old or new buildings
- WUSTL is planning to spend millions on renovating old buildings for energy efficiency
- We believe more Carbon Dioxide Equivalent (CDE)/Dollar can be achieved by making them energy proportional



Summary

1. Green buildings = Energy efficient by design
   ≠ Energy efficient in operation
2. Centralized heating and cooling systems = Cost Efficient
   ≠ Energy efficient
3. Energy Proportional Buildings are those whose energy consumption reduces depending on occupancy and weather
4. Energy proportionality is more cost effective than green renovations
5. It is important to compare the energy savings and cost of renovations and energy proportional operation

Energy Proportional Buildings are more CDE/$ efficient

Publications

- Jianli Pan, Raj Jain, Pratim Biswas, Weining Wang, Sateesh Addepalli, "Toward an Energy-Proportional Building Prospect: Evaluation and Analysis of the Energy Consumption in a Green Building Testbed," To be submitted to IEEE Transactions on Smart Grid.
- Jianli Pan, Raj Jain, Pratim Biswas, Weining Wang, Sateesh Addepalli, "A Framework for Smart Location-Based Automated Energy Controls in a Green Building Testbed," Submitted to 2012 IEEE EnergyTech Workshop of IEEE Power and Energy Society, Cleveland, OH, June 2012.

Desperately seeking Social Science and Economics collaborators