# CAE 465/526 Building Energy Conservation Technologies

Fall 2023

## August 31, 2023

Building energy consumption patterns and performance analysis

Built Environment Research @ IIT

*Advancing energy, environmental, and sustainability research within the built environment*

www.built-envi.com

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# ANNOUNCEMENTS

# Announcement

- Assignment 1 is posted

# INTRODUCTION

# Introduction

- Understanding energy consumption patterns in:
  - Campus buildings
  - Residential/Commercial buildings

- Starting to look into calculating and predicting energy consumption patterns using building energy models

# Classify Buildings

- Understand approaches to analyze building energy consumption patterns
- Use a classification procedure
- Characterize weather data
- Consider a building selection criteria
- Capture all energy consumption commodities
- Utilize different energy modeling methods

# Understand Energy Use Pattern of Buildings

- Select buildings with different ages, shapes, and occupancy patterns
- Install sensors to track energy consumption of buildings and weather data
- Clean the monitored energy and weather data
- Establish a procedure to analyze and classify buildings based on their energy use pattern

# CAMPUS BUILDINGS

# Why Campus Buildings

- Campuses Typically:
  - Have sustainability programs that monitor energy consumption of buildings. Record energy commodities with different level of granularity such as 15 minutes, hourly, monthly
  - Open to share monitored energy consumption of buildings with the research community
  - Operate with different energy commodities such as electricity, natural gas, steam, and chilled water, enabling better disaggregation of end-uses without sub-metering end-uses.
  - Spend close to $2 billon each year on energy*
  - Endeavor to construct new buildings or renovate existing buildings to meet the requirements for energy efficient buildings



* Sub-metering for higher education campuses with EnergyStar http://www.aashe.org/files/aashe2011-materials/p515311.pdf

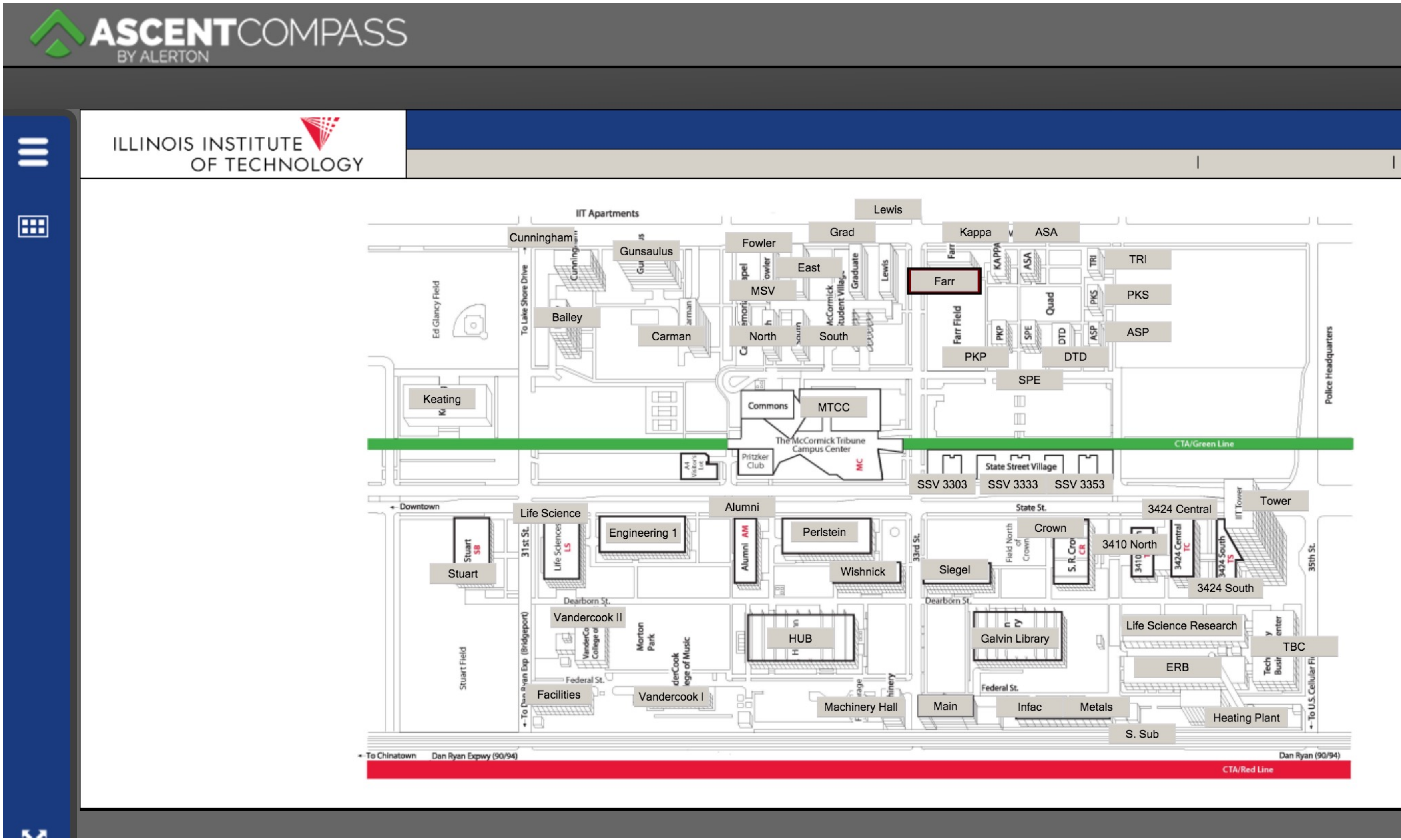
# Campus Buildings Are Unique

- Campus buildings are unique due to the existence of:
  - Buildings with different ages with different HVAC systems (e.g., baseboards, VAV with reheat)
  - Buildings with different sizes and shapes
  - Buildings with different principal activity (e.g., offices, classrooms, laboratories), meaning buildings have different occupancy pattern.
  - Energy intense laboratories (e.g., laboratories with fume hoods, bio-safety cabinet)

- This enables opportunities to retrofit buildings and save energy consumption of the buildings

# Monitoring System

- IIT monitoring system database:



# Monitoring System

- Stuart building energy data summary:

| Meter Number | Electric 1 (kWh)<br>Summary | Steam 1 (lbs)<br>1DD2-1-P01 | Chilled Water (kBTU)<br>#1 |
|---|---|---|---|
| Current Meter Reading | - | 21,356,710 lbs | 15,188,800 kBTU |
| Yesterday's Meter Reading | - | 21,356,710 lbs | 15,183,500 kBTU |
| Last Month's Meter | - | 21,356,710 lbs | 15,140,000 kBTU |
| Last Hour's Consumption | 47 kWh | 0 lbs | 900 kBTU |
| Today's Consumption | 461 kWh | 0 lbs | 5,300 kBTU |
| Yesterday's Consumption | 1,078 kWh | 0 lbs | 14,400 kBTU |
| Month Consumption | 3,672 kWh | 0 lbs | 48,800 kBTU |
| Last Month Consumption | 30,431 kWh | 0 lbs | 424,600 kBTU |
| kBTUs This Month | 12,529 kBTU | 0 kBTU | 48,800 kBTU |
| kBTUs Last Month | 103,835 kBTU | 0 kBTU | 424,600 kBTU |
| Cost this Month ($) | 302.43 | 0.00 | 835.29 |
| Cost Last Month ($) | 2,506.30 | 0.00 | 7,267.74 |

**Totals**

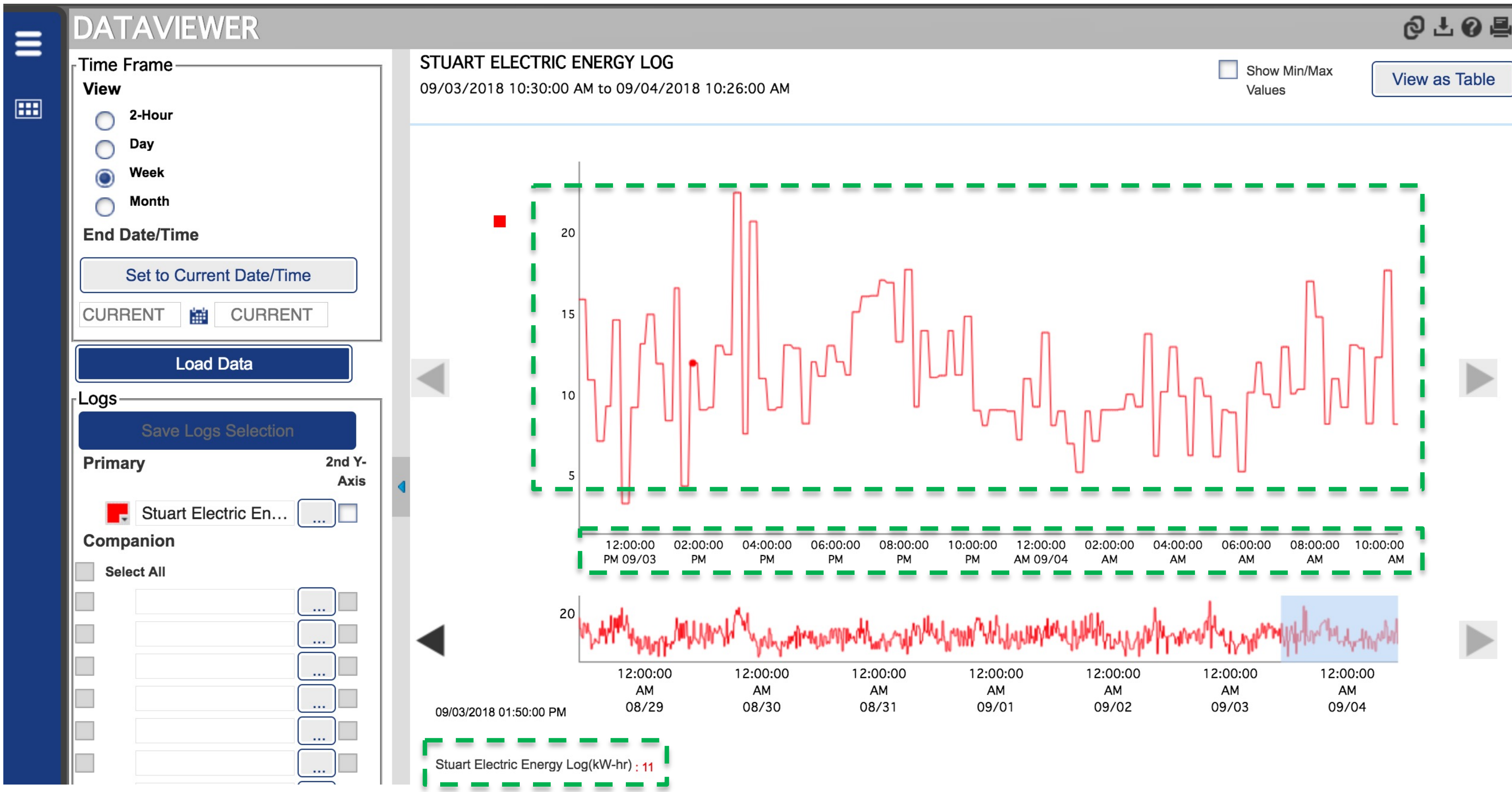
| | | | |
|---|---|---|---|
| Total Building Cost ($) | 1,137.72 | kBTUs/Sq. Ft this Month | 0.77 |
| Last Month Cost ($) | 9,774.03 | Total Building kBTUs | 61,329 |

# Monitoring System

- Stuart building chilled water energy pattern

# Monitoring System

- Stuart building electric energy pattern



# Monitoring System

- Some campuses are more open to share the data to public

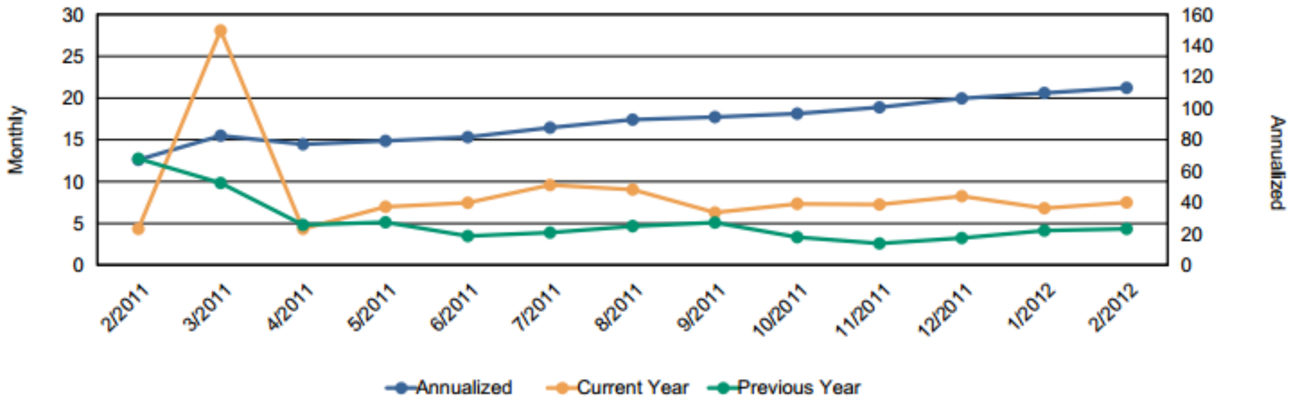
**DIVISION OF ADMINISTRATION**
**UTILITIES & ENERGY MANAGEMENT**

TEXAS A&M UNIVERSITY

**Energy Use Index (EUI) Monthly Report Card By Cost**
**For the Period Ending February 28, 2012**

**Buildings >= 2,000 gsf**

| # | Building | GSF | EUI | Annual Cost |
|---|---|---|---|---|
| 0039 | aquaculture research teaching facility | 4,333 | 113 | $9,344 |

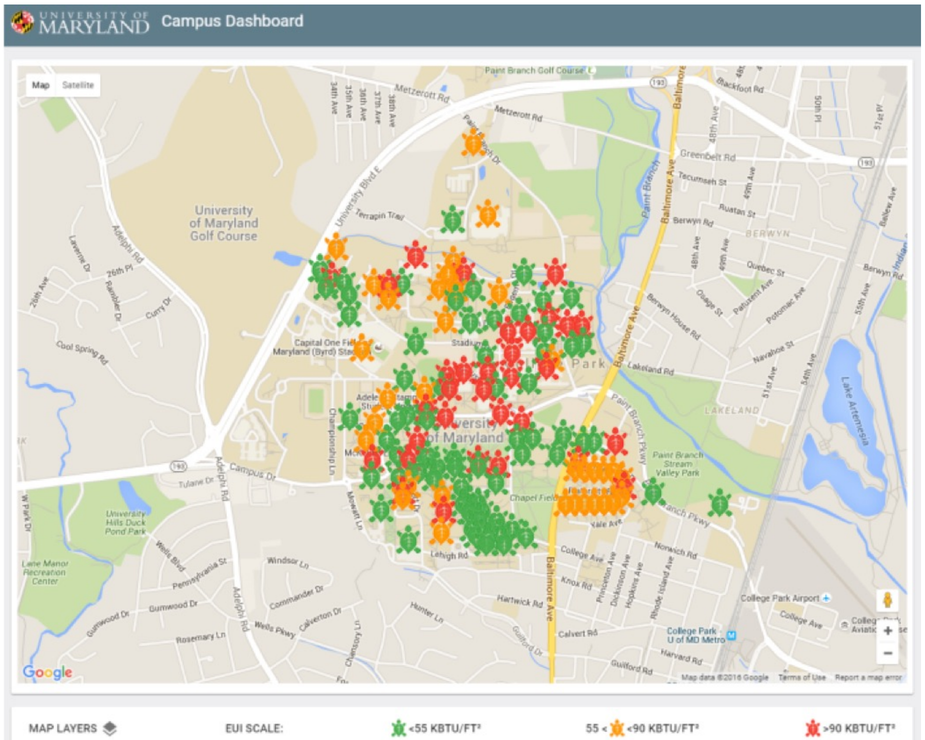


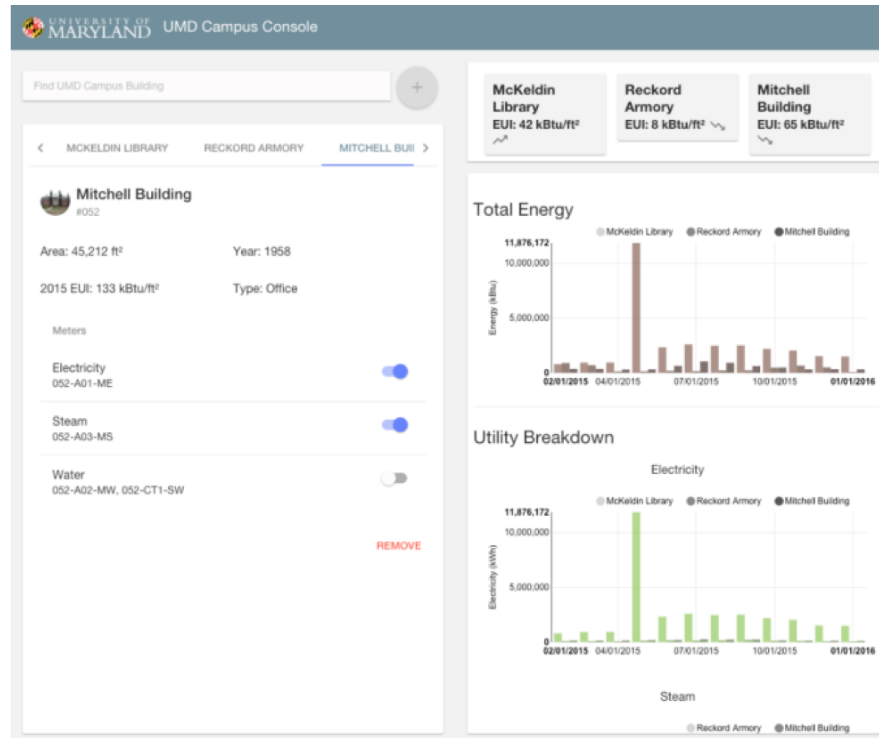

| # | Building | GSF | EUI | Annual Cost |
|---|---|---|---|---|
| 0040 | field lab and office bldg | 2,275 | 134 | $7,548 |

https://utilities.tamu.edu/wp-content/uploads/2012/04/EUIMonthlyVersusAnnual_SortByBldgNumber.pdf

# Monitoring System

- University of Maryland Energy Dashboard



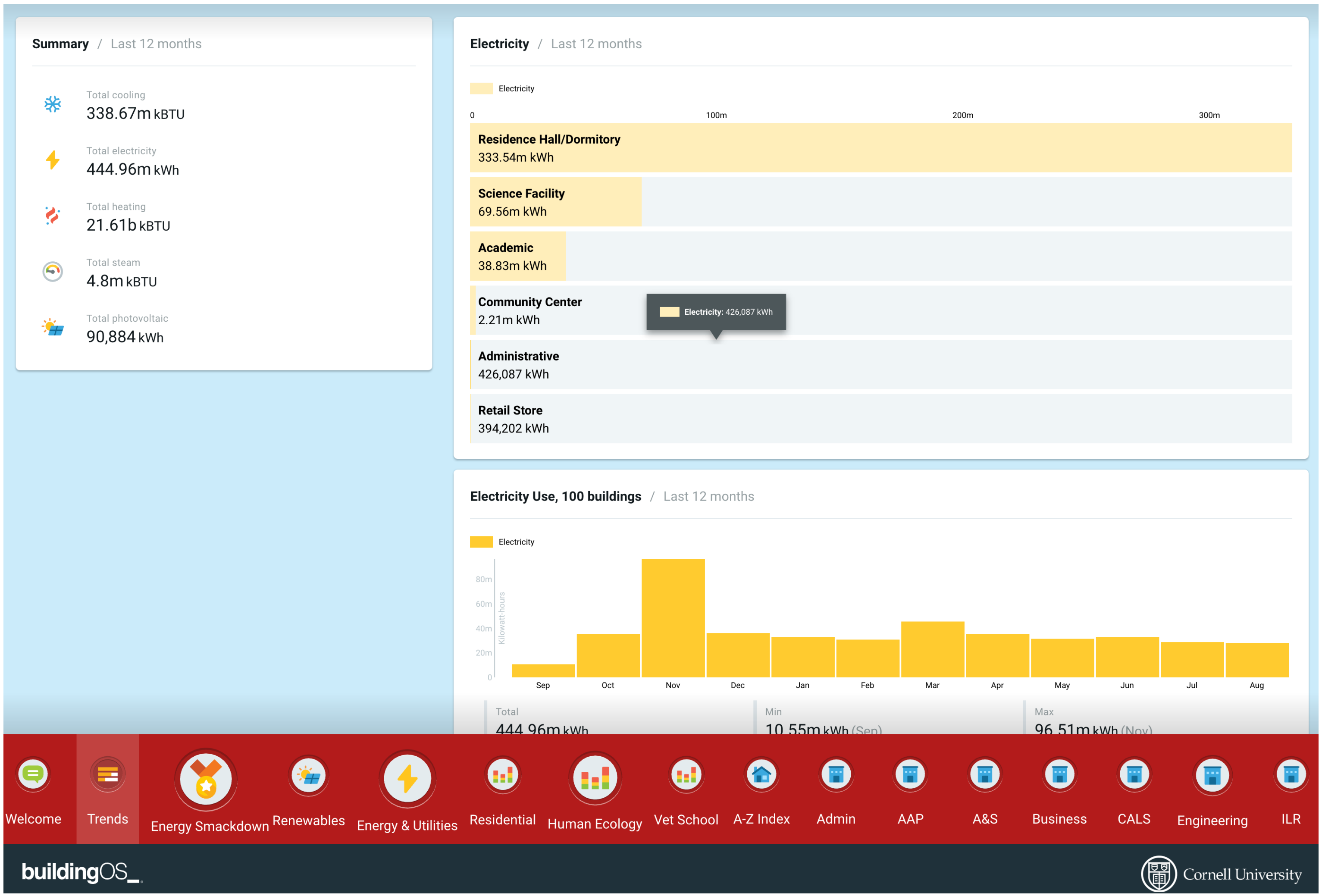






*Heidarinejad and Srebric, building energy modeling*

# Monitoring System

- Cornell University Energy Dashboard

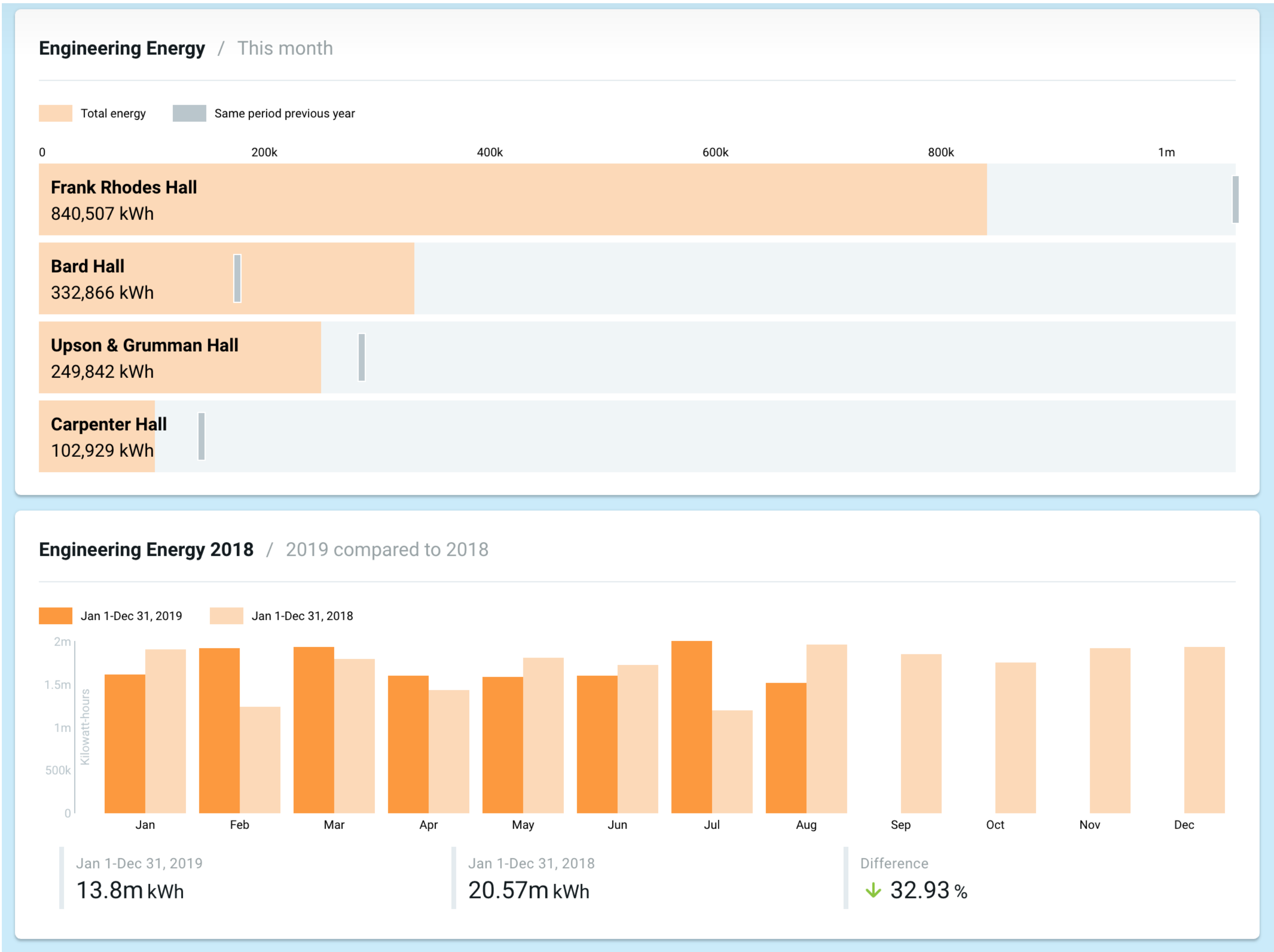





https://buildingos.com/s/cornell/storyboard3763/?chapterId=22033

# Monitoring System

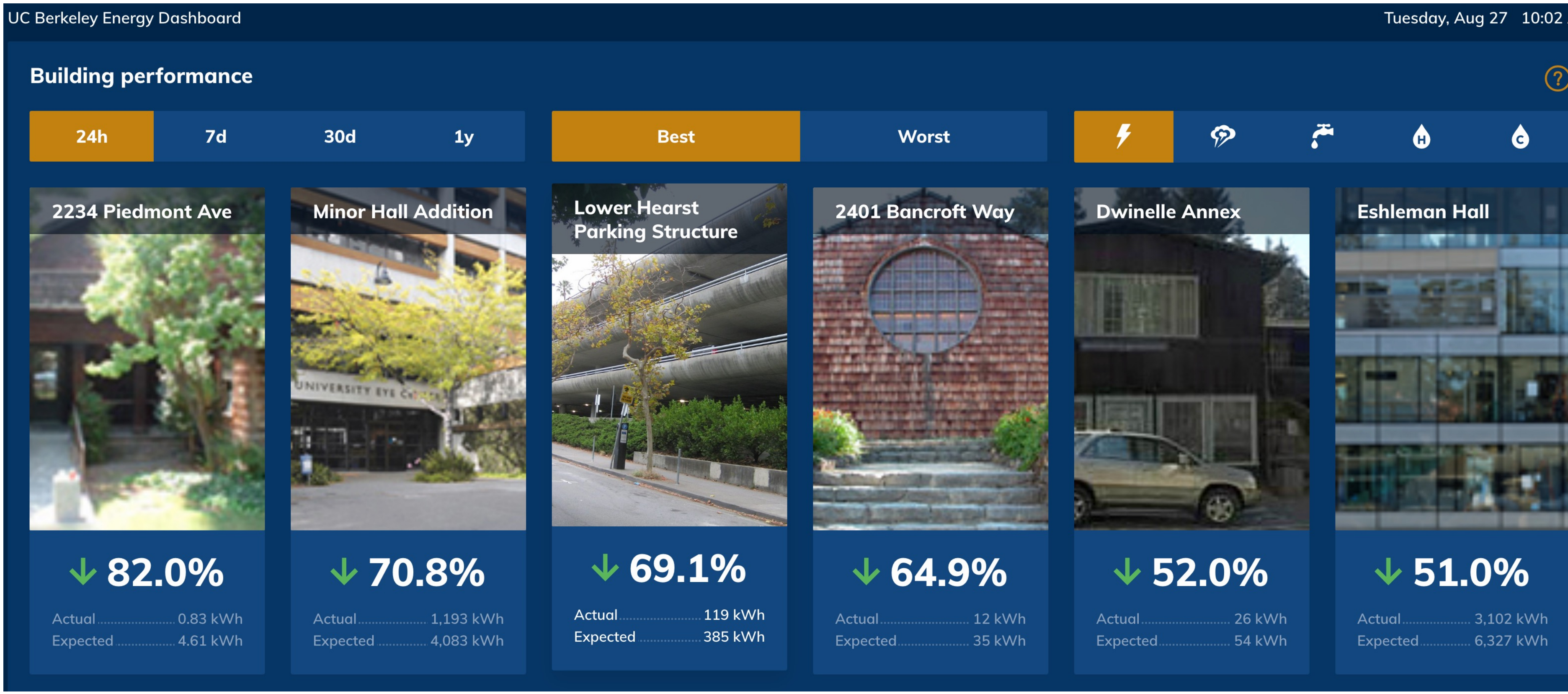
- Cornell University Energy Dashboard




https://buildingos.com/s/cornell/storyboard3763/?chapterId=22033

# Monitoring System

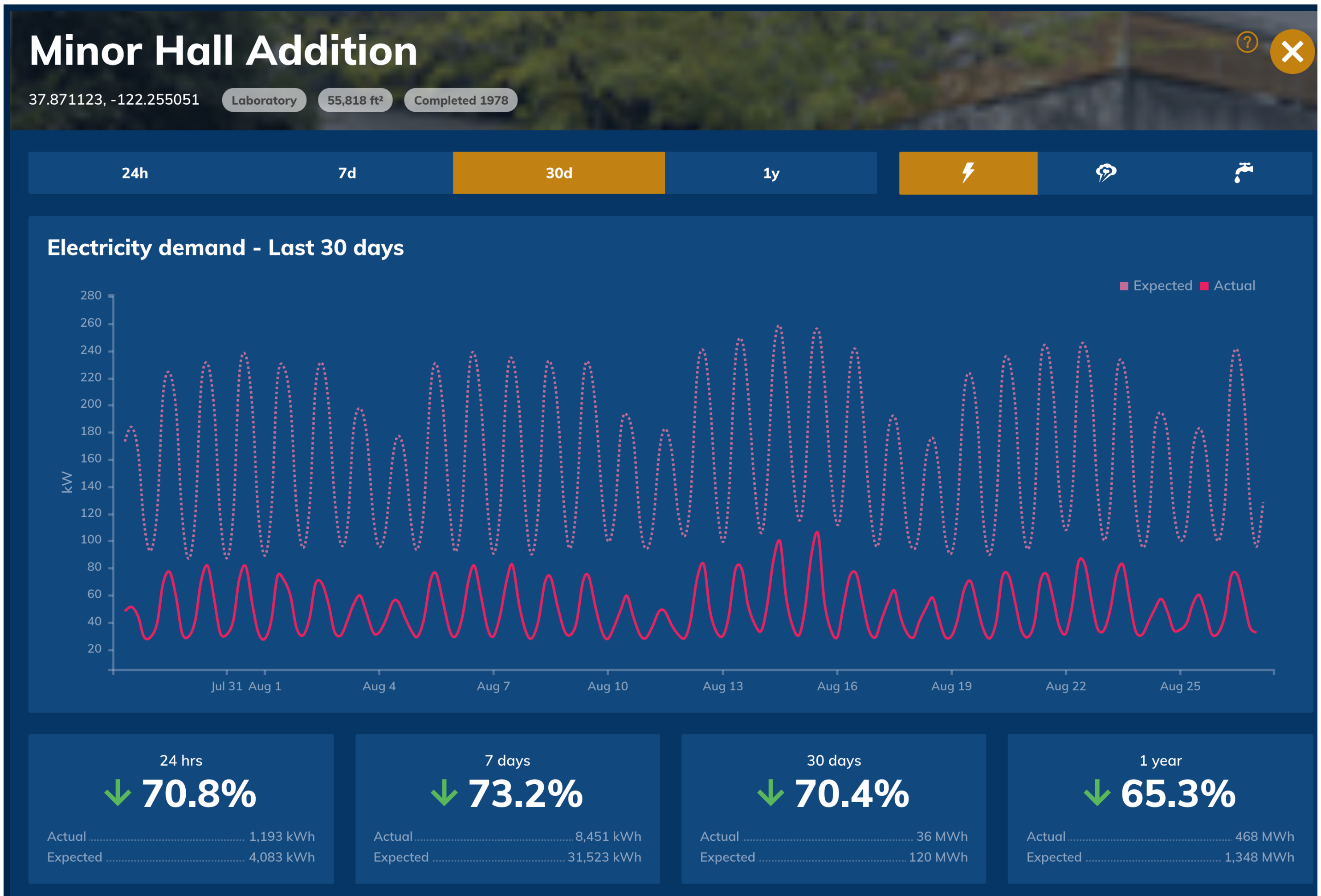
- UC Berkeley Energy Dashboard




https://engagementdashboard.com/universityofcaliforniaberkeley/ucb/building-performance

# Monitoring System

- UC Berkeley Energy Dashboard






https://engagementdashboard.com/universityofcaliforniaberkeley/ucb/building-performance

# Classification Procedure: Campus Buildings

Step 1: → Weather data characterization

Step 2: → Building Selection →

- Primary building categories:
  1. Classroom/Office
  2. Lab mixes
  3. Office areas
  4. Research laboratories
  5. Residential facilities
- Secondary building categories:
  6. Student activity center
  7. Recreational and gym facility
  8. Auditorium (theater)
  9. Multipurpose
  10. Museum
  11. Health Center
  12. Library
  13. Hospitality Services

Step 3: → End-use energy consumption of buildings →

- Chilled water
- Steam/hot water
- Electricity

Step 4: → Normalized energy consumption with weather data →

- Use energy modeling methods
  1. Degree Days
  2. Energy Utilization Index (EUI)
  3. Whole building energy simulation

# Weather Data Characterization

- Common variables:
  - Dry bulb temperature
  - Dew point temperature
  - Cooling Degree Days (CDD)
  - Heating Degree Days (HDD)

- Degree Days (DD): is the difference in temperature between the outdoor mean temperature over a 24-hour period and a given base temperature. For the purposes of determining building envelope requirements*



** ASHRAE Standard 169: Weather Data for Building Design Standards*

# Weather Data Characterization

$$HDD(balance) = 1\ day \times \sum_{number\ of\ days} (T_{outdoor} - T_{balance})^{+}$$

$$CDD(balance) = 1\ day \times \sum_{number\ of\ days} (T_{outdoor} - T_{balance})$$



** ASHRAE Standard 169: Weather Data for Building Design Standards*

# Weather Data Characterization

- CDD base 50°F, CDD50, or 10°C, CDD10:
  - When the mean temperature is more than 50°F or 10°C, temperature difference between the mean temperature for the day and 50°F or 10°C
  - Annual CDDs are the sum of the degree-days over a calendar year *

- **Example:** What's the CDD for a day with mean day outdoor air temperature of 68°F (20°C)?



* ASHRAE Standard 169: Weather Data for Building Design Standards

# Weather Data Characterization

- HDD base 65°F, HDD65, or 18°C, HDD18:
  - When the mean temperature is less than 65°F or 18°C, temperature difference between the mean temperature for the day and 65°F or 18°C *.
  - Annual HDDs are the sum of the degree-days over a calendar year.
  - An example:

- **Example:** What’s is the HDD for a mean day outdoor air temperature of 32°F (0°C)?

* ASHRAE Standard 169: Weather Data for Building Design Standards

# CLASS ACTIVITY

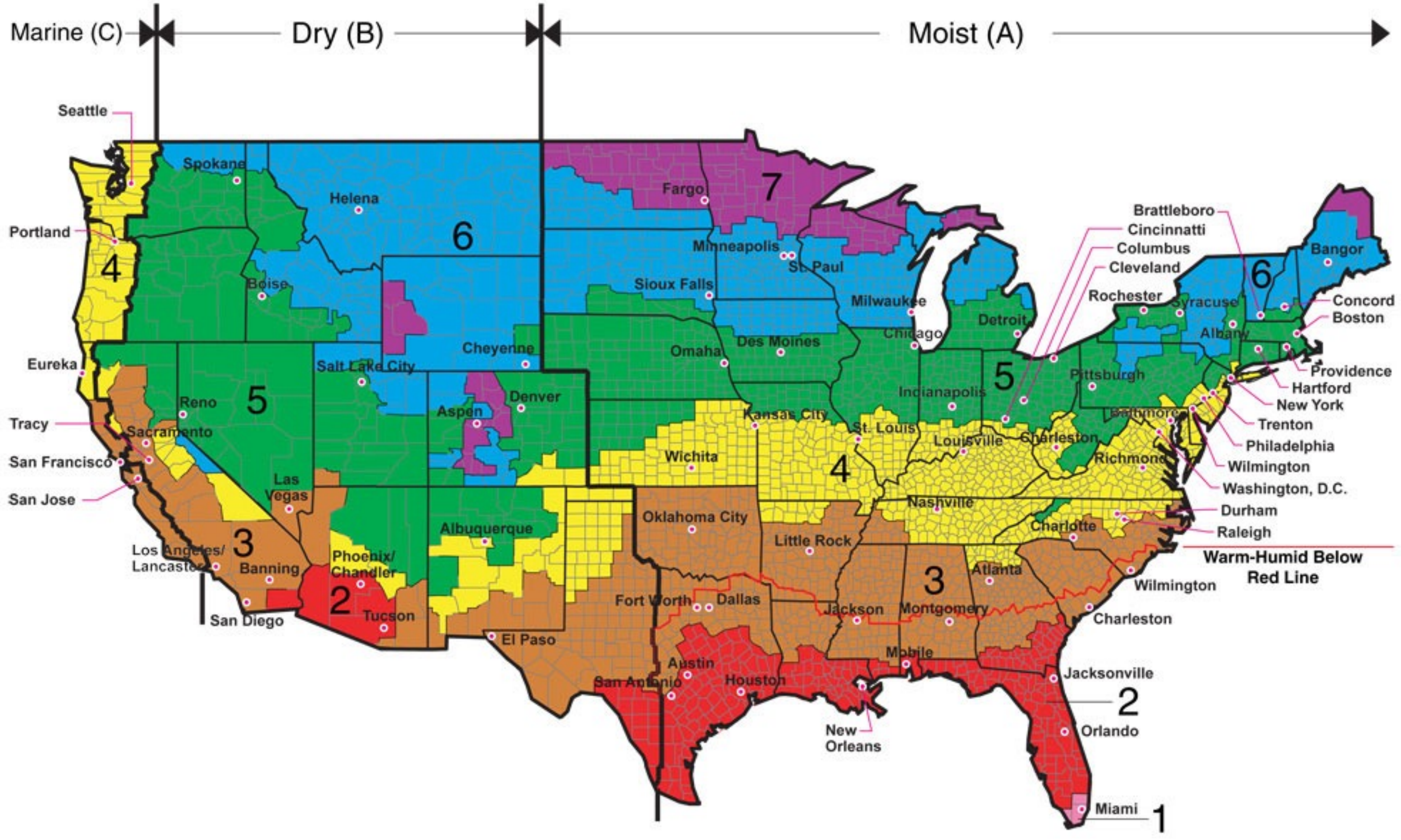
# Class Activity

- **Example:** Calculate heating and cooling degree days for Chicago in using a TMY3 file?

- Additional notes:
  - ❑ Download files from here: http://climate.onebuilding.org/WMO_Region_4_North_and_Central_America/USA_United_States_of_America/index.html
  - ❑ Unzip the folder
  - ❑ Change the extension to CSV from EPW.
  - ❑ Understand the columns: https://bigladdersoftware.com/epx/docs/8-2/auxiliary-programs/epw-csv-format-inout.html#:~:text=EPW%20CSV%20Format%20to%20the,shown%20and%20then%20the%20data.

# Weather Data Characterization

- ASHRAE Climate Zones




What's our climate zone?



* ASHRAE Standard 169: Weather Data for Building Design Standards

# Weather Data Characterization

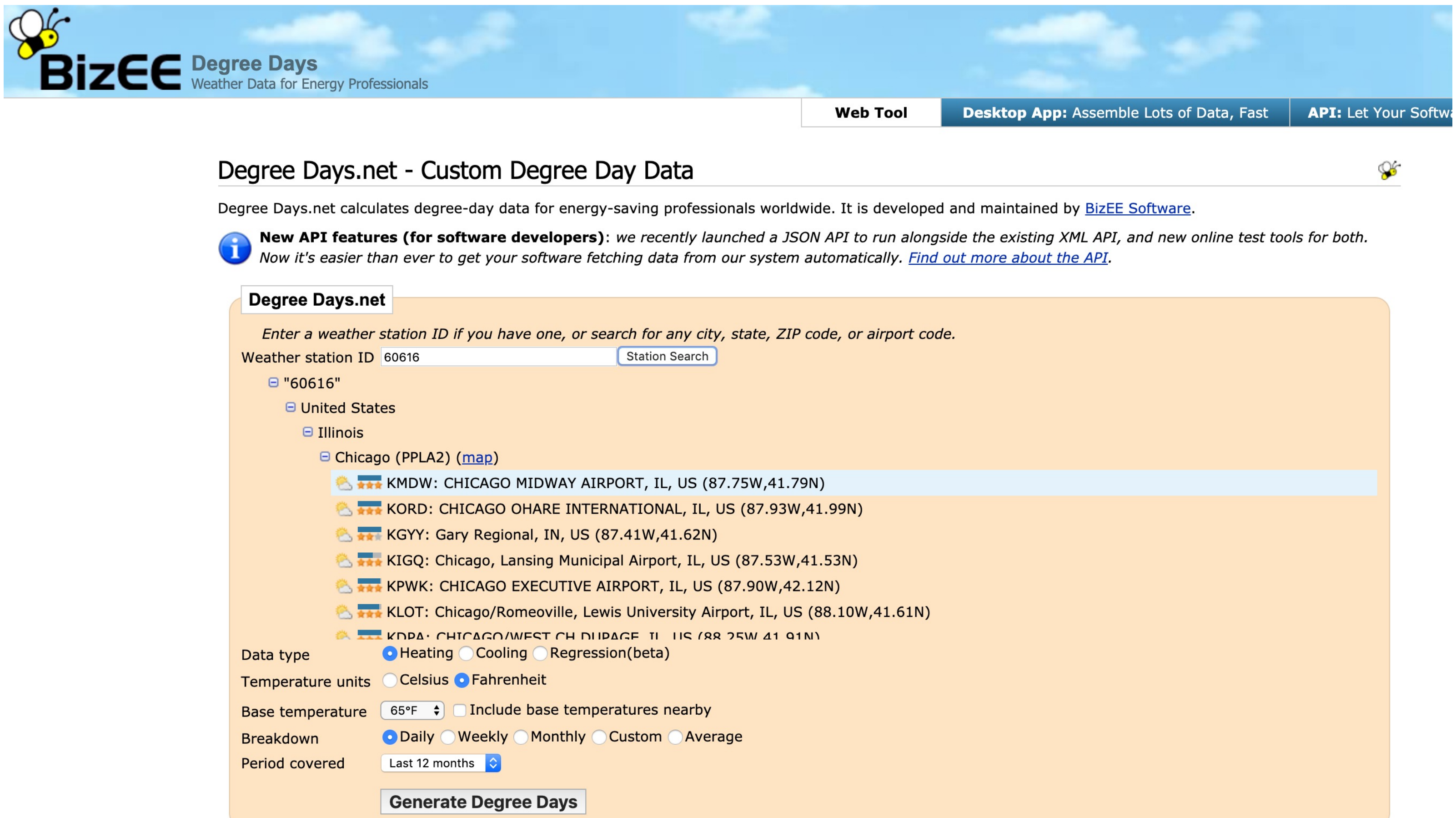
- ASHRAE Climate Zones

| Zone Number | Name | Thermal Criteria | |
|---|---|---|---|
| | | I-P Units | SI Units |
| 1 | Very Hot – Humid (1A), Dry (1B) | 9000 < CDD50ºF | 5000 < CDD10ºC |
| 2 | Hot – Humid (2A), Dry (2B) | 6300 < CDD50ºF ≤ 9000 | 3500 < CDD10ºC ≤ 5000 |
| 3A and 3B | Warm – Humid (3A), Dry (3B) | 4500 < CDD50ºF ≤ 6300 | 2500 < CDD10ºC ≤ 3500 |
| 3C | Warm – Marine | CDD50ºF ≤ 4500 and HDD65ºF ≤ 3600 | CDD10ºC ≤ 2500 and HDD18ºC ≤ 2000 |
| 4A and 4B | Mixed – Humid (4A), Dry (4B) | CDD50ºF ≤ 4500 and 3600 < HDD65ºF ≤ 5400 | CDD10ºC ≤ 2500 and HDD18ºC ≤ 3000 |
| 4C | Mixed – Marine | 3600 < HDD65ºF ≤ 5400 | 2000 < HDD18ºC ≤ 3000 |
| 5A, 5B and 5C | Cool– Humid (5A), Dry (5B), Marine (5C) | 5400 < HDD65ºF ≤ 7200 | 3000 < HDD18ºC ≤ 4000 |
| 6A and 6B | Cold – Humid (6A), Dry (6B) | 7200 < HDD65ºF ≤ 9000 | 4000 < HDD18ºC ≤ 5000 |
| 7 | Very Cold | 9000 < HDD65ºF ≤ 12600 | 5000 < HDD18ºC ≤ 7000 |
| 8 | Subarctic | 12600 < HDD65ºF | 7000 < HDD18ºC |

* ASHRAE Standard 169: Weather Data for Building Design Standards

# Weather Data Characterization

- Online tools:






https://www.degreedays.net/

# Weather Data Characterization

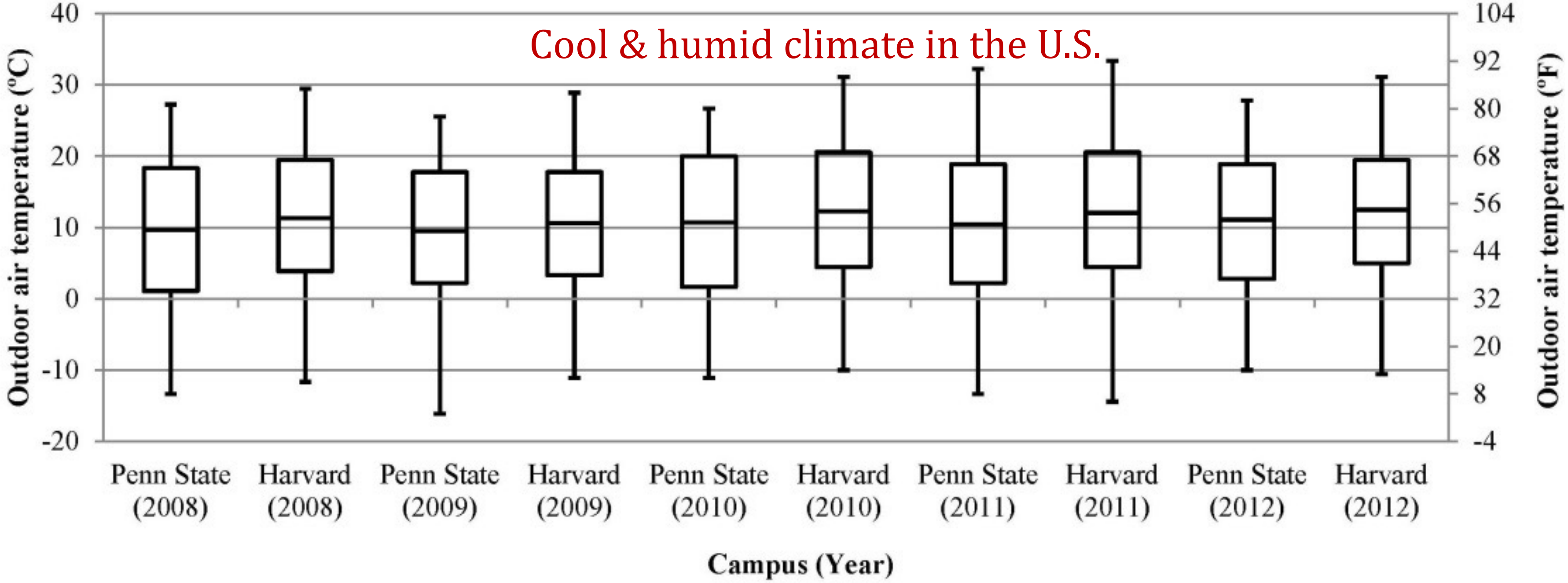
**TABLE D-1 U.S. and U.S. Territory Climatic Data *(Continued)***

| State/City | Latitude | Longitude | Elev., ft | HDD65 | CDD50 | Heating Design Temperature | Cooling Design Temperature | | Number of Hours 8 a.m.–4 p.m. |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Dry-Bulb | Wet-Bulb | |
| | | | | | | 99.6% | 1.0% | 1.0% | $55 < T_{db} < 69$ |
| **Illinois (IL)** | | | | | | | | | |
| Aurora | 41.75 N | 88.35 W | 644 | 6699 | 2880 | NA | NA | NA | NA |
| Belleville/Scott AFB | 38.55 N | 89.85 W | 453 | 4878 | 4146 | 3 | 93 | 77 | NA |
| Carbondale Sewage Plt | 37.73 N | 89.17 W | 390 | 4865 | 3934 | NA | NA | NA | NA |
| Champaign | 40.03 N | 88.28 W | 755 | 5689 | 3697 | NA | NA | NA | NA |
| Chicago Midway AP | 41.73 N | 87.77 W | 620 | 6176 | 3251 | NA | NA | NA | NA |
| Chicago O'Hare WSO AP | 41.98 N | 87.90 W | 674 | 6536 | 2941 | –6 | 88 | 73 | 613 |
| Chicago University | 41.78 N | 87.60 W | 594 | 5753 | 3391 | NA | NA | NA | NA |

*ASHRAE 90.1 2013*

# Weather Data Characterization

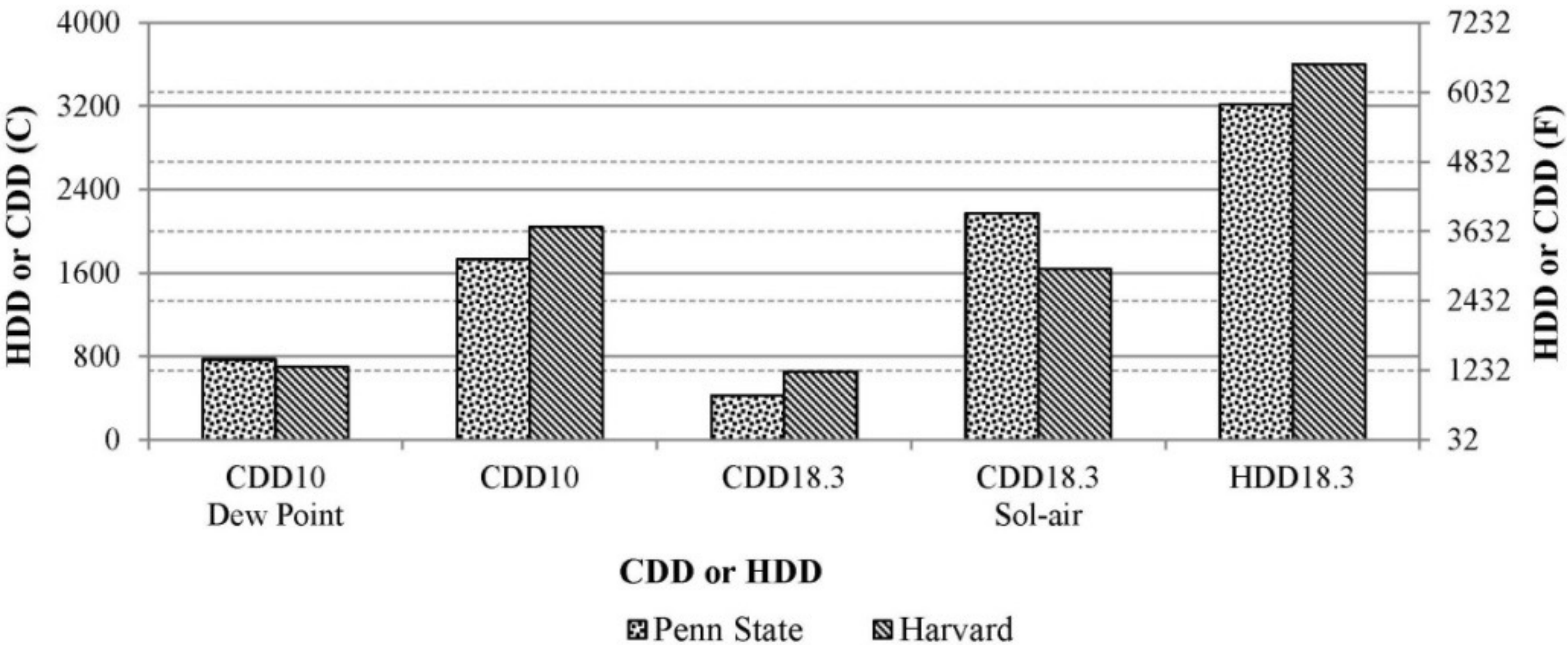
- An example from the Penn State and Harvard campus study.




*Average daily temperature for five years*

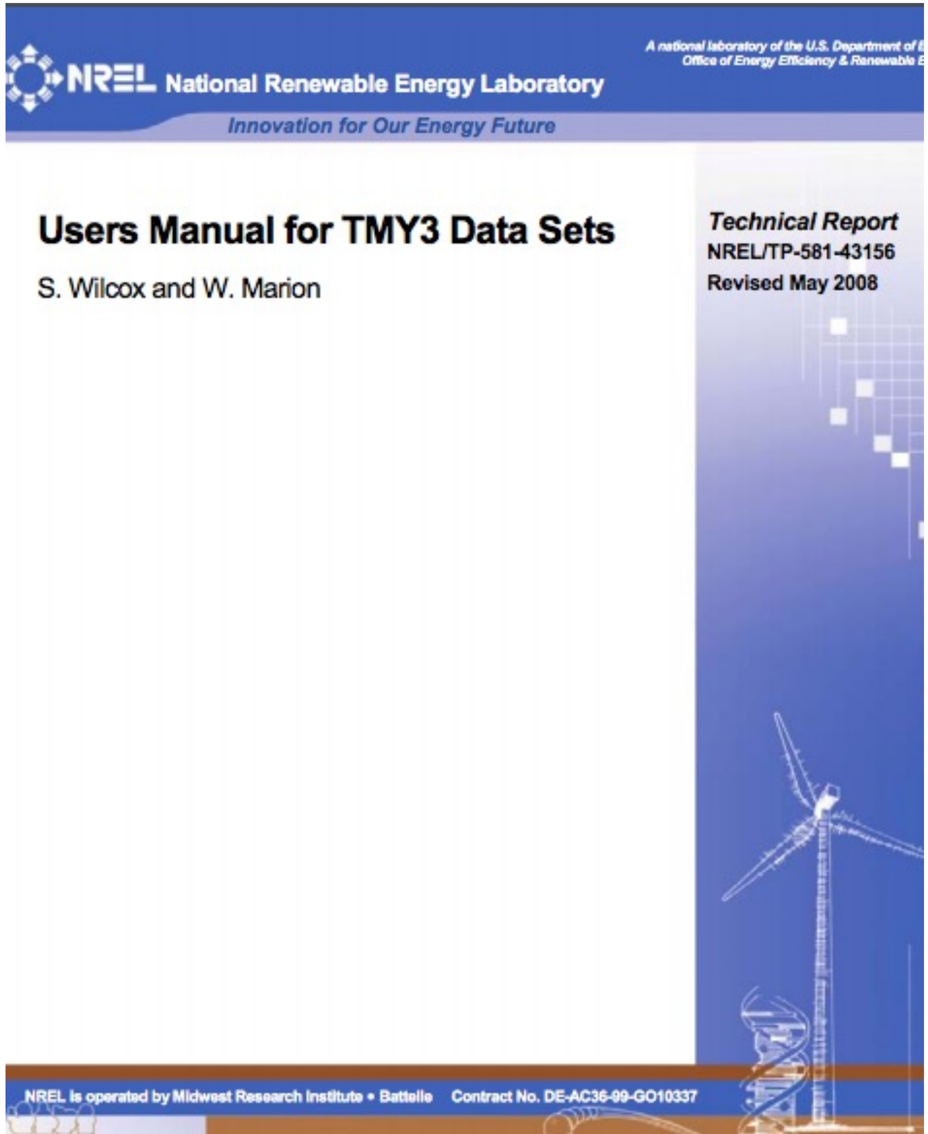
# Weather Data Characterization

- An example from the Penn State's campus.



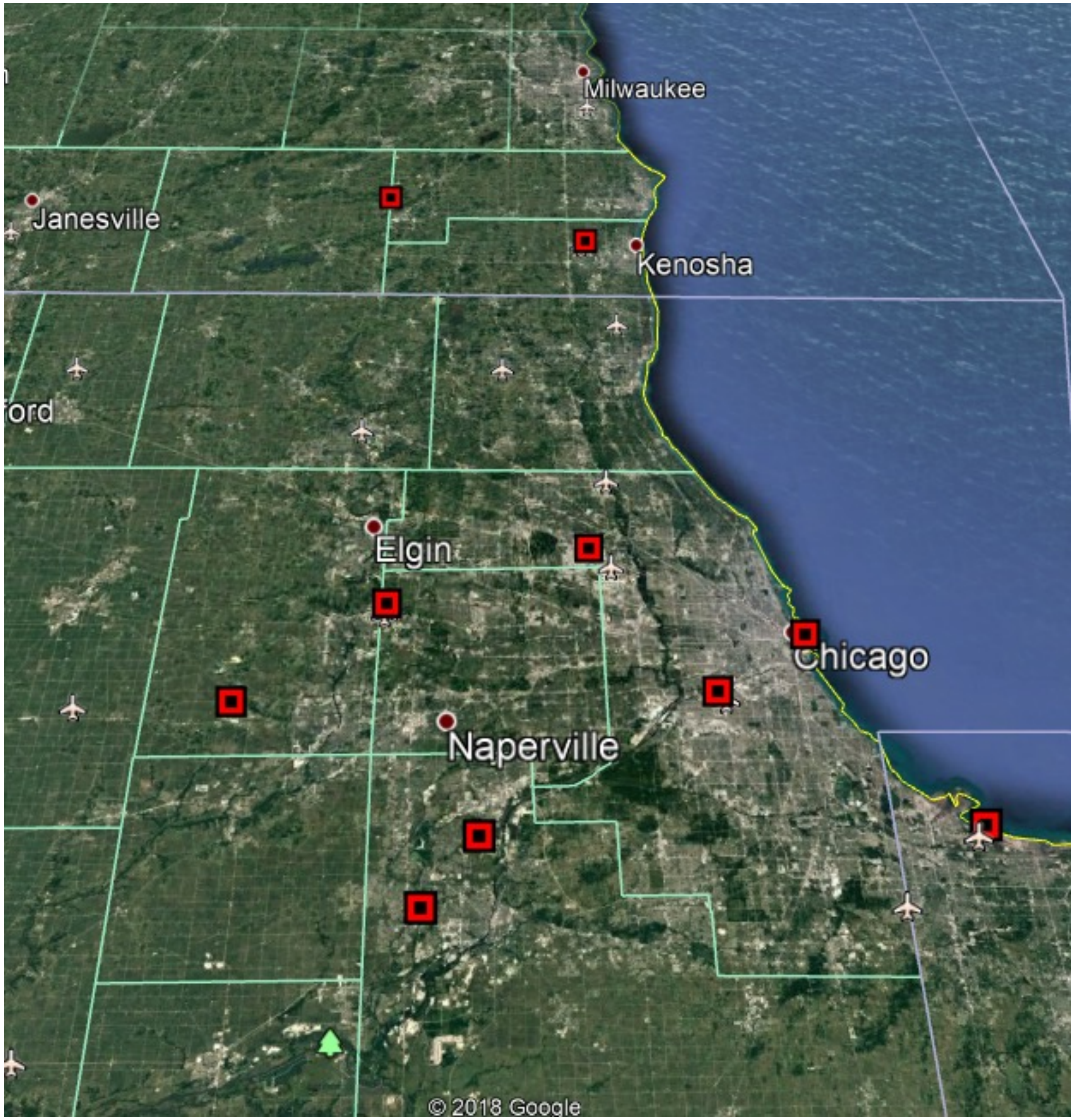

- Dew point and sol-air as well as different base point temperature can be used to calculate CDDs

# Weather Data




https://www.nrel.gov/docs/fy08osti/43156.pdf

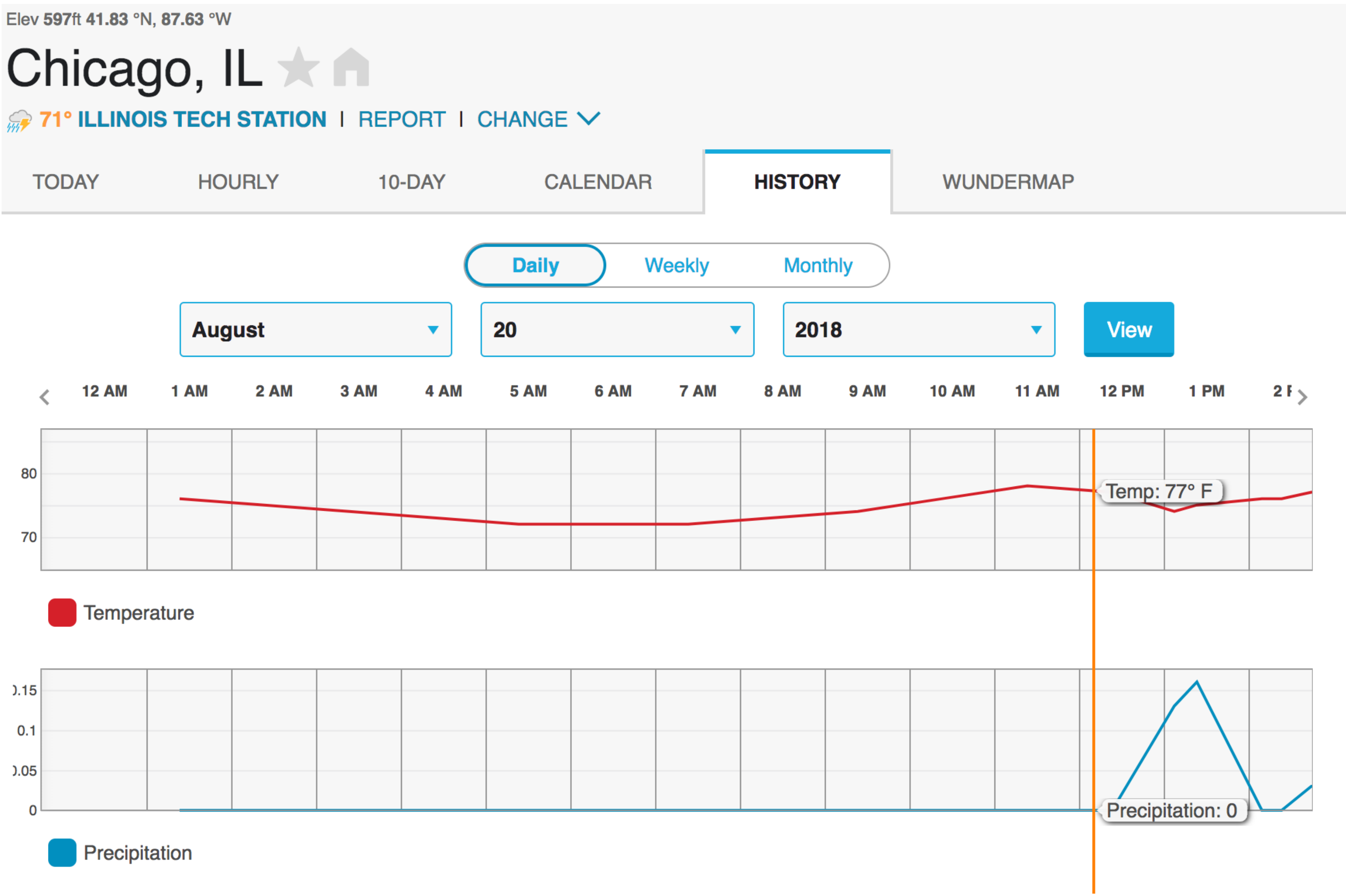
# Weather Stations in Chicago






http://climate.onebuilding.org

# IIT Weather Station






https://www.wunderground.com/history/daily/us/il/chicago/KILCHICA534/date/2018-8-20?cm_ven=localwx_history

# IIT Weather Station

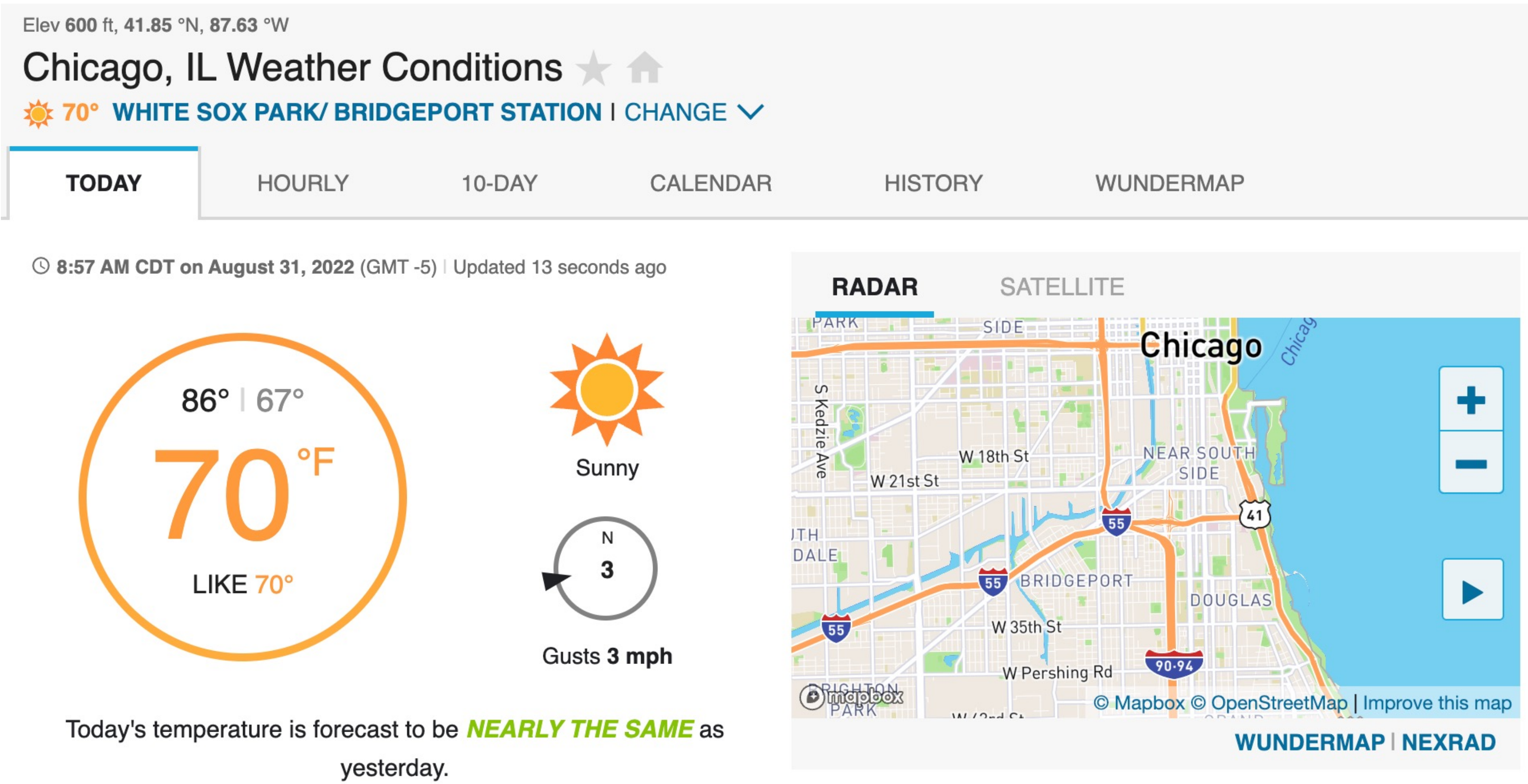
## Daily Observations

| Time | Temperature | Dew Point | Humidity | Wind | Wind Speed | Wind Gust | Pressure | Precip. | Precip Accum | Condition |
|---|---|---|---|---|---|---|---|---|---|---|
| 1:39 PM | 76 ° F | 72 ° F | 87 % | ESE | 10 mph | 0 mph | 29.2 in | 0.0 in | 0.0 in | Cloudy |
| 12:53 AM | 76 ° F | 66 ° F | 71 % | ESE | 8 mph | 0 mph | 29.3 in | 0.0 in | 0.0 in | Cloudy |
| 2:53 AM | 74 ° F | 65 ° F | 73 % | SE | 8 mph | 0 mph | 29.3 in | 0.0 in | 0.0 in | Cloudy |
| 3:53 AM | 73 ° F | 64 ° F | 73 % | ESE | 9 mph | 0 mph | 29.3 in | 0.0 in | 0.0 in | Mostly Cloudy |
| 4:53 AM | 72 ° F | 64 ° F | 76 % | ESE | 10 mph | 0 mph | 29.3 in | 0.0 in | 0.0 in | Mostly Cloudy |
| 5:53 AM | 72 ° F | 64 ° F | 76 % | ESE | 9 mph | 0 mph | 29.3 in | 0.0 in | 0.0 in | Mostly Cloudy |
| 6:53 AM | 72 ° F | 64 ° F | 76 % | ESE | 9 mph | 0 mph | 29.3 in | 0.0 in | 0.0 in | Mostly Cloudy |
| 7:53 AM | 73 ° F | 64 ° F | 73 % | SE | 10 mph | 0 mph | 29.3 in | 0.0 in | 0.0 in | Cloudy |
| 8:53 AM | 74 ° F | 64 ° F | 71 % | ESE | 13 mph | 0 mph | 29.3 in | 0.0 in | 0.0 in | Cloudy |
| 9:53 AM | 76 ° F | 65 ° F | 69 % | E | 12 mph | 0 mph | 29.2 in | 0.0 in | 0.0 in | Cloudy |
| 10:53 AM | 78 ° F | 67 ° F | 68 % | ESE | 15 mph | 0 mph | 29.2 in | 0.0 in | 0.0 in | Cloudy |
| 11:53 AM | 77 ° F | 69 ° F | 76 % | E | 10 mph | 0 mph | 29.2 in | 0.0 in | 0.0 in | Light Rain |
| 12:37 PM | 74 ° F | 71 ° F | 91 % | ESE | 8 mph | 0 mph | 29.2 in | 0.1 in | 0.0 in | Light Rain |
| 12:53 PM | 75 ° F | 72 ° F | 90 % | E | 8 mph | 0 mph | 29.2 in | 0.2 in | 0.0 in | Rain |
| 1:53 AM | 75 ° F | 65 ° F | 71 % | SE | 10 mph | 0 mph | 29.3 in | 0.0 in | 0.0 in | Cloudy |
| 1:53 PM | 76 ° F | 72 ° F | 87 % | ESE | 17 mph | 23 mph | 29.2 in | 0.0 in | 0.0 in | Cloudy |
| 2:14 PM | 77 ° F | 73 ° F | 88 % | E | 20 mph | 0 mph | 29.2 in | 0.0 in | 0.0 in | Mostly Cloudy |
| 2:53 PM | 77 ° F | 73 ° F | 88 % | E | 14 mph | 23 mph | 29.2 in | 0.0 in | 0.0 in | Cloudy |
| 3:00 PM | 76 ° F | 72 ° F | 87 % | E | 14 mph | 0 mph | 29.1 in | 0.0 in | 0.0 in | Cloudy |
| 3:53 PM | 77 ° F | 72 ° F | 84 % | ESE | 14 mph | 0 mph | 29.1 in | 0.0 in | 0.0 in | Cloudy |
| 4:53 PM | 78 ° F | 73 ° F | 84 % | ESE | 13 mph | 0 mph | 29.1 in | 0.0 in | 0.0 in | Cloudy |
| 5:53 PM | 79 ° F | 71 ° F | 77 % | ESE | 17 mph | 22 mph | 29.1 in | 0.0 in | 0.0 in | Mostly Cloudy |



https://www.wunderground.com/history/daily/us/il/chicago/KILCHICA534/date/2018-8-20?cm_ven=localwx_history

# Close to IIT Weather Station




https://www.wunderground.com/weather/us/il/chicago/60616

# Weather Station Calibration

Description

## Historical Hourly Weather Data

Who amongst us doesn't small talk about the weather every once in a while?
The goal of this dataset is to elevate this small talk to medium talk.

Just kidding, I actually originally decided to collect this dataset in order to demonstrate basic signal processing concepts, such as filtering, Fourier transform, auto-correlation, cross-correlation, etc..., (for a data analysis course I'm currently preparing).
I wanted to demonstrate these concepts on signals that we all have intimate familiarity with and hope that this way these concepts will be better understood than with just made up signals.

The weather is excellent for demonstrating these kinds of concepts as it contains periodic temporal structure with two very different



https://www.kaggle.com/selfishgene/historical-hourly-weather-data

# Building Selection

- Do you recall the CBECS building data types?

U.S. National Median Reference Values for All Portfolio Manager Property Types

| Broad Category | Primary Function | Further Breakdown (where needed) | Source EUI (kBtu/ft²) | Site EUI (kBtu/ft²) | Reference Data Source - Peer Group Comparison |
|---|---|---|---|---|---|
| Banking/Financial Services | Bank Branch * | | 209.9 | 88.3 | CBECS - Bank/Financial |
| | Financial Office* | | 116.4 | 52.9 | CBECS - Office & Bank/Financial |
| Education | Adult Education | | 110.4 | 52.4 | CBECS - Education |
| | College/University | | 180.6 | 84.3 | CBECS - College/University |
| | K-12 School* | | 104.4 | 48.5 | CBECS - Elementary/Middle & High School |
| | Pre-school/Daycare | | 131.5 | 64.8 | CBECS - Preschool |
| | Vocational School | | 110.4 | 52.4 | CBECS - Education |
| | Other - Education | | | | |
| Entertainment/Public Assembly | Convention Center | | 109.6 | 56.1 | CBECS - Social/Meeting |
| | Movie Theater | | 112.0 | 56.2 | CBECS - Public Assembly |
| | Museum | | | | |
| | Performing Arts | | | | |
| | Recreation | Bowling Alley | 112.0 | 50.8 | CBECS - Recreation |
| | | Fitness Center/Health Club/Gym | | | |
| | | Ice/Curling Rink | | | |
| | | Roller Rink | | | |
| | | Swimming Pool | | | |
| | | Other - Recreation | | | |
| | Social/Meeting Hall | | 109.6 | 56.1 | CBECS - Social/Meeting |

# Campus Building Selection

| Primary categories | |
|---|---|
| **Classrooms / Offices** | This category is a combination of classroom and office areas where none of the classroom or office areas occupies more than 60% of the total building area. This type of the building represents a building that comprises both Full Time Employee (FTE) and visor/transient occupants. While the visitor/transient occupants influence the energy consumption pattern and operation schedule of the classroom space type, FTEs in the office space type affect the building's energy consumption patterns. |
| **Office Areas** | It is a category that more than 80% of the building area is dedicated to the academic and administrative office areas. It is expected that the operational schedule for this type of space be shorter compared to the Classrooms/Offices space types. |
| **Research Laboratories** | This category contains buildings that exhibit high-intensity in terms of energy consumption and more than 40% of the building area is occupied by research laboratories. |
| **Laboratory Mixes** | Laboratory mixes category is the building area with a combination of classroom/office, office, and research laboratory areas. In this category more than 20% of the building area is used for research laboratories, and each of the categories occupy at least more than 15% of the building area. |
| **Residential Facilities** | This category includes students, staff, and faculty housing buildings. |

# Campus Building Selection

| Secondary categories | |
|---|---|
| **Student Activity Centers** | This category contains buildings where 40% of the building area is used for student activities. |
| **Health Facilities** | Health facilities are buildings that provide patient care within university campuses. |
| **Sports & Gym Facilities** | It is a category dedicated to indoor student recreational activities and fitness centers. |
| **Auditoriums & Theaters** | This category is used for exhibition and performance buildings within university campuses. |
| **Residential Facility Mixes** | This category is a combination of residential facilities and areas allocated for food and cooking purposes. |
| **Hospitality Services** | Hospitality services category contains temporary accommodation facilities, such as university hotels within university campuses. |
| **Libraries** | This category defines university libraries. |
| **Museums** | This category includes museum buildings within university campuses. |

# Campus Building Selection

- An example from Penn State's and Harvard's campuses:
  - Building with different types, ages, and sizes are selected
  - For five main categories, six buildings are considered

| **Building Type** | **Range of building ages (Years)** | | **Building number(s)** | | **Approximate Building Gross Area $m^2$ ($ft^2$)** | |
|---|---|---|---|---|---|---|
| **Campus** | Penn State | Harvard | Penn State | Harvard | Penn State | Harvard |
| **Classrooms / Offices** | 5 – 108 | 19 – 113 | 1P – 6P | 1H – 6H | 4,000 – 21,000 (43,055 – 129,167) | 5,000 – 8,000 (53,820 – 86,111) |
| **Office areas** | 10 – 107 | 21 – 112 | 7P – 12P | 7H – 13H | 3,000 – 13,000 (32,292 – 139,931) | 4,000 – 18,000 (43,056 – 193,750) |
| **Research laboratories** | 6 – 81 | 6 – 131 | 13P – 18P | 14H – 19H | 8,000 – 13,000 (86,111 - 139931) | 5,000 – 20,000 (53,820 – 215,278) |
| **Laboratory mixes** | 8 – 91 | 5 – 112 | 19P – 24P | 20H – 25H | 7,000 – 17,000 (75,347 – 182,986) | 6,000 – 50,000 (64,583 – 538,196) |
| **Residential facilities** | 47 – 87 | 5 – 124 | 25P – 35P | 26H – 31H | 3,000 – 20,000 (32,291 – 215,278) | 6,000 – 23,000 (64,583 – 247,570) |

# Campus Building Selection

- An examples from Penn State's campus:
  - Nine secondary categories are considered

| Building Type | Range of building ages (Years) | Building number(s) | Approximate Building Gross Area $m^2$ ($ft^2$) |
|---|---|---|---|
| **Campus** | | Penn State | |
| **Student Activity Center** | 57 | 36P | 23,000 (247,570) |
| **Health Facilities** | 4 | 37P | 6,000 (64,583) |
| **Sports and Gym Facilities** | 45 – 83 | 38P – 39P | 8,000 – 29,000 (86,111 – 312,153) |
| **Auditoriums and Theatres** | 38 – 109 | 40P – 42P | 2,000 – 10,000 (21,528 – 107,639) |
| **Residential Facility Mixes** | 45 – 55 | 43P – 45P | 2,000 – 7,000 (21,528 – 75,347) |
| **Hospitality Services** | 81 | 46P | 22,000 (236,806) |
| **Library** | 72 | 47P | 24,000 (258,334) |
| **Museum** | 41 | 48P | 5,000 (53,820) |

# CLASS ACTIVITY

# Class Activity

- Consider IIT Buildings:

| Building Name | Building Name |
|---|---|
| Perlstein Hall | Engineering |
| Alumni Memorial Hall | Life Sciences |
| Wishnick Hall | Stuart |
| Siegel Hall | Keating Sports Center |
| Crown Hall | IIT Apartments |
| IIT Tower | The Commons |
| Paul Galvin | McCormick Tribune |
| Main | Residence Hall Complex |
| Machinery Hall | Farr Hall |
| Hermann Union | Quad |

# Class Activity

- Provide two examples for each type at the IIT campus:

| Building Type | IIT Building |
|---|---|
| Classrooms/Offices | ??? |
| Office Areas | ??? |
| Research Laboratories | ??? |
| Laboratory Mixes | ??? |
| Residential Facilities | ??? |

# Class Activity

- Provide an example for each type at the IIT campus:

| Building Type | IIT Building |
|---|---|
| Student Activity Center | ??? |
| Health Facilities | ??? |
| Sports and Gym Facilities | ??? |
| Auditoriums and Theatres | ??? |
| Residential Facility Mixes | ??? |
| Hospitality Services | ??? |
| Library | ??? |
| Museum | ??? |

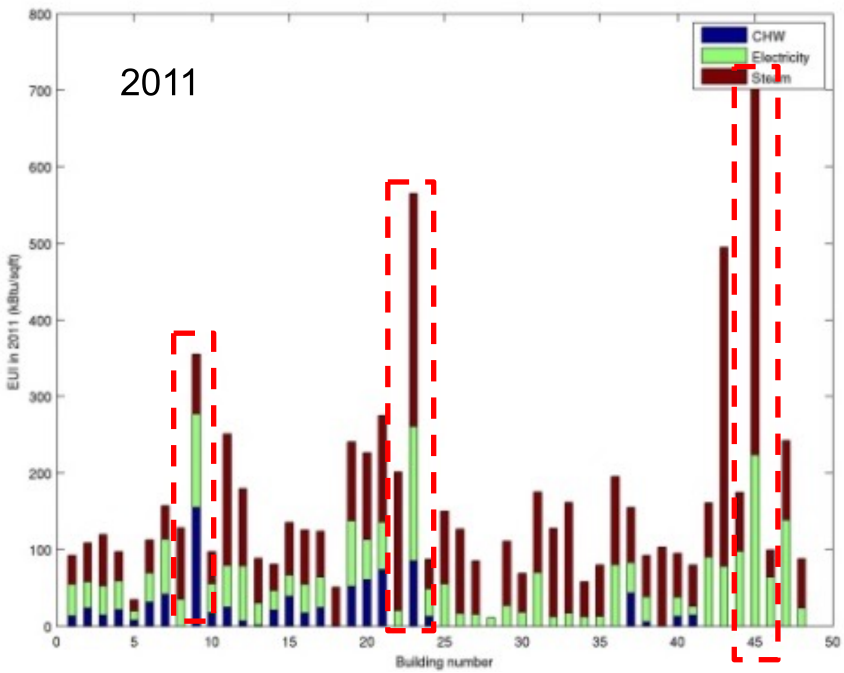
# Class Activity

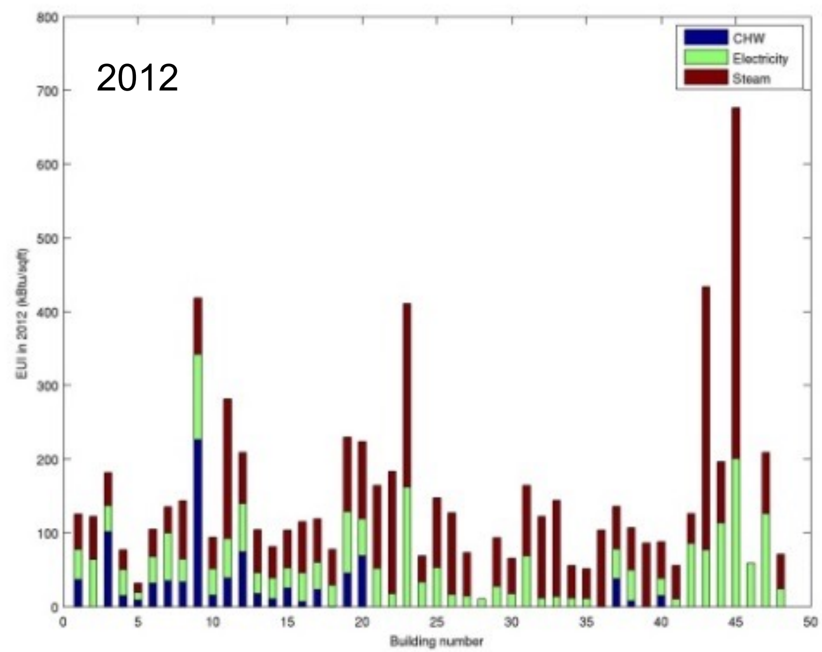
- From previous students:

| | Area ($ft^2$) | Year Built | # of floors | Dimensions | WWR | Space Type | Shape |
|---|---|---|---|---|---|---|---|
| **Perlstein Hall** | 124,800 | 1945 | 3 | 320'x130' | 0.65 | Office/Class/Lab | RECT |
| **Alumni Hall** | 33,000 | 1945 | 3 | 225'x75' | 0.425 | Office/Class/Lab | RECT |
| **Wishnick Hall** | 81,500 | 1945 | 4 | 91'x224' | 0.68 | Office/Class | RECT |
| **Siegel Hall** | 75,840 | 1956 | 4 | 80'x237' | 0.63 | Office/Class | RECT |
| **Crown Hall** | 52,800 | 1956 | 2 | 120'x220' | 0.88 | Class/Library | RECT |
| **Common** | 52,800 | 1962 | 2 | 120'x220' | 0.88 | Dining | RECT |
| **Material** | 339,329 | 1943 | 2 | 243'x500' | 0.38 | Office/Lab/Class | RECT |
| **Main** | 78,698 | 1892 | 5 | 248.65'x63.3' | 0.35 | historic landmark | RECT |
| **Machinery Hall** | 27,515 | 1901 | 5 | 88.9' x 61.92' | 0.3 | historic landmark | RECT |

# Energy Consumption

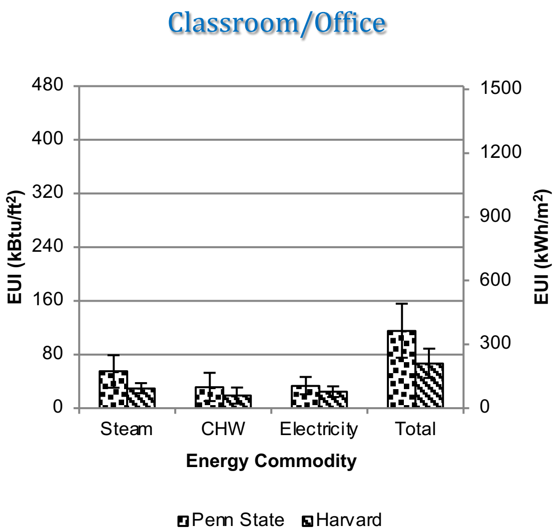
- An example from Penn State's study. Energy consumption commodities are:
  - Chilled water
  - Steam
  - Electricity
  - Service hot water

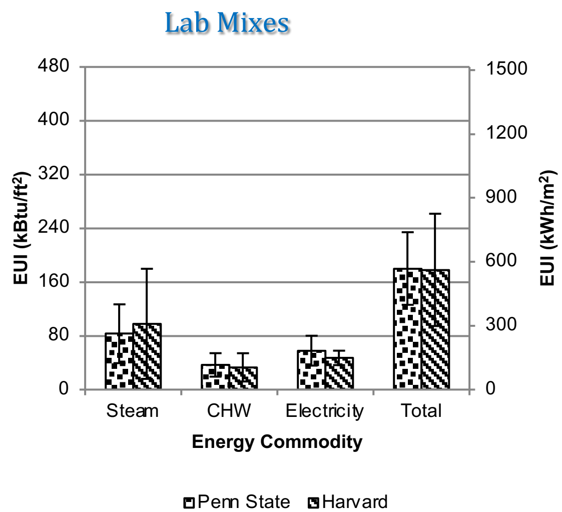


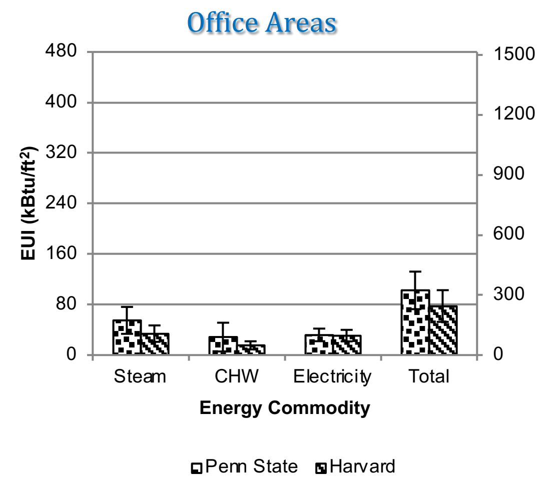



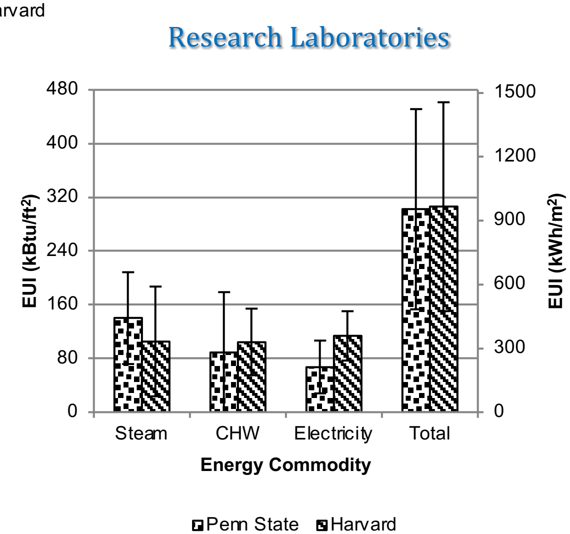
# Energy Consumption

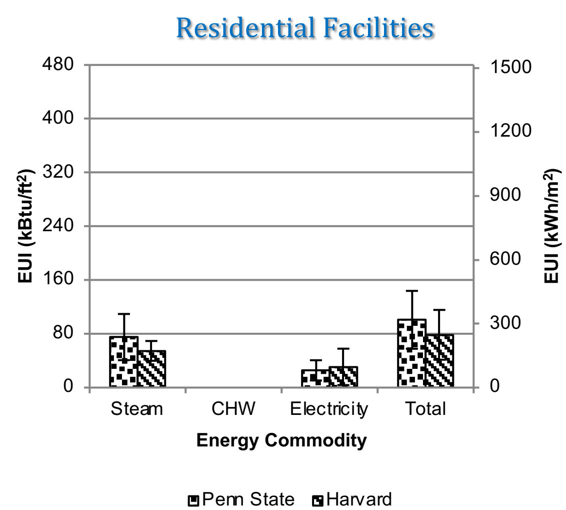
- An example for the five primary categories:




1 MJ/m$^2$=11.357 kBtu/ft$^2$

# CLASS ACTIVITY

# Class Activity

- Let's calculate EUI (electricity, steam, and total EUI) for the uploaded file on BB.

# Common Energy Modeling Methods

- Six common methods to analyze energy consumption of campus buildings are listed below
- Methods 1-5 are simpler than Method 6
- Method 6 requires using simulation programs such as EnergyPlus

| Method # | Energy modeling criteria name |
|---|---|
| 1 | Degree day calculations |
| 2 | Estimated savings based on the utility bills (disaggregation) |
| 3 | Temperature bin spreadsheet calculations |
| 4 | 8760-hour spreadsheet calculations |
| 5 | Energy Utilization Index (EUI) |
| 6 | Whole building energy simulations |

# Energy Consumption

- Order of magnitude for the regression analysis determines three types of buildings in terms of the energy consumption in response to the outdoor weather conditions. These types are:
  - Externally-load dominated buildings
  - Internally-load dominated buildings
  - Mixed-load dominated buildings

- It is useful to determine whether internal, external or mixed-loads dominate building energy use patterns in order to inform design, retrofit and energy simulation efforts

# Energy Consumption

- Externally-load dominated buildings:
  - Have their energy consumption controlled by the outdoor weather conditions, ventilation systems, and heat loss/gain through the building envelope
  - Known as envelope-dominated or skin-load dominated buildings
  - Dominated buildings require additional focuses on the building envelop and ventilation systems
  - Space types such as single-family and warehouse buildings tend to be externally-load dominated
  - For campus buildings located in the Northeastern of the U.S., the steam consumption do follow the outdoor condition, suggesting opportunities to benefit from a better space heating management strategies

# Energy Consumption

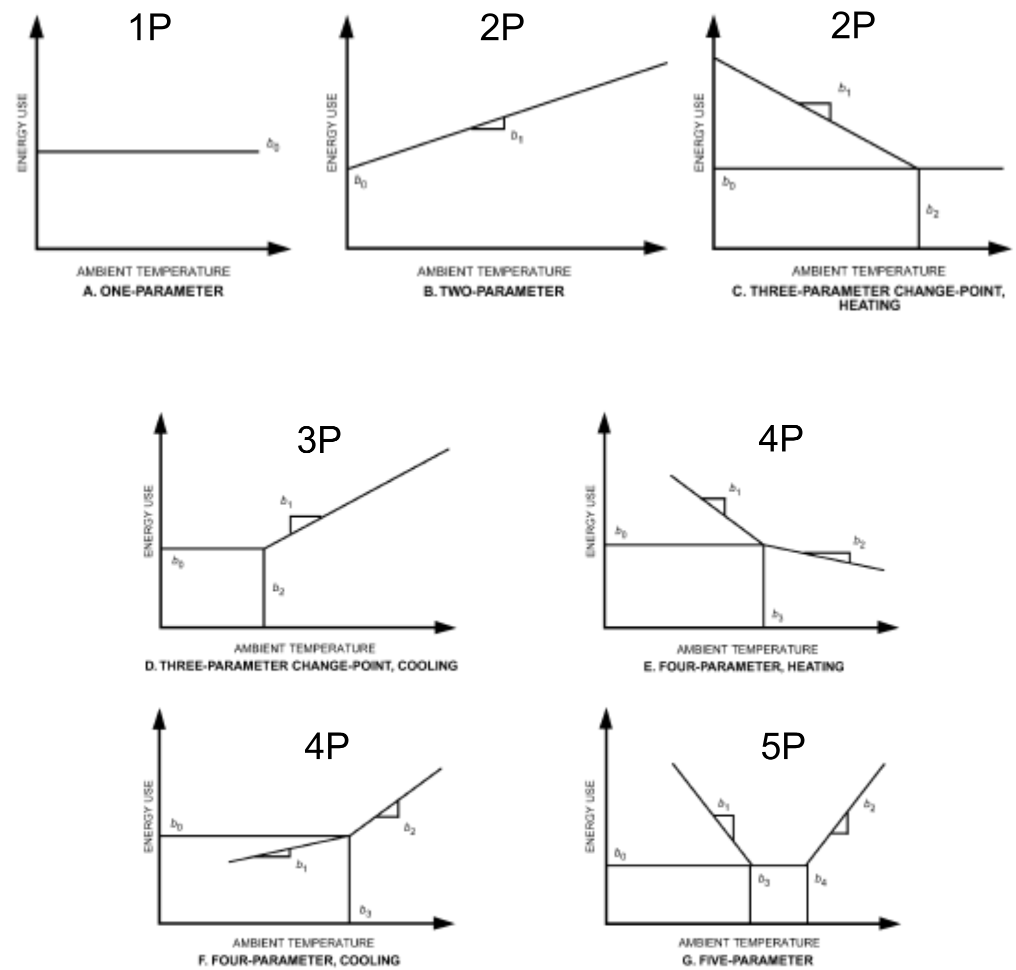
- Internally-load dominated buildings:
  - Outdoor conditions do not have significant influence on the energy consumption of these buildings
  - Internal loads such as receptacle, occupancy, lighting loads and their schedules are the main drivers to control the energy consumption of these buildings
  - Space types such as offices, hospitals, and research laboratories tend to be more internally-load dominated
  - The results of this study indicates that the research laboratories and laboratory mixes tend to be internally-load dominated.

# Energy Consumption

- Mixed-load dominated buildings:
  - In these buildings, external and internal thermal loads have the same order of magnitude
  - Energy use patterns for these types of buildings are a combination of external and internal loads
  - The complex interaction of the heat transfer processes render mixed-load dominated buildings difficult to model
  - Modeling these buildings requires consideration of combined methodologies for externally-load and internally-load dominated building
  - Campus buildings with good management strategies usually are mixed-load dominated since the energy consumption during the peak time follows the outdoor condition while during off peak, e.g., nighttime, the building cooling does not follow the outdoor condition

# Degree Days

- Seven methods:
  - 1P: Non-weather dominated
  - 2P: Linear correlation with a fixed baseline
  - 3P: Linear correlation with a change point temperature constant baseline
  - 4P: Linear correlation with a change point temperature weather dependent baseline
  - 5P: Cooling and heating in the same plot

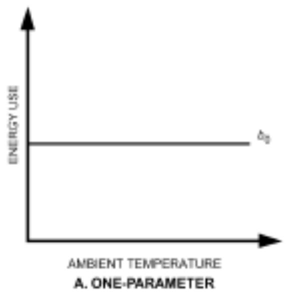



Provide and example for each method?

*Source: 2005 ASHRAE Handbook Fundamentals: Chapter 32 Energy Estimating and Modeling Methods*

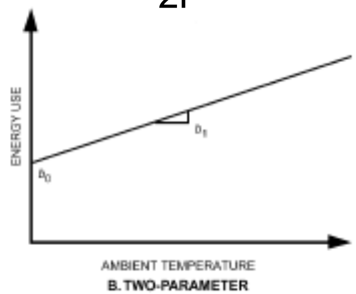
# Degree Days

1P



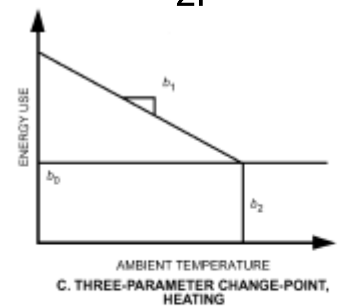

Electricity consumption for a building with chilled water and steam end-uses

2P



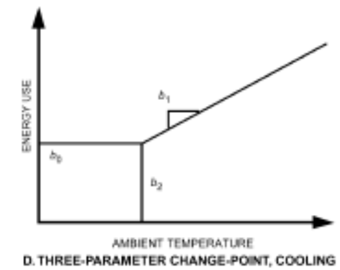

Chilled water consumption for a building for a typical campus building

2P



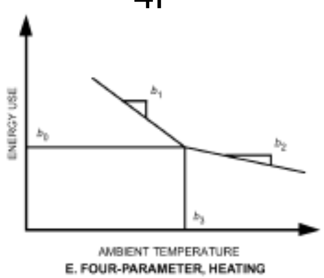

Steam consumption for a building with research laboratory

3P



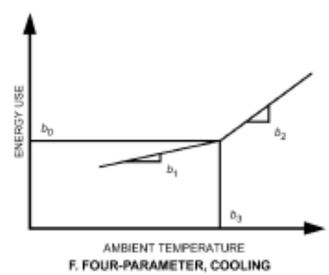

Chilled water consumption for a building with research laboratory

4P



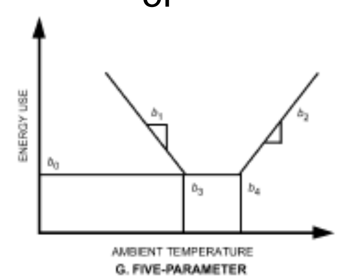

Steam consumption for a campus building with two different temperature setpoint control

4P




Chilled water consumption for a campus building with two different temperature setpoint control

5P




Electricity consumption for a campus building that uses electricity for heating and cooling



*Source: 2005 ASHRAE Handbook Fundamentals: Chapter 32 Energy Estimating and Modeling Methods*

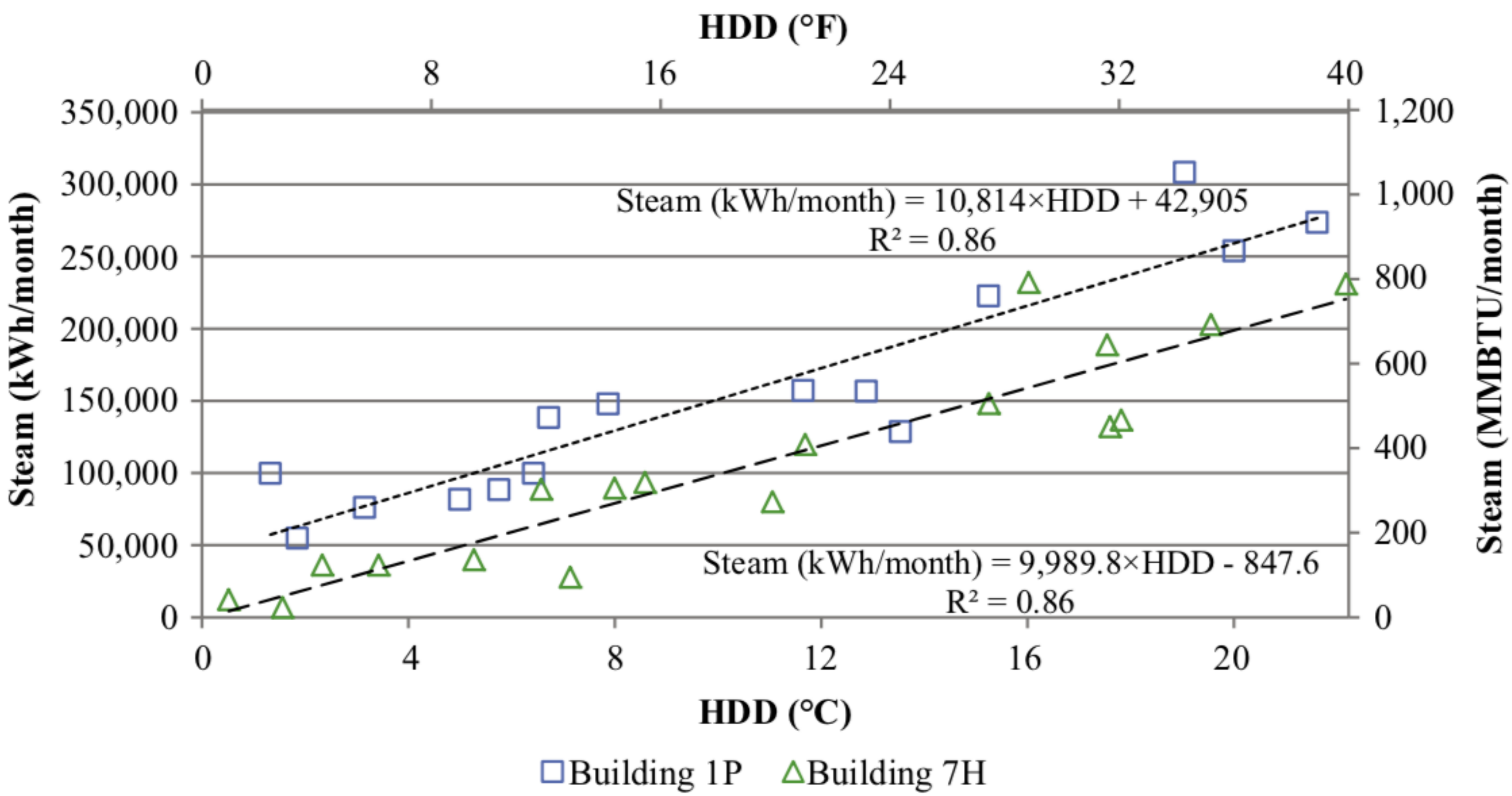
# Normalization of Energy End-uses

- Used two approaches:
    1. All year: works better for campus buildings due to simultaneous heating and cooling.
    2. Cooling and heating seasons:
        - Cooling season: June – August
        - Heating season: Jan –May & September – December

*This method fails for some of the buildings (especially for CHW)*

# Normalization of Energy End-uses

- Normalized steam with HDD for one building at Penn State campus and one building at Harvard campus.



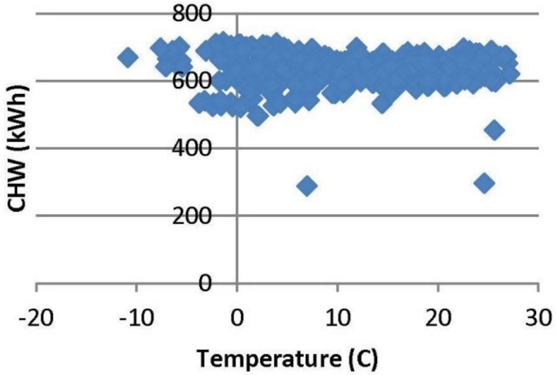



Heidarinejad et al. 2017

# Normalization of Energy End-uses

- Different pattern exists for the campus building:

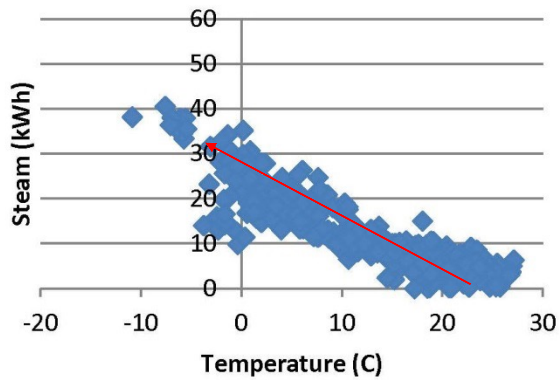
1P




*No correlations*

CHW= $a \times Temp + b$

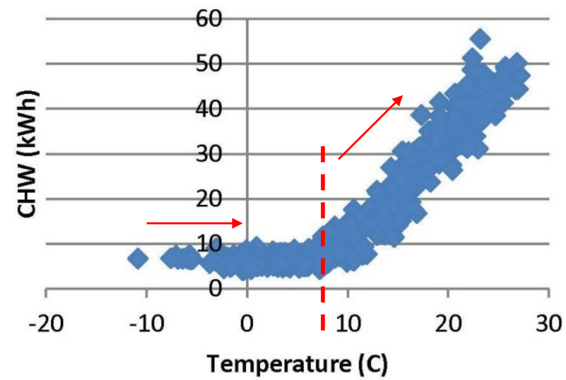
2P




*Two points model*

$$Steam = a\ Temp + b$$

3P



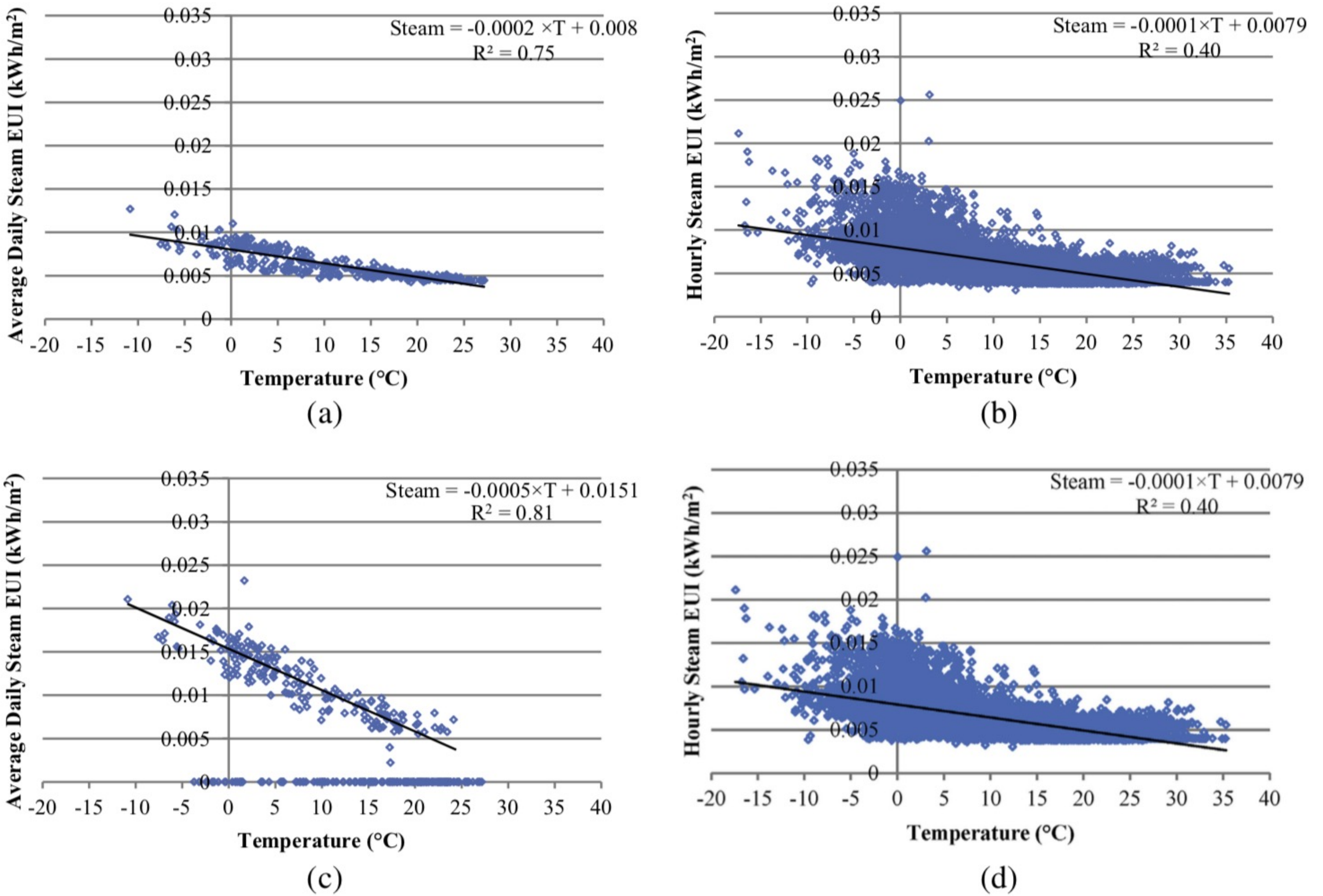

*Three points model*

$$CHW = (a_1\ Temp + b_1) + (a_2\ Temp + b_2)$$



*Heidarinejad et al. 2017*

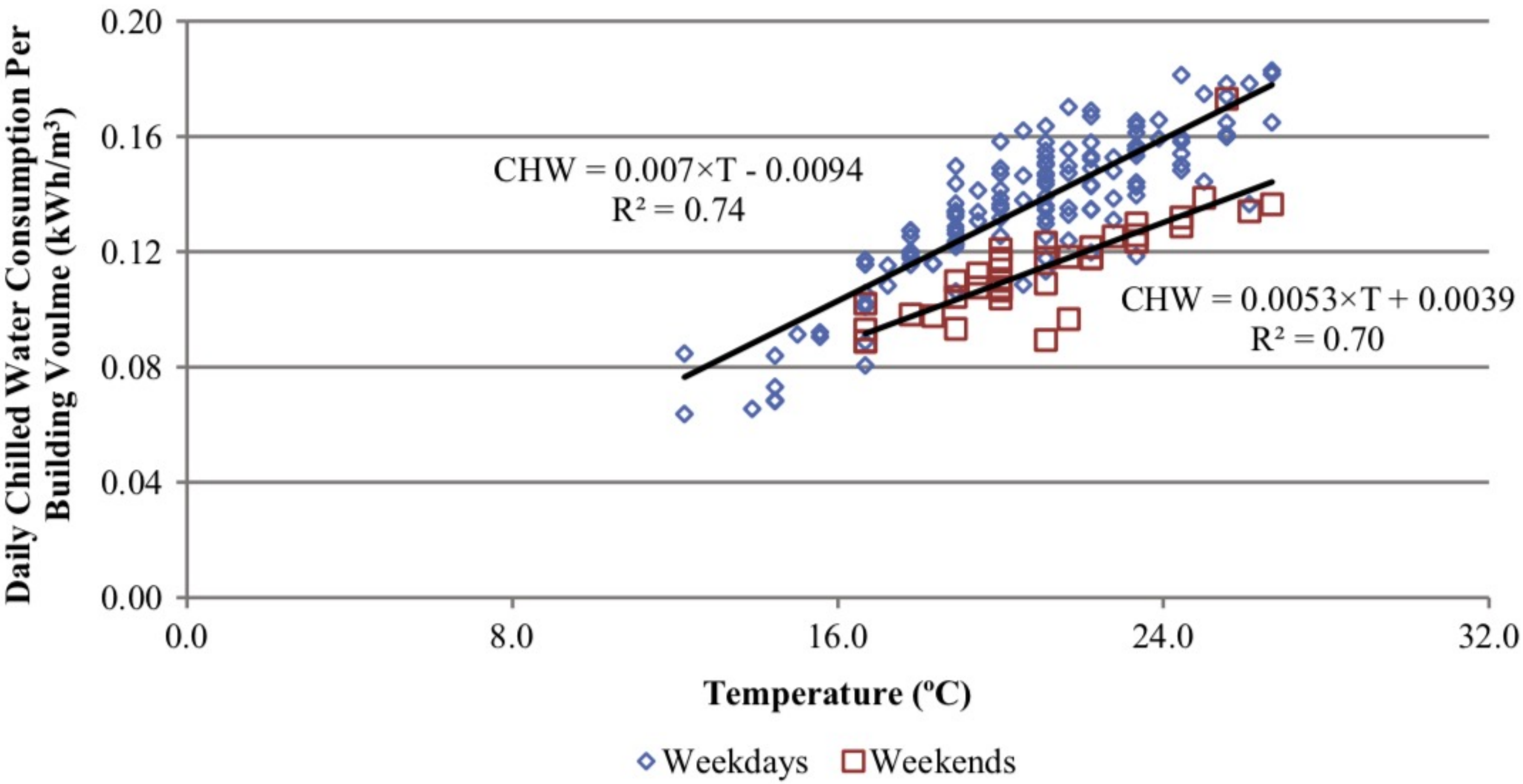
# Normalization of Energy End-uses




*Heidarinejad et al. 2017*

# Normalization of Energy End-uses

- Sometimes for the same building, the occupancy and operation can change the patterns.

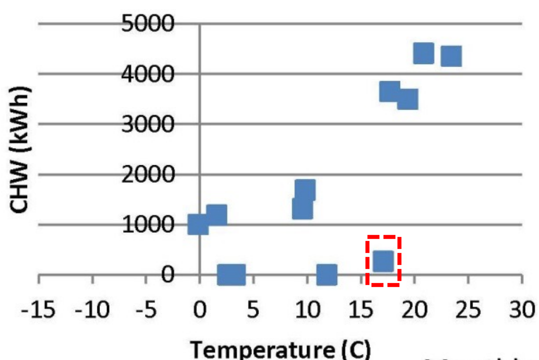




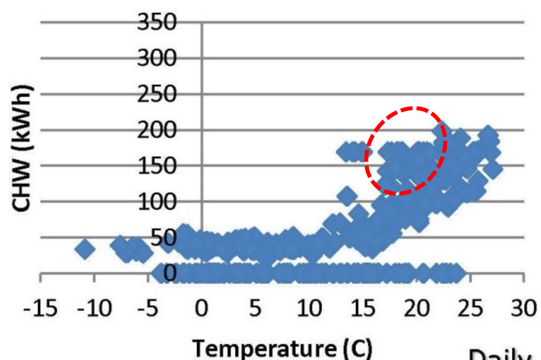

*Heidarinejad et al. 2017*

# Normalization of Energy End-uses

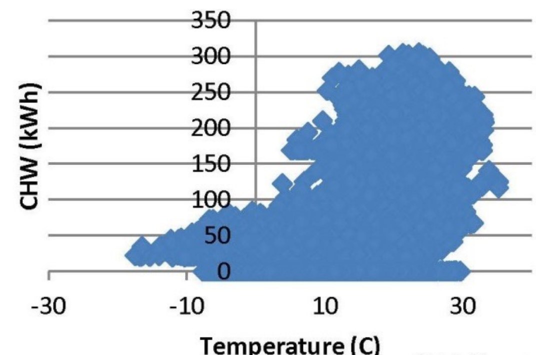
- Granularity of the data:
  - Monthly
  - Daily
  - 15 Minute / Hourly



Monthly



Daily



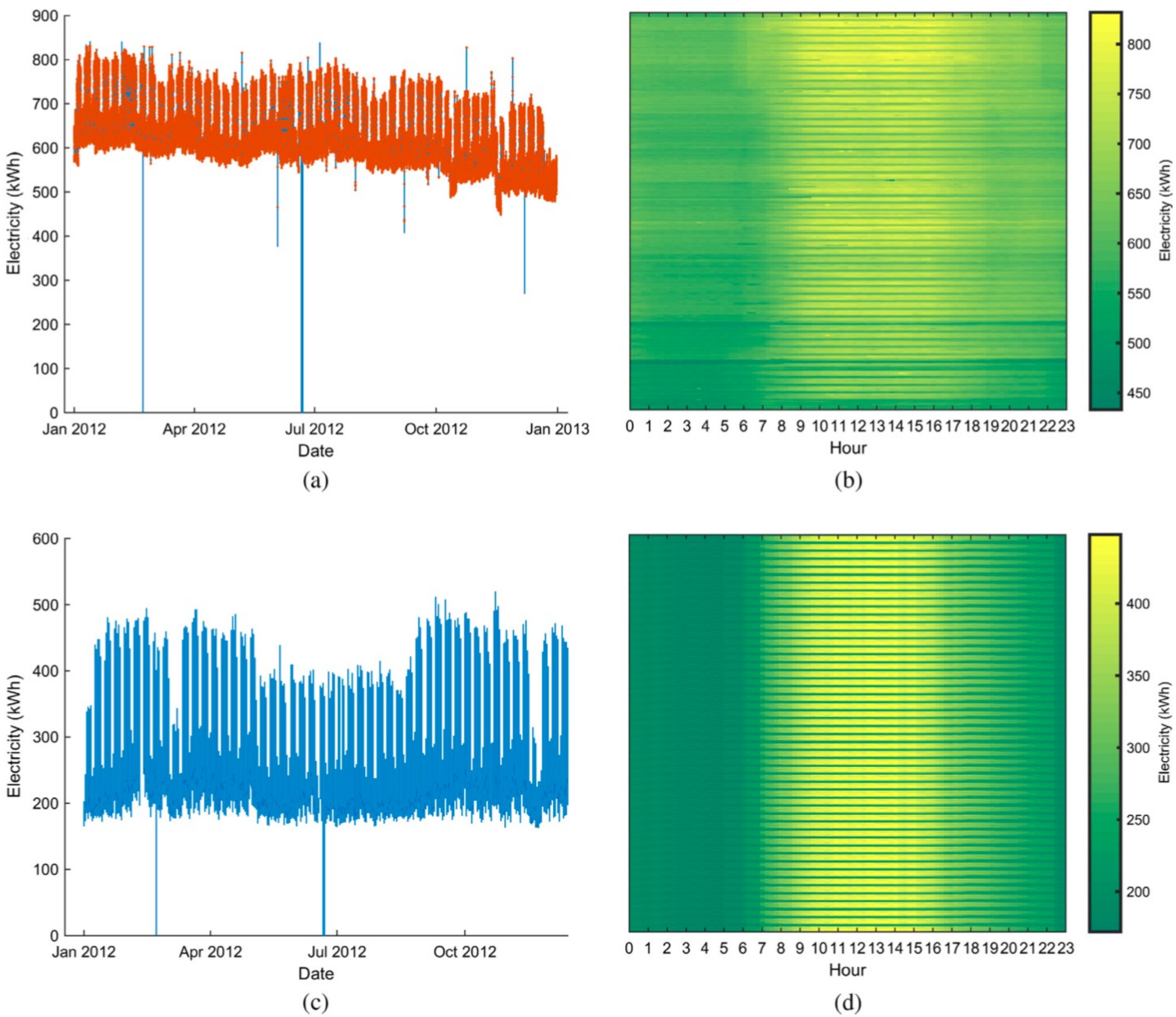
15 Minute

| Granularity Level | Description |
|---|---|
| Monthly | • Exists for most of the buildings<br>• Works better for the steam consumptions than the CHW consumptions |
| Daily | • Provides a better response than the monthly<br>• Enable reduce the sampling rate for the existing sub-metering sensors |
| Hourly / 15 Minute | • Provide detailed information about the building operation and schedules<br>• Include noises associated with the data |



*Heidarinejad et al. 2017*

# Normalization of Energy End-uses




Heidarinejad et al. 2017

# Class Activity

- Consider this building EUIs, which one is the accurate building EUI?

| Year | Electricity EUI ($kBtu/ft^2$) | Heating EUI ($kBtu/ft^2$) | Cooling EUI ($kBtu/ft^2$) | Total EUI ($kBtu/ft^2$) |
|---|---|---|---|---|
| 2016 | 20 | 40 | 15 | 75 |
| 2017 | 19 | 49 | 11 | 79 |
| 2018 | 22 | 42 | 18 | 82 |

TABLE D-1 U.S. and U.S. Territory Climatic Data *(Continued)*

| State/City | Latitude | Longitude | Elev., ft | HDD65 | CDD50 | Heating Design Temperature | Cooling Design Temperature | | Number of Hours 8 a.m.–4 p.m. |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Dry-Bulb | Wet-Bulb | |
| | | | | | | 99.6% | 1.0% | 1.0% | $55 < T_{db} < 69$ |
| **Illinois (IL)** | | | | | | | | | |
| Aurora | 41.75 N | 88.35 W | 644 | 6699 | 2880 | NA | NA | NA | NA |
| Belleville/Scott AFB | 38.55 N | 89.85 W | 453 | 4878 | 4146 | 3 | 93 | 77 | NA |
| Carbondale Sewage Plt | 37.73 N | 89.17 W | 390 | 4865 | 3934 | NA | NA | NA | NA |
| Champaign | 40.03 N | 88.28 W | 755 | 5689 | 3697 | NA | NA | NA | NA |
| Chicago Midway AP | 41.73 N | 87.77 W | 620 | 6176 | 3251 | NA | NA | NA | NA |
| Chicago O'Hare WSO AP | 41.98 N | 87.90 W | 674 | 6536 | 2941 | –6 | 88 | 73 | 613 |
| Chicago University | 41.78 N | 87.60 W | 594 | 5753 | 3391 | NA | NA | NA | NA |

# Benefits and Limitations

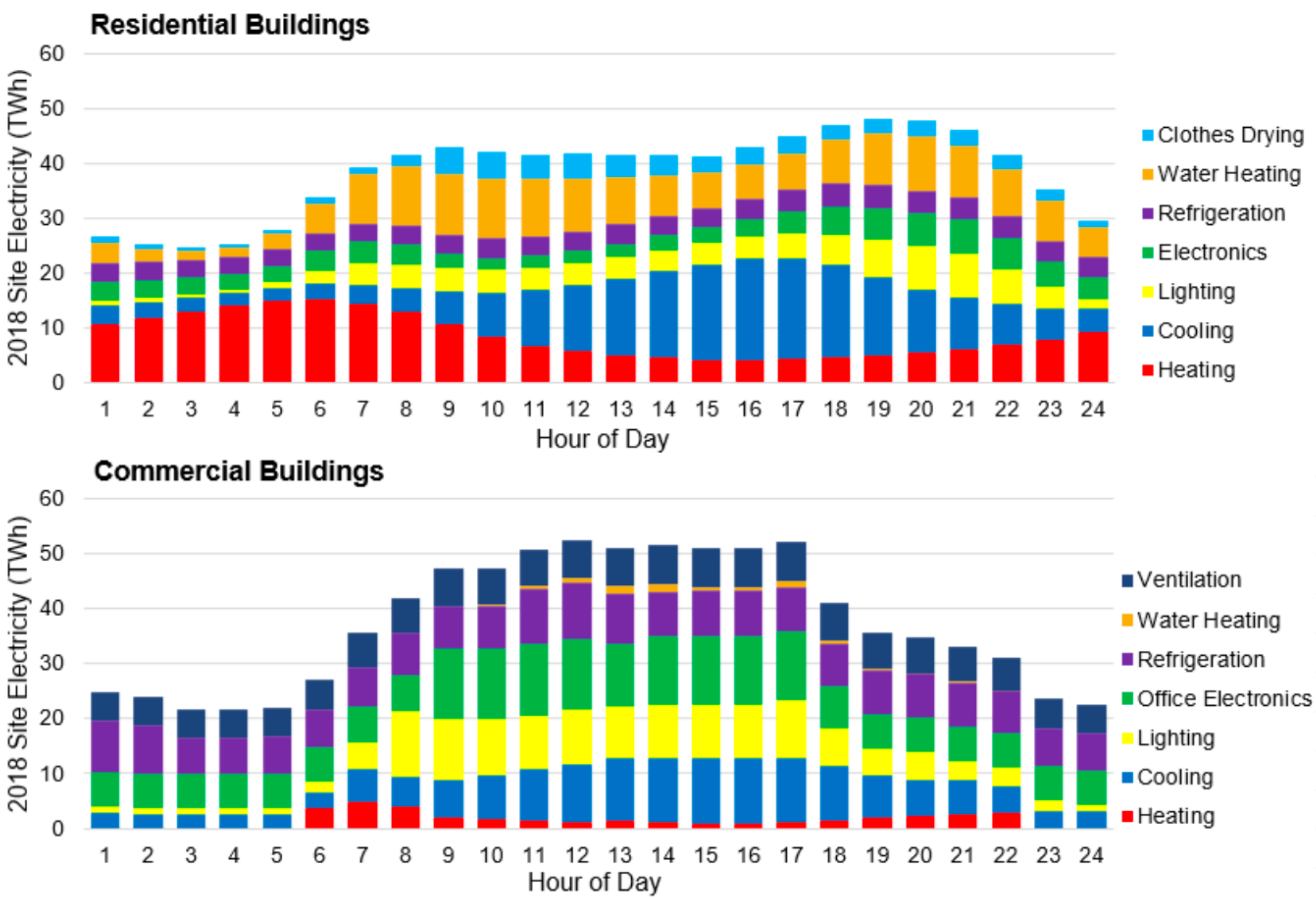
- Benefits:
  - Provide rapid normalization results
  - Provide accurate results for most of the situations

- Limitations:
  - Assume steady-state conditions
  - Fail for cases where there is rapid changes in the building (internally-load dominated)

# COMMERCIAL/RESIDENTIAL BUILDINGS

# Commercial/Residential Buildings

- Hourly electricity use in residential and commercial buildings in 2018:

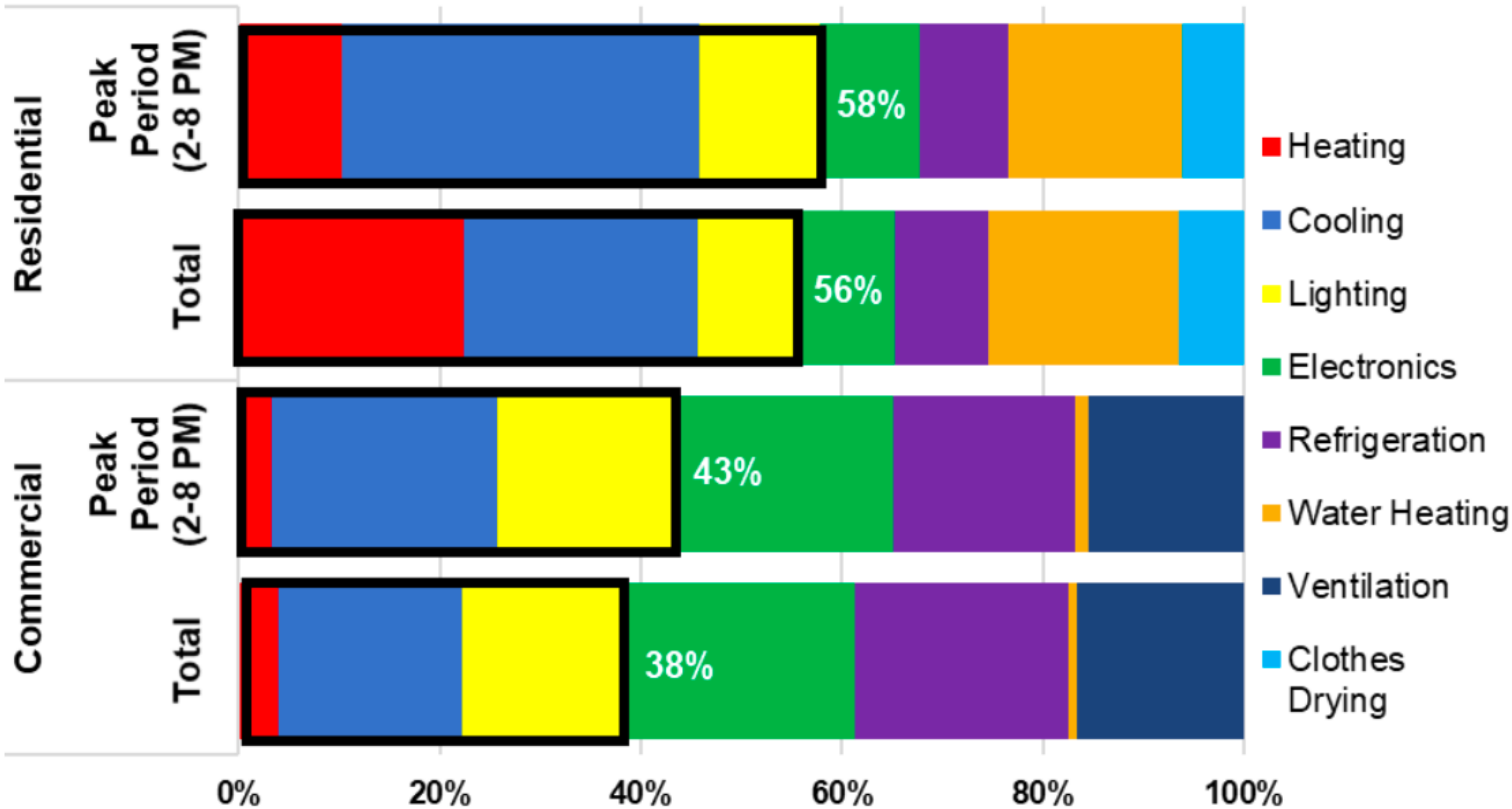





https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings

# Commercial/Residential Buildings

- Total and peak electricity end-uses in 2018:

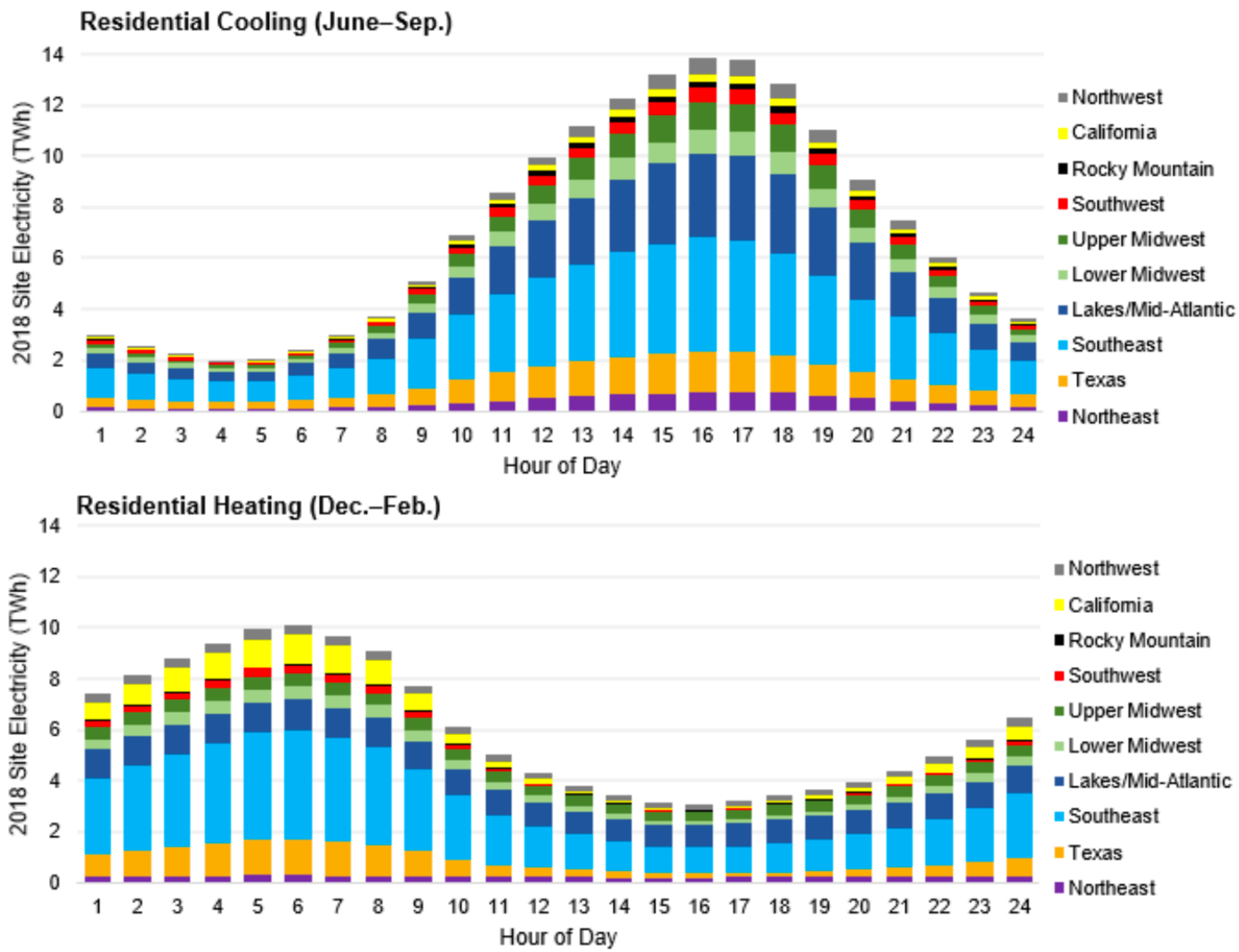





https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings

# Commercial/Residential Buildings

- Residential cooling and heating hourly profile:

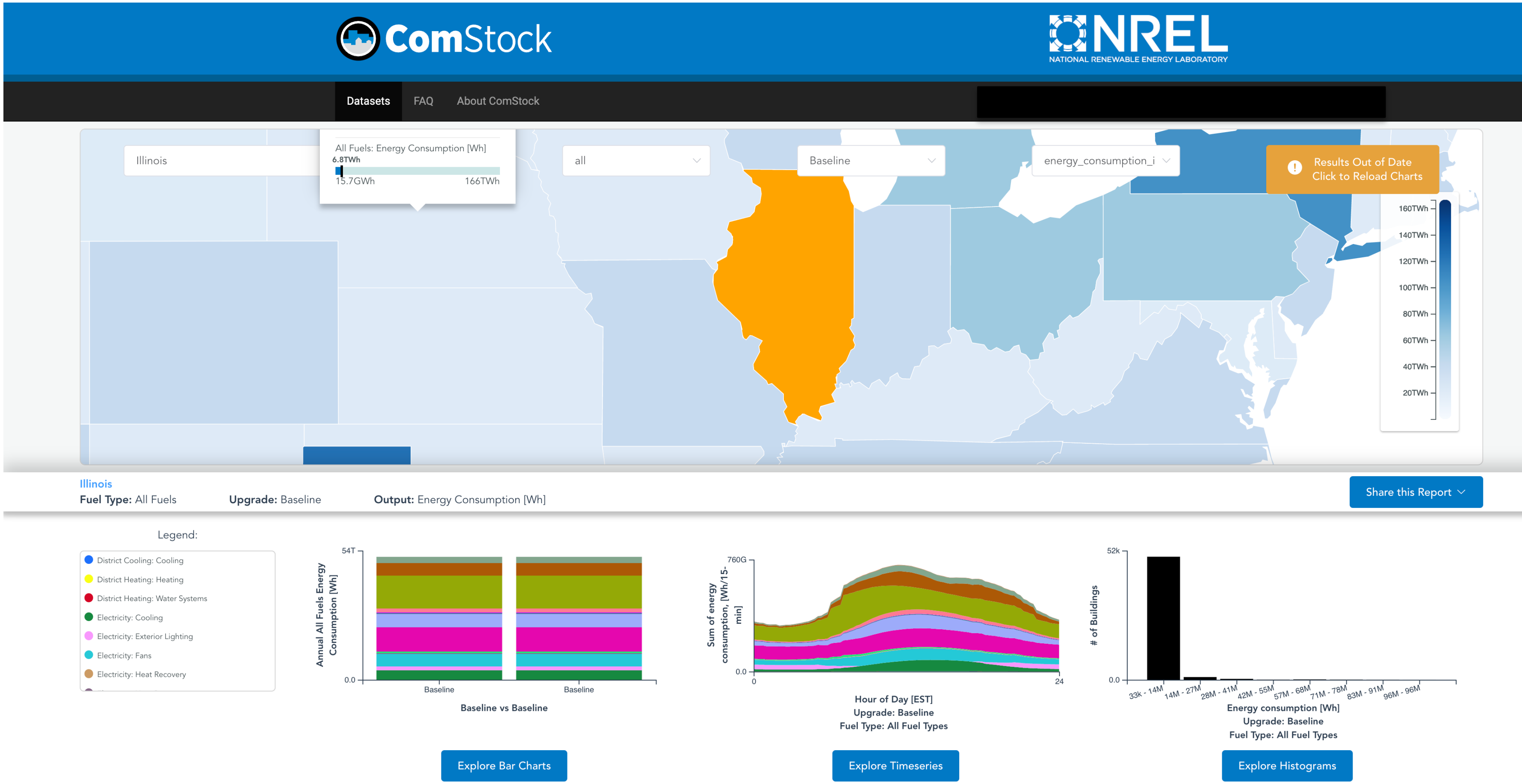



https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings

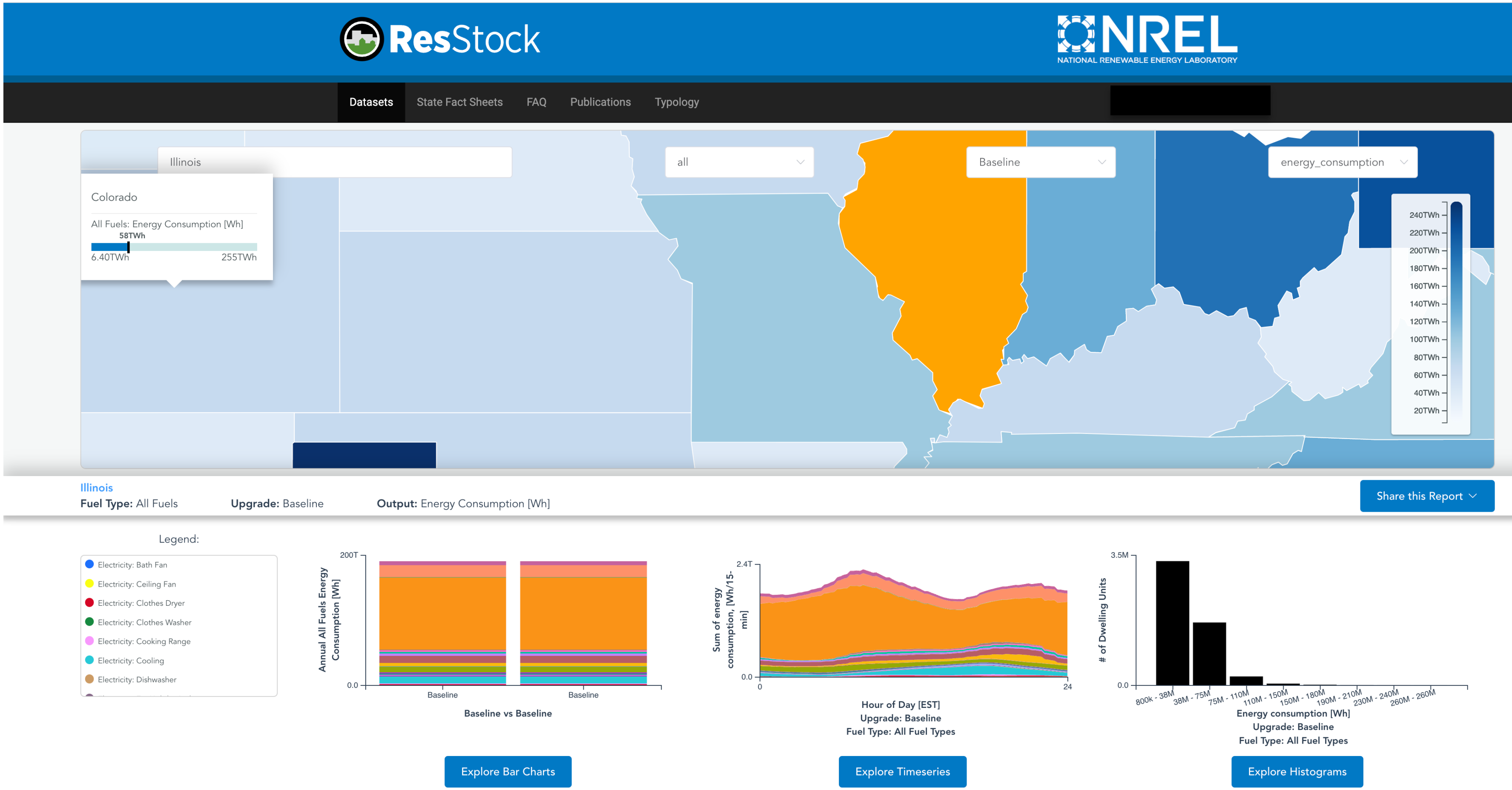
# Commercial/Residential Buildings

- See ResStock and ComStock:
  - https://www.nrel.gov/buildings/comstock.html (for viewing data: https://comstock.nrel.gov/dataviewer)
  - https://www.nrel.gov/buildings/resstock.html (for viewing data: https://resstock.nrel.gov/dataviewer/)

# Commercial/Residential Buildings



# Commercial/Residential Buildings



# Commercial Buildings

- City of Chicago Benchmarking

Building type, sub-type and their frequency in the dataset.

| Building Type | Building Subtype | | | | | | |
|---|---|---|---|---|---|---|---|
| | Commercial | Municipal | Industrial | Multi 7 + | Multi < 7 | Single Family | Total |
| Residential | 0 | 0 | 0 | 2192 | 19,213 | 25,506 | 46,911 |
| Commercial | 4864 | 154 | 0 | 1652 | 4609 | 0 | 11,279 |
| Industrial | 0 | 0 | 15 | 0 | 0 | 0 | 15 |
| Total | 4864 | 154 | 15 | 3844 | 23,822 | 25,506 | 58,205 |

Building characteristics and occupancy features for the buildings in the dataset.

| Variable | Observations | Mean | Standard Deviation | Min | Max |
|---|---|---|---|---|---|
| Building Height | 58,205 | 1.87 | 2.20 | 1 | 110 |
| Building Size (Gross Floor Area) | 58,205 | 35,820 ($ft^2$) | 116,948 ($ft^2$) | 300 ($ft^2$) | 6,143,038 ($ft^2$) |
| | | 3328 ($m^2$) | 10,865 ($m^2$) | 28 ($m^2$) | 570,707 ($m^2$) |
| Year Built | 58,205 | 1935.27 | 31.81463 | 1852 | 2014 |
| Total Occupants | 58,205 | 83.90 | 84.65 | 0 | 3000 |
| Average Household Size | 58,205 | 2.34 | 1.39 | 0 | 9 |
| Occupied Unit Percentage | 58,205 | 87% | 13% | 0% | 100% |



*Abbasabdi et al. Applied Energy 2019*

# Commercial Buildings

- City of Chicago Benchmarking

Summary statistics of building site EUI used in the model.

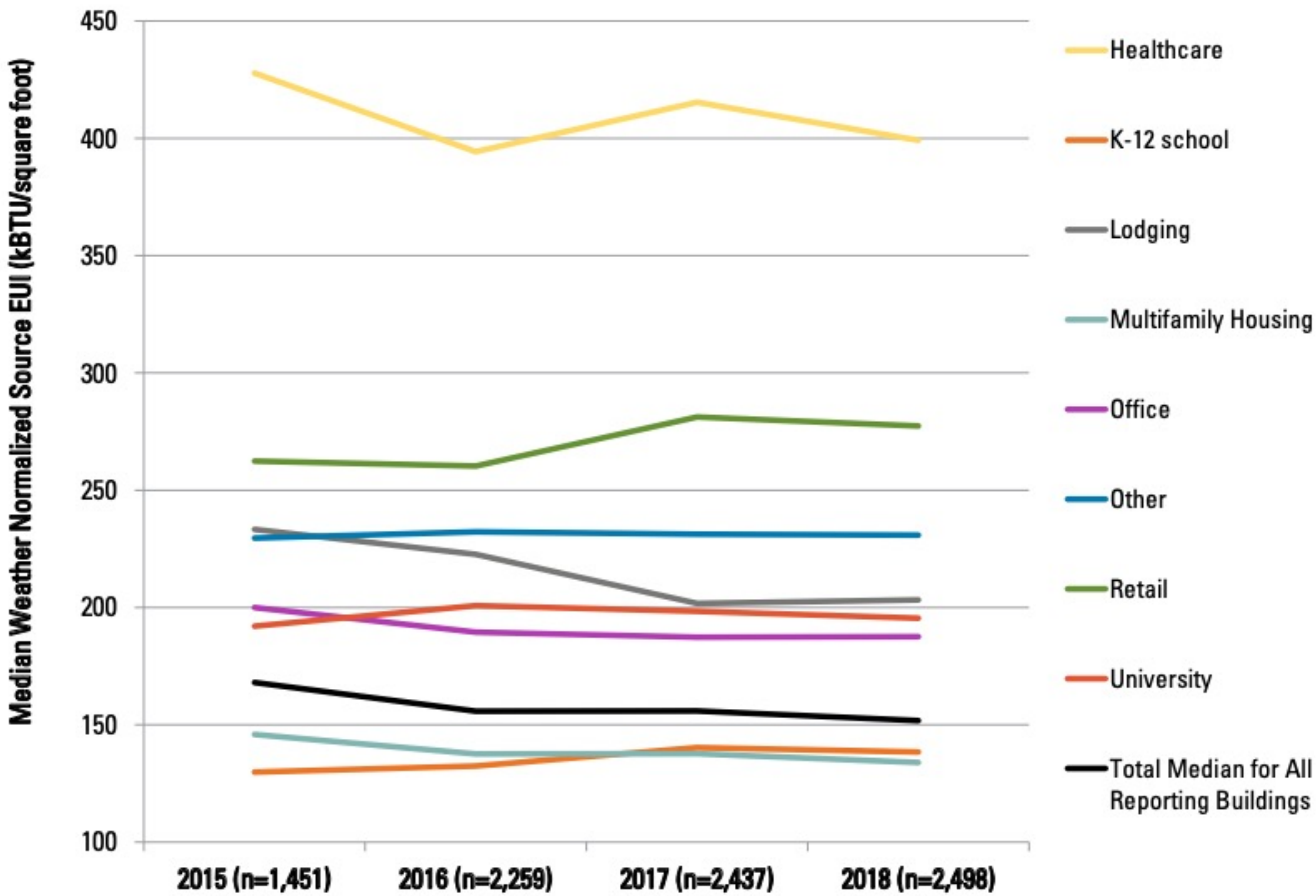
| Variable | Observations | Mean | Standard Deviation | Min | Max |
|---|---|---|---|---|---|
| Building site EUI | 58,205 | 67.29 (kBtu/ft$^2$)<br>212.28 (kWh/m$^2$) | 30.01 (kBtu/ft$^2$)<br>94.68 (kWh/m$^2$) | 10.65 (kBtu/ft$^2$)<br>33.60 (kWh/m$^2$) | 540.00 (kBtu/ft$^2$)<br>1703.48 (kWh/m$^2$) |



*Abbasabdi et al. Applied Energy 2019*

# Commercial Buildings

- City of Chicago Benchmarking

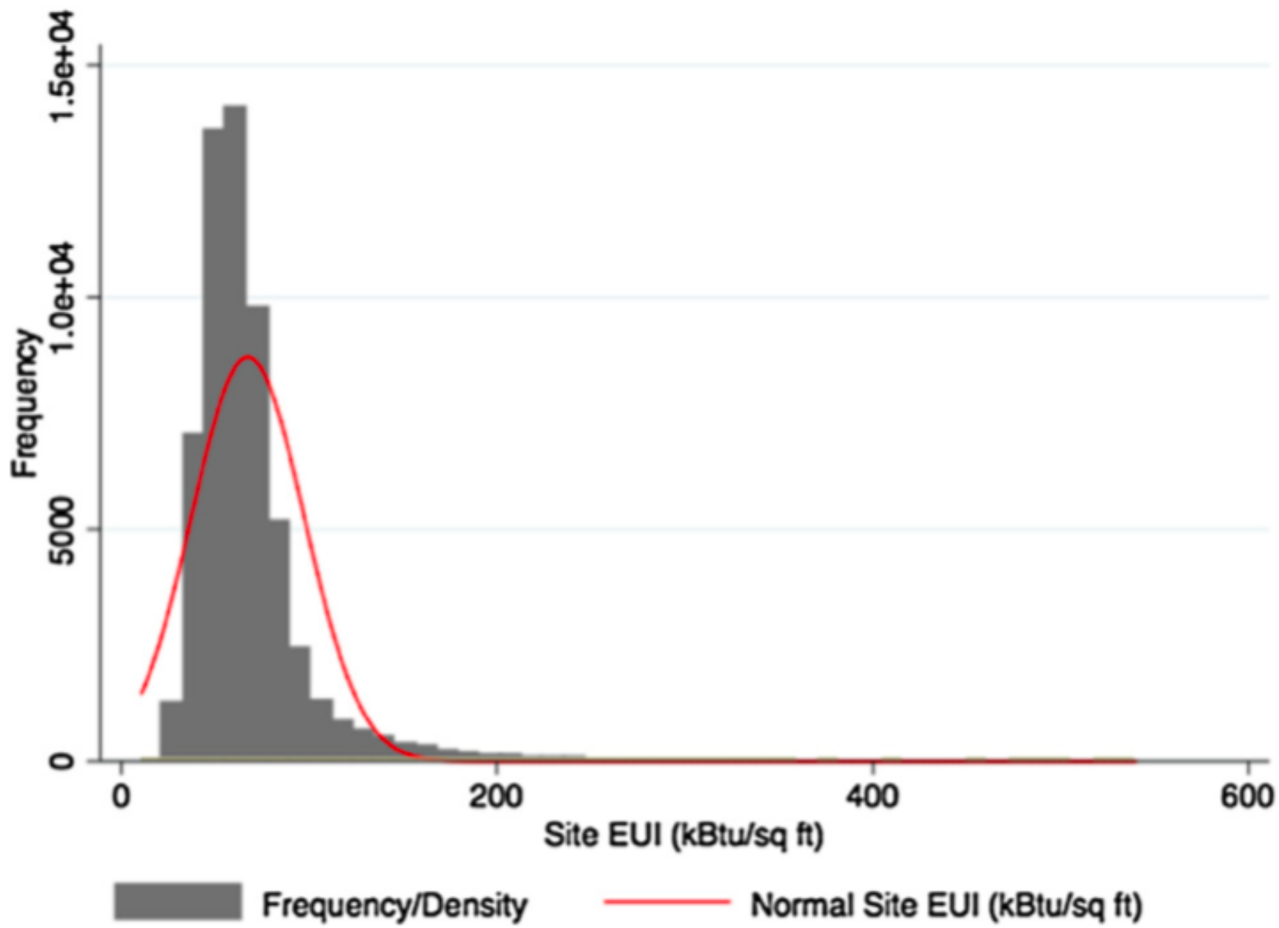





https://www.chicago.gov/city/en/depts/mayor/supp_info/chicago-energy-benchmarking/Chicago_Energy_Benchmarking_Reports_Data.html

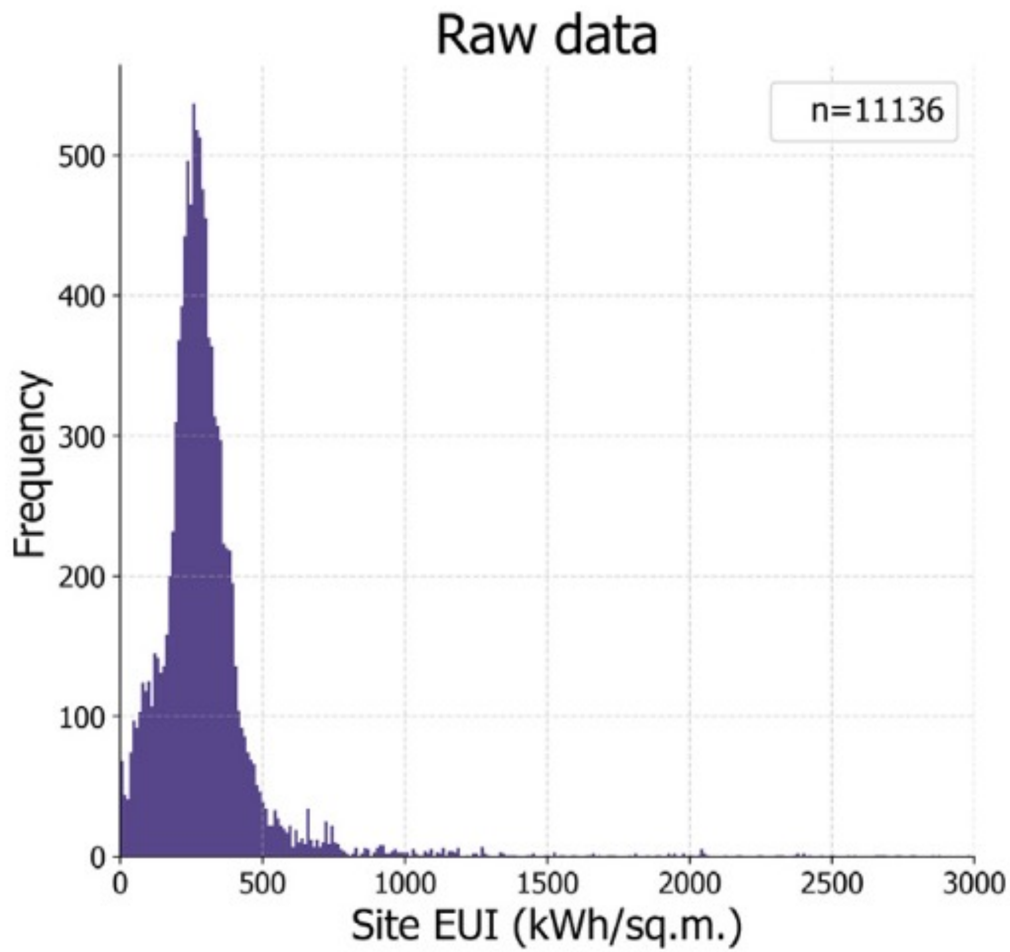
# Commercial Buildings

- City of Chicago Benchmarking



# Commercial Buildings

- New York City Benchmarking






*Popadopoulos et al. Applied Energy 2018*

# CLASS ACTIVITY

# Class Activity

- Plot electricity and steam vs. monthly average temperature plots for AM Hall building.

# CLASS ACTIVITY

# Class Activity

- Let’s aim at using Python or R to re-do the class activates

- Form a team of two

- Present in 20-30 minutes about your progress