CAE 465/526 Building Energy Conservation Technologies

Fall 2022

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Building energy consumption patterns and performance analysis

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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

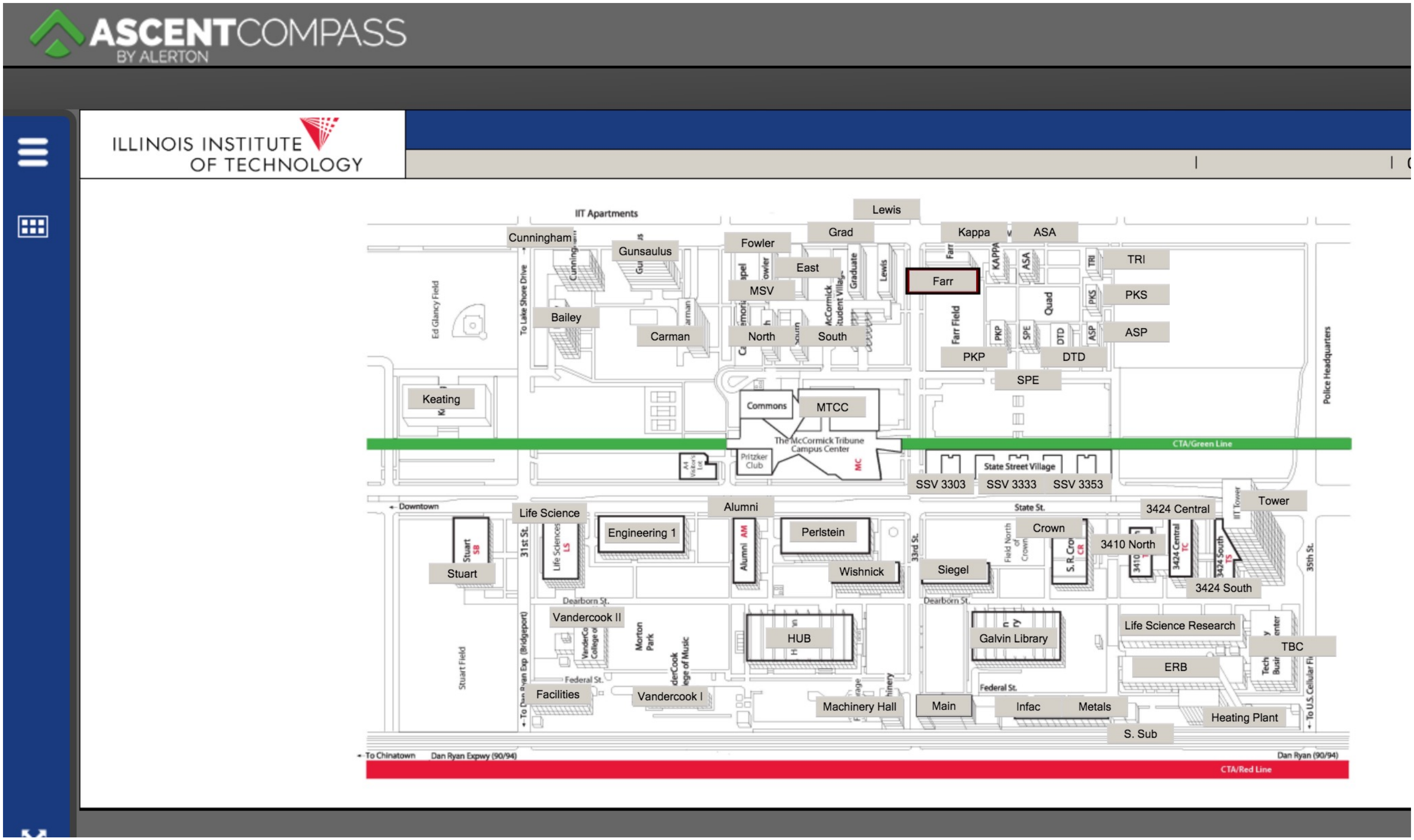
Campus Buildings Are Unique

- 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) Summary	Steam 1 (lbs) 1DD2-1-P01	Chilled Water (kBTU) #1
Current Meter Reading	-	21,356,710 lbs	15,188,800 kBTU
Yesterday's Meter	-	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

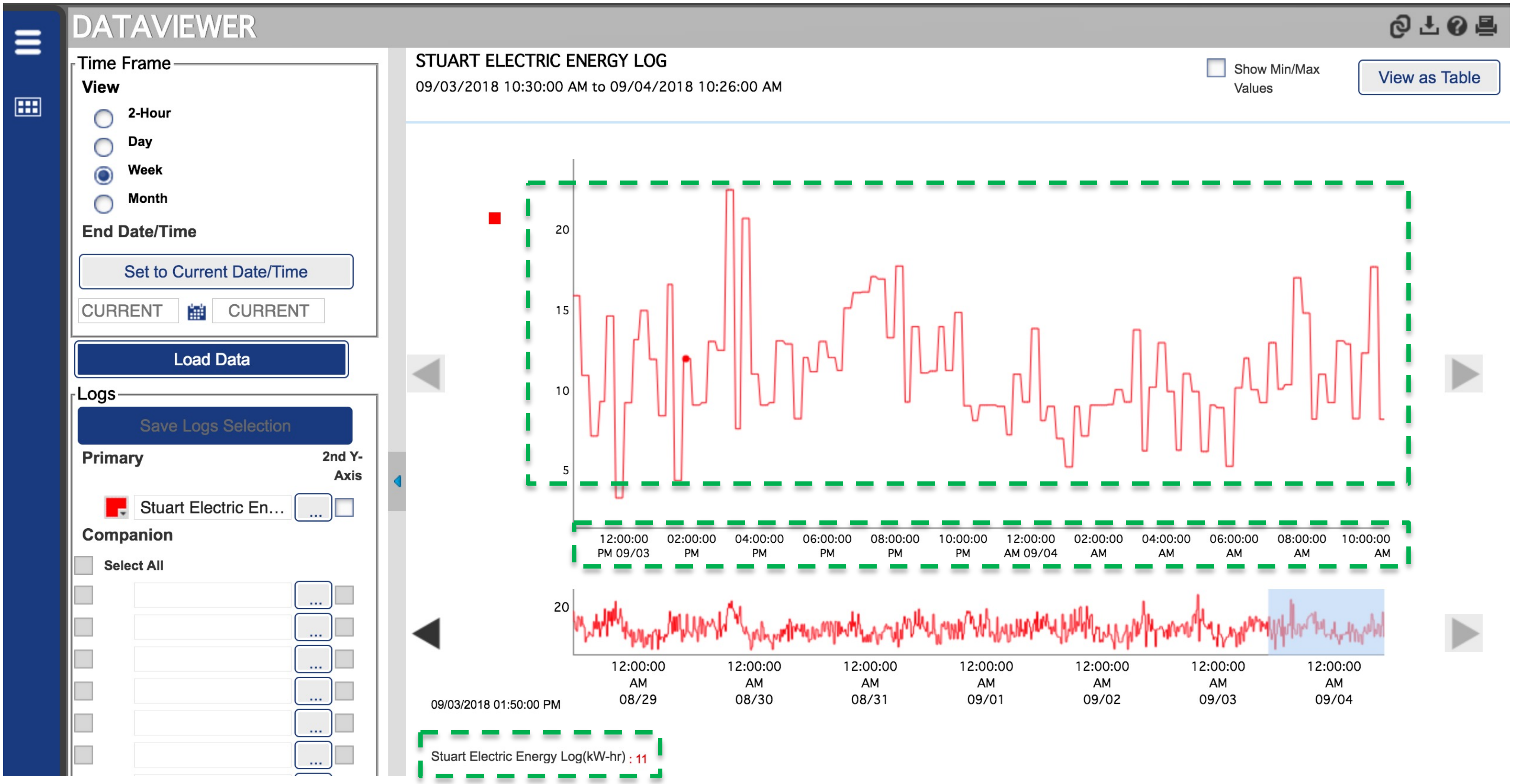
Total Building Cost ($)	**1,137.72**	**kBTUs/Sq. Ft this Month**	**0.77**
Last Month Cost ($)	**9,774.03**	**Total Building kBTUs**	**61,329**

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

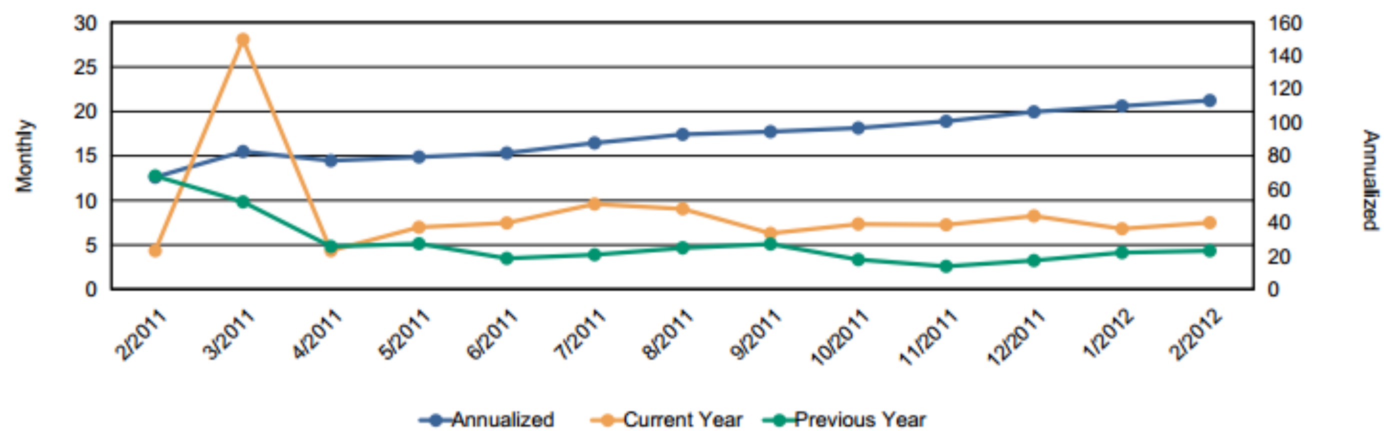
DIVISION OF ADMINISTRATION
UTILITIES & ENERGY MANAGEMENT

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

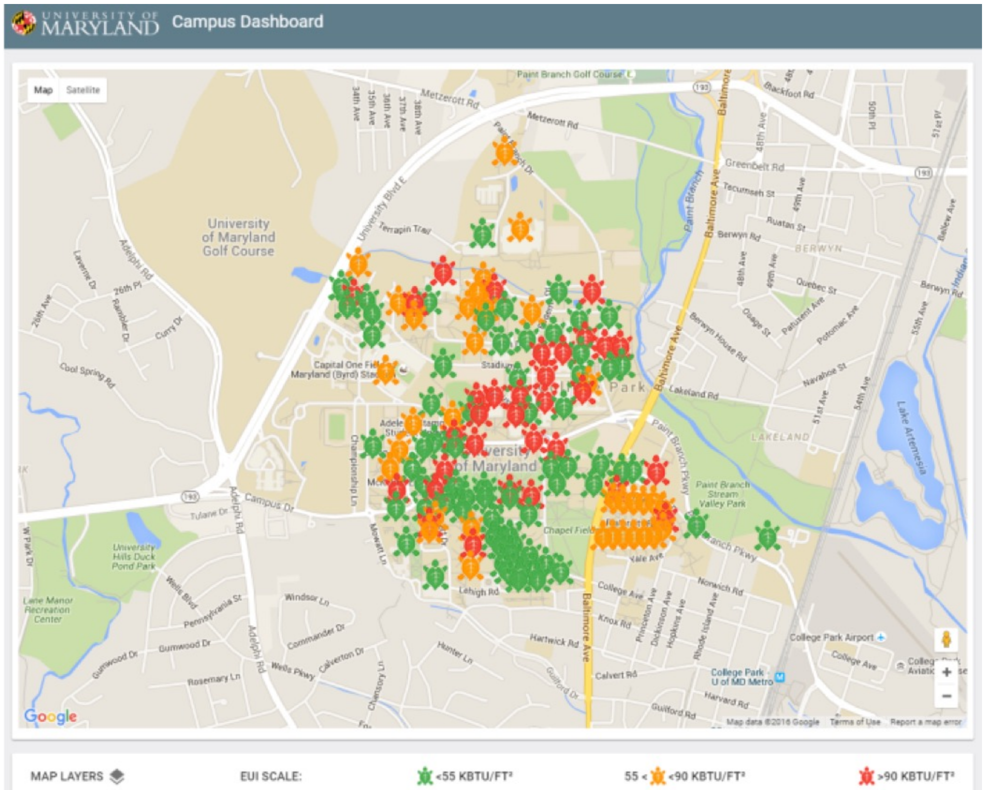


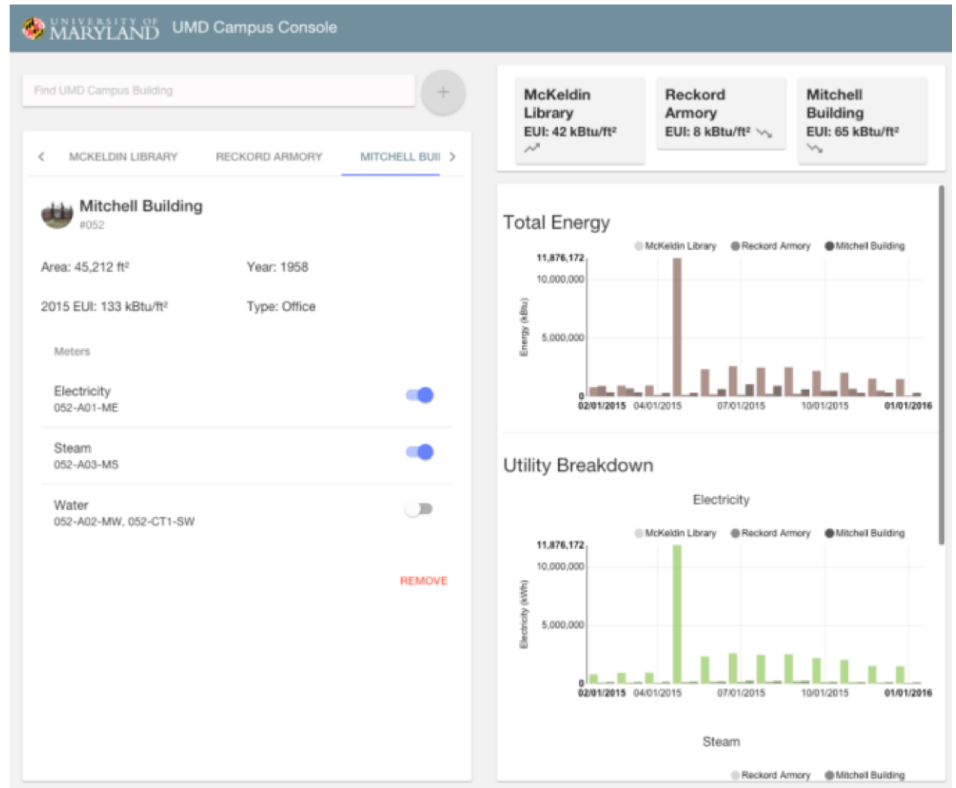
#	Building	GSF	EUI	Annual Cost
0040	field lab and office bldg	2,275	134	$7,548

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

Monitoring System

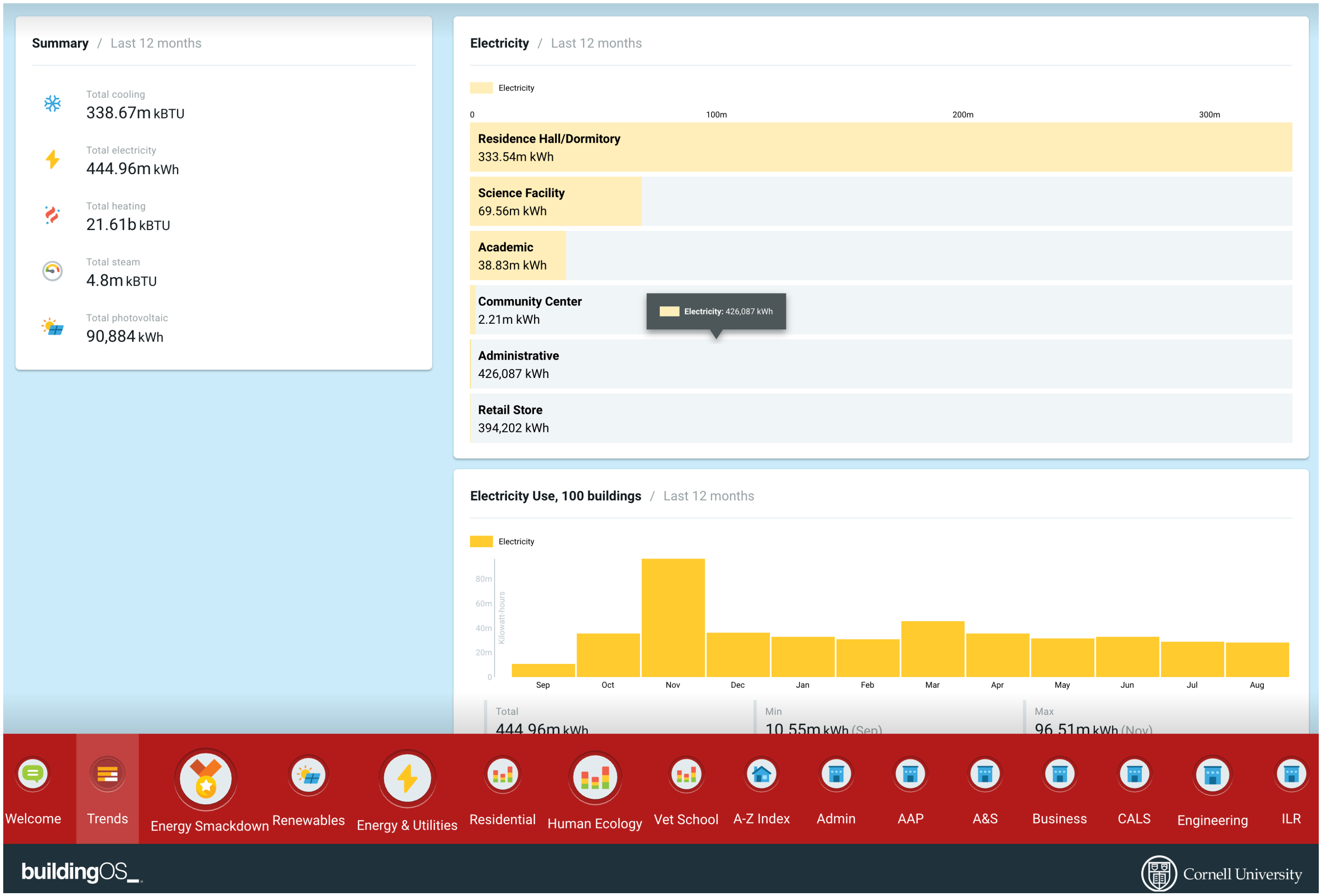
- University of Maryland Energy Dashboard





Monitoring System

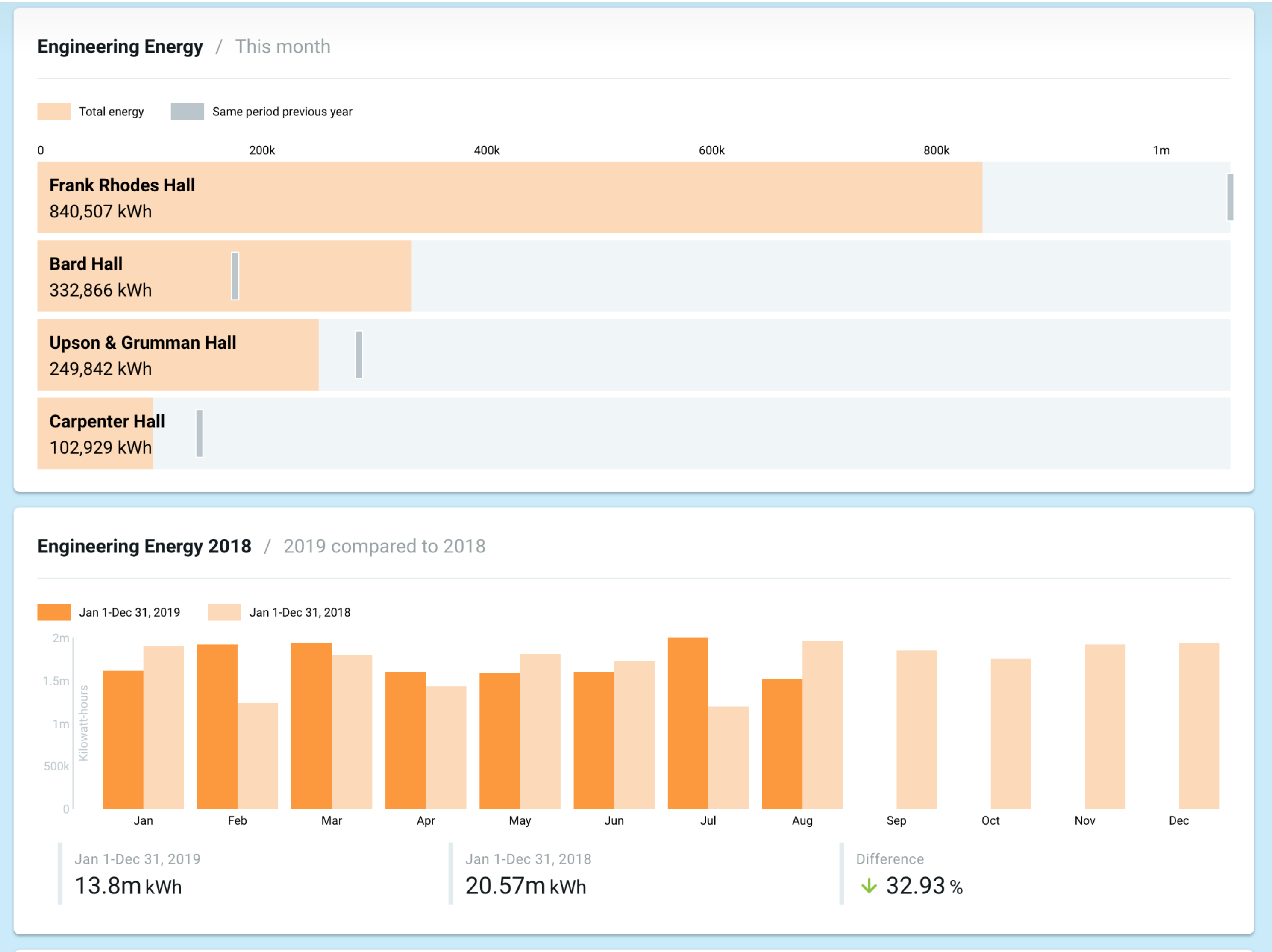
- Cornell University Energy Dashboard



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

Monitoring System

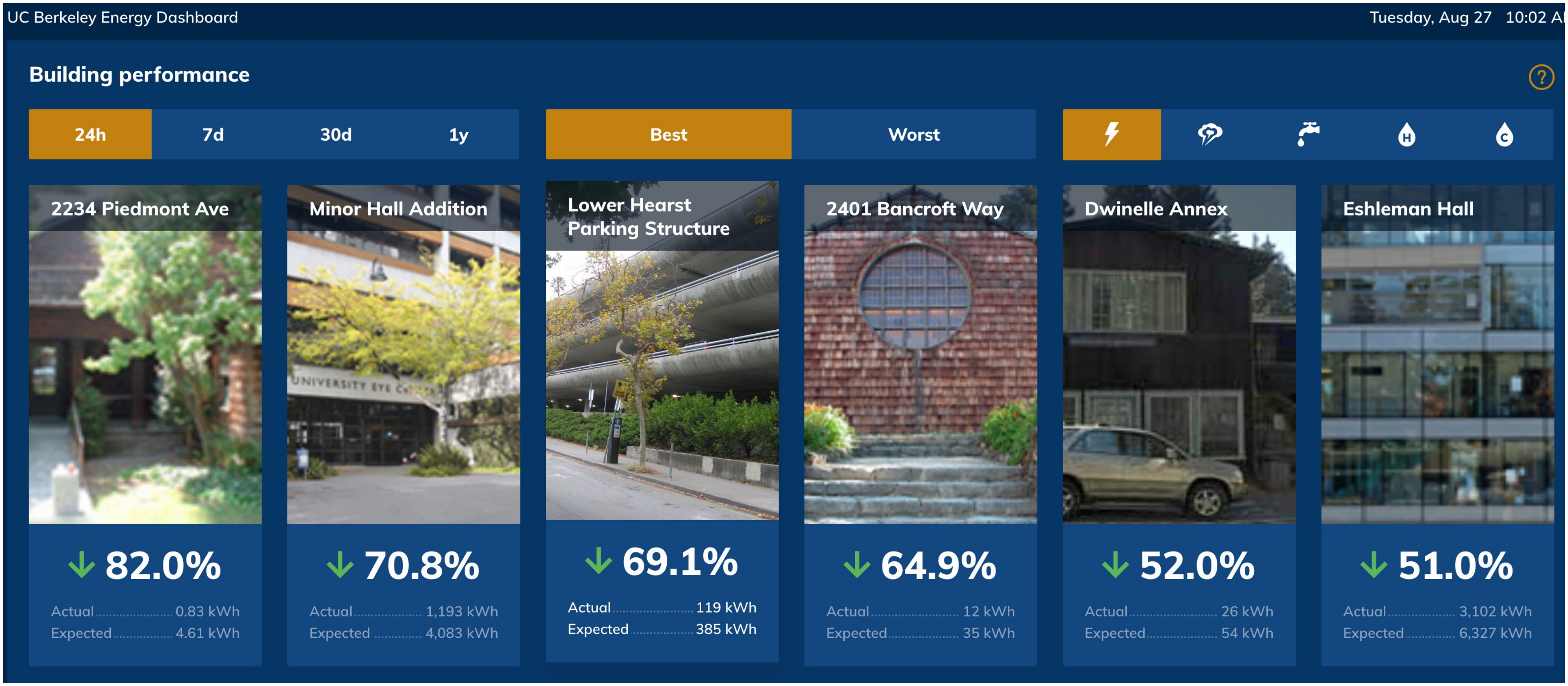
- Cornell University Energy Dashboard



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

Monitoring System

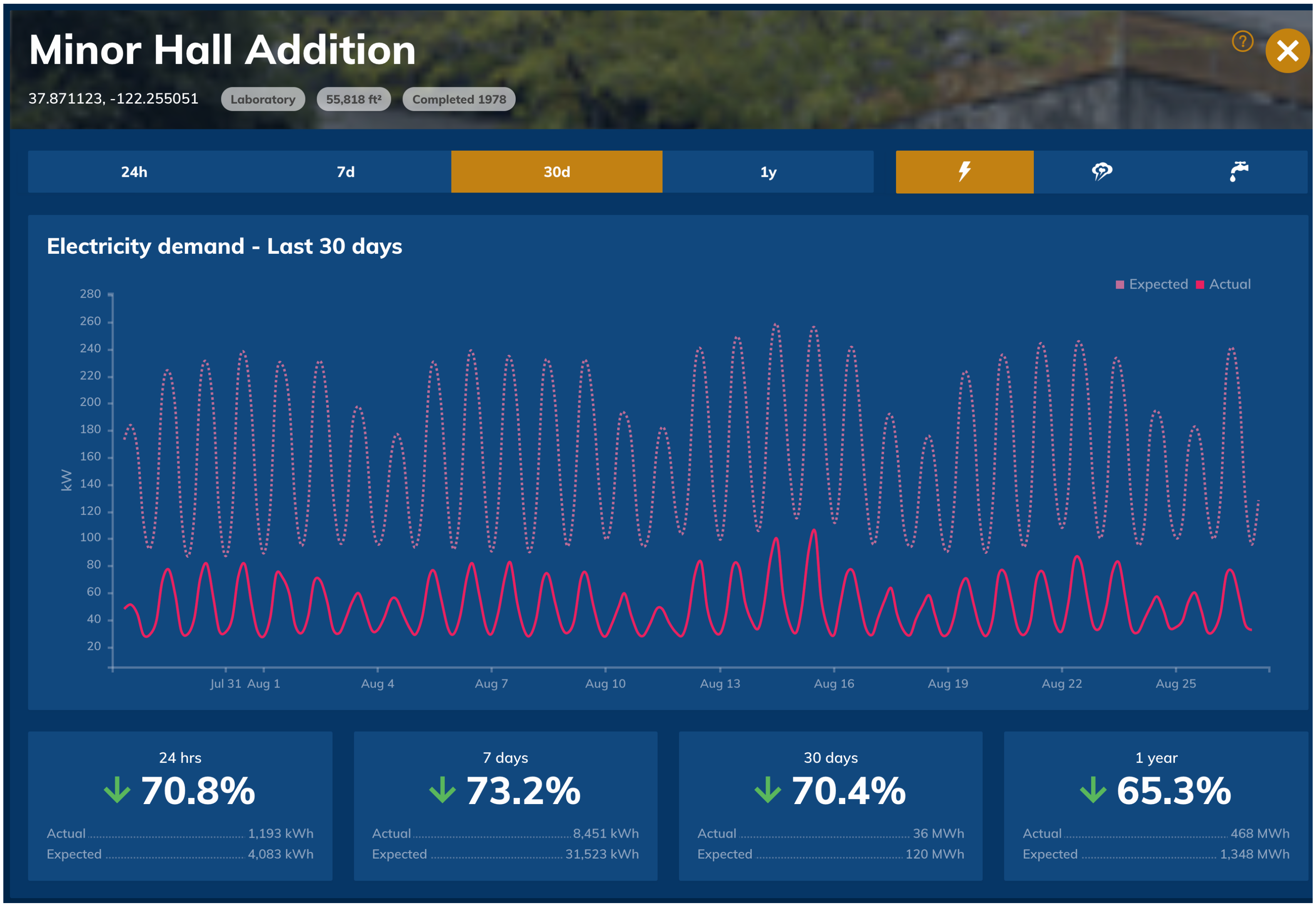
- UC Berkeley Energy Dashboard



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

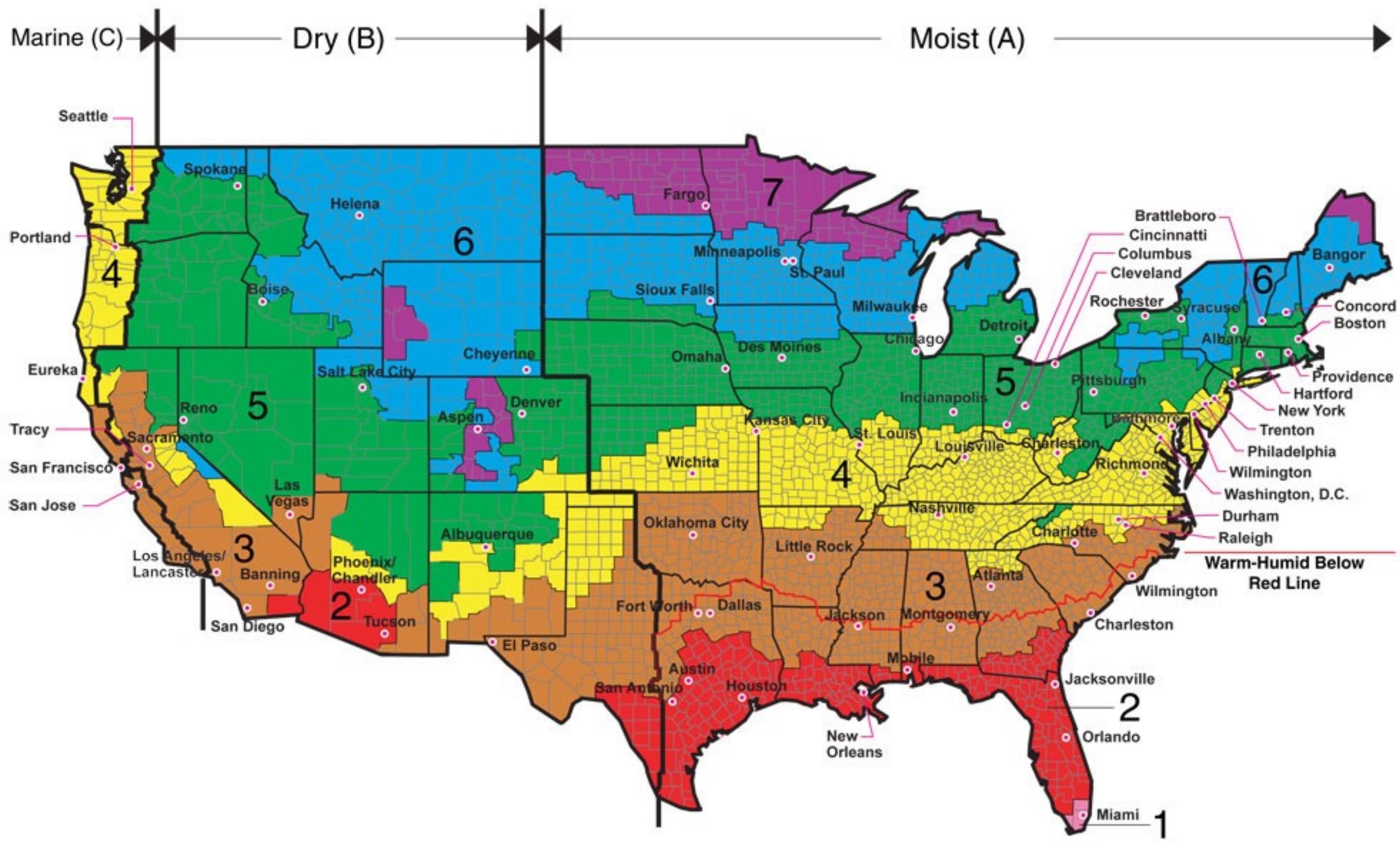
Class Activity

- **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

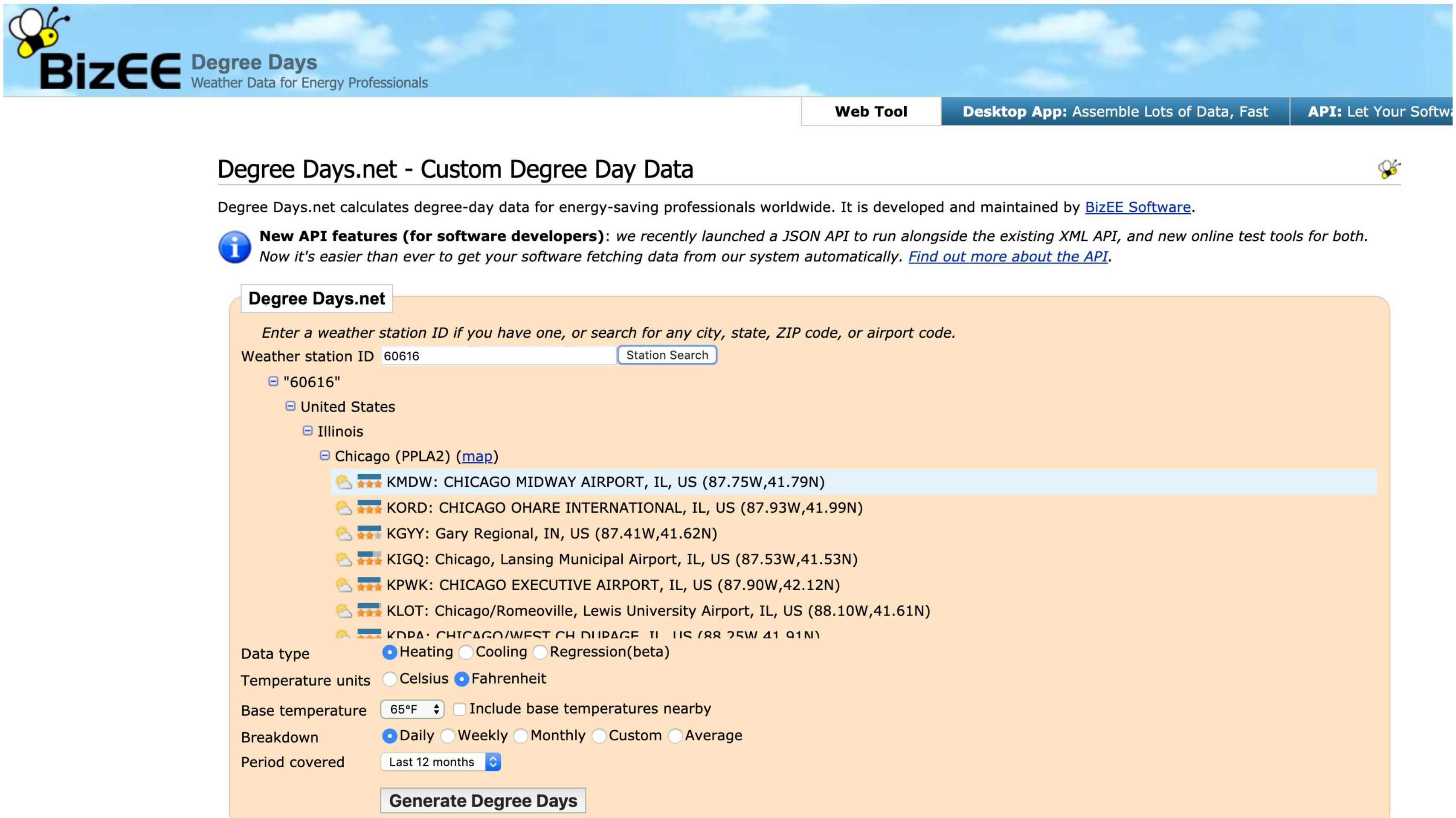
- ASHRAE Climate Zones

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

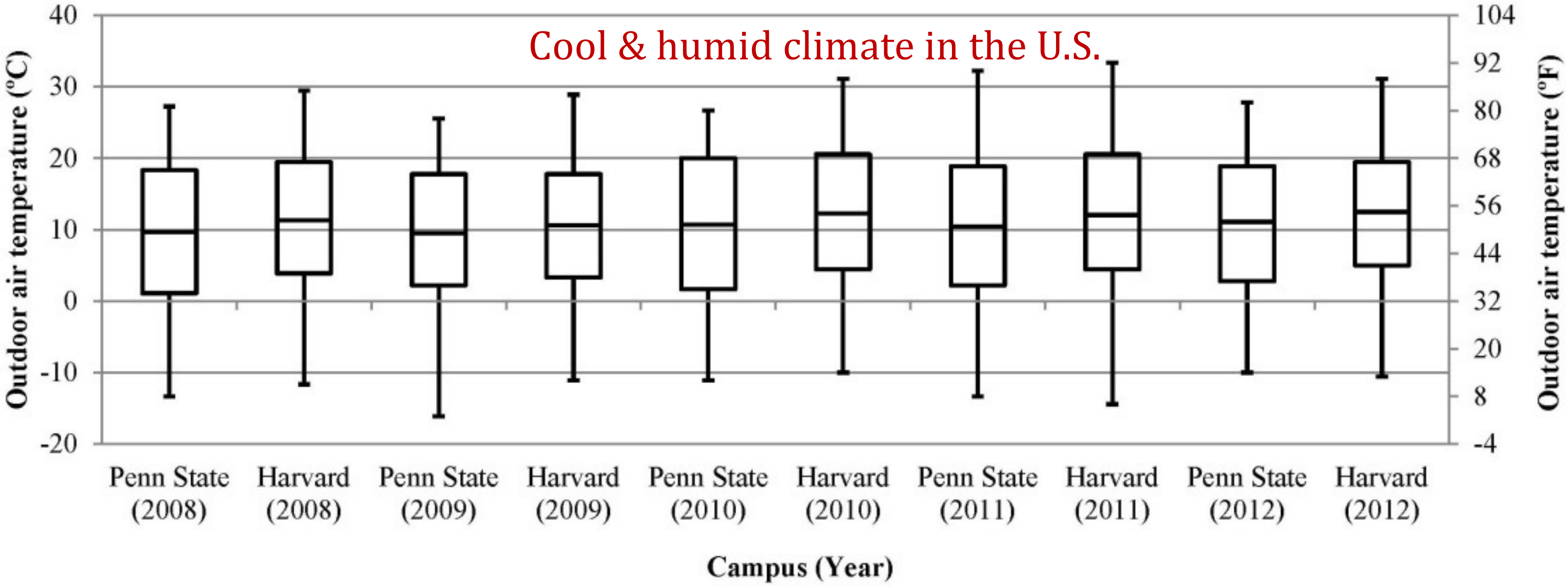
TABLE D-1 U.S. and U.S. Territory Climatic Data *(Continued)*

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

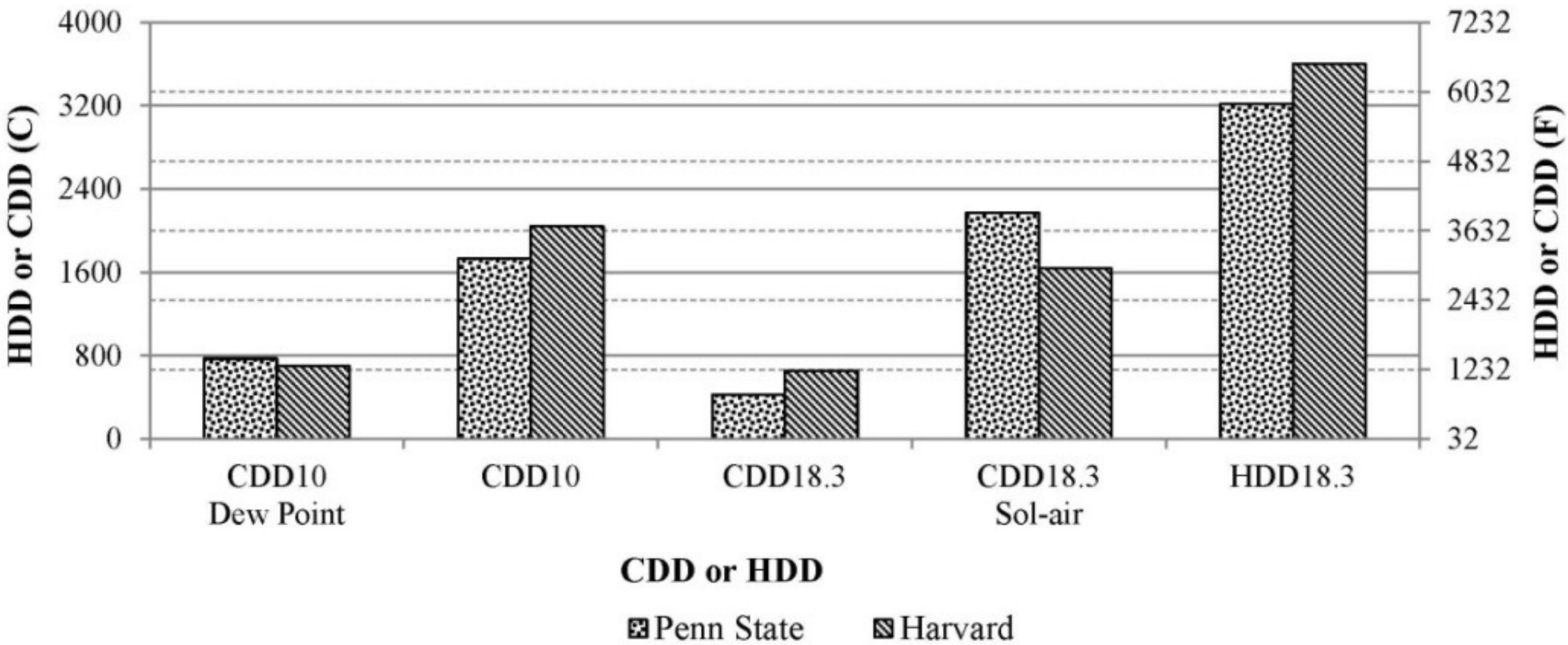
- An example from the Penn State and Harvard campus study.



Average daily temperature for five years

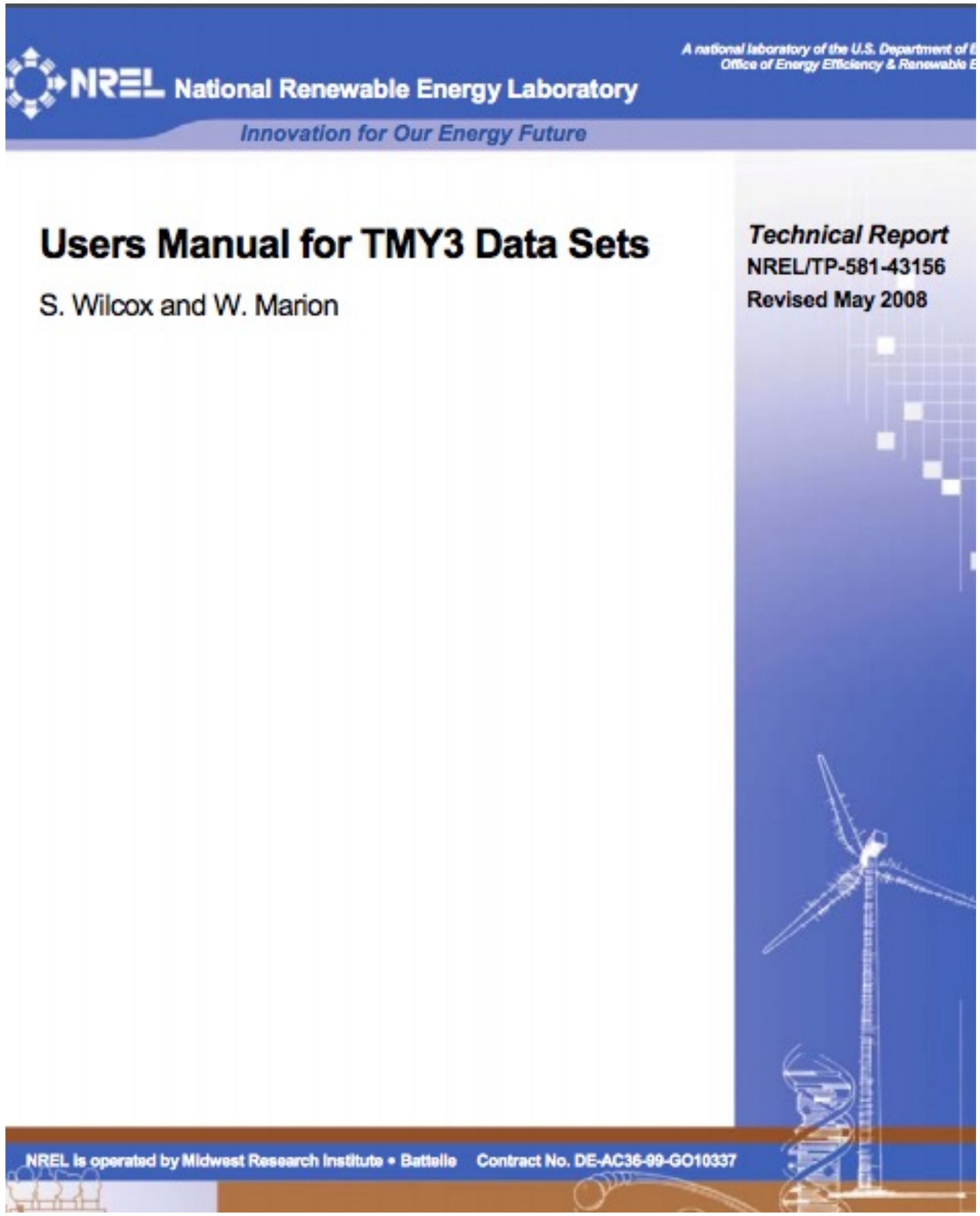
Weather Data Characterization

- 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



A national laboratory of the U.S. Department of E
Office of Energy Efficiency & Renewable E

NREL National Renewable Energy Laboratory

Innovation for Our Energy Future

Users Manual for TMY3 Data Sets

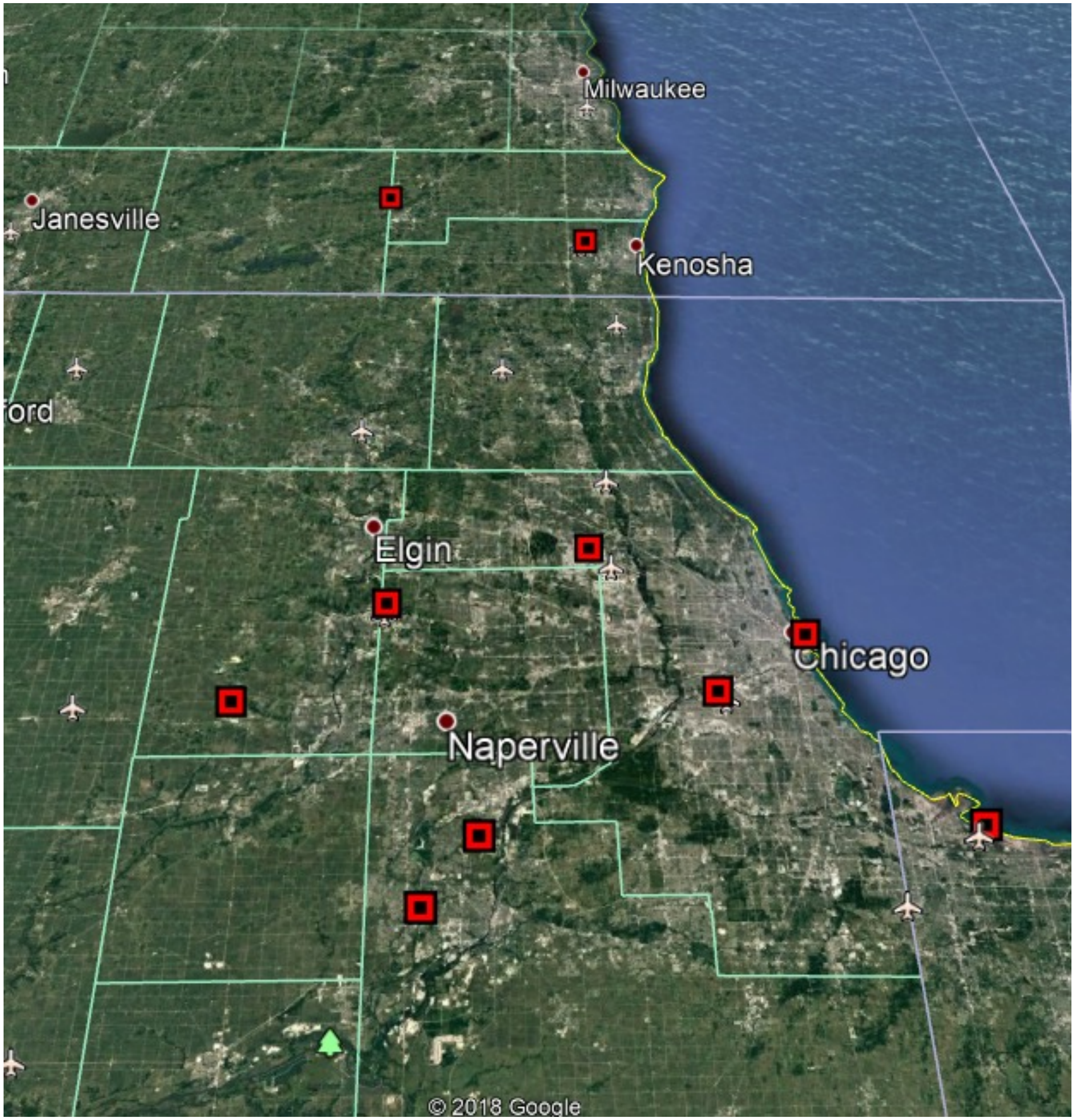
S. Wilcox and W. Marion

Technical Report
NREL/TP-581-43156
Revised May 2008

NREL is operated by Midwest Research Institute • Battelle   Contract No. DE-AC36-99-GO10337

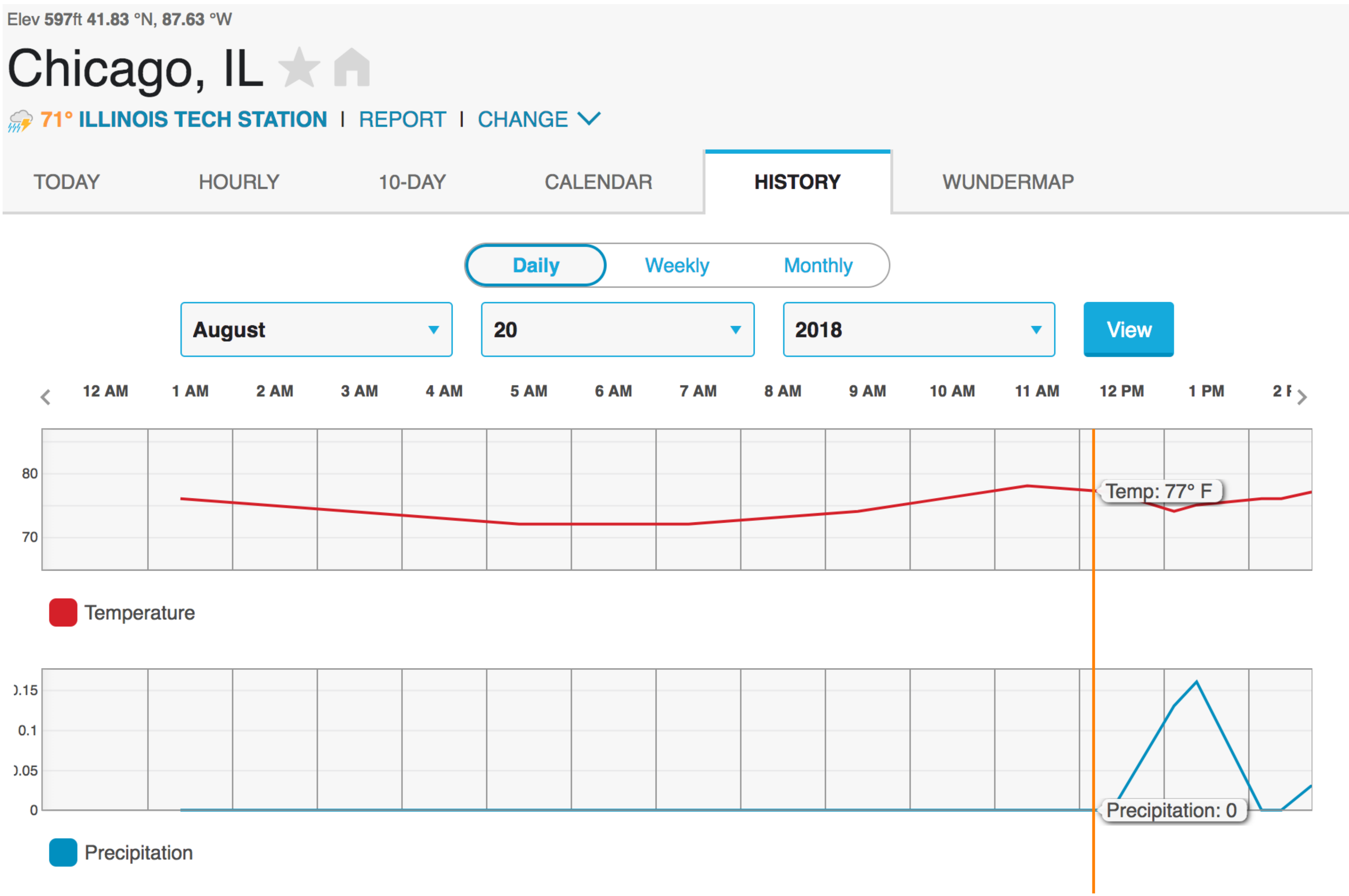
https://www.nrel.gov/docs/fy08osti/43156.pdf

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

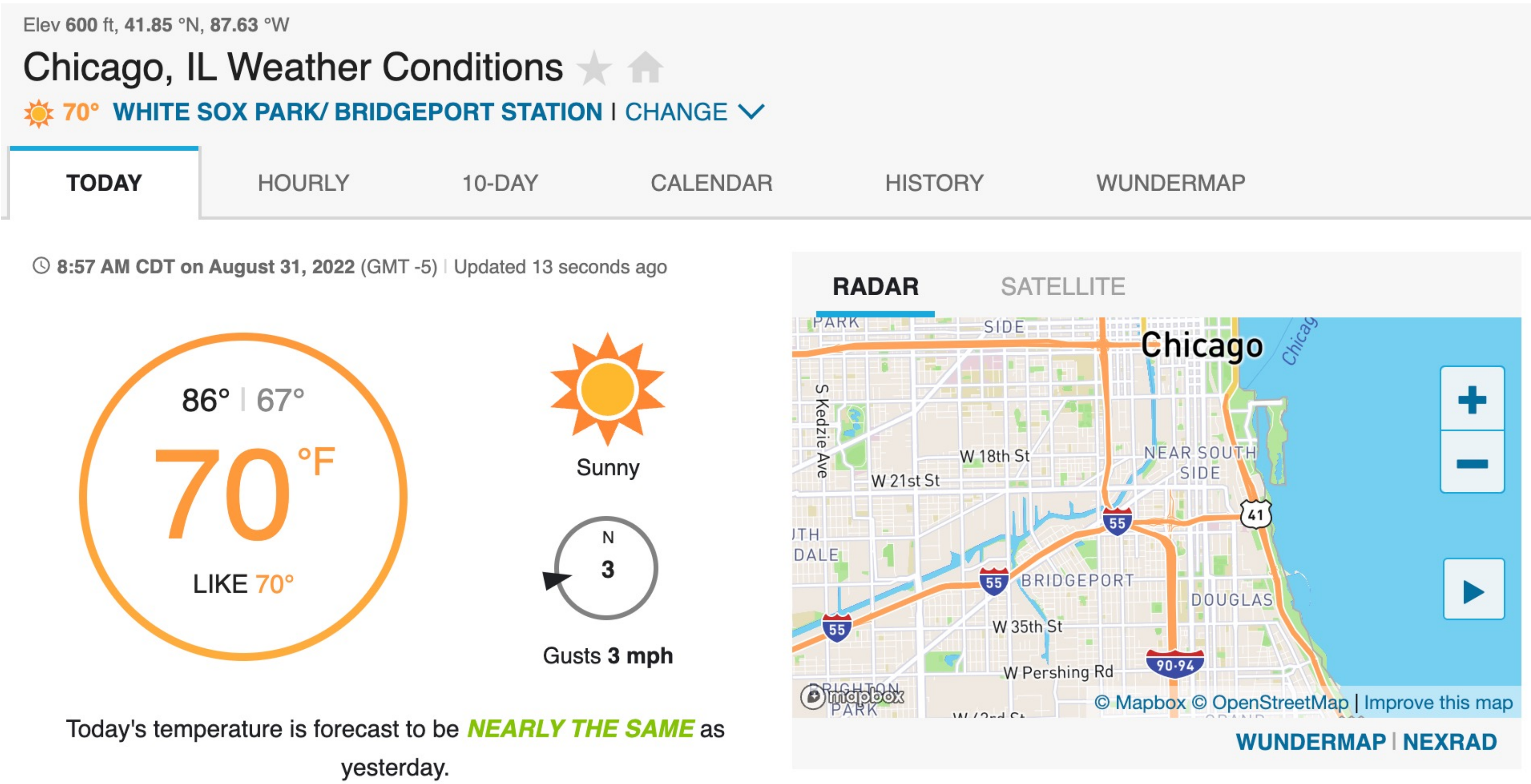
IIT Weather Station

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/ft^2)	Site EUI (kBtu/ft^2)	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	???

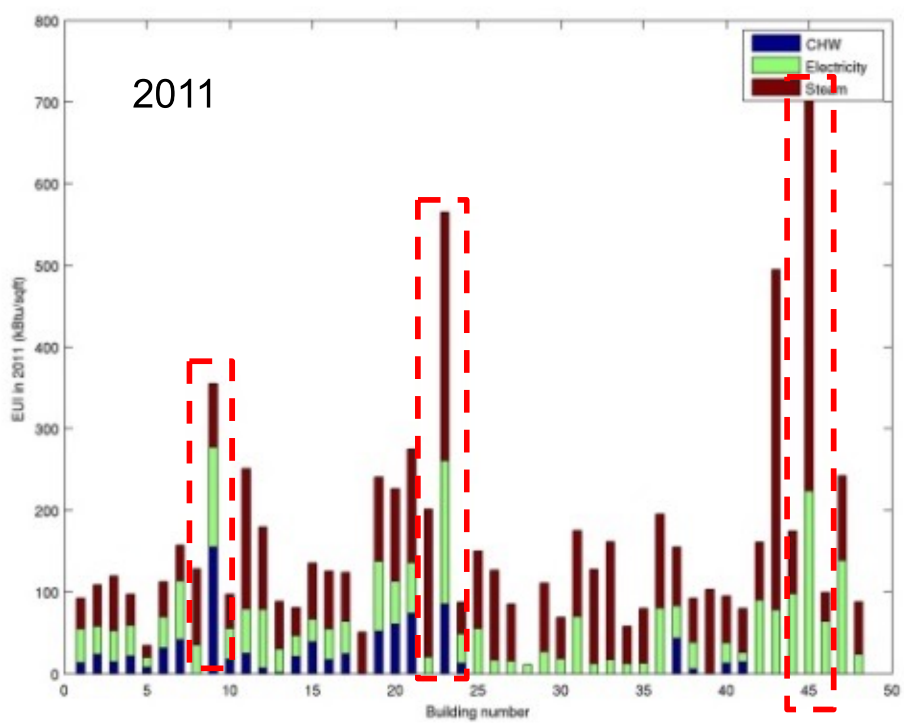
Class Activity

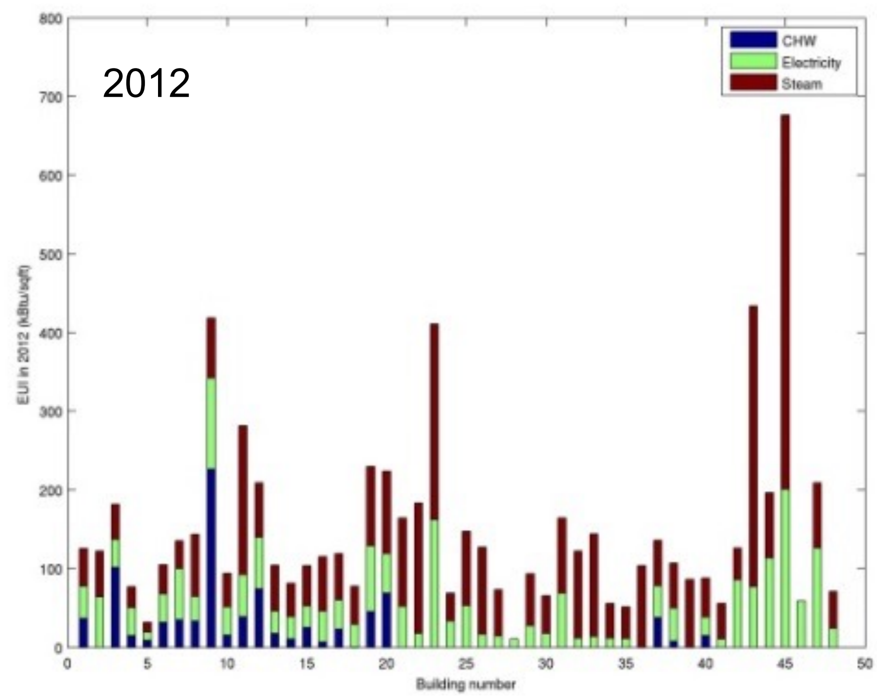
- From previous students:

	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

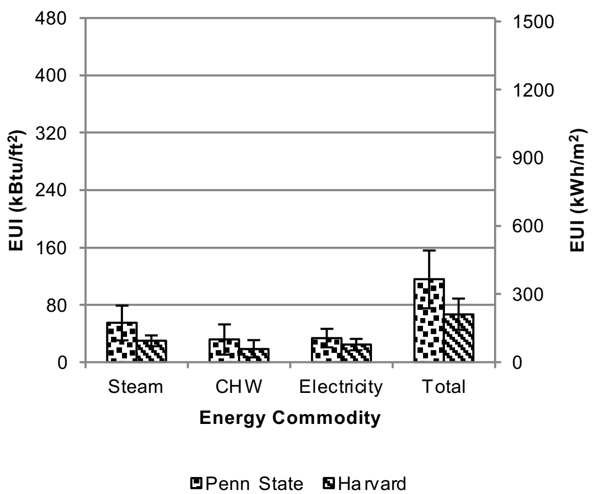




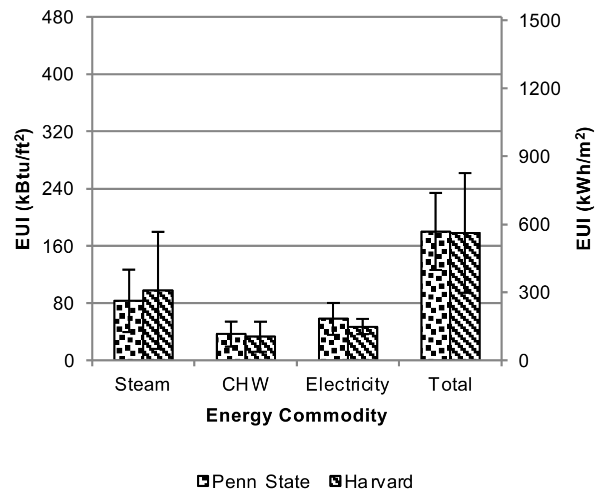
Energy Consumption

- An example for the five primary categories:

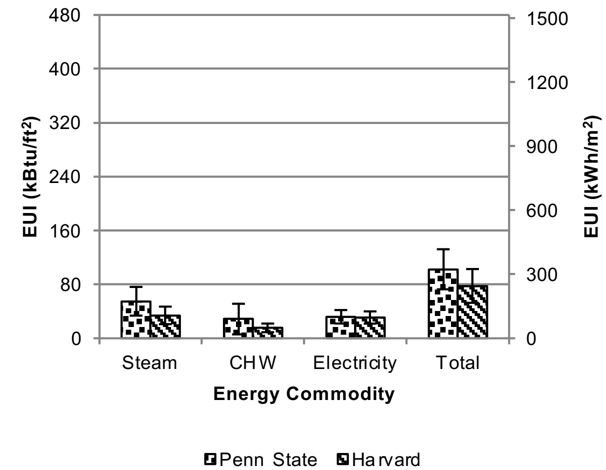
Classroom/Office



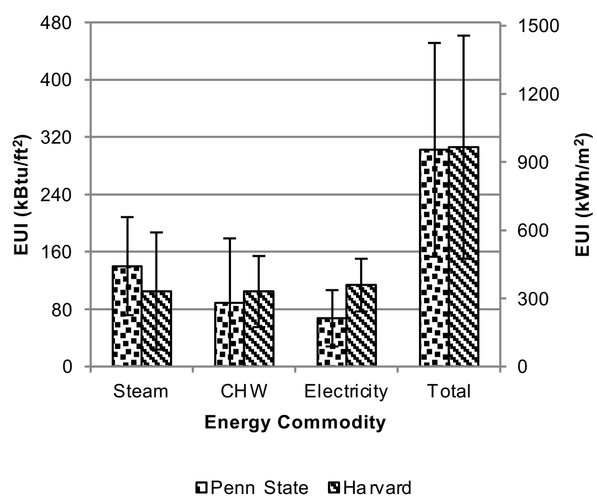
Lab Mixes



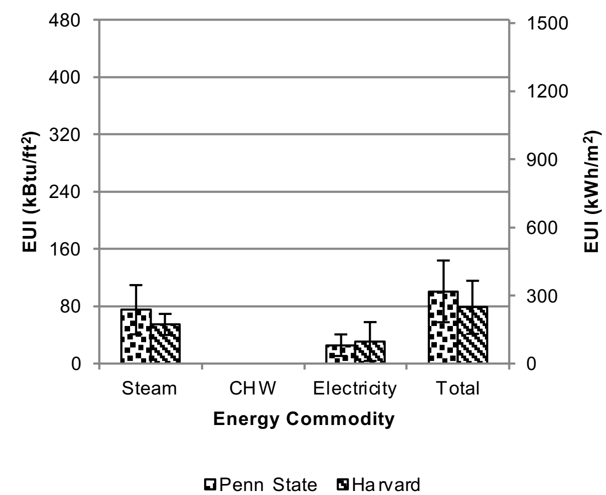
Office Areas



Research Laboratories



Residential Facilities



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

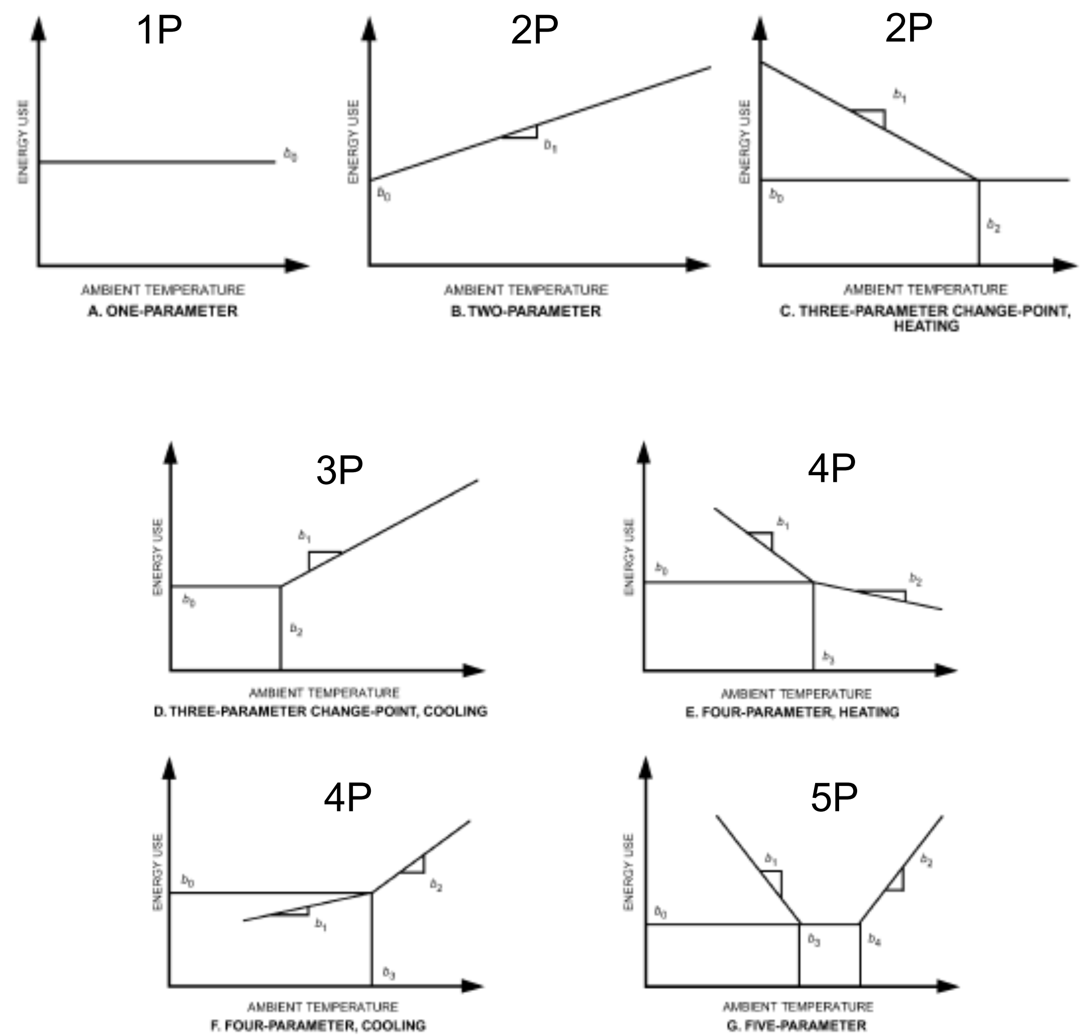
- Internally-load dominated buildings:
  - Outdoor conditions do not have significant influence on the energy consumption of these buildings
  - Internal loads such as receptacle, occupancy, lighting loads and their schedules are the main drivers to control the energy consumption of these buildings
  - 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

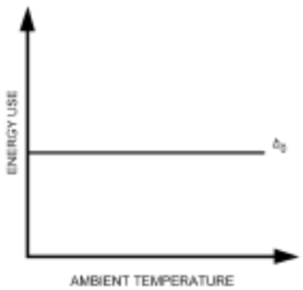


Provide and example for each method?

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

Degree Days

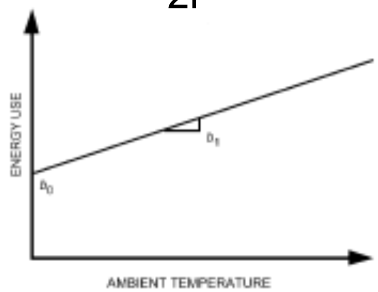
1P



A. ONE-PARAMETER

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

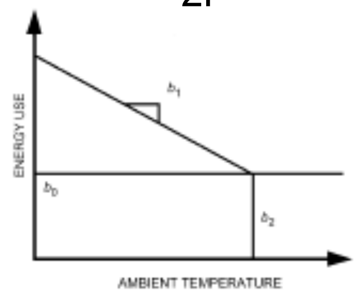
2P



B. TWO-PARAMETER

Chilled water consumption for a building for a typical campus building

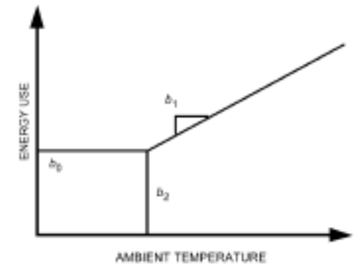
2P



C. THREE-PARAMETER CHANGE-POINT, HEATING

Steam consumption for a building with research laboratory

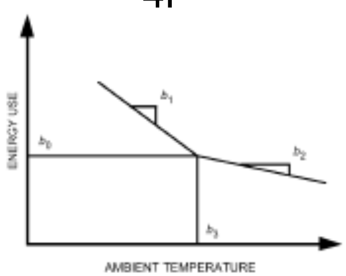
3P



D. THREE-PARAMETER CHANGE-POINT, COOLING

Chilled water consumption for a building with research laboratory

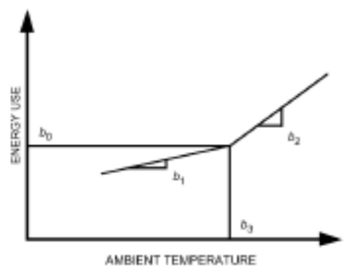
4P



E. FOUR-PARAMETER, HEATING

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

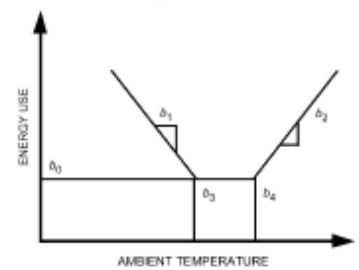
4P



F. FOUR-PARAMETER, COOLING

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

5P



G. FIVE-PARAMETER

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

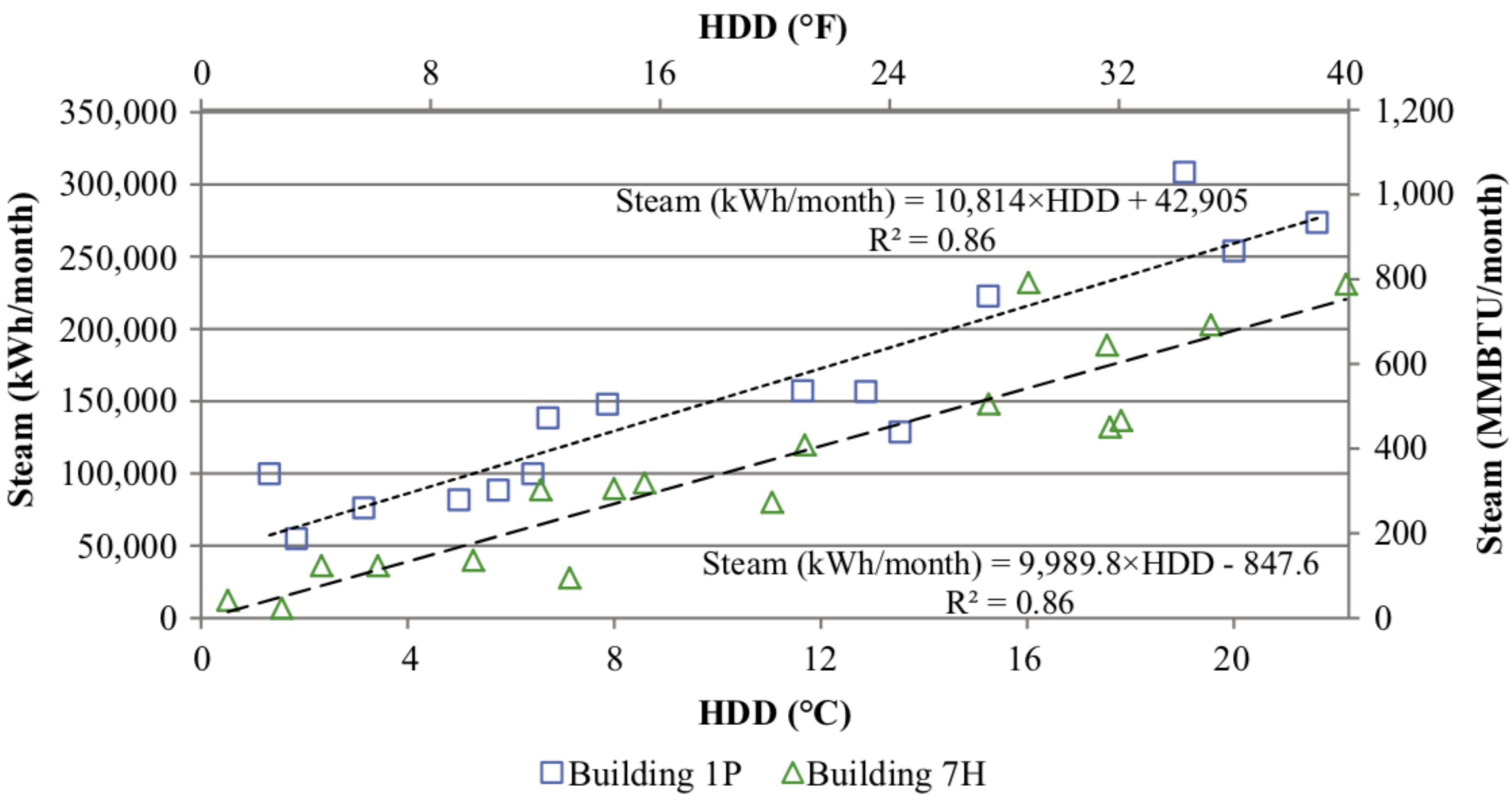
- Used two approaches:
  1. All year: works better for campus buildings due to simultaneous heating and cooling.

  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.

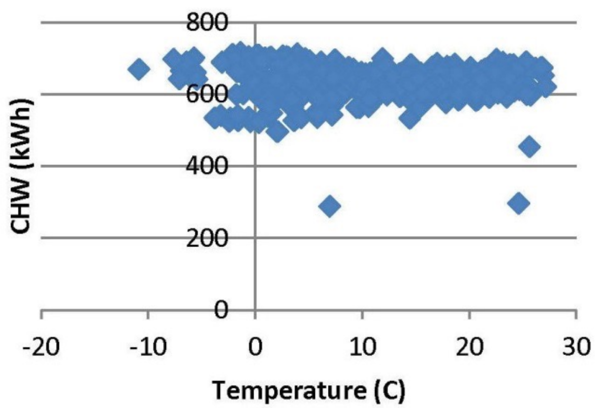


Heidarinejad et al. 2017

Normalization of Energy End-uses

- Different pattern exists for the campus building:

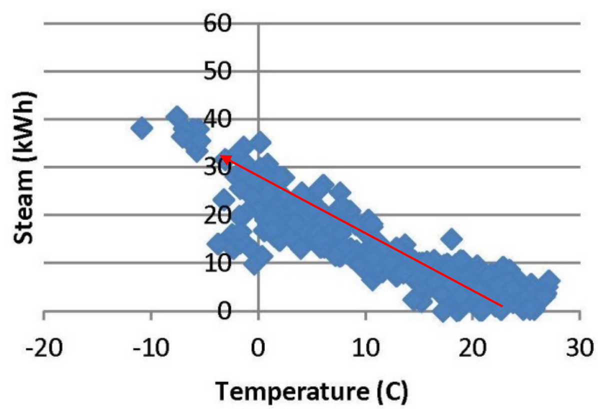
1P



No correlations

CHW= $a \times Temp + b$

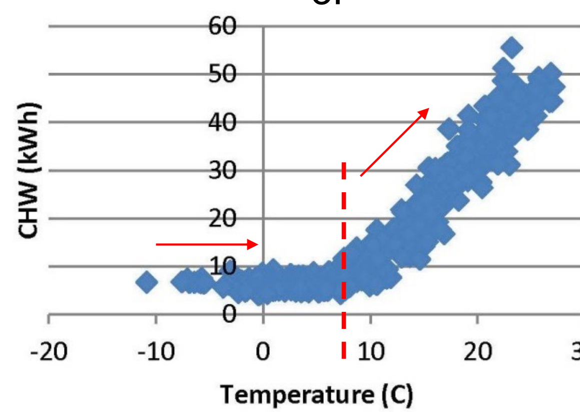
2P



Two points model

$Steam = a\ Temp + b$

3P

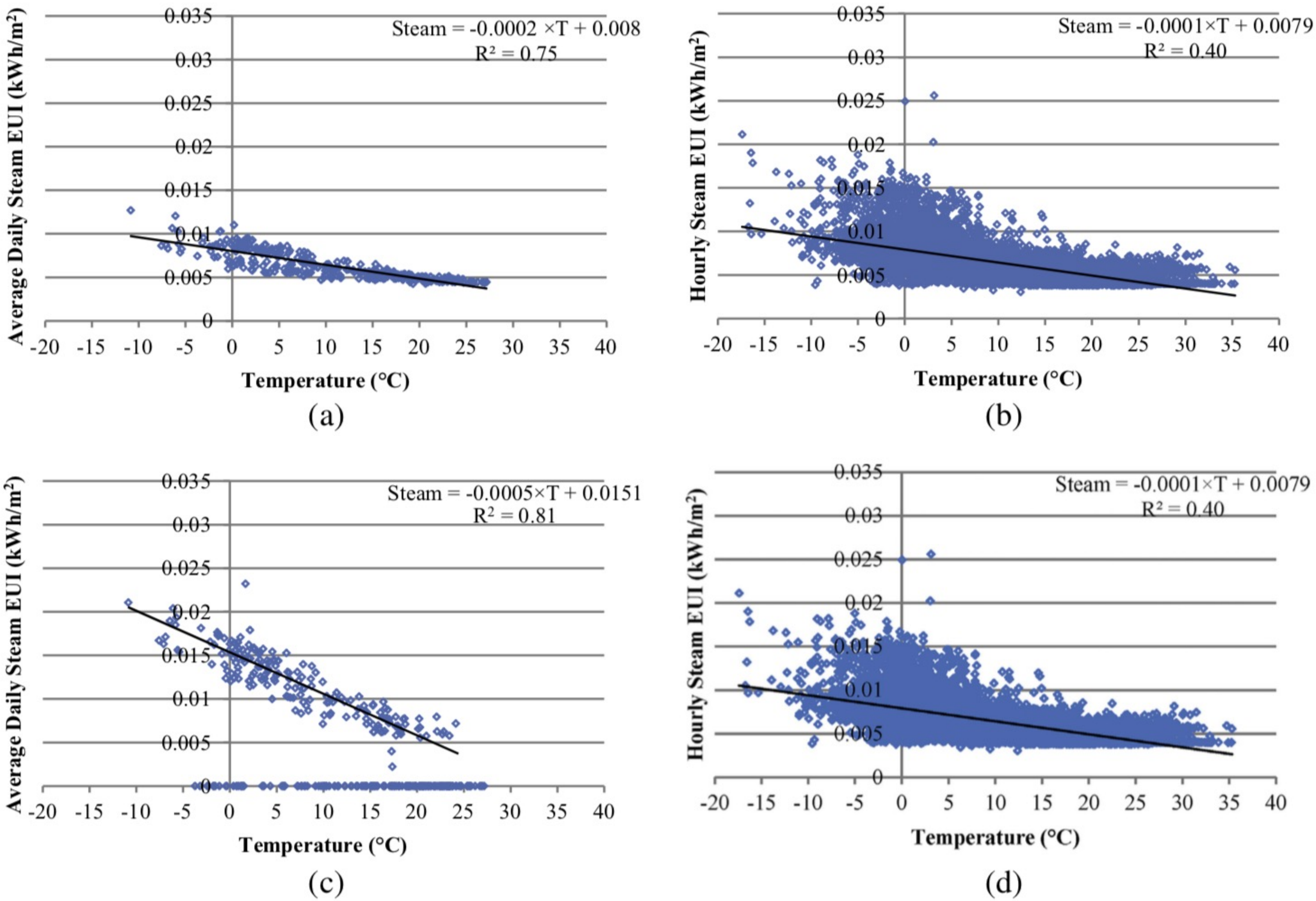


Three points model

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

Heidarinejad et al. 2017

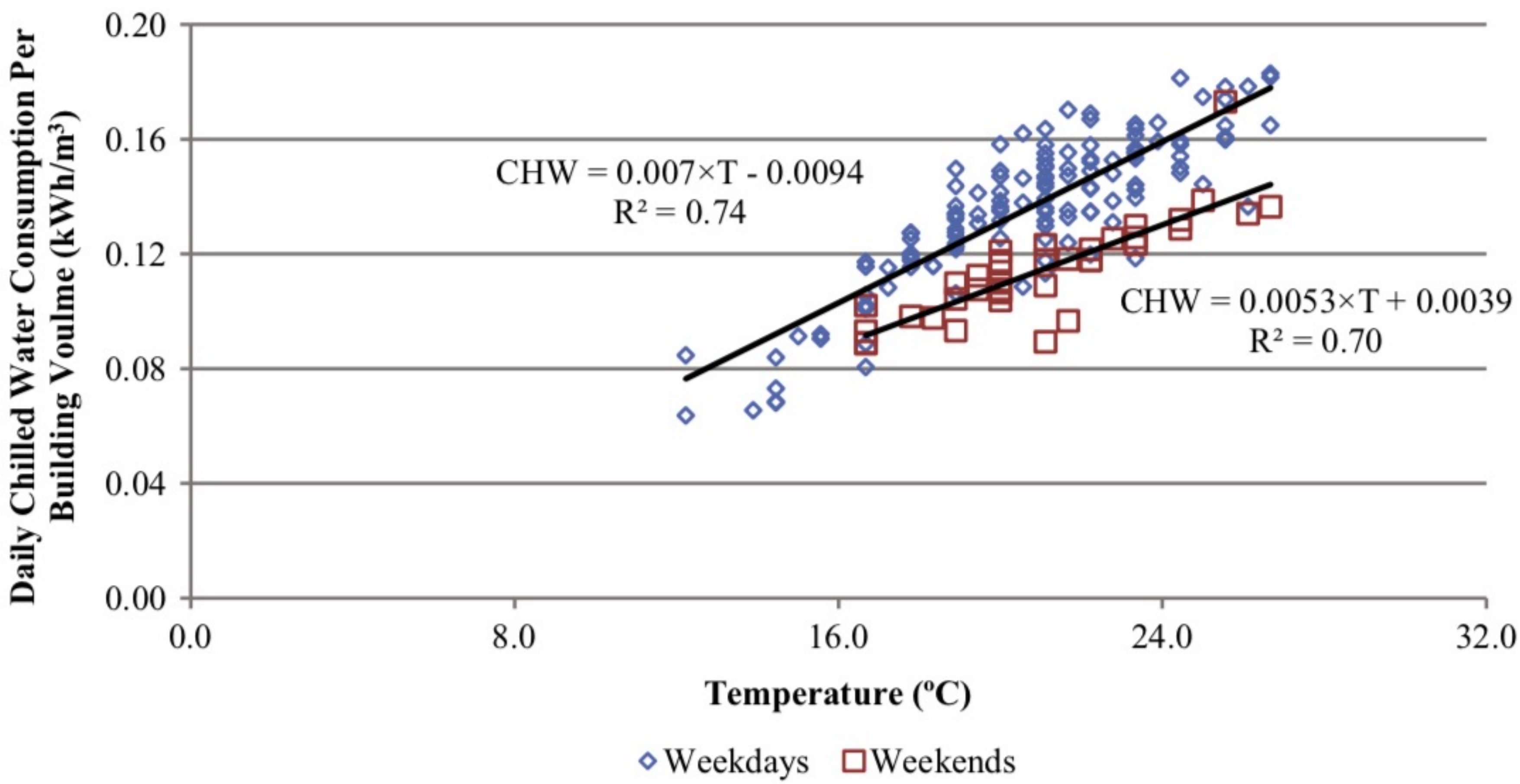
Normalization of Energy End-uses



Heidarinejad et al. 2017

Normalization of Energy End-uses

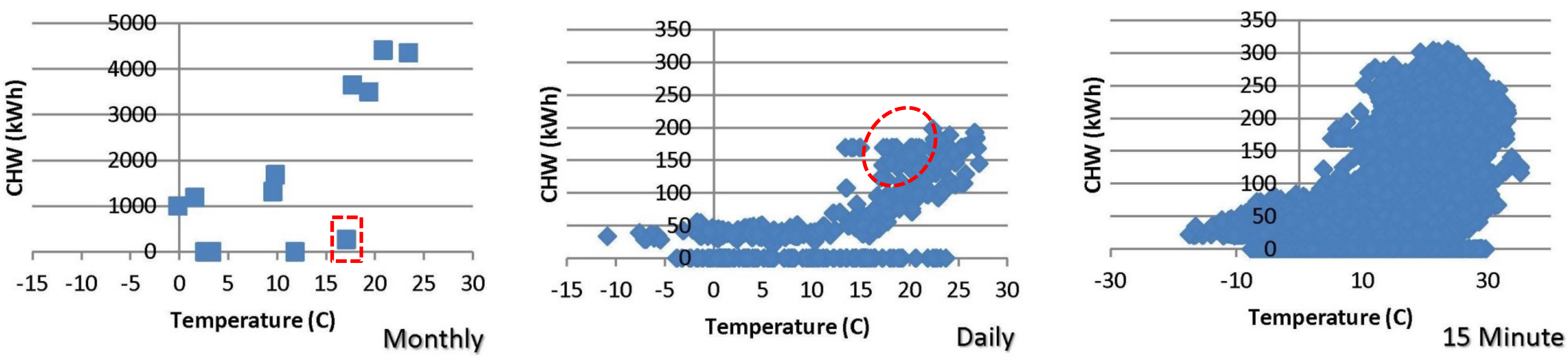
- Sometimes for the same building, the occupancy and operation can change the patterns.



Heidarinejad et al. 2017

Normalization of Energy End-uses

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



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

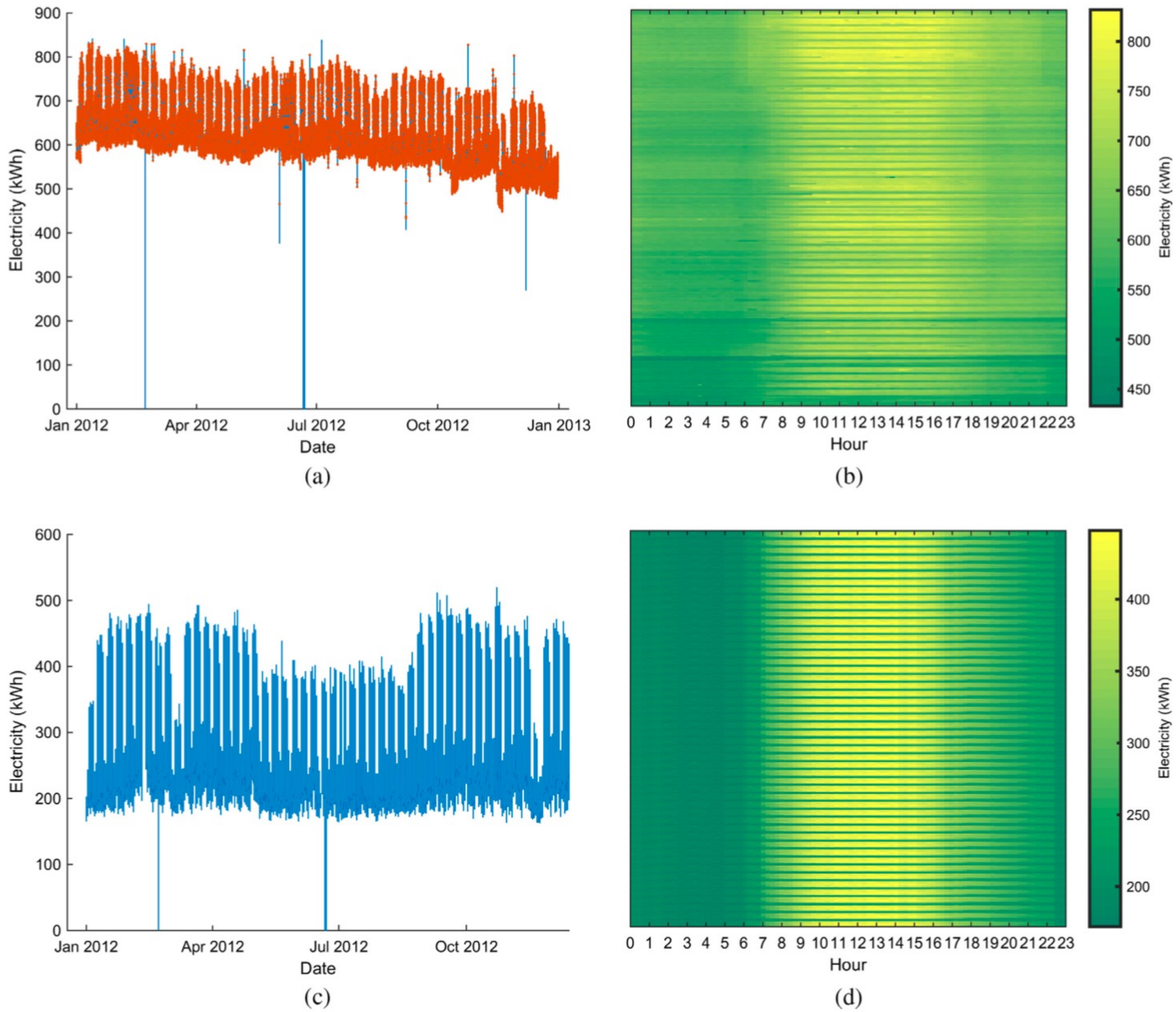
Heidarinejad et al. 2017

CLASS ACTIVITY

Class Activity

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

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

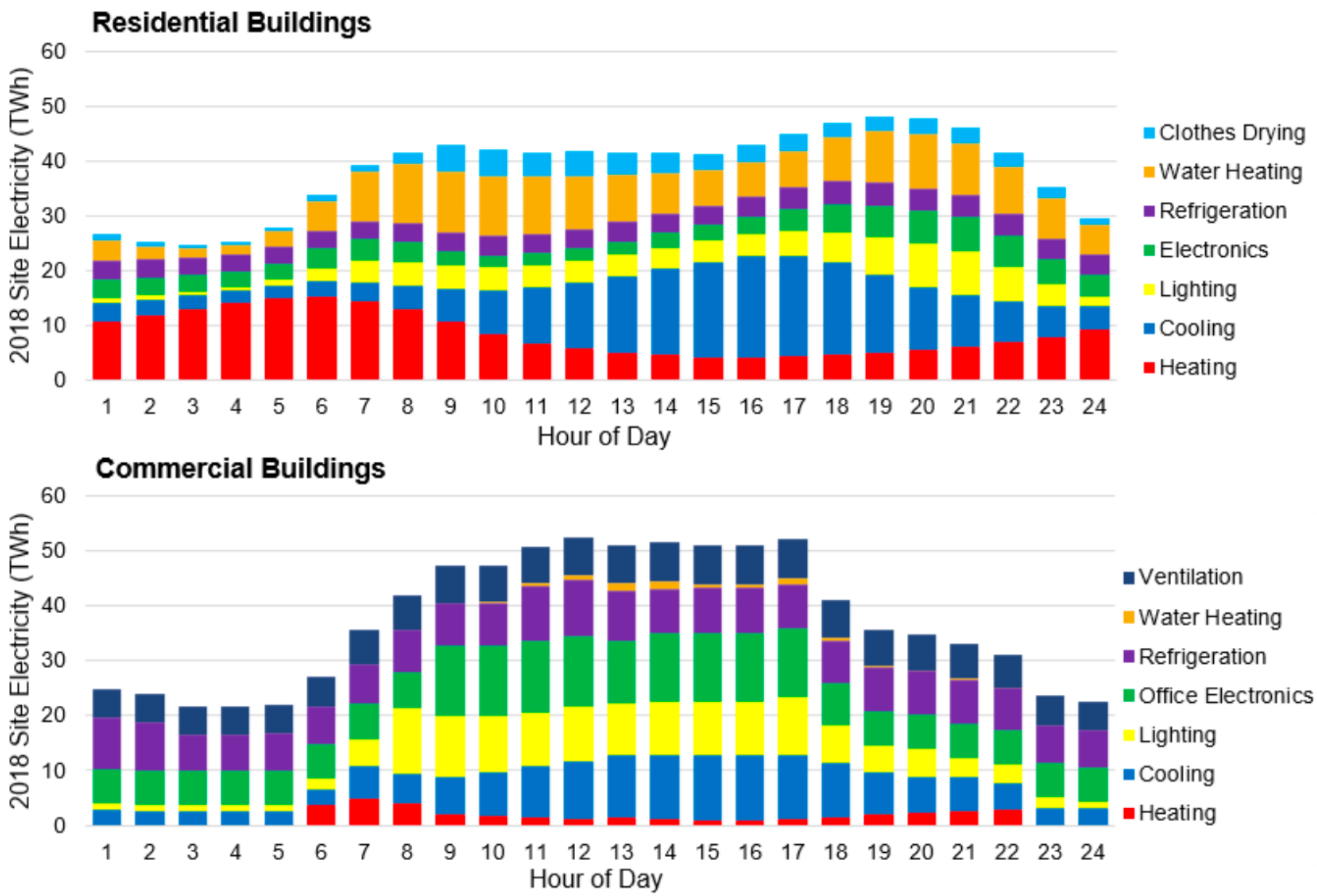
- Benefits:
  - Provide rapid normalization results
  - Provide accurate results for most of the situations

- 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

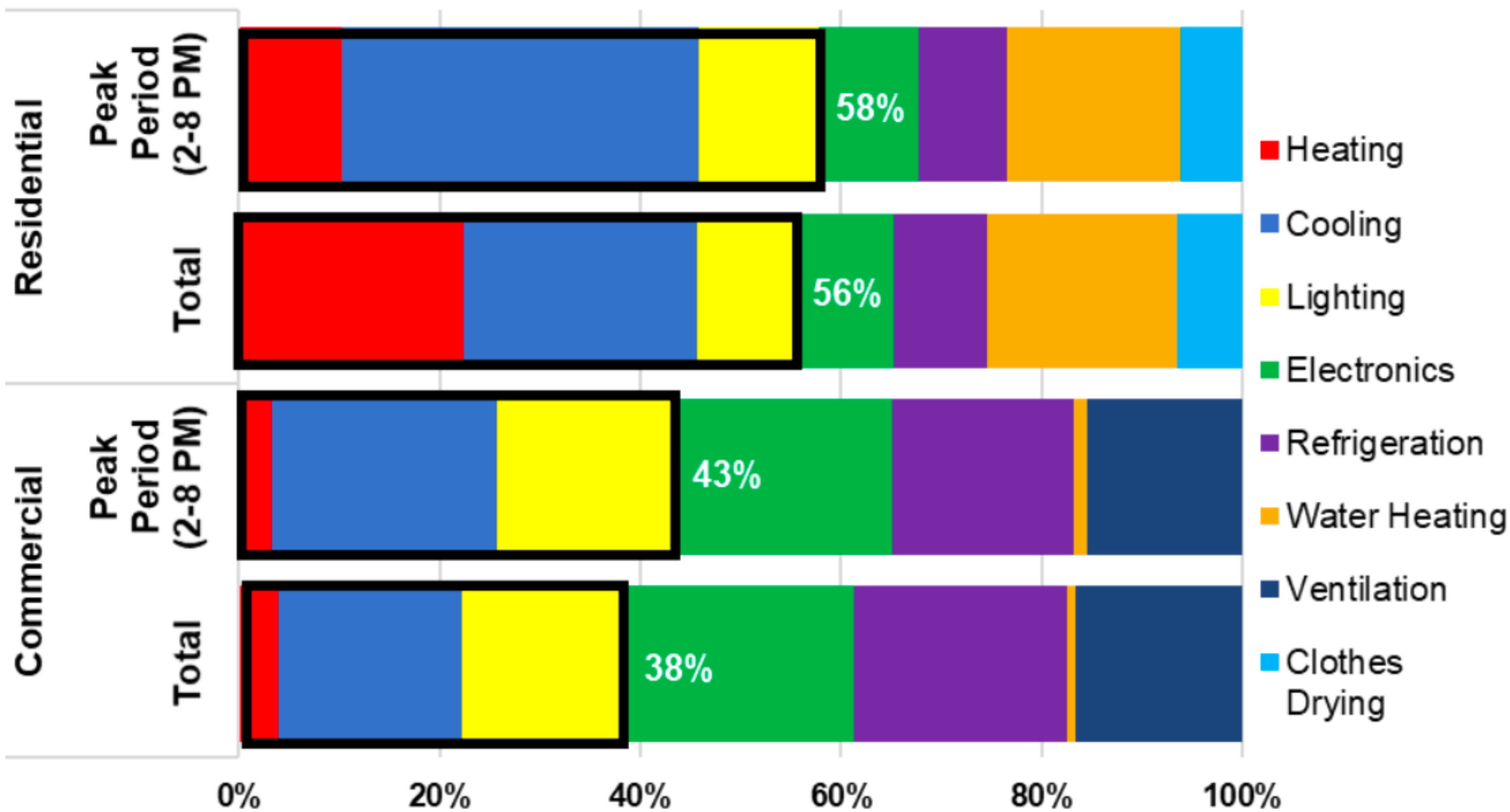
- Hourly electricity use in residential and commercial buildings in 2018:



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

Commercial/Residential Buildings

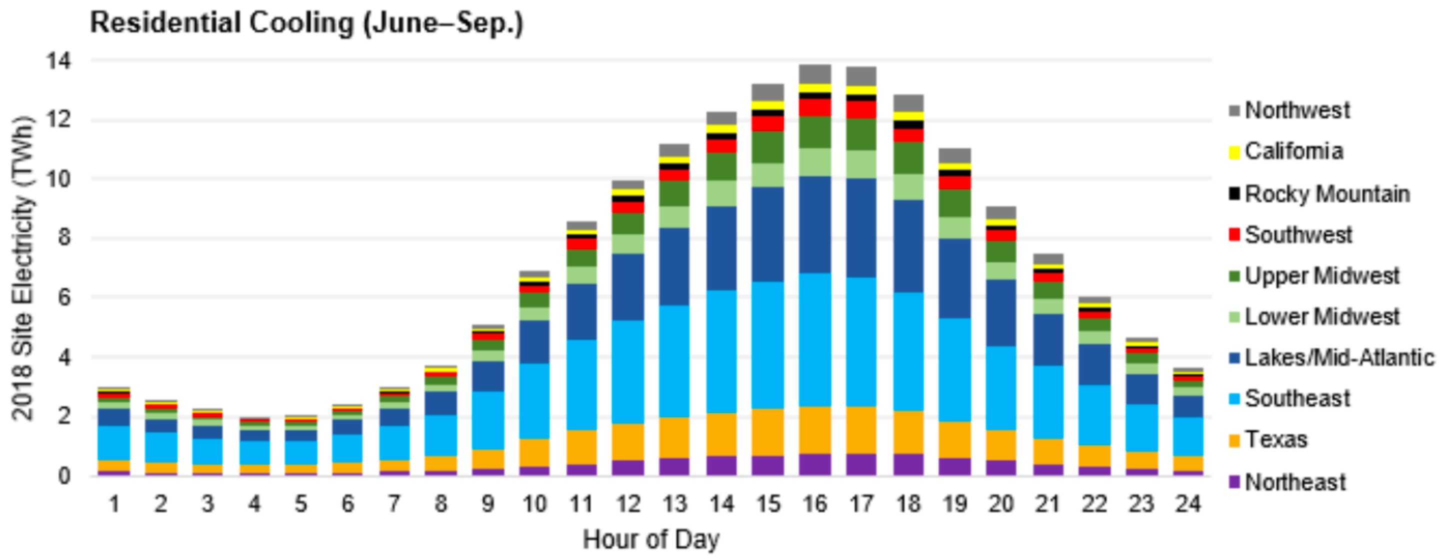
- Total and peak electricity end-uses in 2018:

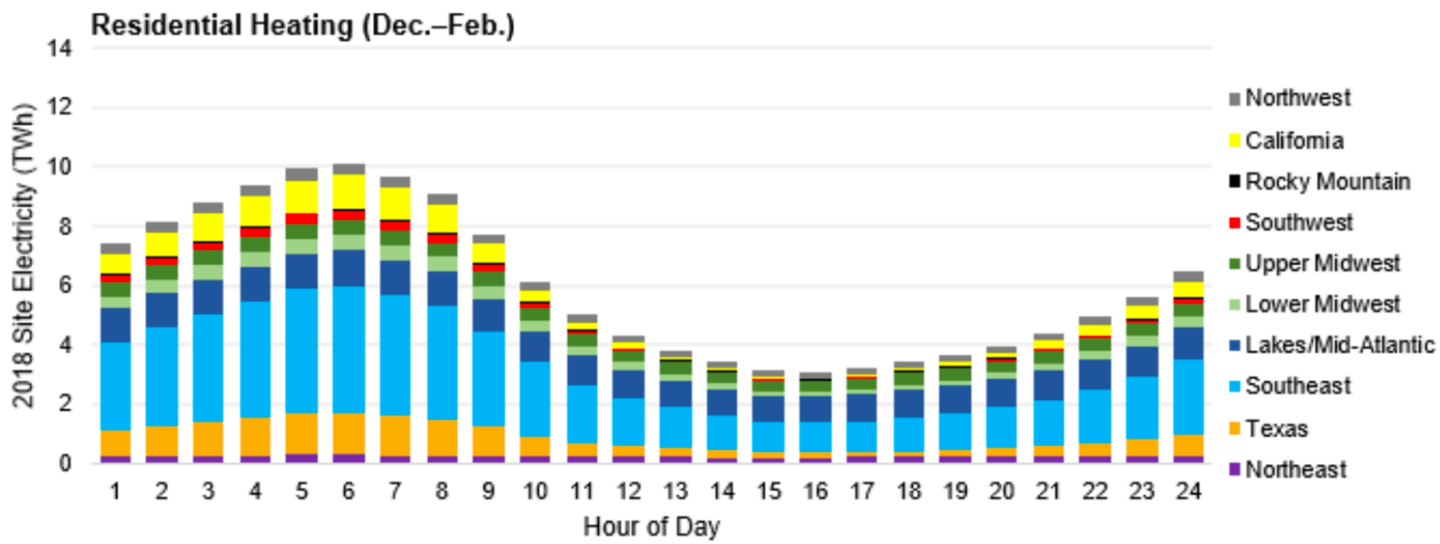


https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings

Commercial/Residential Buildings

- Residential cooling and heating hourly profile:



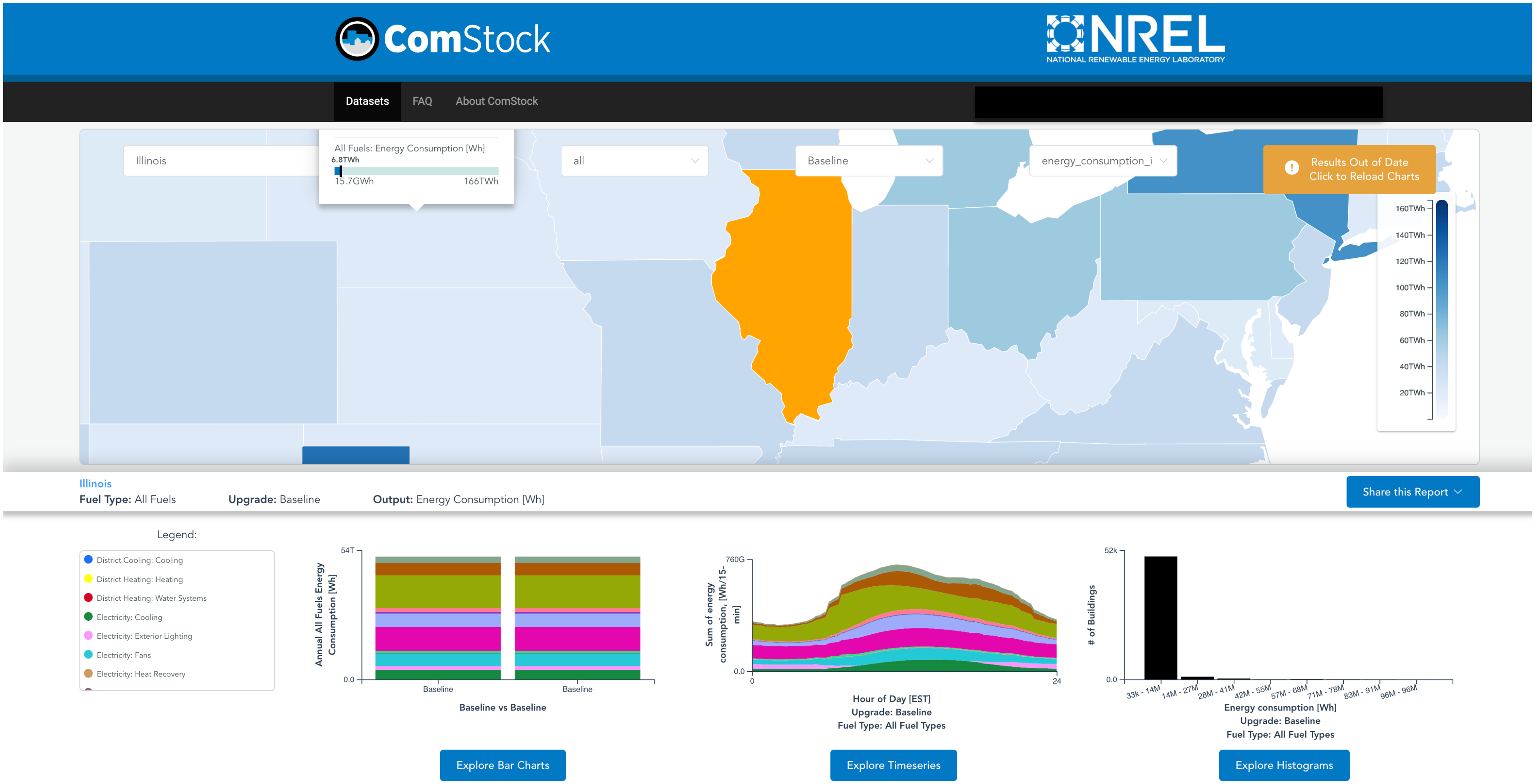


https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings

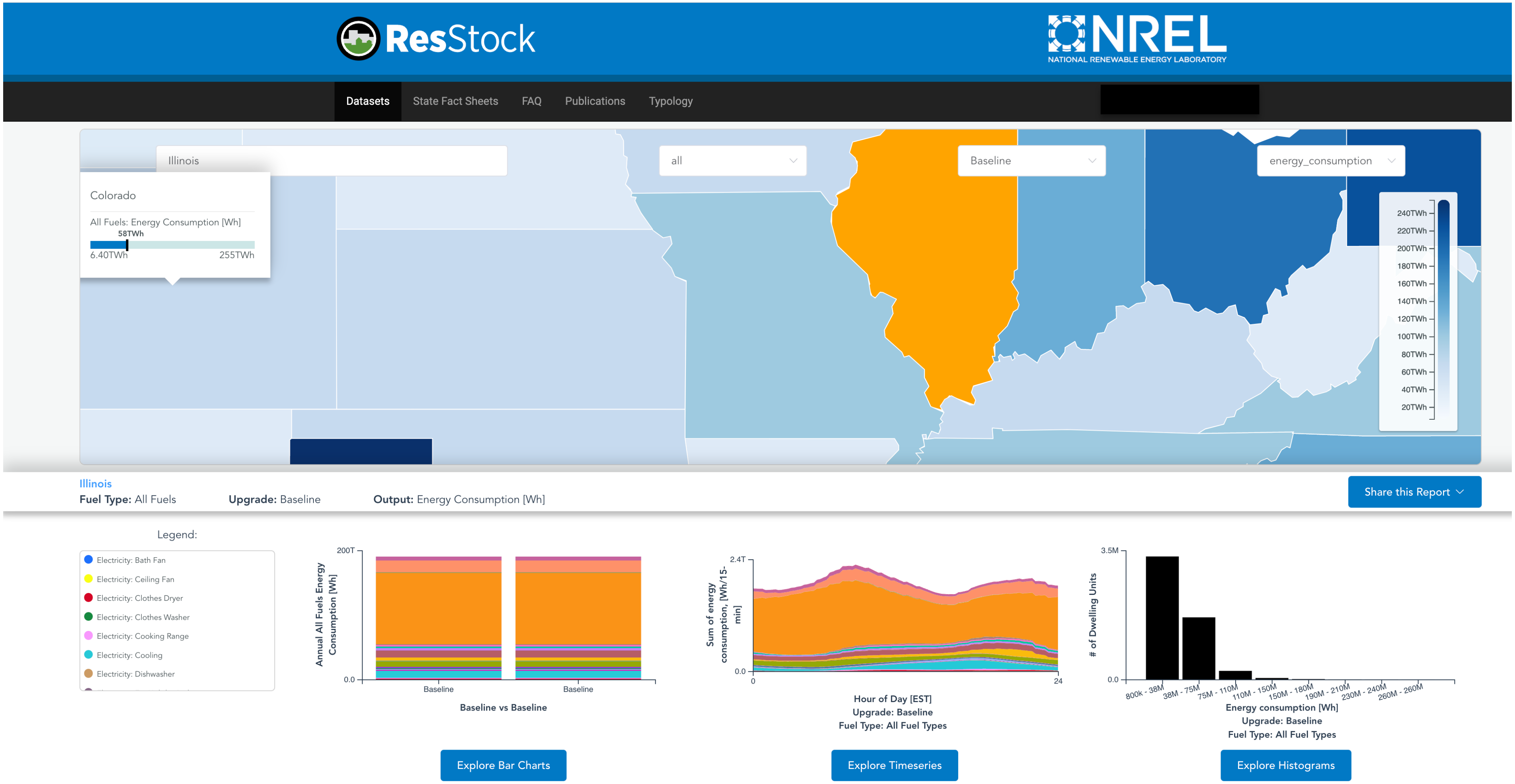
Commercial/Residential Buildings

- 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) 3328 (m^2)	116,948 (ft^2) 10,865 (m^2)	300 (ft^2) 28 (m^2)	6,143,038 (ft^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

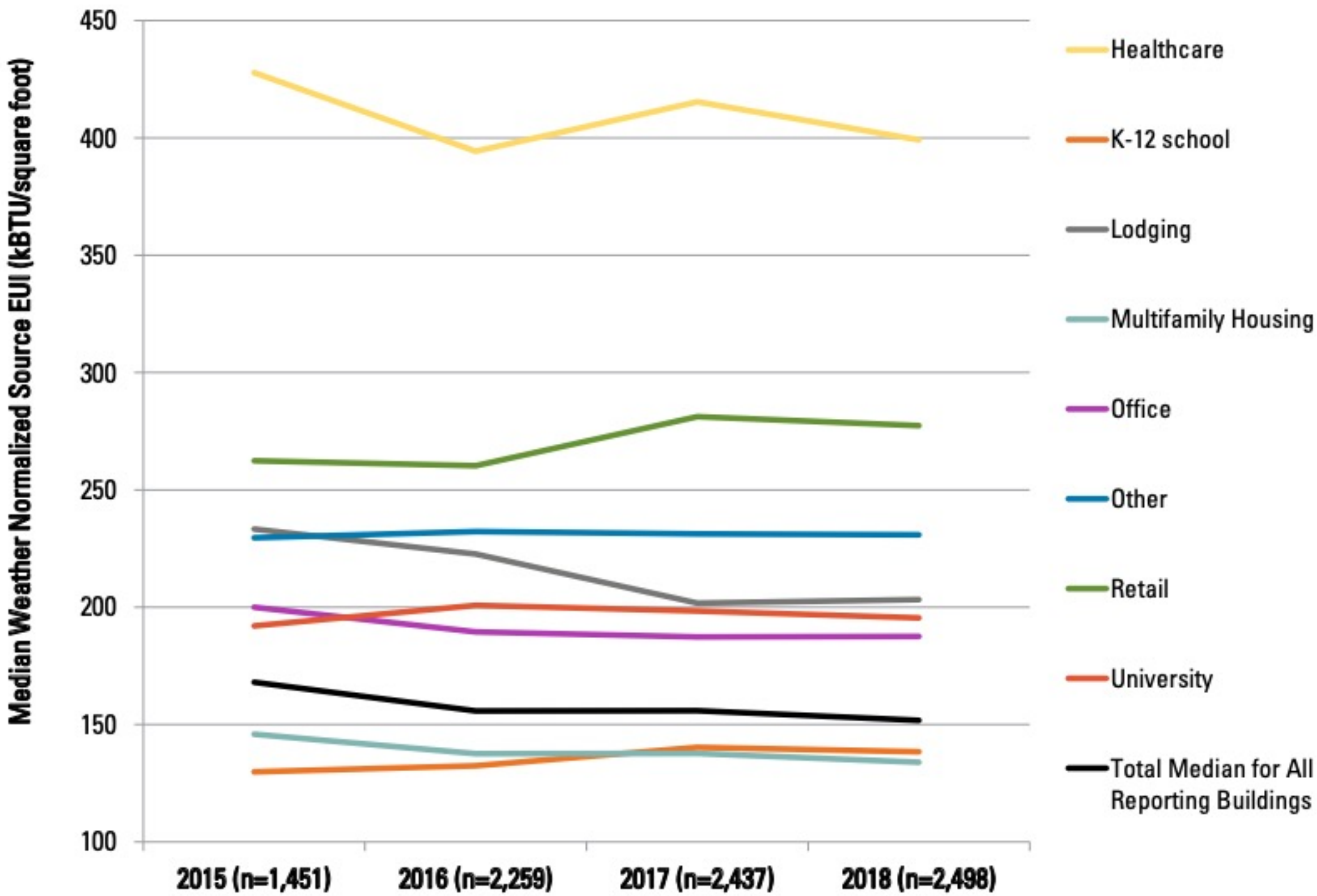
Summary statistics of building site EUI used in the model.

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

Abbasabdi et al. Applied Energy 2019

Commercial Buildings

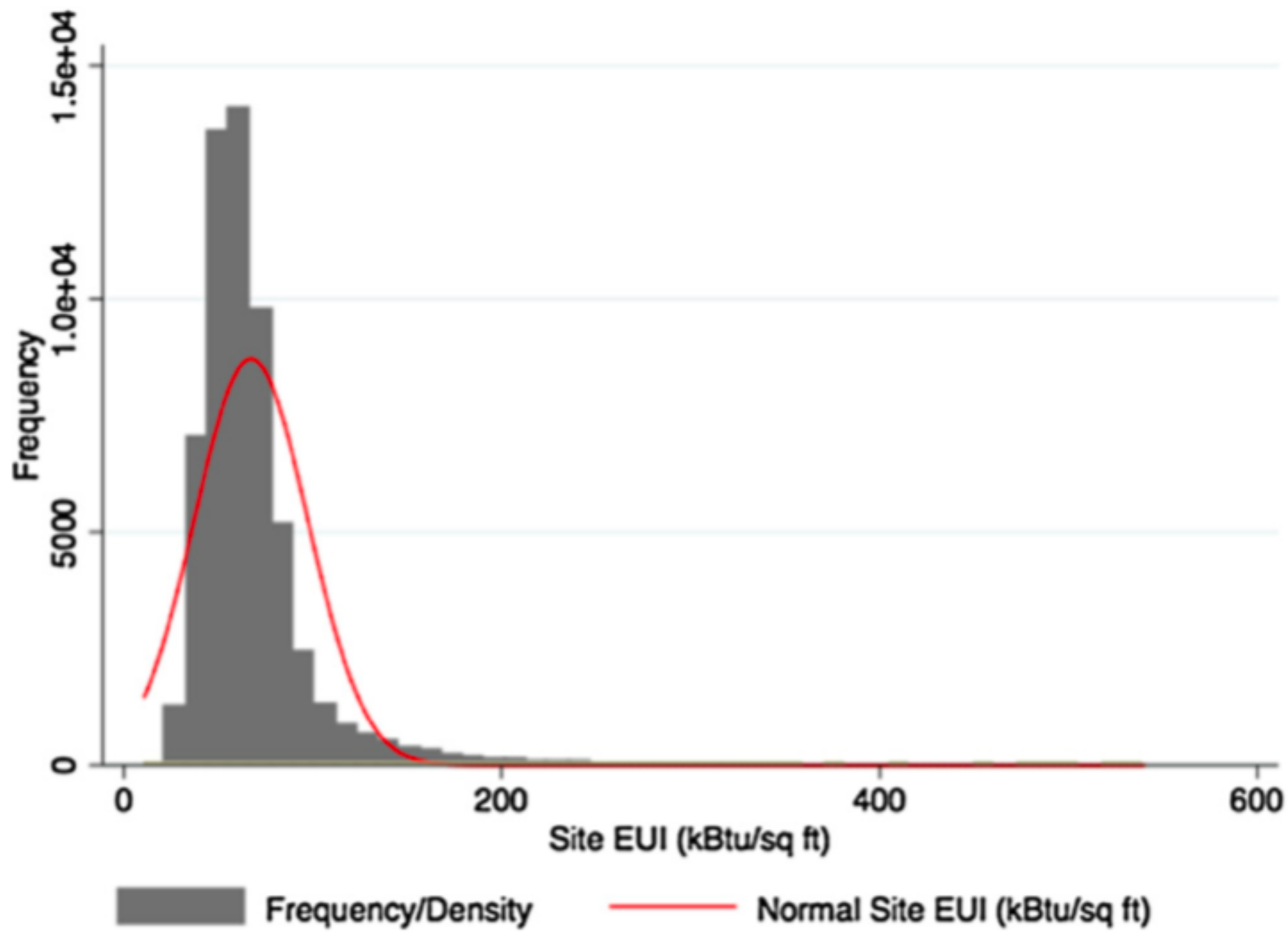
- City of Chicago Benchmarking



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

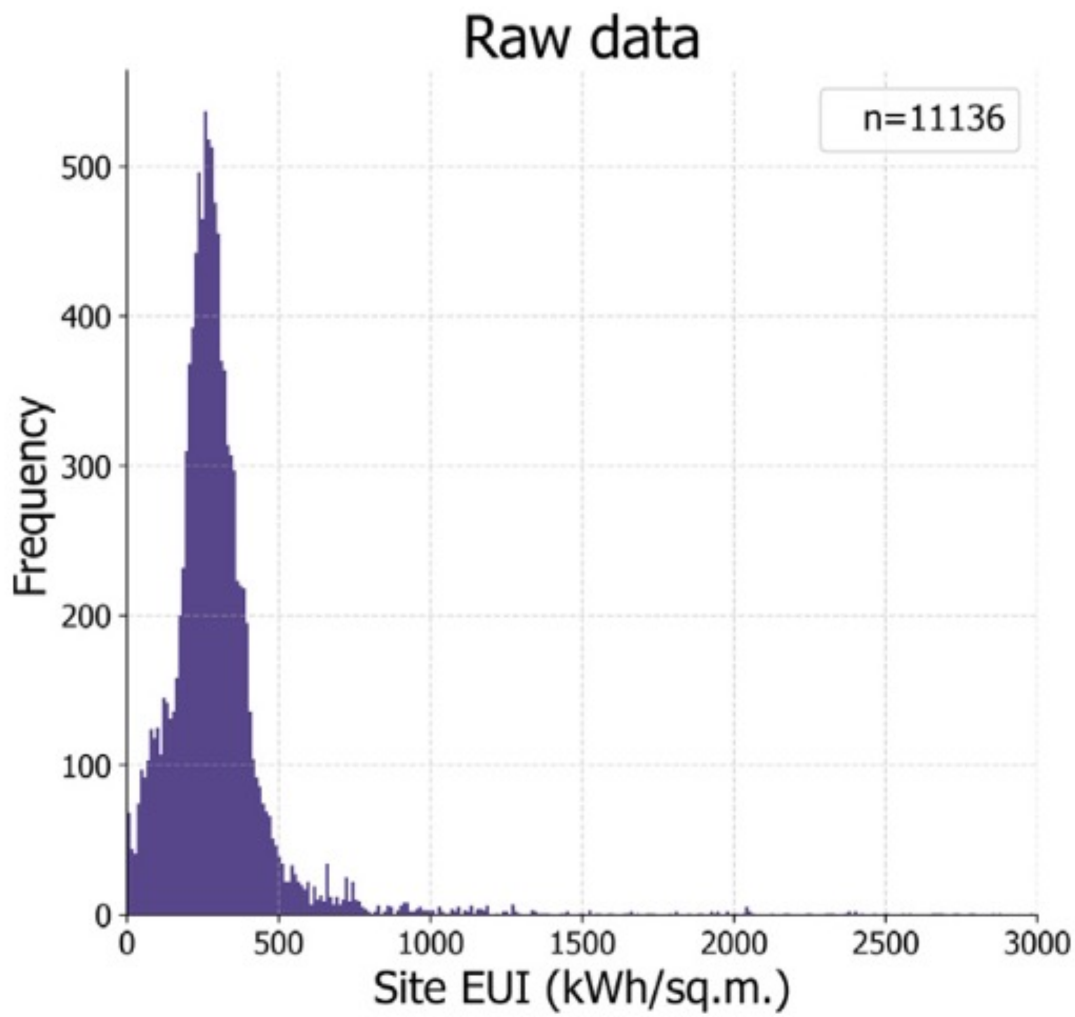
Commercial Buildings

- City of Chicago Benchmarking



Commercial Buildings

- New York City Benchmarking



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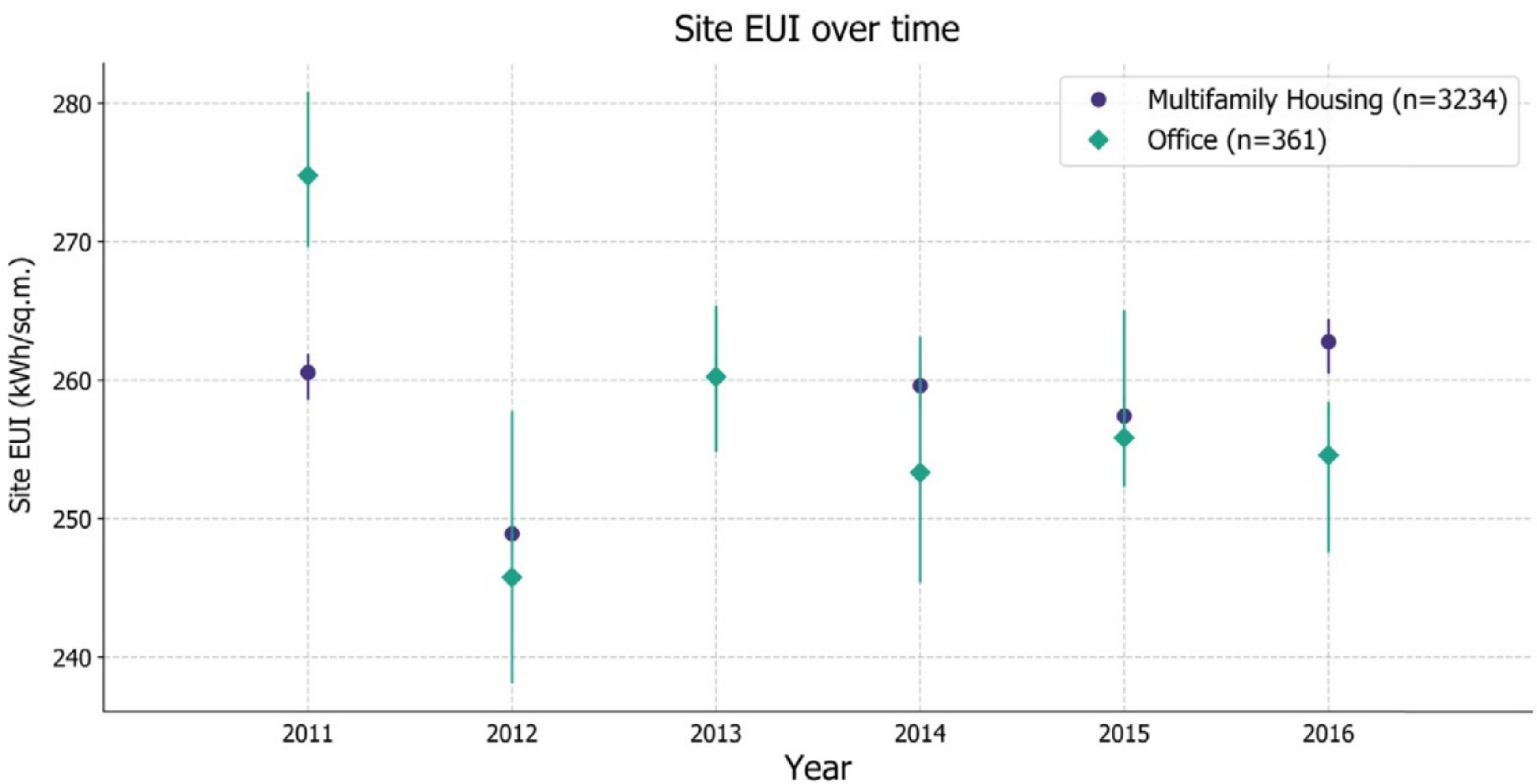
Commercial Buildings

- New York City Benchmarking



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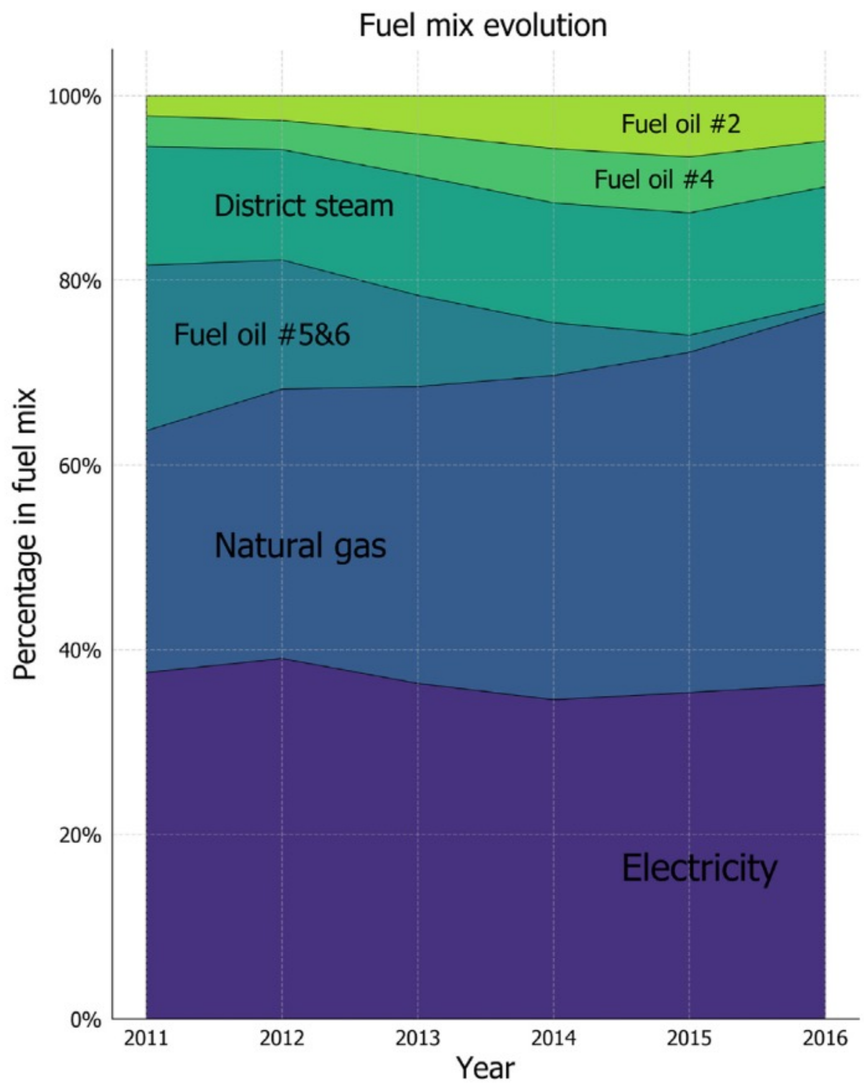
Commercial Buildings

- New York City Benchmarking



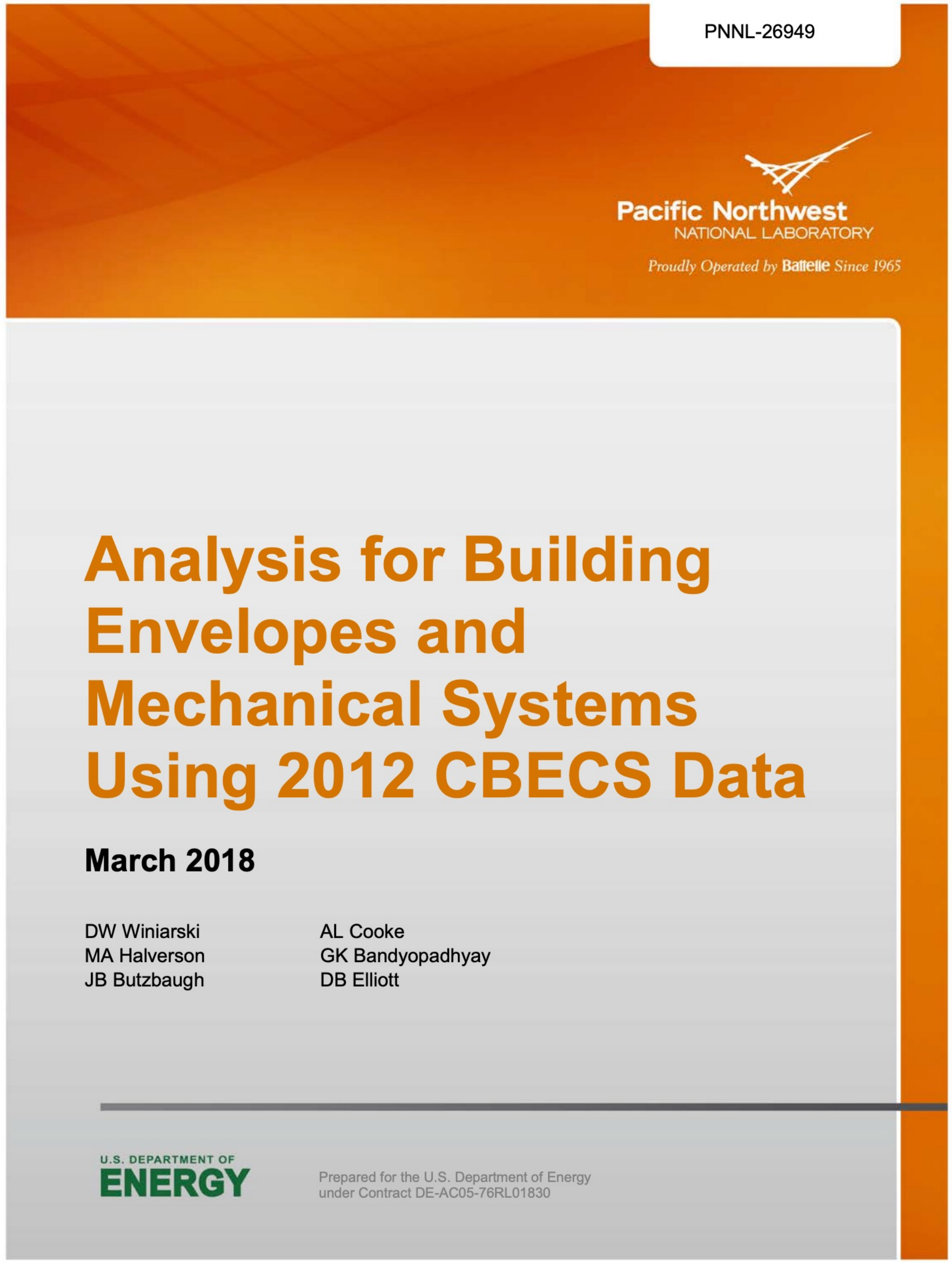
Popadopoulos et al. Applied Energy 2018

Commercial Buildings

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

Commercial Buildings


PNNL-26949

Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

Analysis for Building Envelopes and Mechanical Systems Using 2012 CBECS Data

March 2018

DW Winiarski
MA Halverson
JB Butzbaugh
AL Cooke
GK Bandyopadhyay
DB Elliott

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

WHOLE BUILDING ENERGY MODELING

Whole Building Energy Simulation

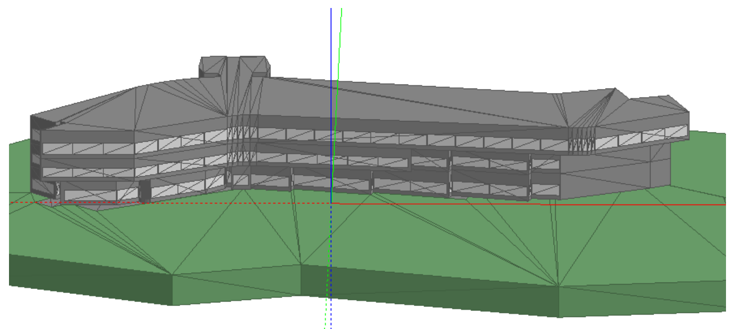
- Benefits:
  - Simulate accurate hourly simulation results with load calculations for each thermal zone
  - Enable modification of the energy model to predict future changes in the building
- Limitations:
  - Require an expert to create energy models
  - Require access to detailed mechanical drawings and detailed information to prepare the energy models
  - Require careful consideration for the campus buildings to meet the building energy use pattern

Whole Building Energy Simulation

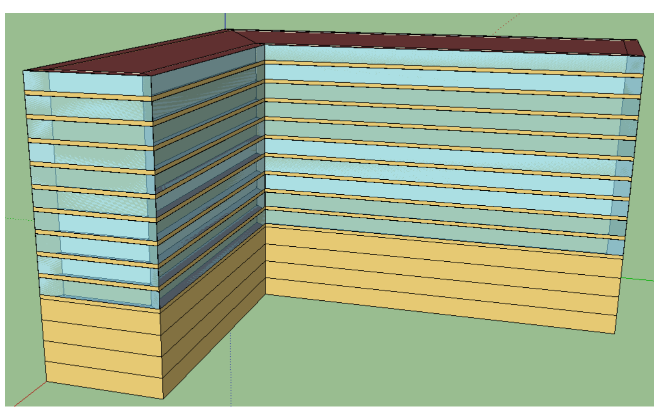
- Design requirements based on ASHRAE 90.1 requires a simulation software that is capable of
  - A minimum of 1400 hours per year
  - Hourly variations in occupancy, lighting power, miscellaneous equipment power, thermostat setpoints, and HVAC system operation, defined separately for each day of the week and holidays
  - Thermal mass effects
  - Ten or more thermal zones
  - Part-load performance curves for mechanical equipment Capacity and efficiency correction curves for mechanical heating and cooling equipment
    Air-side and water-side economizers with integrated control
    The budget building design characteristics specified in Section 11.4.5

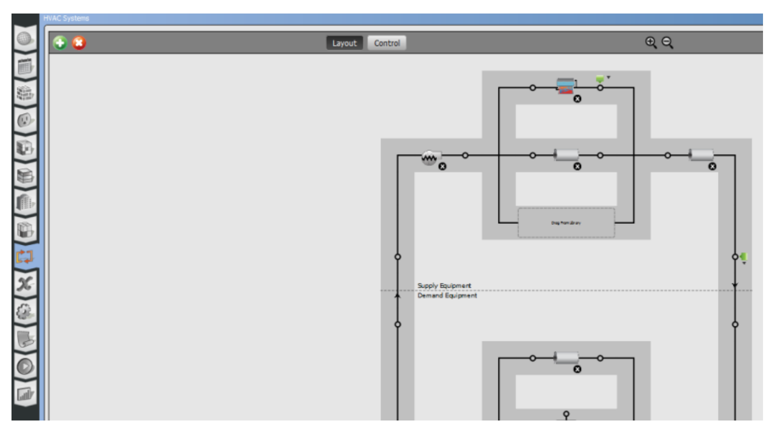
Whole Building Energy Simulation

- Examples of the energy simulation tools:
  - EnergyPlus (text-based energy simulation tools sponsored with DOE).
  - DesignBuilder (A commercial interface for EnergyPlus):



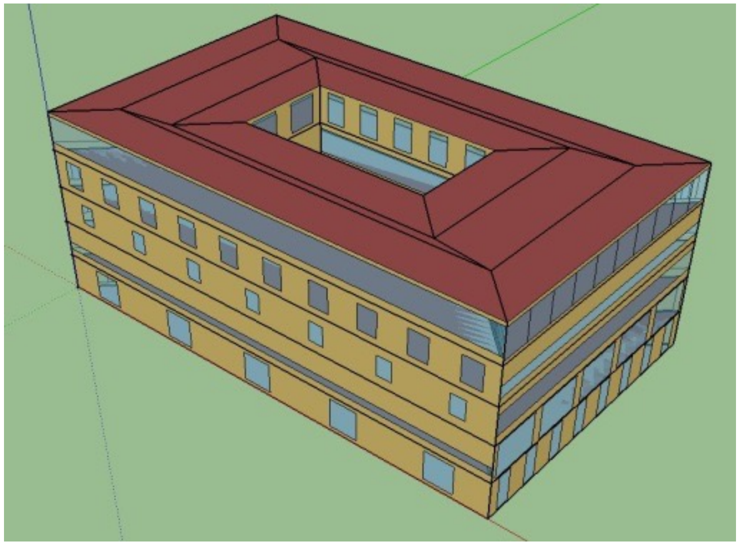
- OpenStudio (middleware of simulation tools including EnergyPlus):

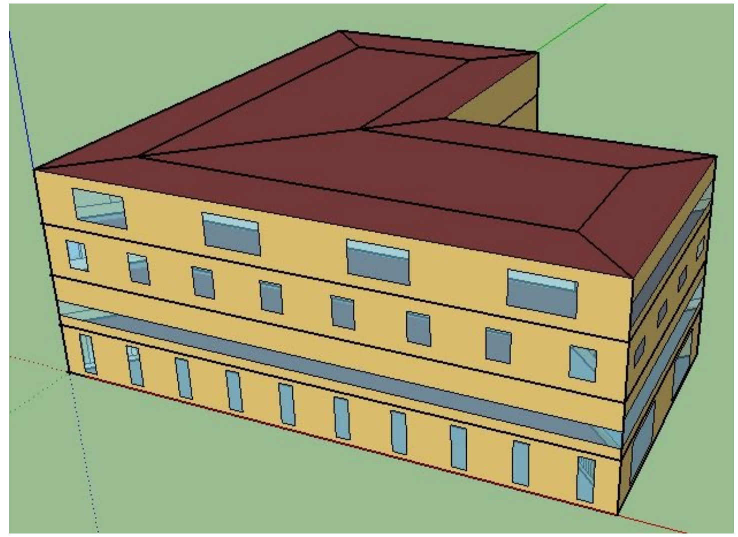


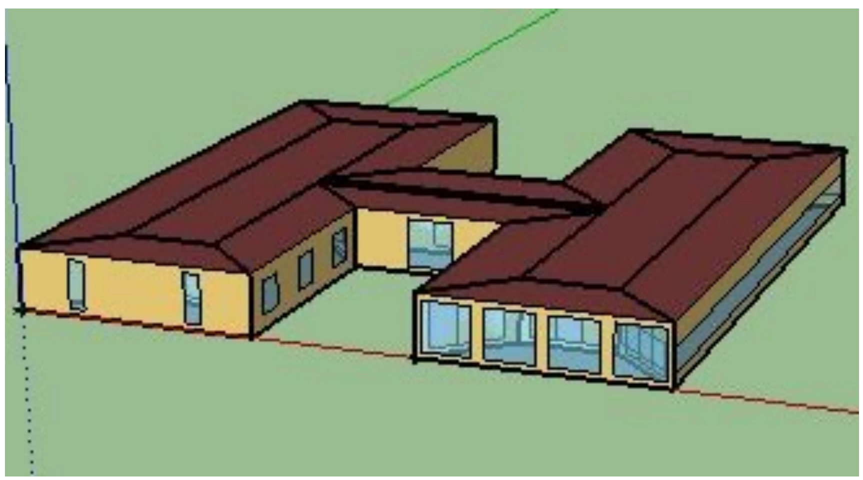


Whole Building Energy Simulation

- Complex building energy models





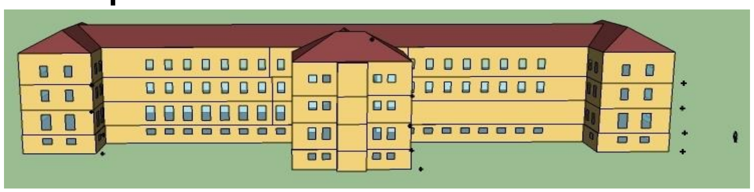


Heidarinejad et al. 2017

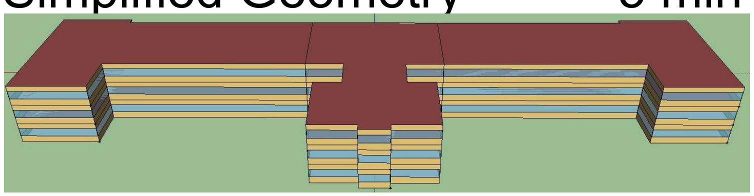
Whole Building Energy Simulation

Detailed 15 min

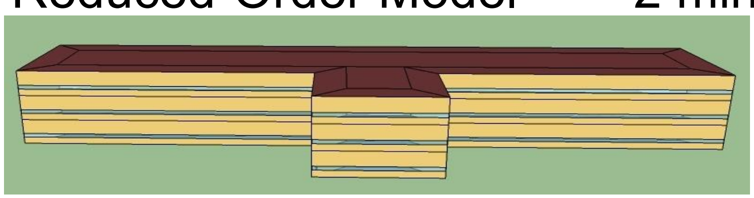
Simplified Thermal 7

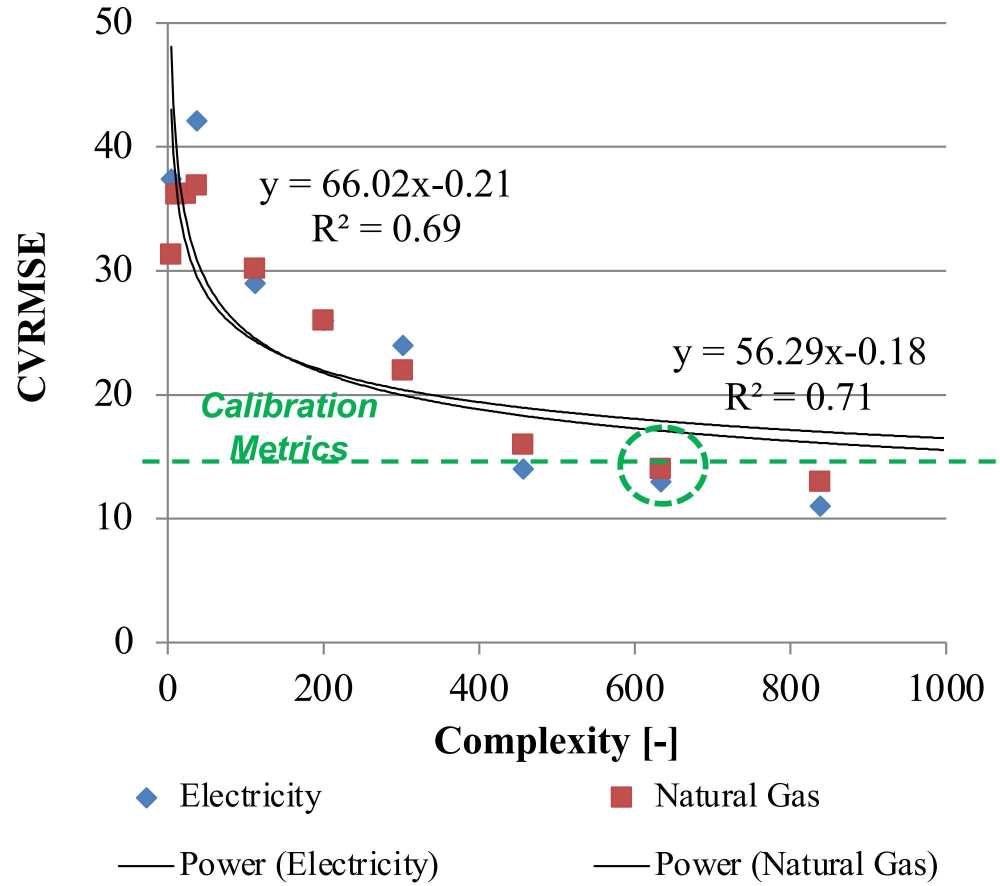


Simplified Geometry 5 min



Reduced-Order Model 2 min



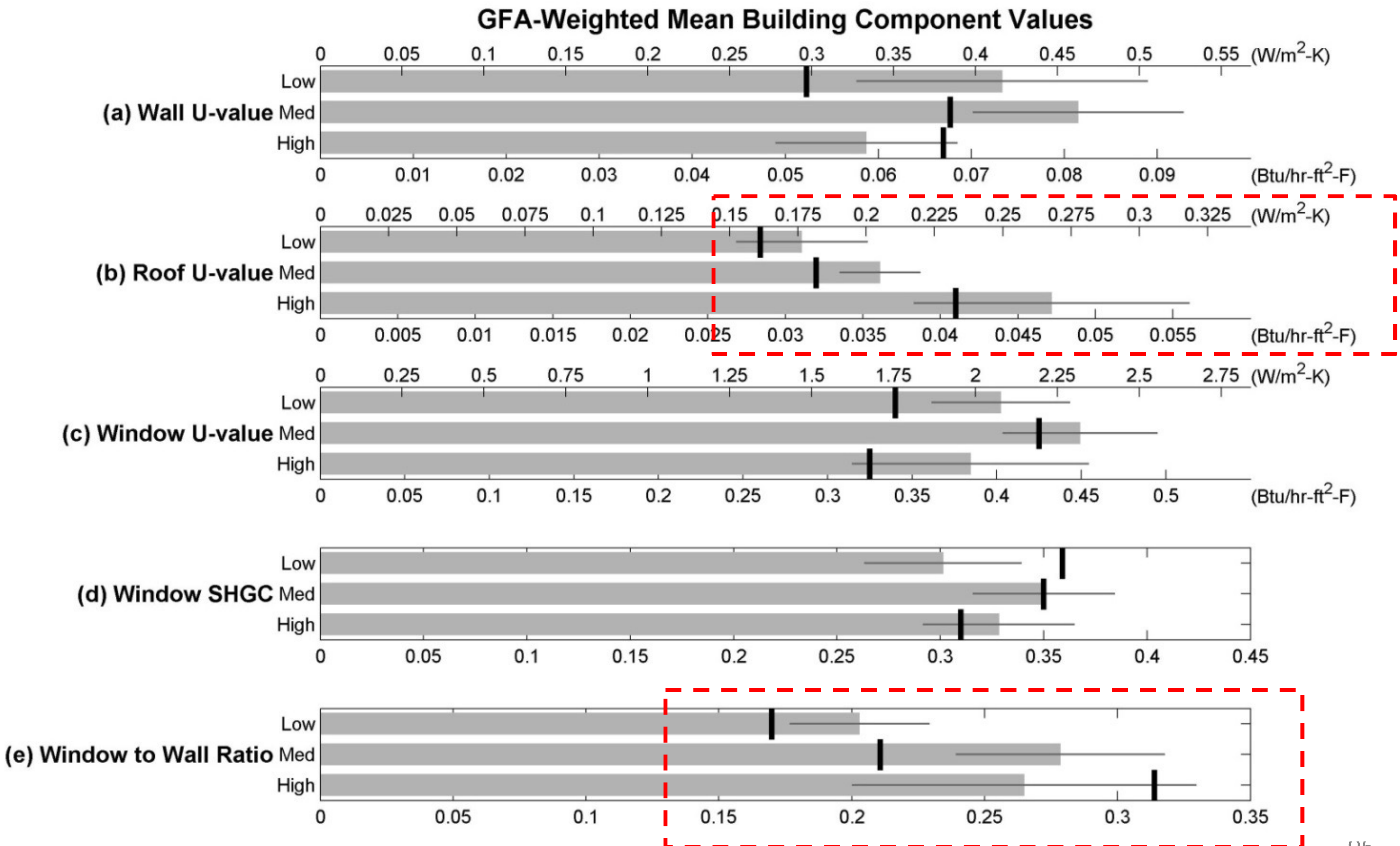


CVRSME = Coefficient of Variation Root Mean Square Error

Whole Building Energy Simulation

- Couple of key variables that are needed for a careful energy modeling:
  - **Internal loads & Operation schedules:** Most of the buildings are internally-load dominated or mixed-used buildings (e.g., lab-mixes or classroom/office)
  - **Occupancy:** Due to the mixed-used space type for a significant number of buildings, the occupancy patterns may not follow the typical occupancy schedules in the energy simulation tools
  - **HVAC system and associated inputs:** Because buildings may have different HVAC systems, it is important to have the correct HVAC system
  - **Building Enclosure:** It may require hand calculations before implementing the correct inputs into the energy models

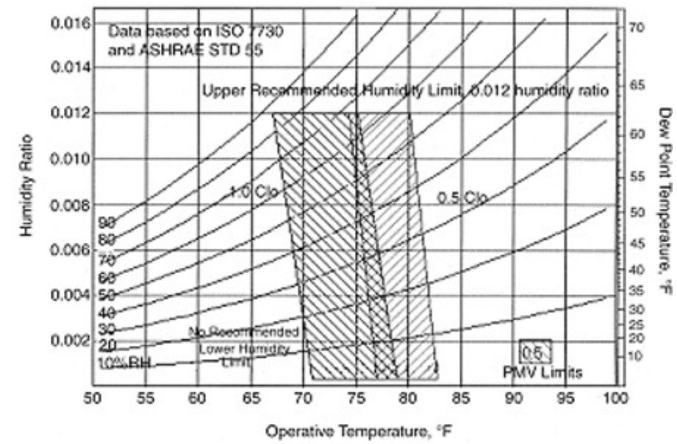
Whole Building Energy Simulation



Heidarinejad et al. 2014

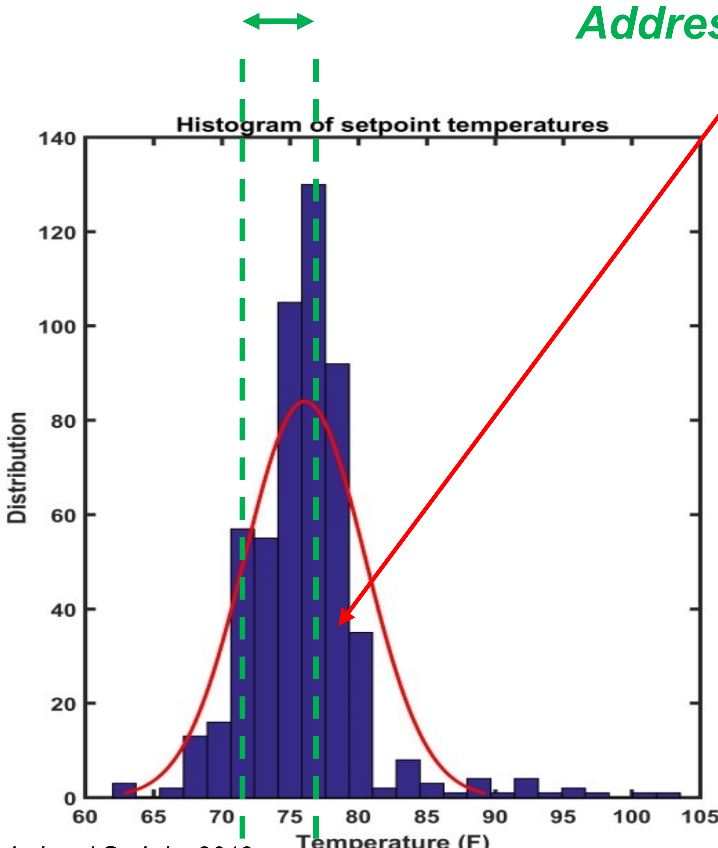
Whole Building Energy Simulation

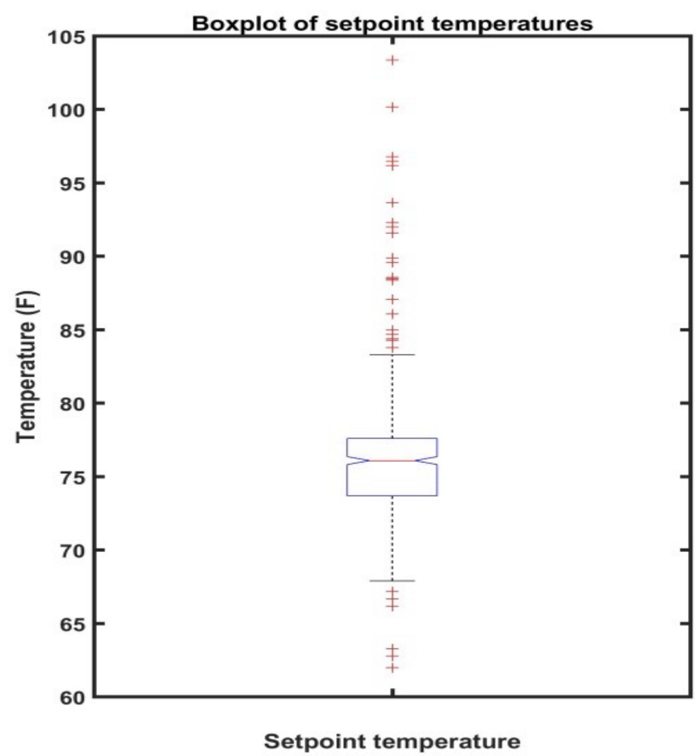
- Poor management of temperature setpoints in the buildings.



Thermal comfort range

Address complaints

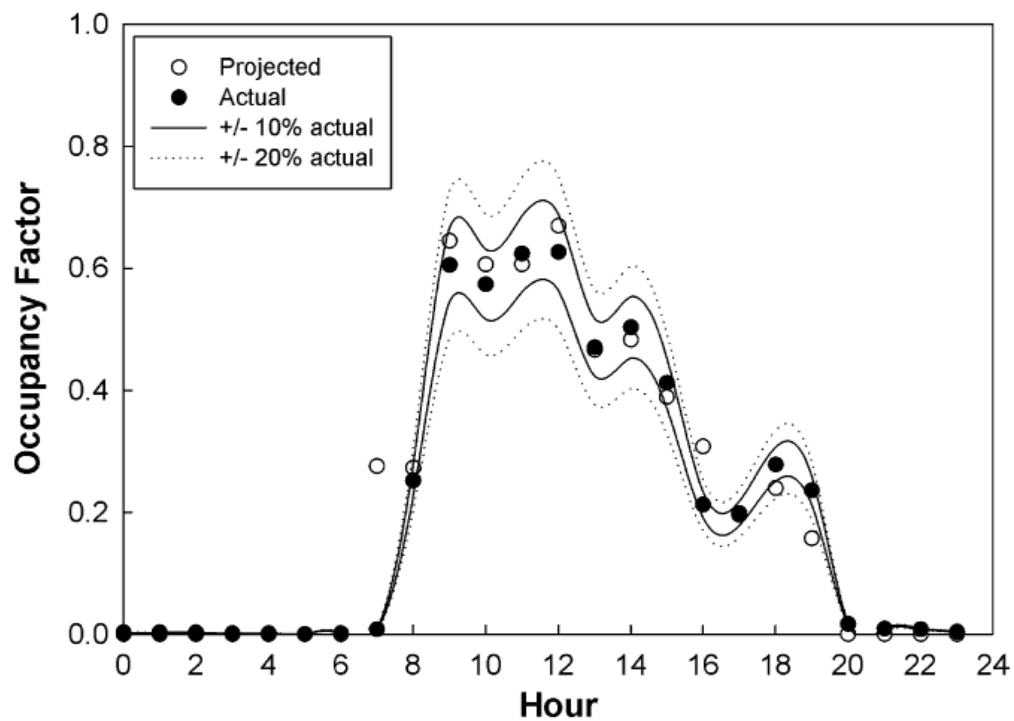




Heidarinejad and Srebric, 2019

Whole Building Energy Simulation

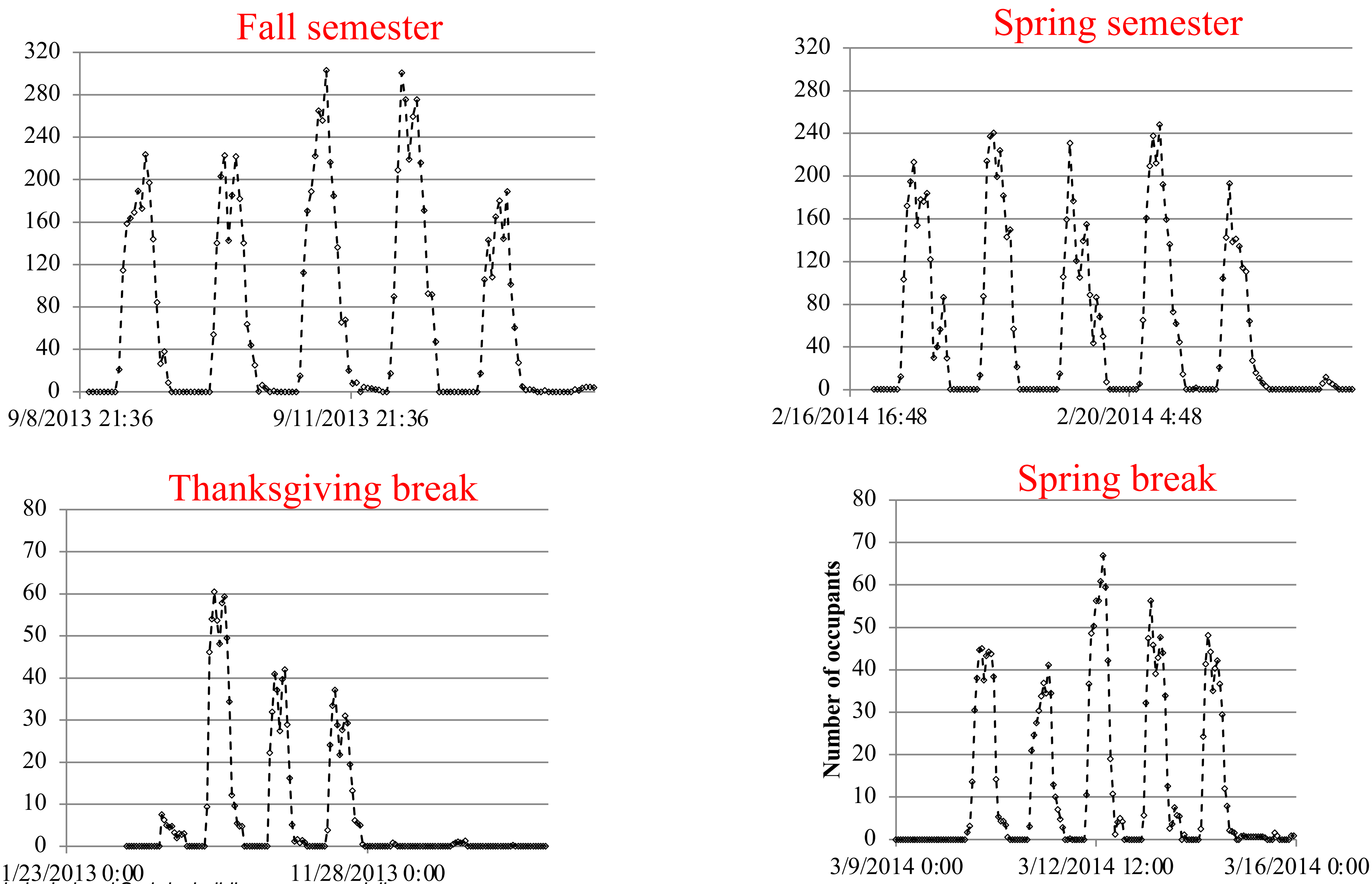
- Careful consideration for are needed to provide occupancy rate of the buildings:
  - Combination of different space types, rendering the campus buildings unique in terms of the occupancy rate
  - Does not follow the typical occupancy rates recommended in the energy simulation programs



Davis III, J.A. and Nutter D.W. 2010

Whole Building Energy Simulation

- From the Penn State's campus study:



Heidarinejad and Srebric, building energy modeling

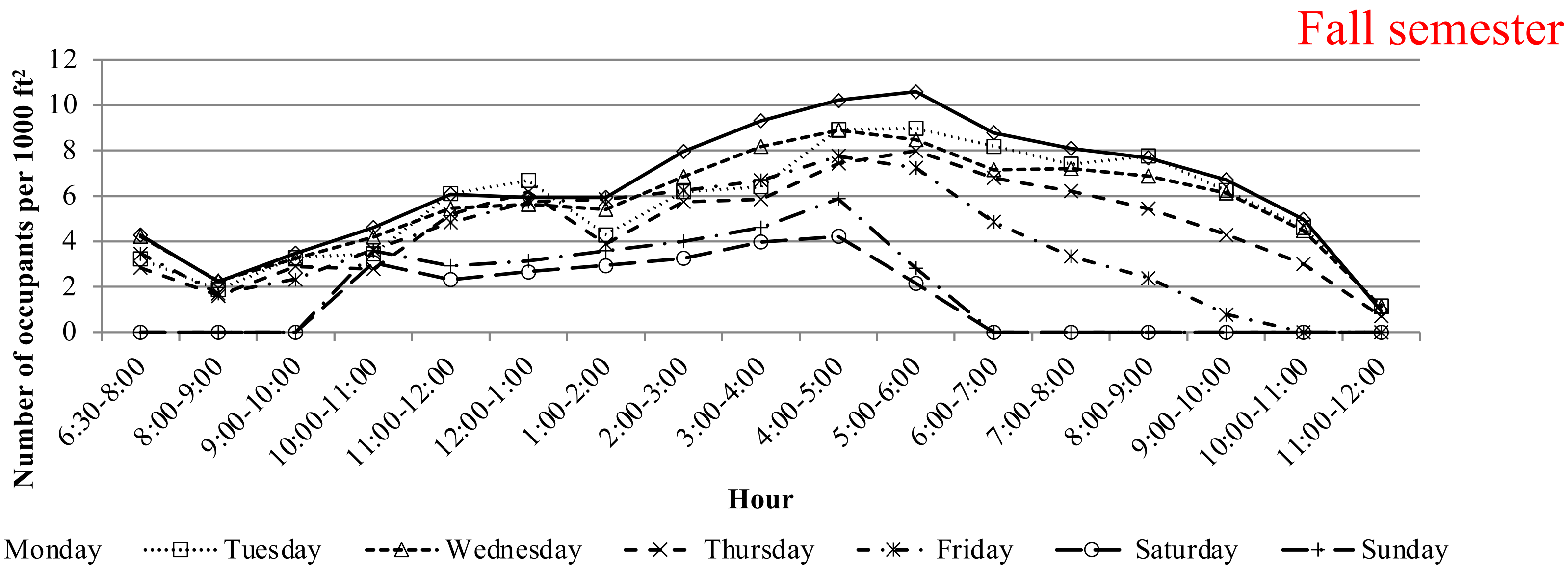
Whole Building Energy Simulation

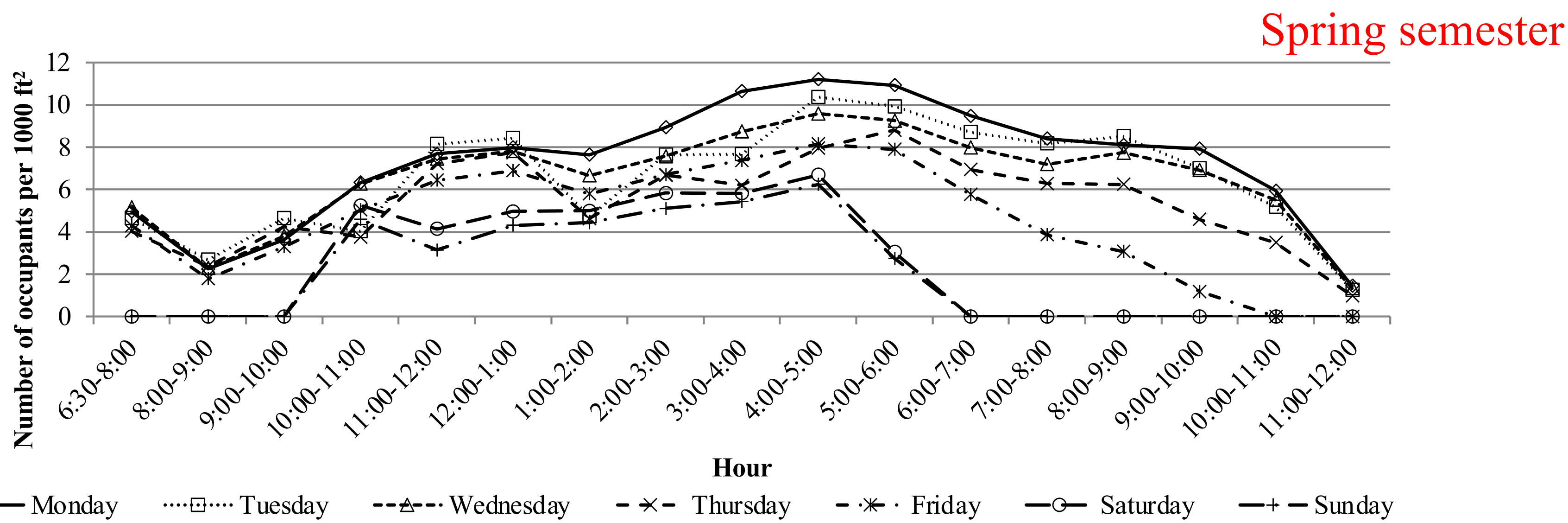
- Beyond installation of fairly expensive occupancy sensors at the entrance and exit of buildings is to benefit from the existing infrastructures at the buildings:

  - Appliance using WiFi or desktop computers connect to the network through their IP address
  - Swipe access card readers for a building or space
  - Class schedules and FTE operation hours
  - CO_2 sensors for the demand control systems

Whole Building Energy Simulation

- From the Penn State's campus study:

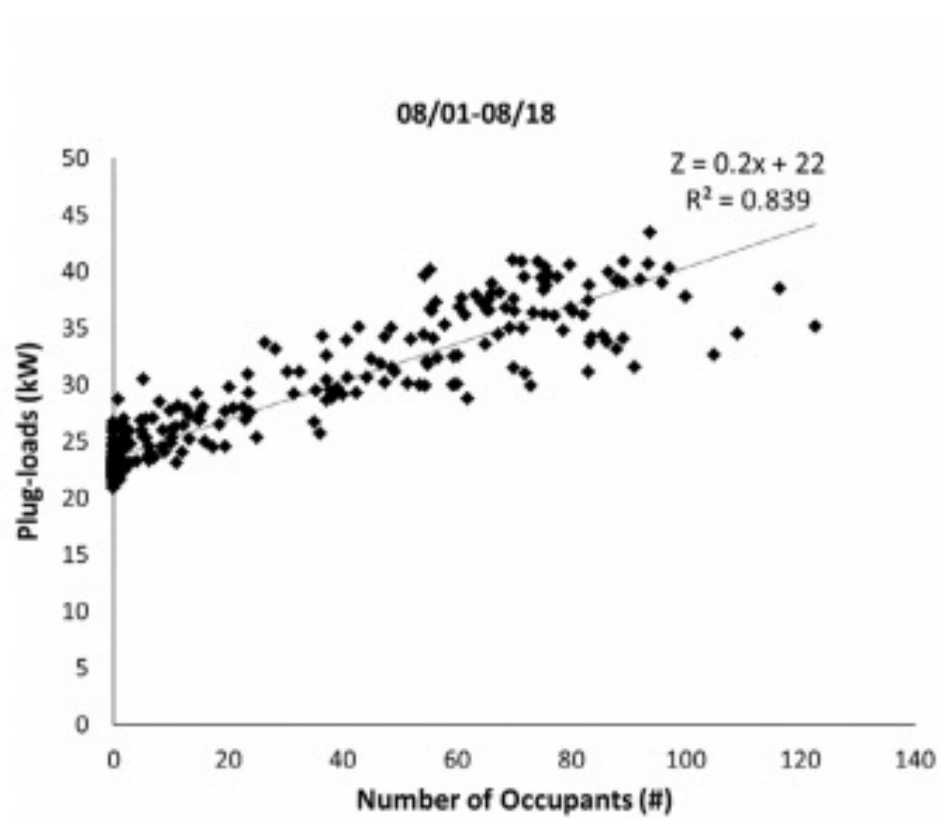


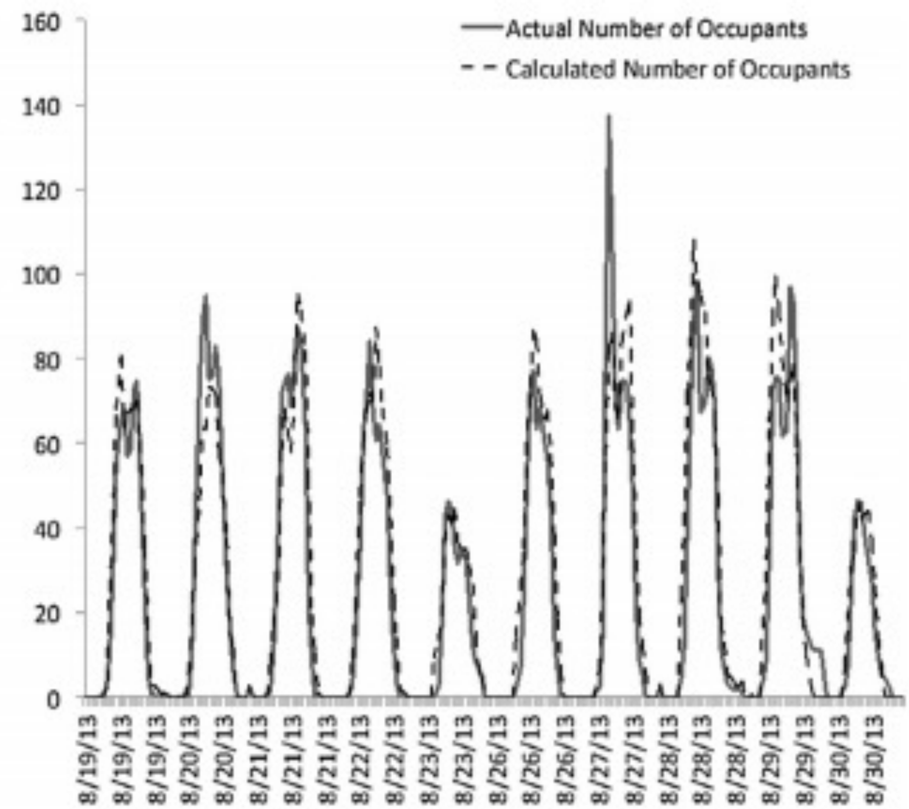


Heidarinejad and Srebric, building energy modeling

Whole Building Energy Simulation

- Plug load and electricity is linearly correlated with the building occupancy



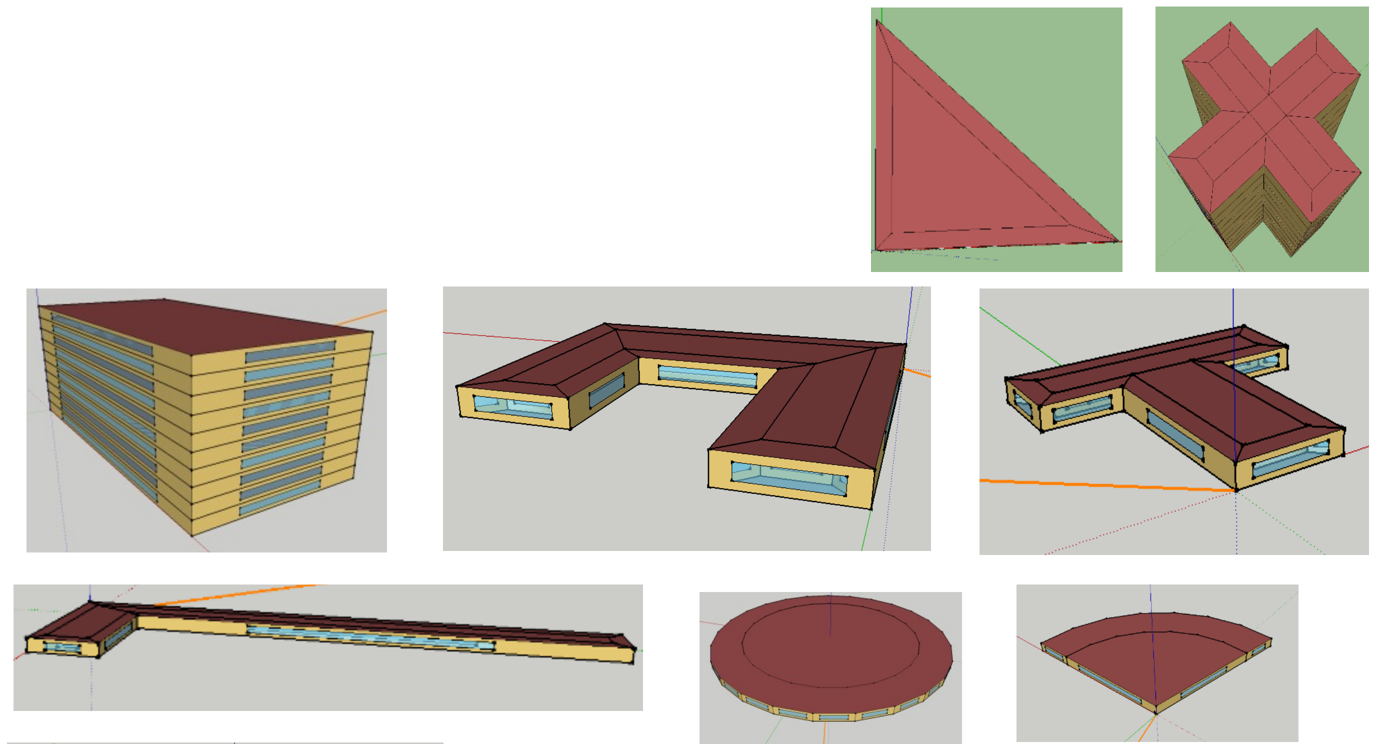


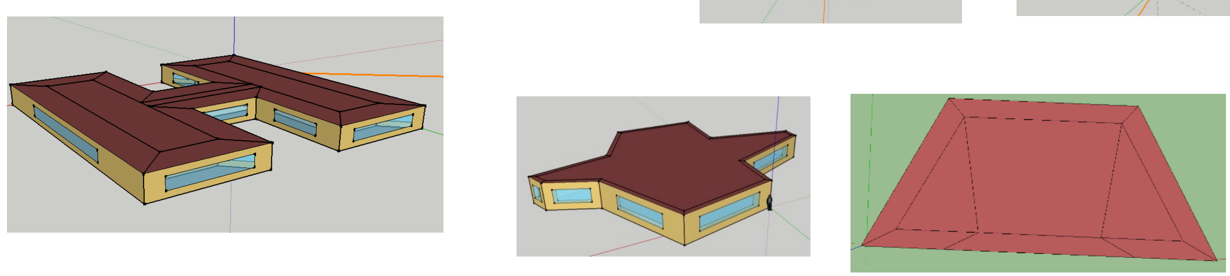
Kim et al. 2017

BUILDING SHAPES

Building Shapes

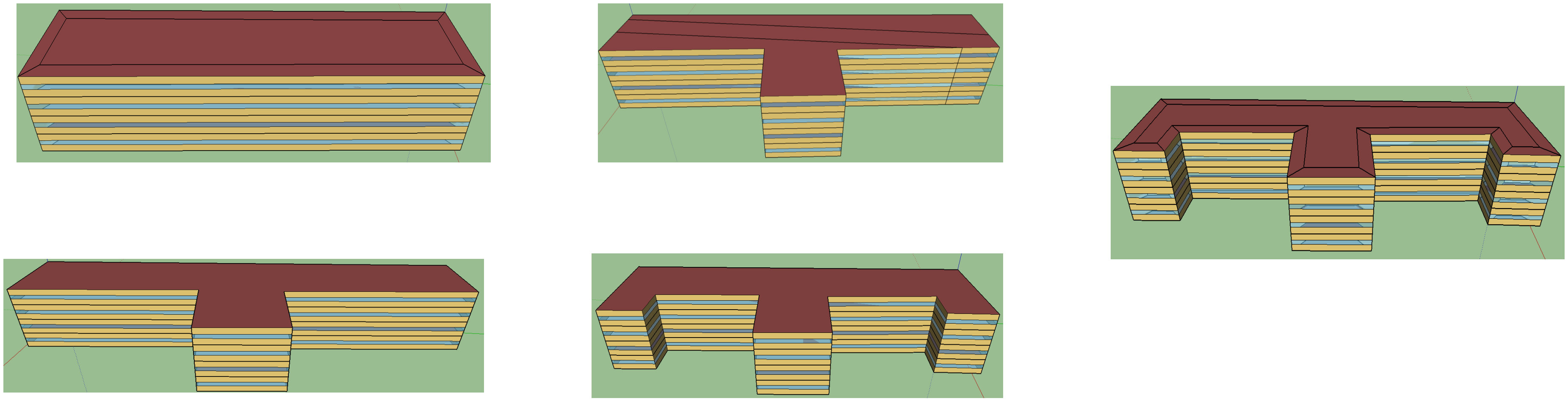
- Building geometry is an important part of the building energy modeling that may take a large portion of the building energy modeler's time. Typical building shapes are:
  - Courtyard
  - Cross
  - Pie
  - Convex polygon
  - Rectangle
  - Trapezoid
  - Triangle
  - Square cutout
  - H
  - L
  - S
  - T
  - U
  - M

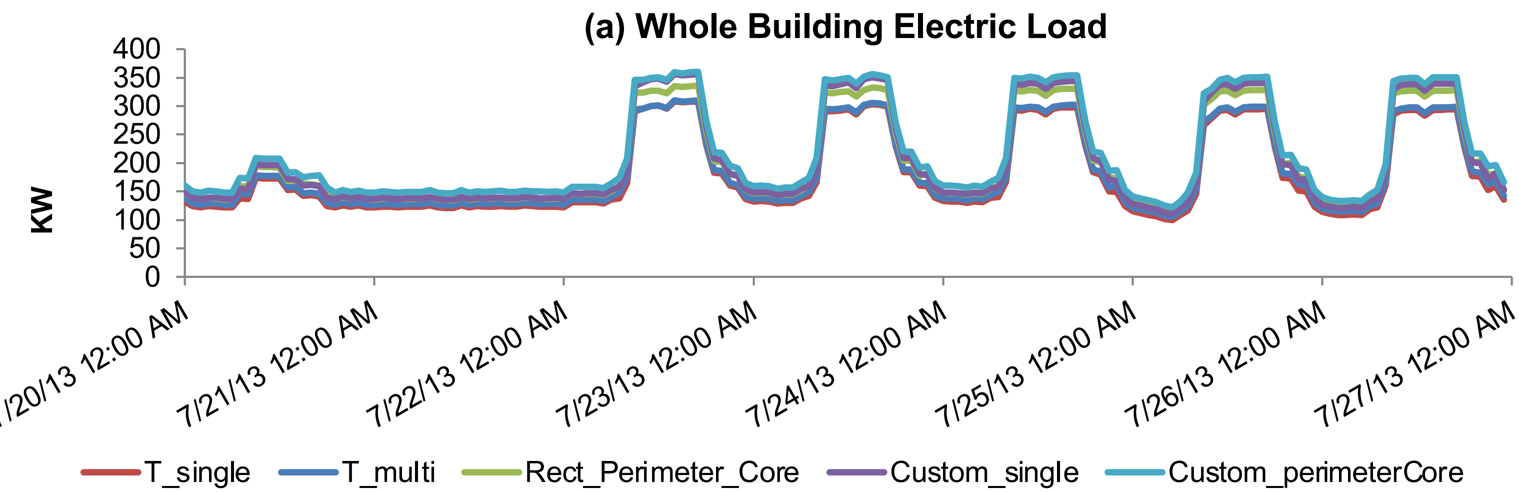




Heidarinejad et al. 2017

Building Shapes

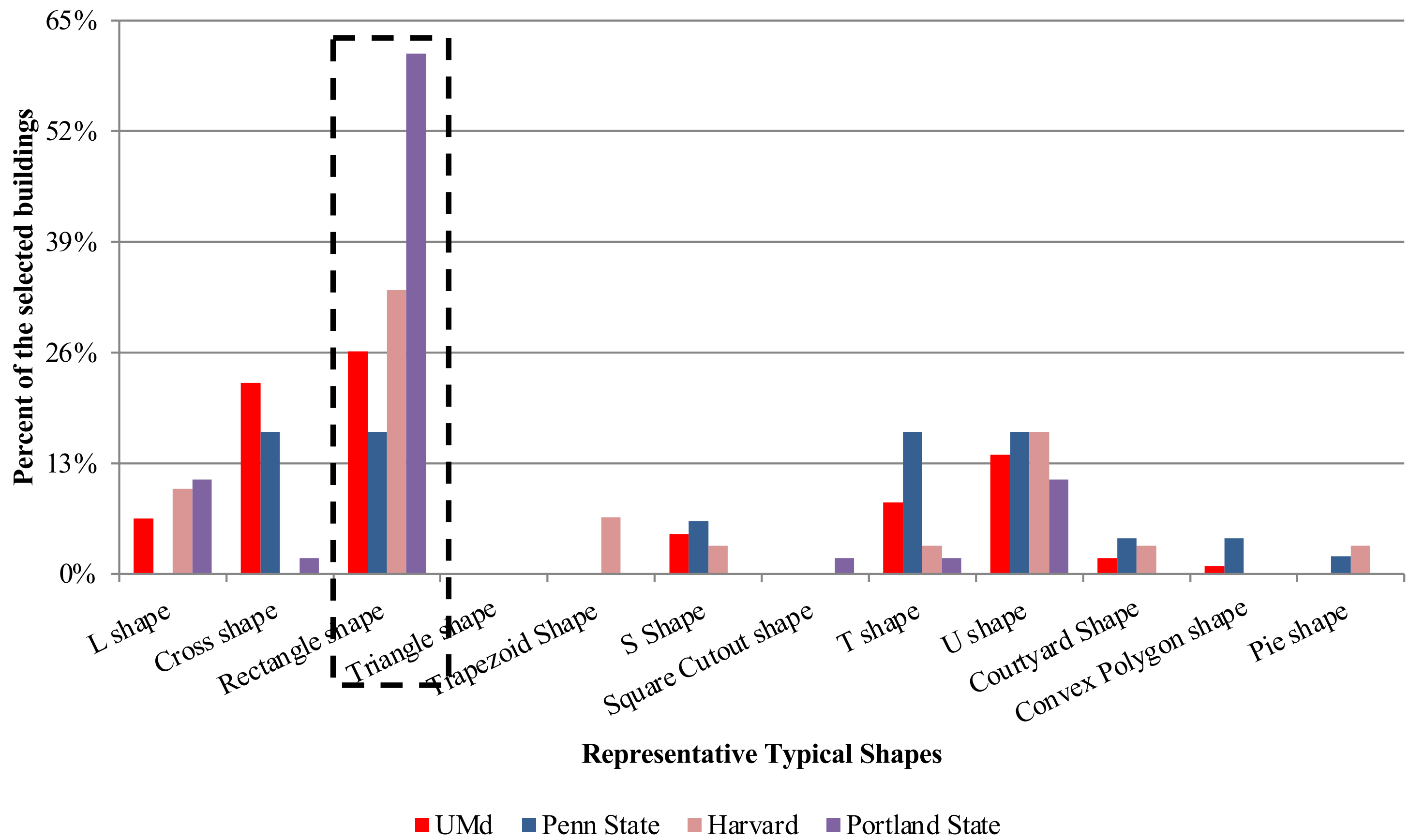




Heidarinejad et al. 2017

Building Shapes

- # of buildings:
  - UMd = 108
  - Penn State = 48
  - Harvard = 30
  - Portland State = 52

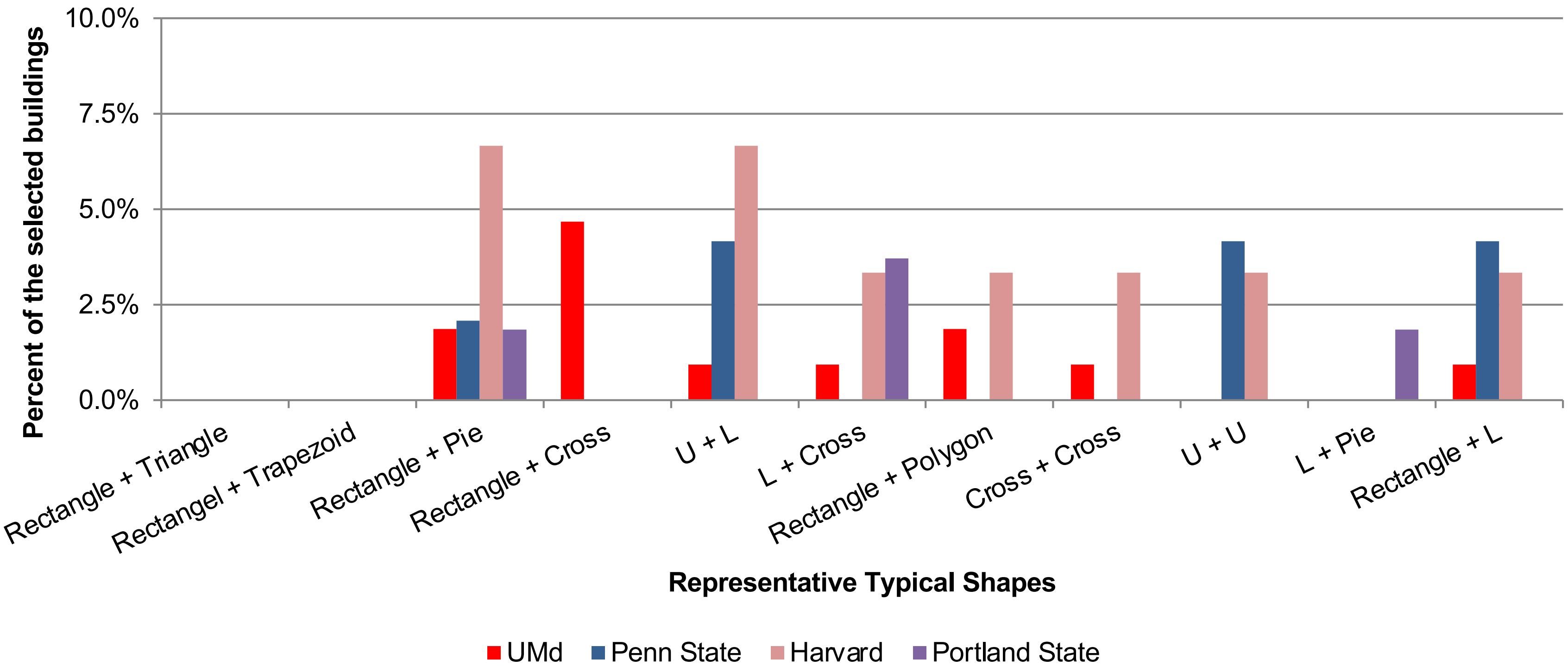


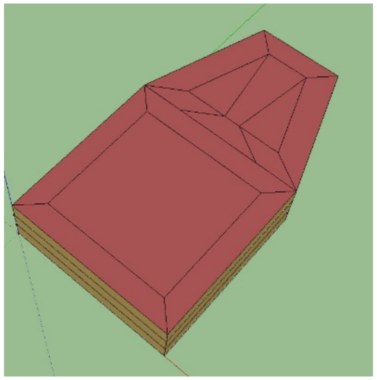
- The results of (CBECS) also confirm buildings could be modeled with typical shapes.

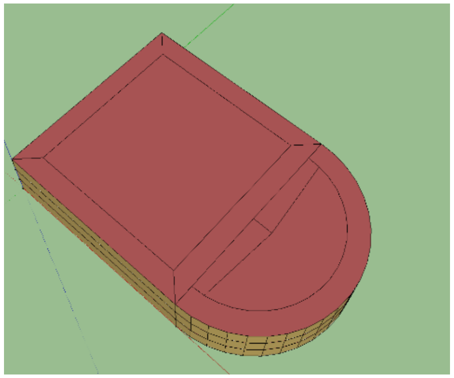
Heidarinejad et al. 2017

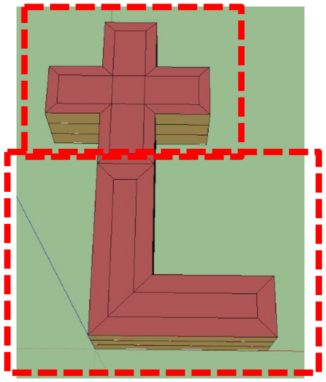
Building Shapes

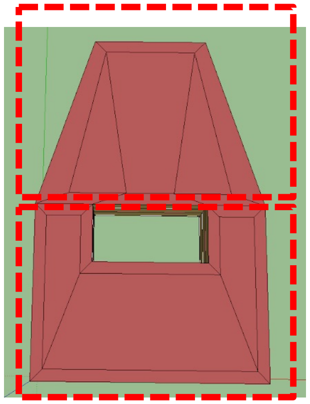
- Combination of the shapes can cover most of the remaining buildings





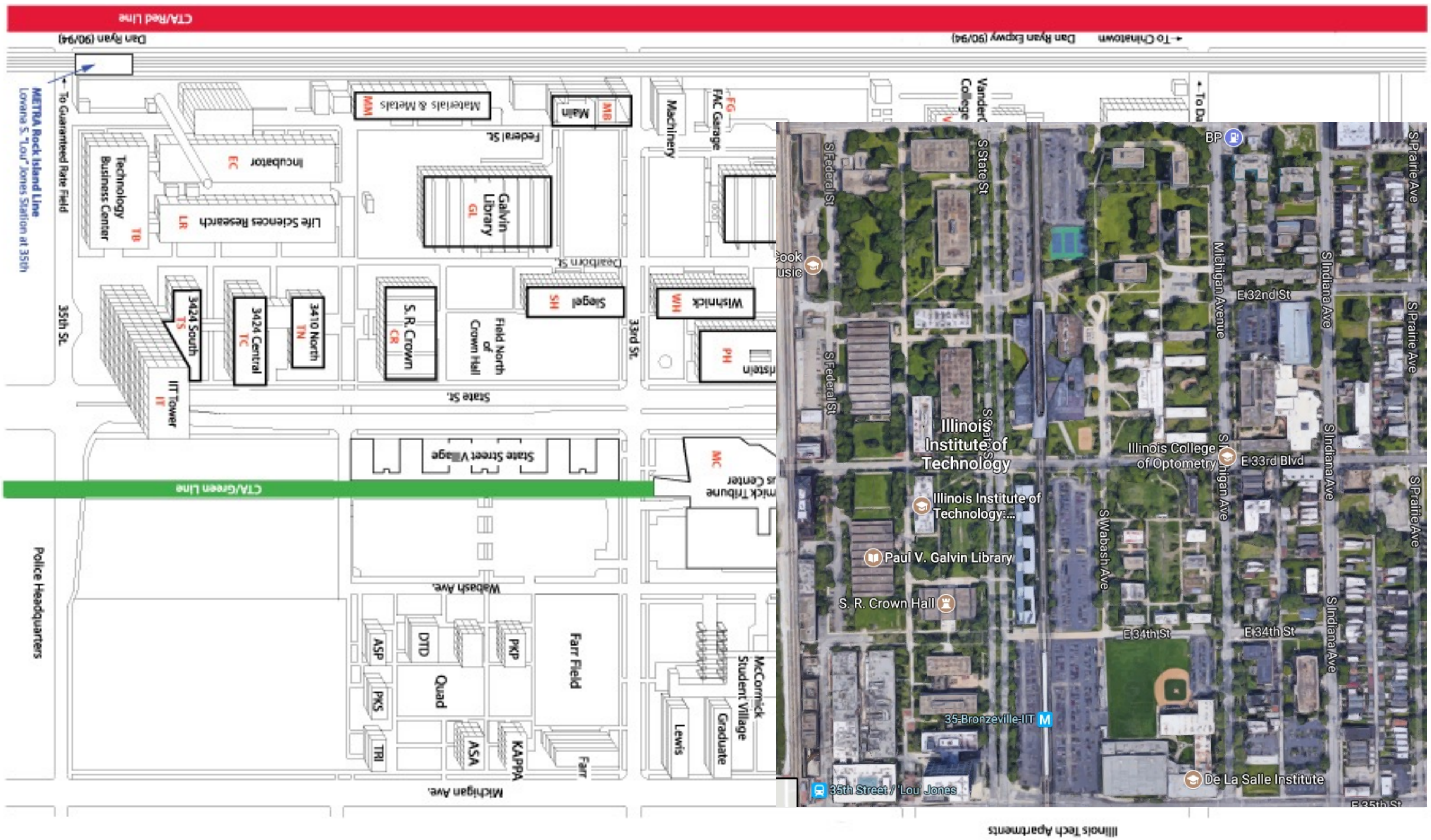






Heidarinejad et al. 2017

Building Shapes



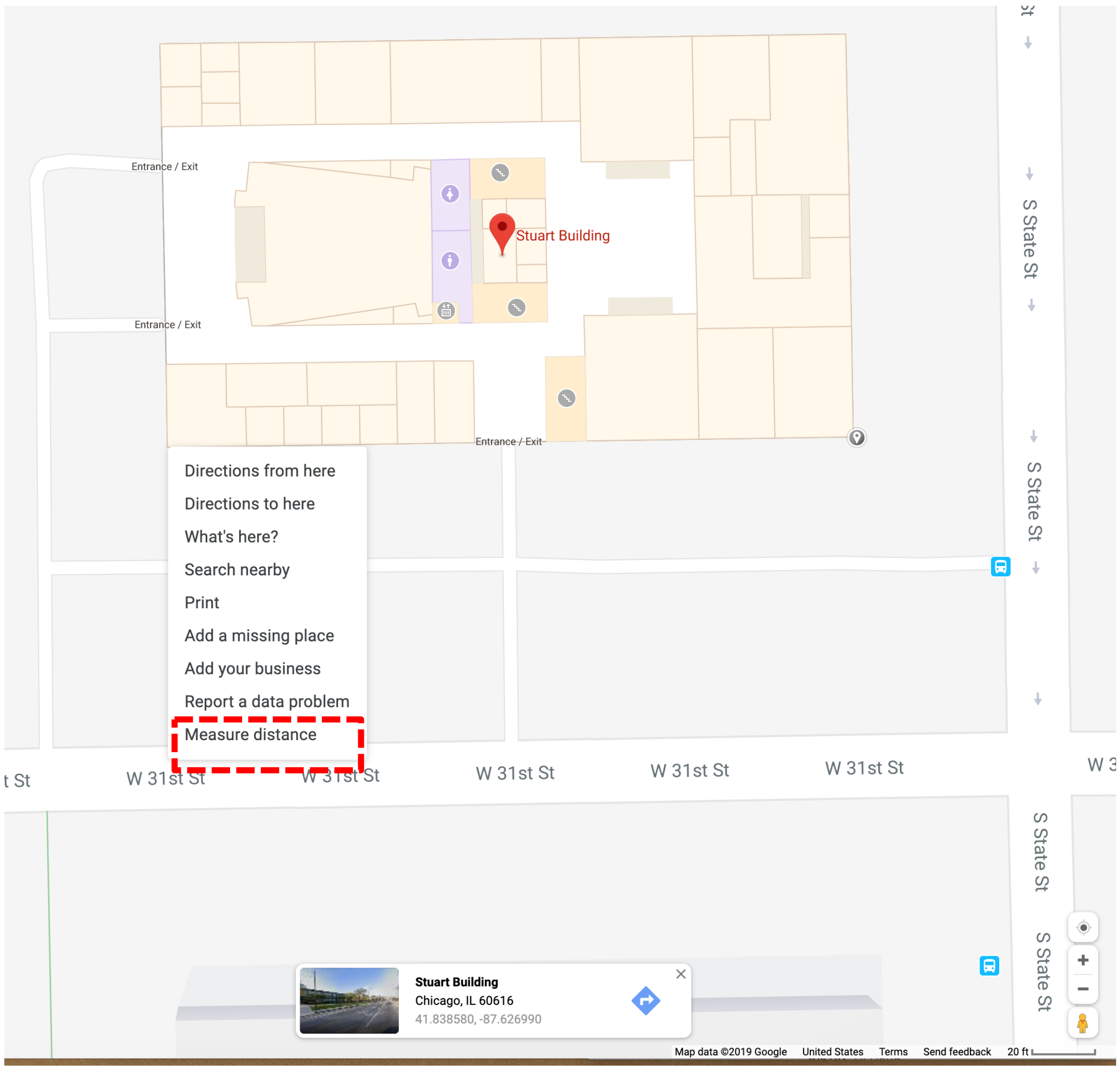
What is the percentage for our campus?

Floor Plan

- Consider Stuart building
- How do we calculate this in absence of the floorplans?

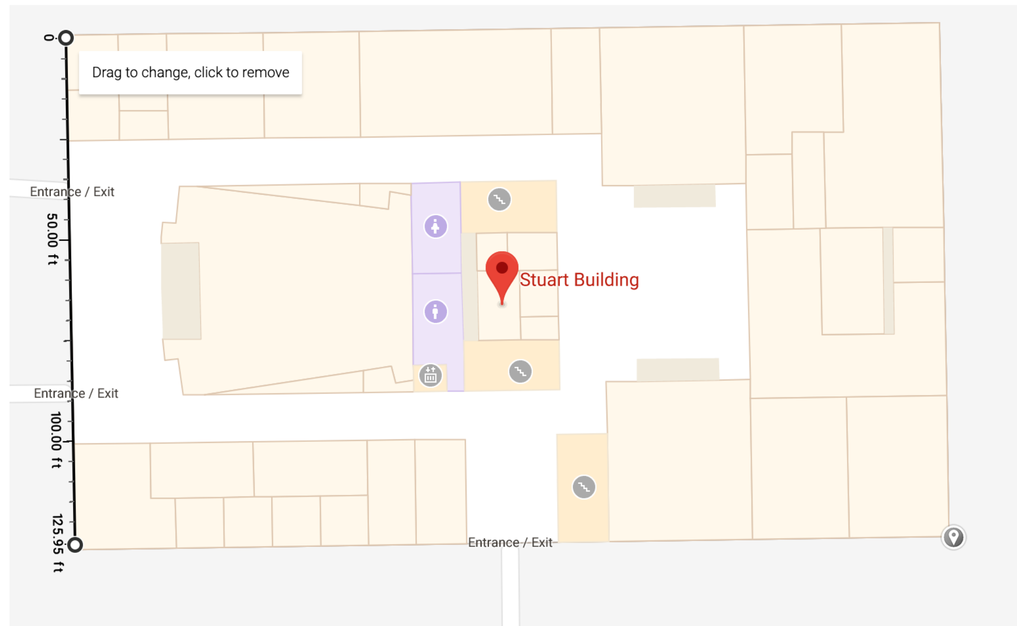
Floor Plan

- One of the easiest options:



Floor Plan

- One of the easiest options:

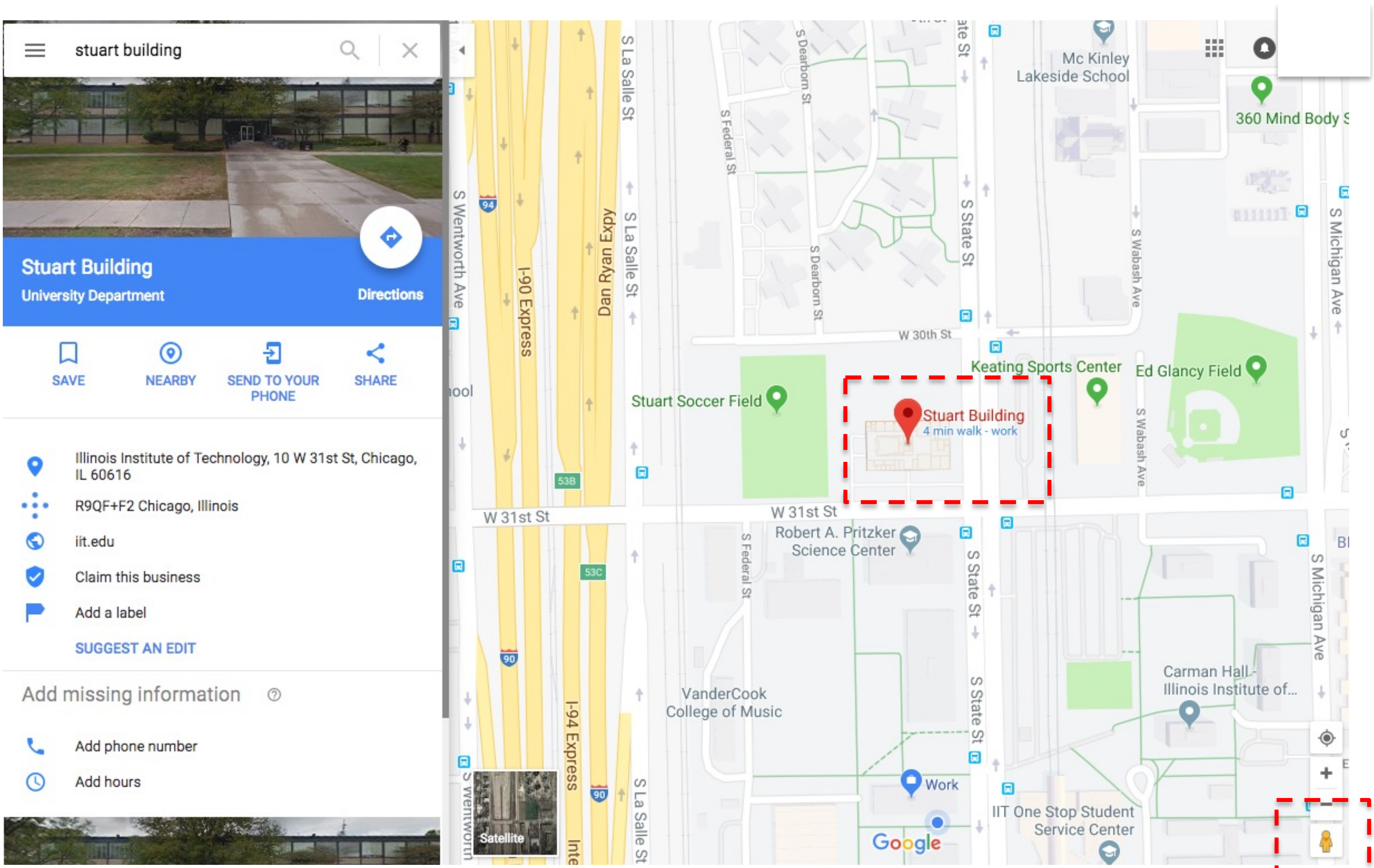


WINDOW-TO-WALL RATIO

Window-to-Wall Ratio

- A simple calculation of Window-to-Wall (WWR) ratio benefit from the following steps:
  - Identify the building on the search engine maps
  - View the building facades
  - Scale the sides and measure the distances

Window-to-Wall Ratio



Window-to-Wall Ratio

Window-to-Wall Ratio

Window-to-Wall Ratio

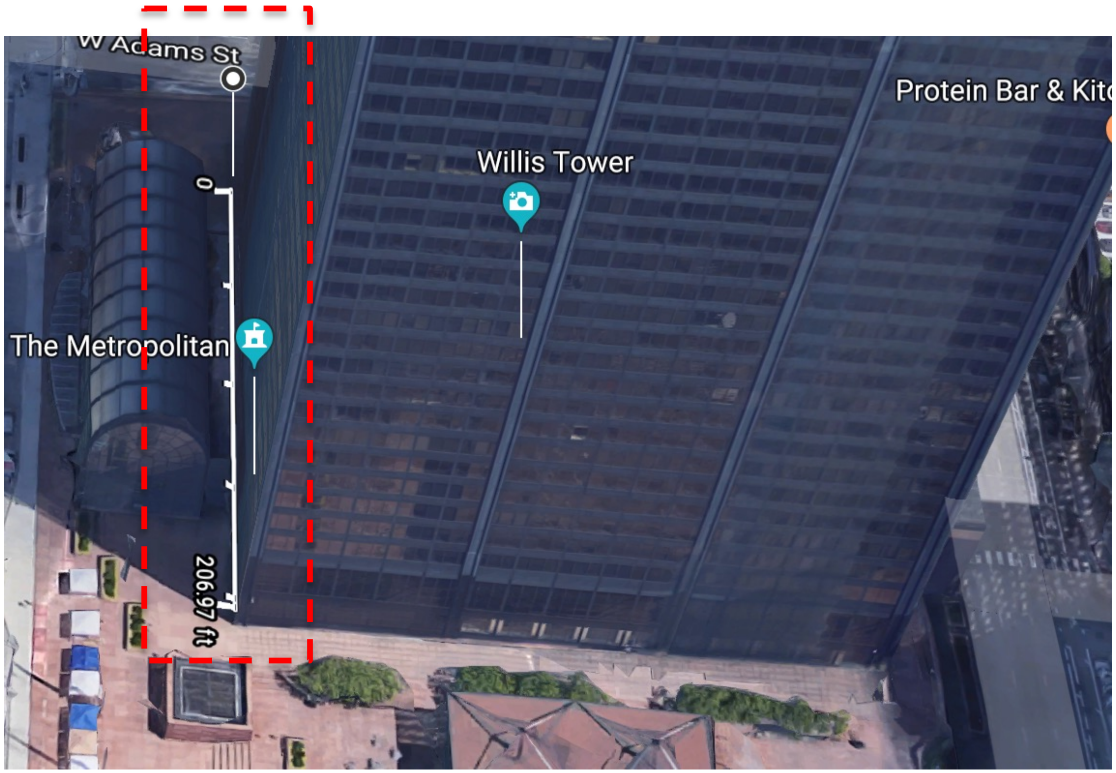
CLASS ACTIVITY

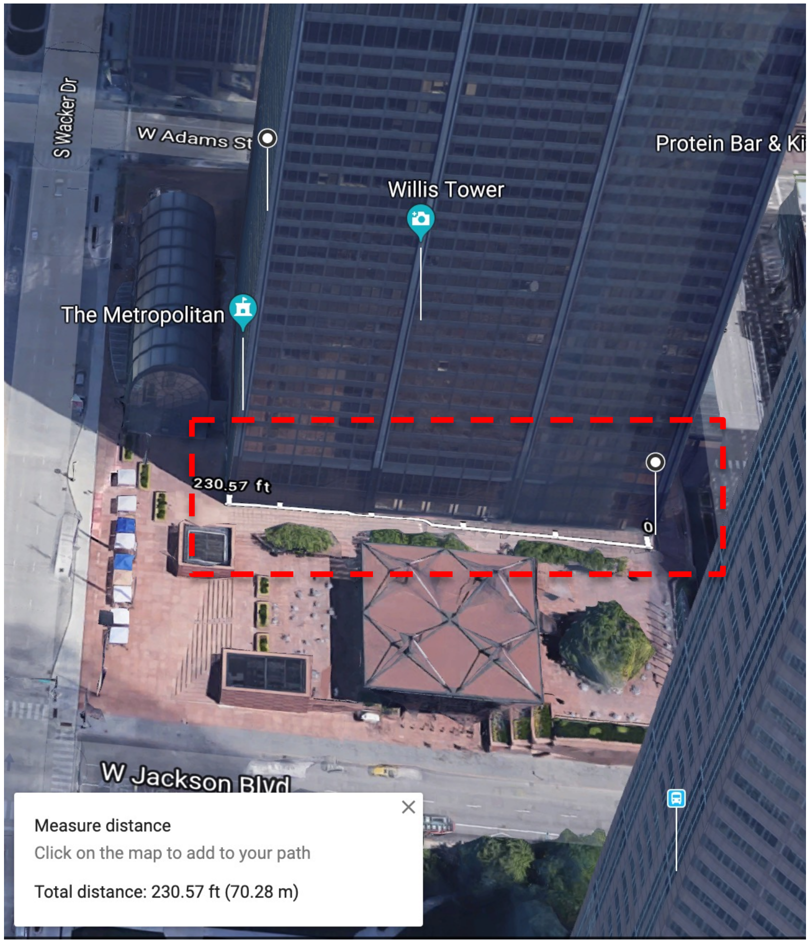
Class Activity

- Calculate WWR, building floor area, and height for the Willis Tower (or a similar commercial building in downtown)

Class Activity

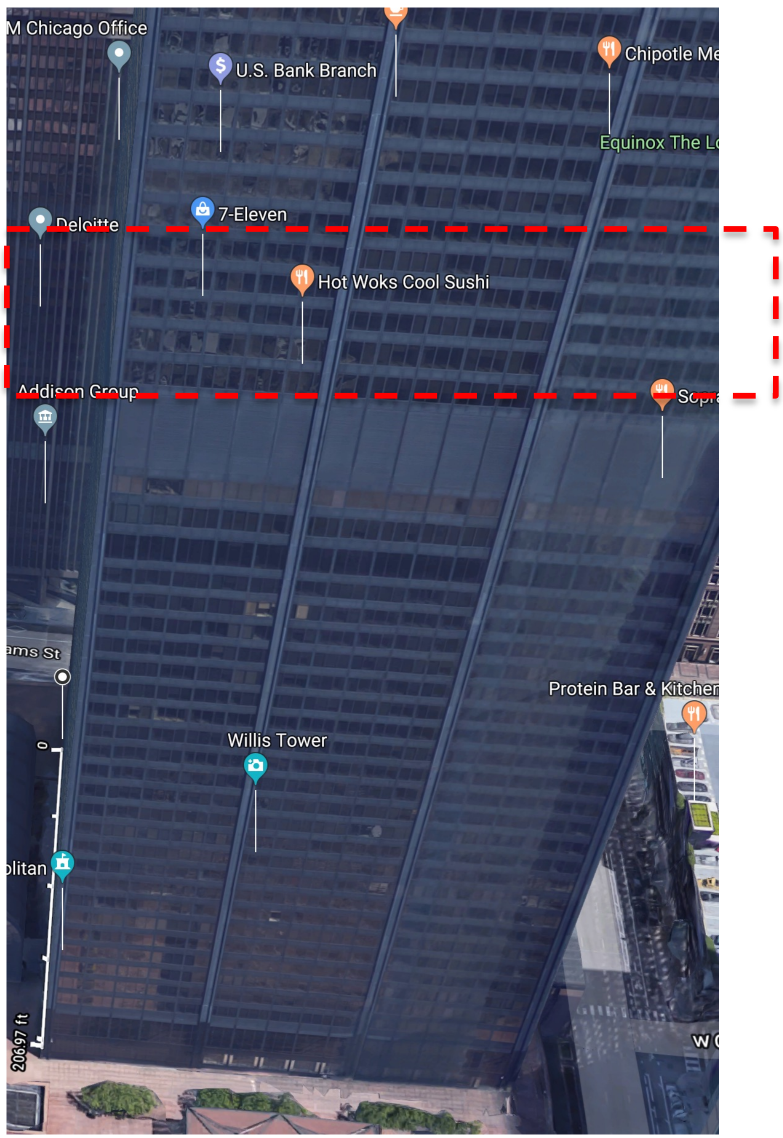
- Building floor area for Willis Tower





Class Activity

- In calculation of WWR, consider windows



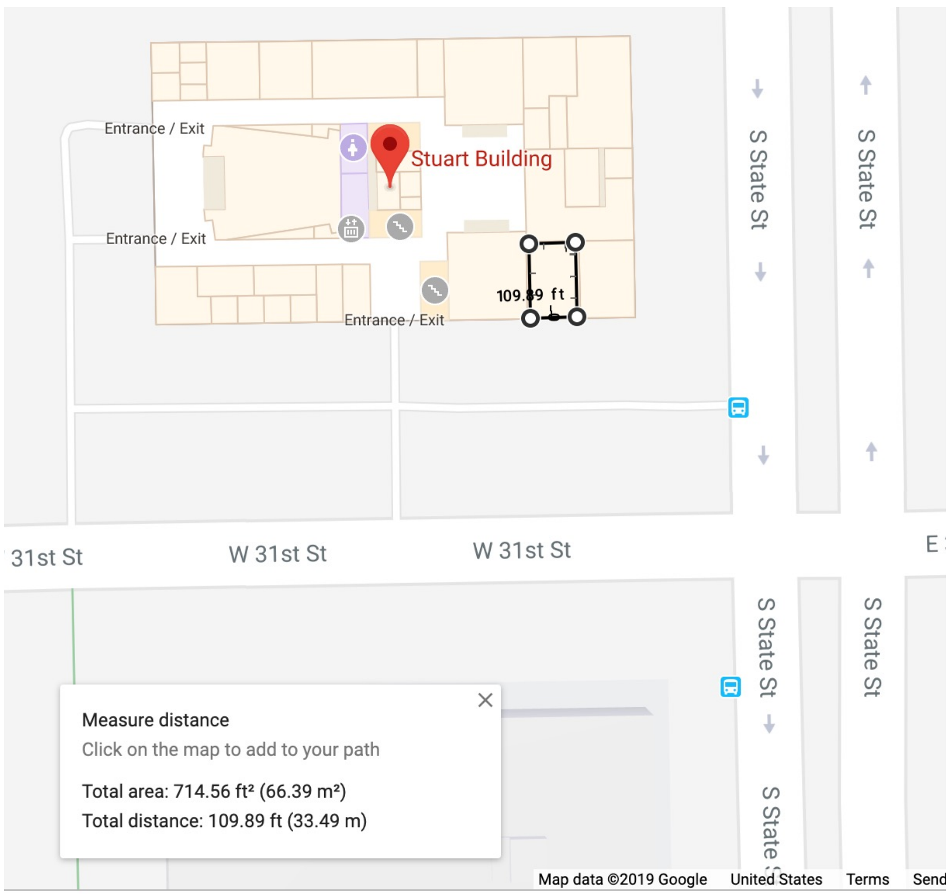
SPACES

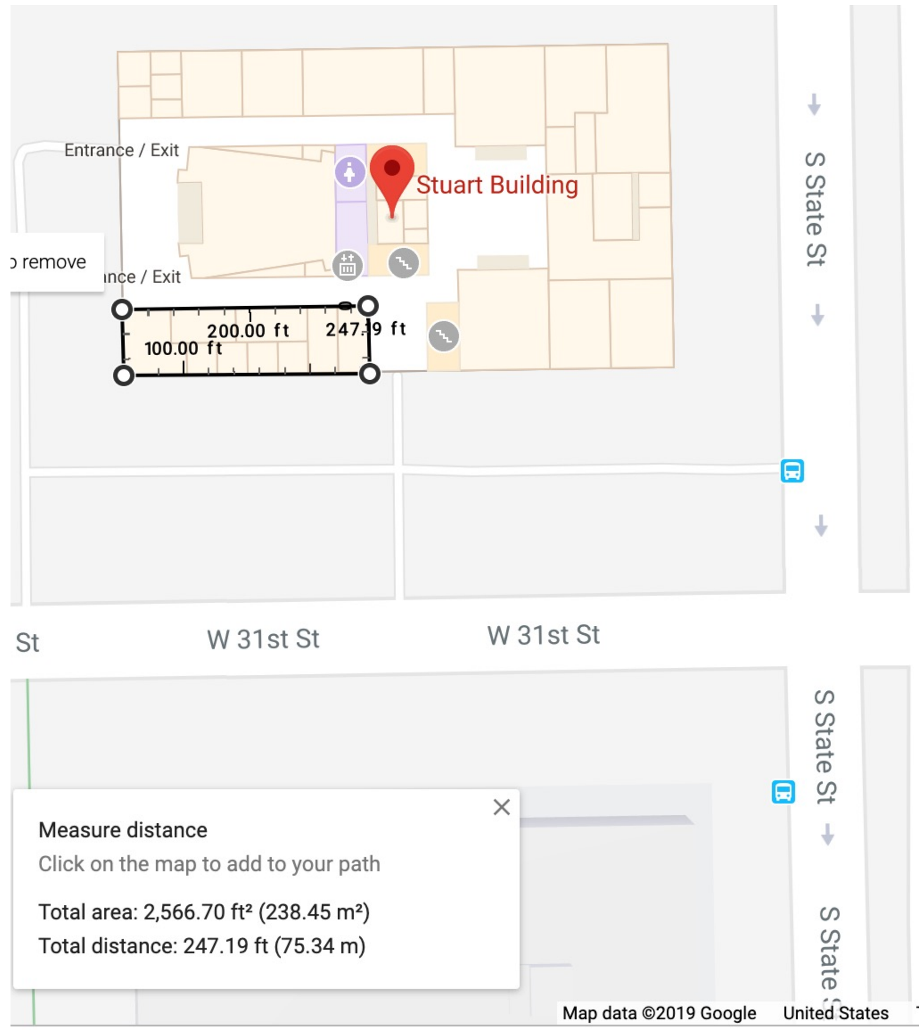
Spaces

- How to find out about the spaces in a building?
  - Use architectural and mechanical drawings
  - Utilize online resources (if possible)

Spaces

- How to find out about the spaces in a building?





THERMAL ZONING

Thermal Zoning

- What's a thermal zone?

  ASHRAE Standard 90.1: "HVAC Zones or Thermal Zone is space or group of spaces within a building with heating and cooling requirements that are sufficiently similar so that desired conditions (e.g., temperature) can be maintained throughout using a single sensor (e.g., thermostat or temperature sensor)"

Spaces that are being served by one thermostat

Thermal Zoning

- Where do we find the standards?

https://www.ashrae.org/technical-resources/standards-and-guidelines

Preview ASHRAE Standards and Guidelines

You may preview the following ASHRAE Standards & Guidelines with the links be
selection with the option to purchase your copy with the buy button. If you need t
ashrae@iengineering.com.

Errata to guidelines and standards can be found here.

Guideline 1.4-2019

Guideline 11-2021

Guideline 12-2020

Guideline 28-2021

Guideline 29-2019

Guideline 36-2021

Standard 15-2019

Standard 34-2019

Standard 52.2-2017

Standard 55-2020

Standard 62.1-2019

Standard 62.2-2019

Standard 84-2020

Standard 90.1-2019 (I-P)

Thermal Zoning

- ASHRAE 90.1-2019:

7. *Thermal Blocks—HVAC Zones* Designed	
Where *HVAC zones* are defined on HVAC design drawings, each *HVAC zone* shall be modeled as a separate *thermal block*. **Exceptions:** Different *HVAC zones* may be combined to create a single *thermal block* or identical *thermal blocks* to which multipliers are applied, provided that all of the following conditions are met: 1. The *space* use classification is the same throughout the *thermal block,* or all of the zones have peak internal loads that differ by less than 10 Btu/h·ft^2 from the average. 2. All *HVAC zones* in the *thermal block* that are adjacent to glazed *exterior walls* and glazed *semiexterior walls* face the same *orientation* or their orientations vary by less than 45 degrees. 3. All of the zones are served by the same *HVAC system* or by the same kind of *HVAC system*. 4. All of the zones have schedules that differ by 40 or less equivalent full-load hours per week.	Same as *proposed design*.

ANSI/ASHRAE/IES Standard 90.1-2019 (I-P) 305

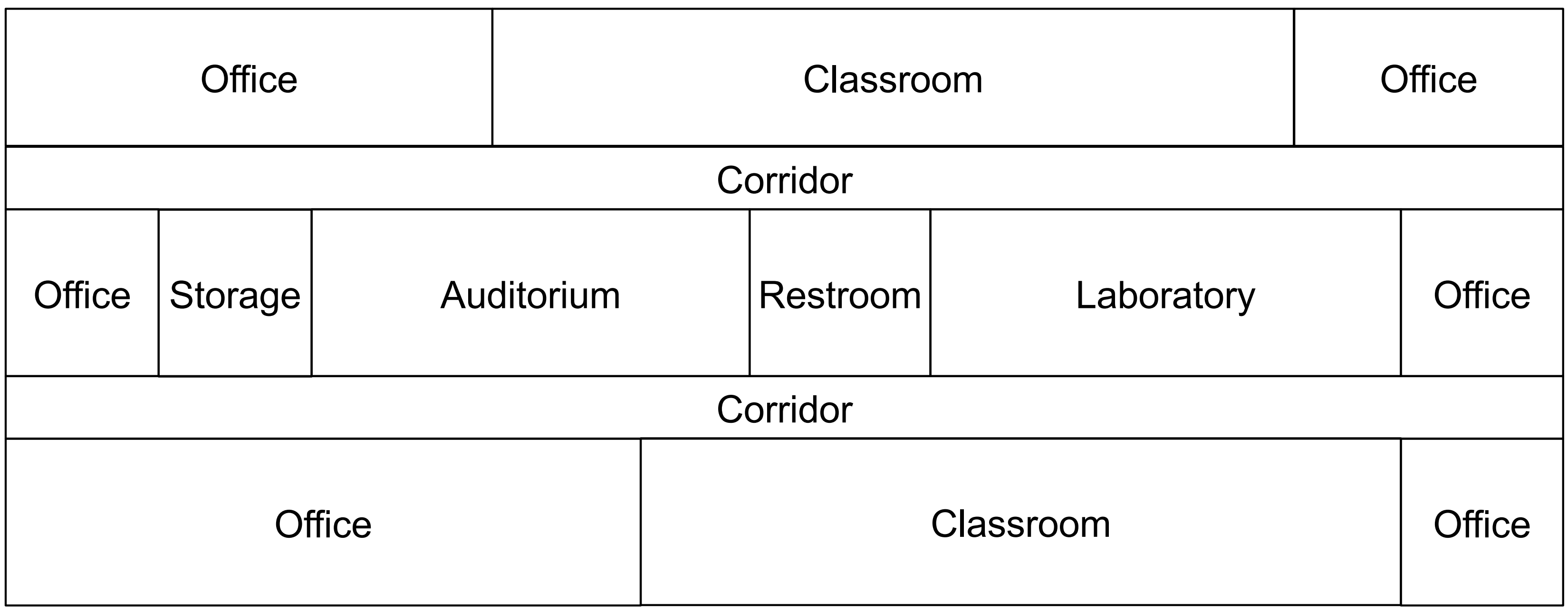
Thermal Zoning

- ASHRAE 90.1-2019:

No.	Proposed Building Performance	Baseline Building Performance
8. *Thermal Blocks—HVAC Zones* Not Designed		
	Where the *HVAC zones* and *systems* have not yet been designed, *thermal blocks* shall be defined based on similar internal load densities, occupancy, lighting, thermal and *space* temperature schedules, and in combination with the following guidelines: a. Separate *thermal blocks* shall be assumed for interior and perimeter *spaces*. Interior *spaces* shall be those located greater than 15 ft from an *exterior wall* or *semiexterior wall*. Perimeter *spaces* shall be those located within 15 ft of an *exterior wall* or *semiexterior wall*. A separate thermal zone does not need to be modeled for areas adjacent to *semiexterior walls* that separate *semiheated space* from *conditioned space*. b. Separate *thermal blocks* shall be assumed for *spaces* adjacent to glazed *exterior walls* or glazed *semiexterior walls*; a separate zone shall be provided for each *orientation*, except that orientations that differ by less than 45 degrees may be considered to be the same *orientation*. Each zone shall include all *floor* area that is 15 ft or less from a glazed perimeter *wall*, except that *floor* area within 15 ft of glazed perimeter *walls* having more than one *orientation* shall be divided proportionately between zones. c. Separate *thermal blocks* shall be assumed for *spaces* having *floors* that are in contact with the ground or exposed to ambient conditions from zones that do not share these features. d. Separate *thermal blocks* shall be assumed for *spaces* having exterior ceiling or *roof* assemblies from zones that do not share these features.	Same as *proposed design*.
9. *Thermal Blocks*—Multifamily *Residential Buildings*		
	Residential spaces shall be modeled using at least one *thermal block* per *dwelling unit*, except that those units facing the same orientations may be combined into one *thermal block*. Corner units and units with *roof* or *floor* loads shall only be combined with units sharing these features.	Same as *proposed design*.

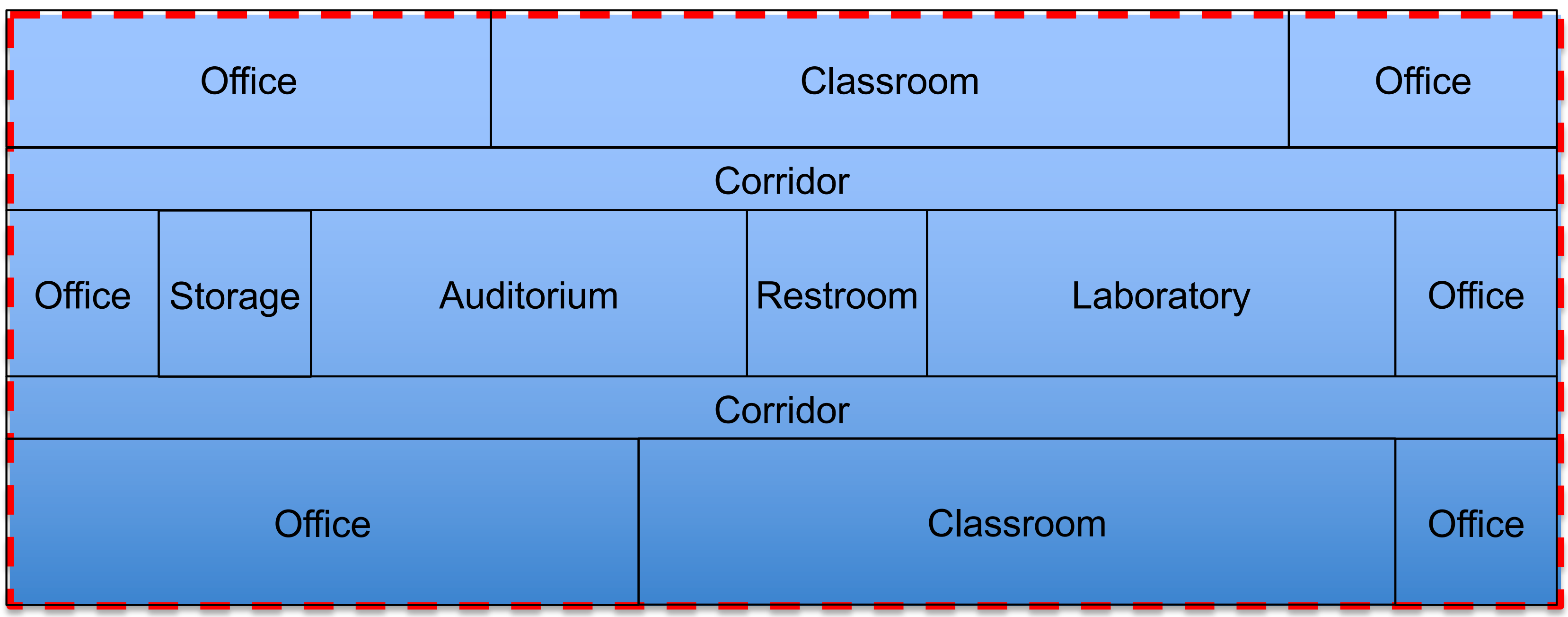
Thermal Zoning

- Always consider looking at the mechanical drawings first:



Thermal Zoning

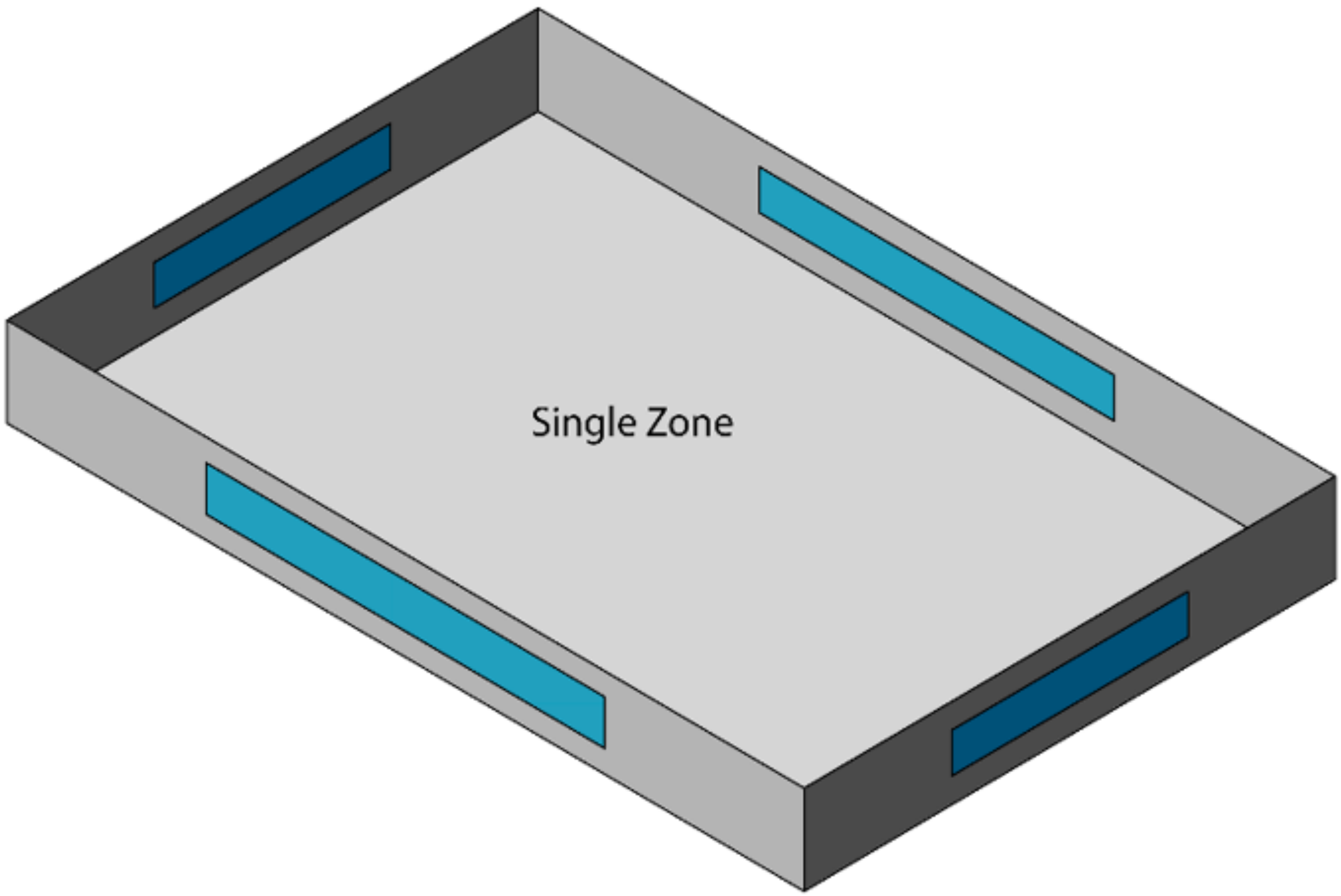
- What's the simplest form of a thermal zone?



"Single Zone"

Thermal Zoning

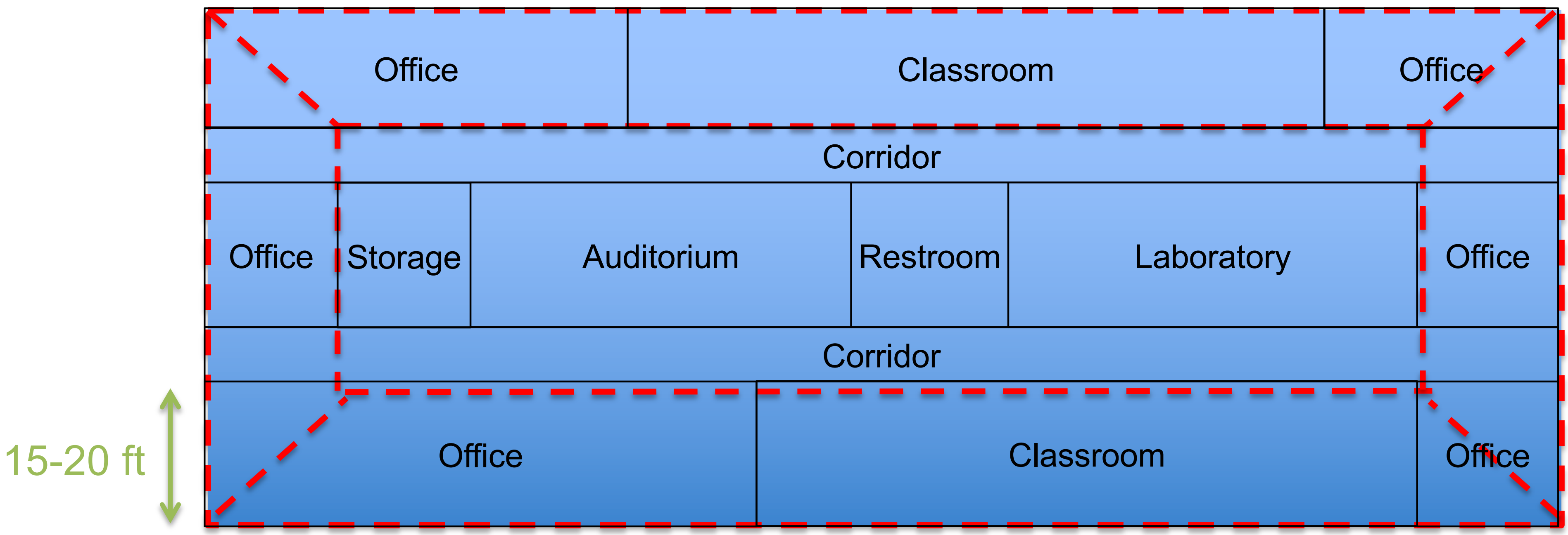
- Single zone



https://www.covetool.com/2019/05/2864/

Thermal Zoning

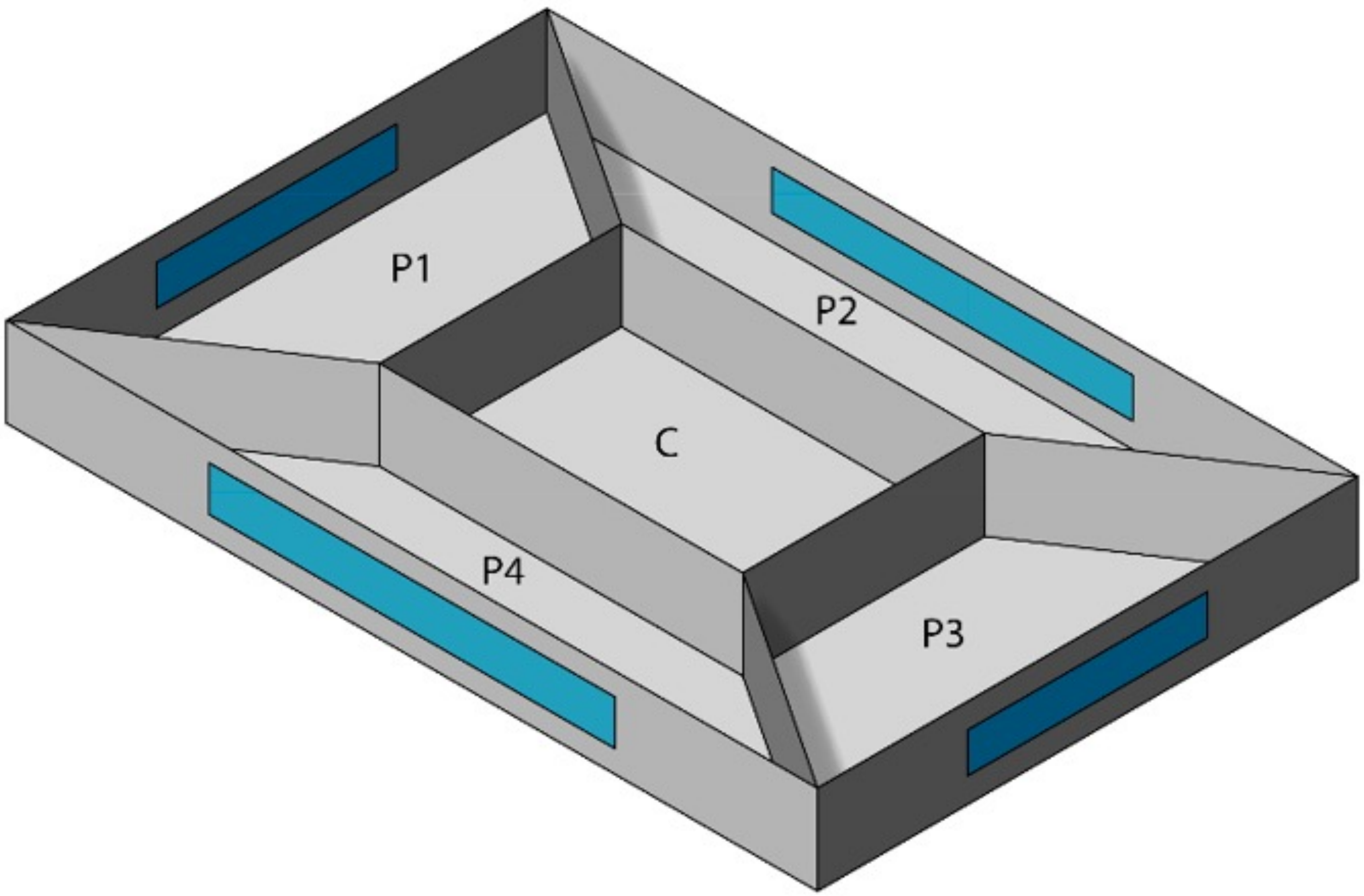
- What's the simplest form of a thermal zone after a single zone mode?



"Core and Perimeter Zone"

Thermal Zoning

- Core zone and perimeter



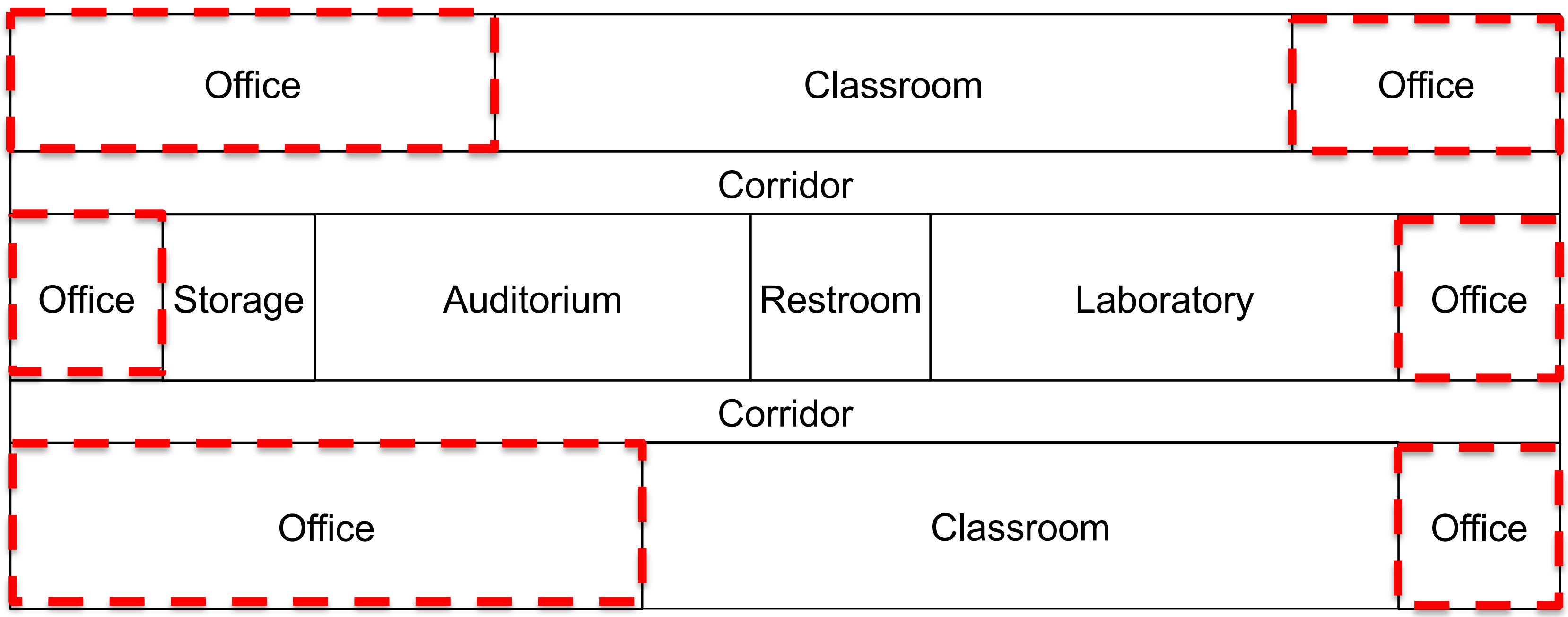
https://www.covetool.com/2019/05/2864/

Thermal Zoning

- What are the most important consideration for a detailed thermal zone modeling:
  - Orientation (e.g., East, West)
    - Daylight
    - Heat gain
  - Areas
    - Similar areas
  - Functionality
    - Similar internal loads and ventilation requirements
  - Proximity
    - Same floor
    - Same location in a floor but at different floors

Thermal Zoning

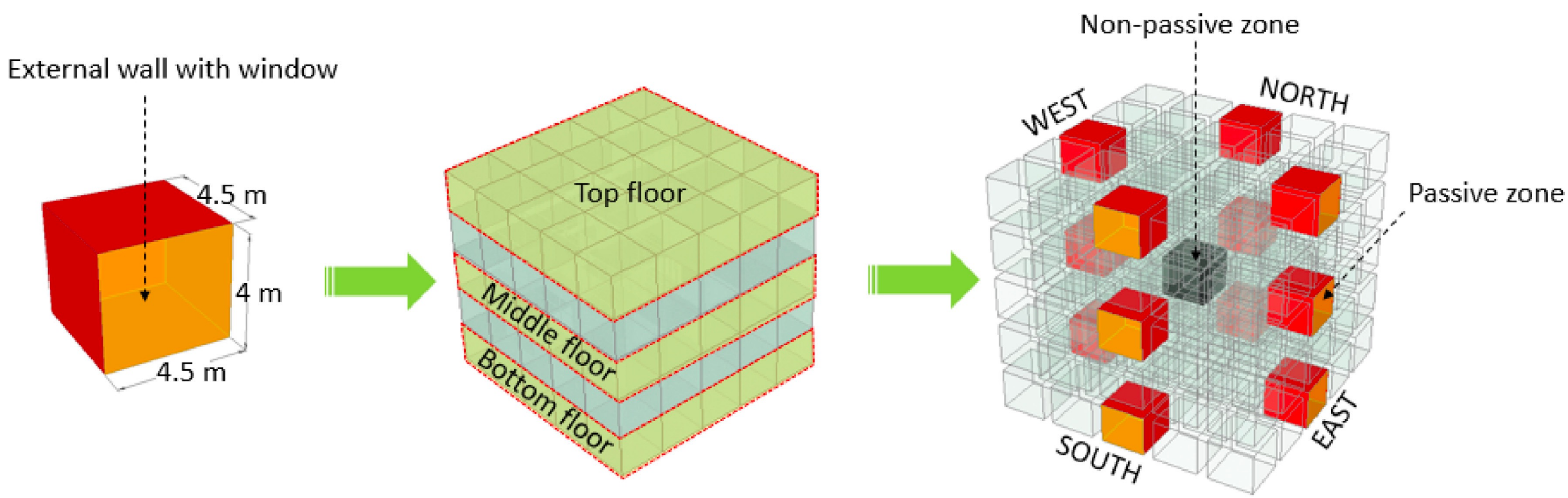
- Consider adding thermal zone for this floor plan.



Do you think the following thermal zone is a good strategy?

Thermal Zoning

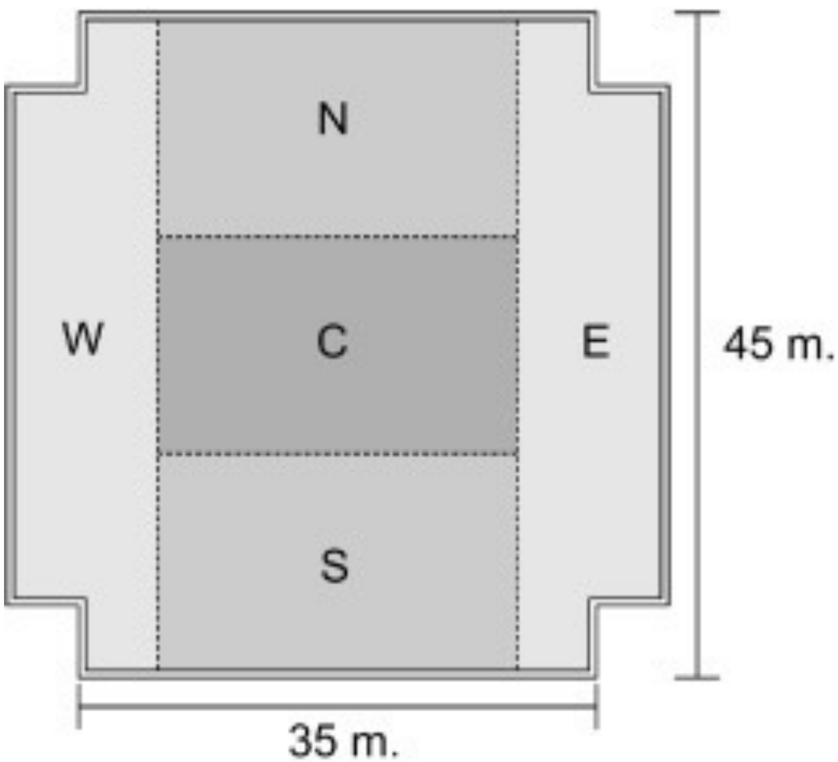
- Let's look at different thermal zone modeling in the literature

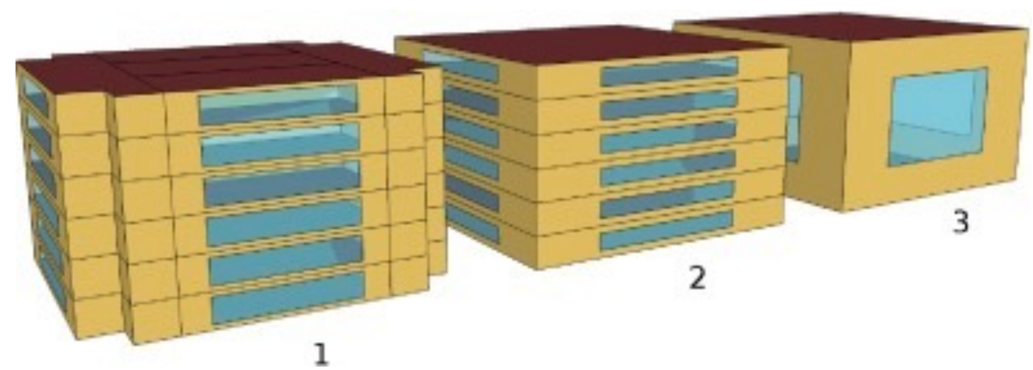


Building Blocks Energy Estimation (BBEE): A method for building energy estimation on district level

Thermal Zoning

- Let's look at different thermal zone modeling in the literature

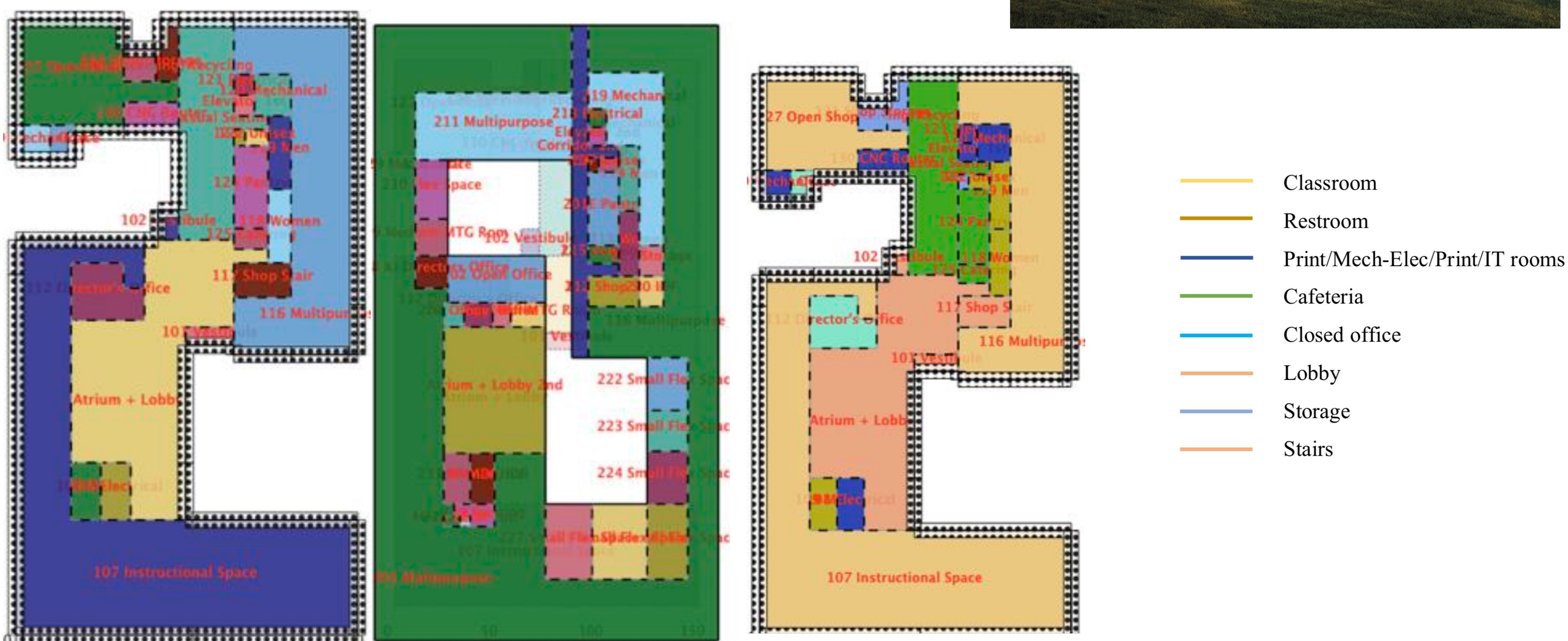




Comparison between simplified and detailed EnergyPlus models coupled with an urban canopy model

Building Energy Modeling

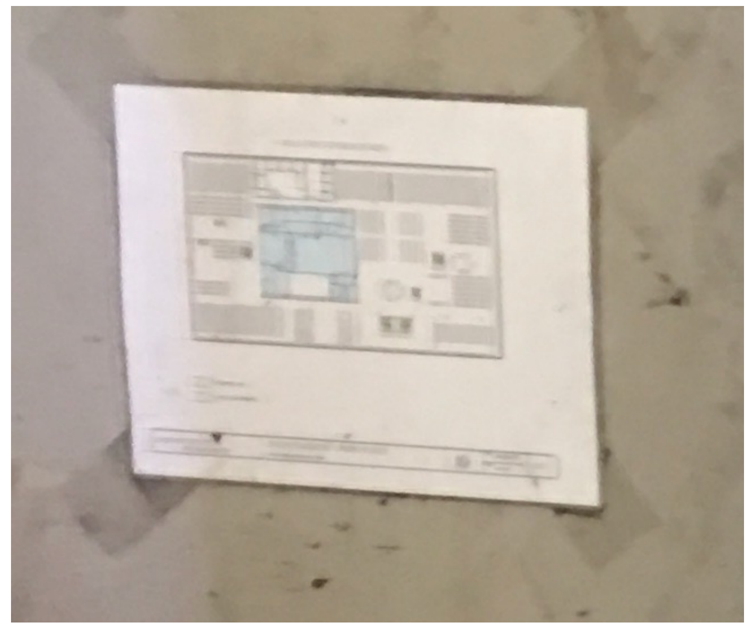
- Our campus models



Maristany, 2019

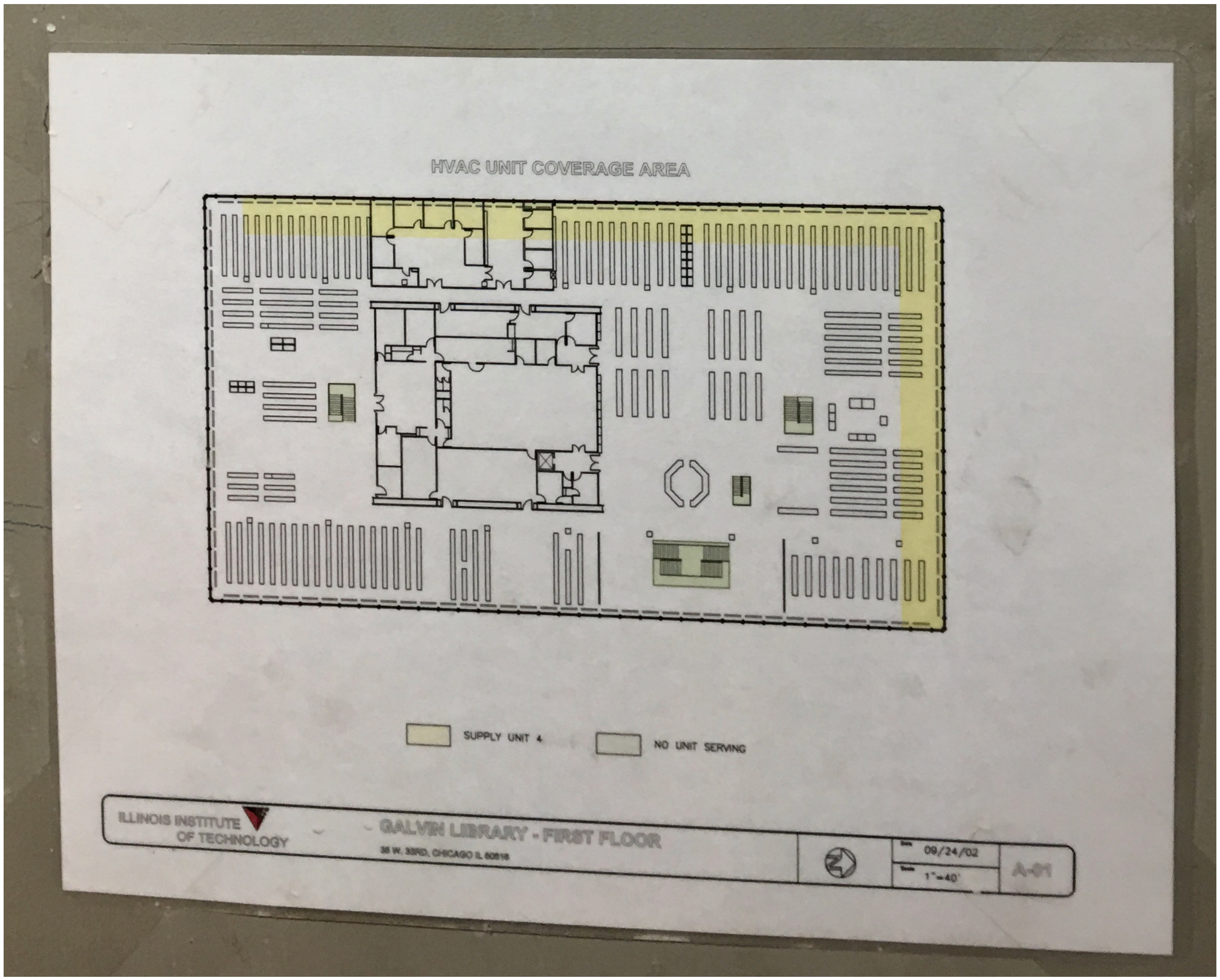
Building Energy Modeling

- In a real building, this is also visualized



Building Energy Modeling

- In a real building, this is also visualized



CLASS ACTIVITY

Class Activity

- Propose thermal zones in the provided floorplans on blackboard