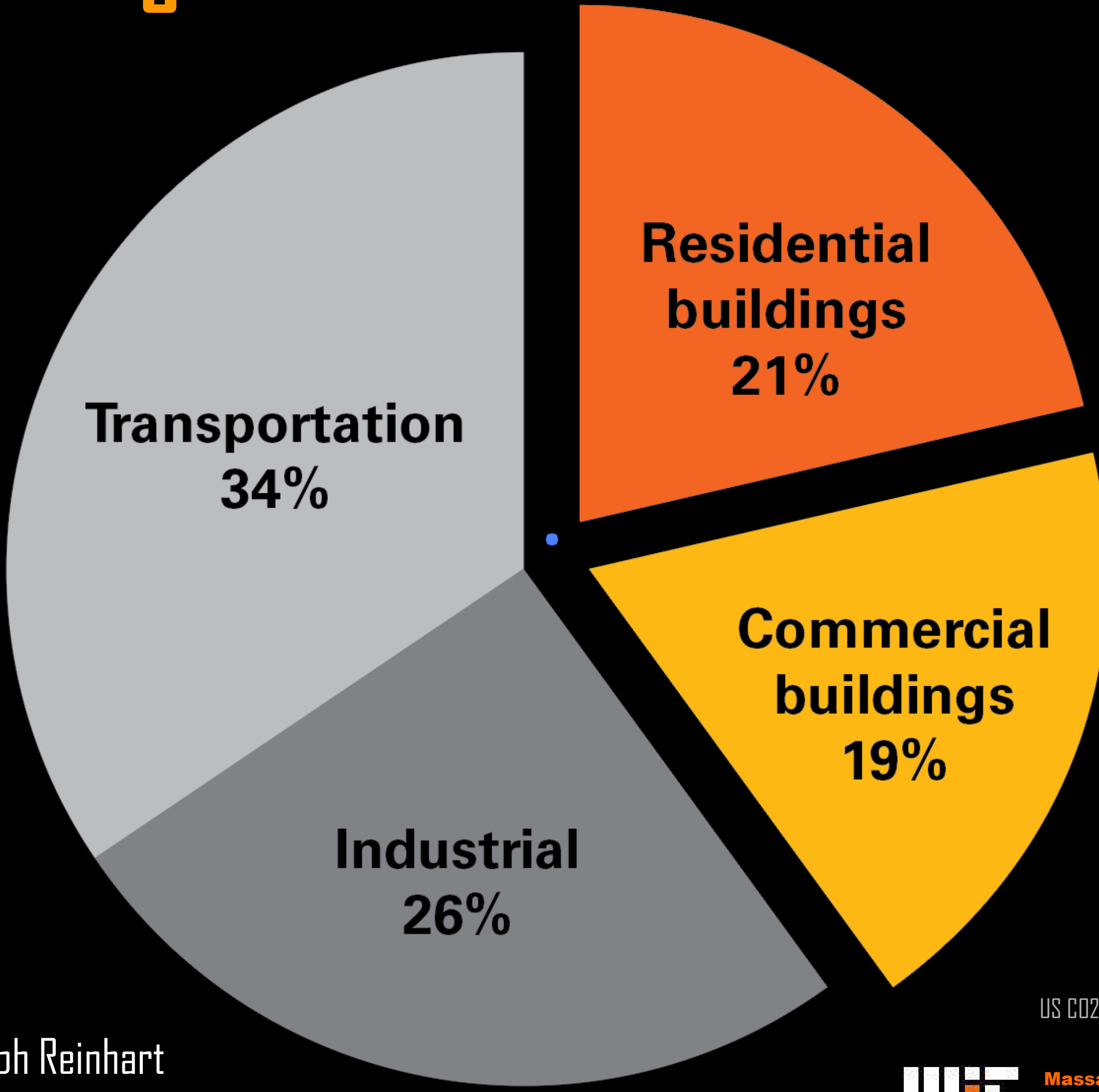
4.401/4.464 Environmental Technologies in Buildings



US CO2 emission by sector

Christoph Reinhart

L02 Energy Use in Buildings

Massachusetts Institute of Technology
Department of Architecture
Building Technology Program

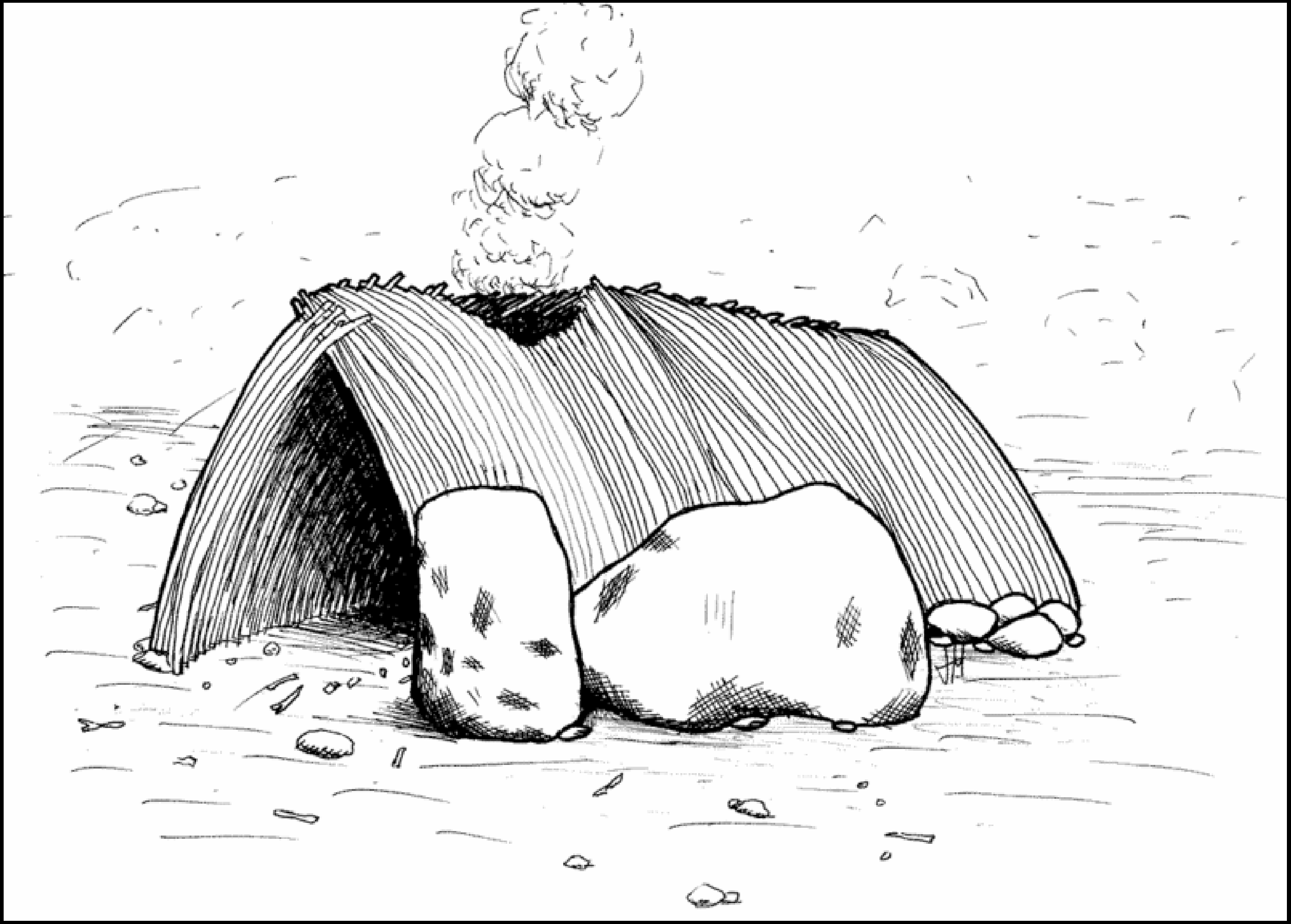
Environmental Technologies

Why comfortable?

Why comfortable?

If you watched *Alpha* you may agree that nobody was ever comfortable in today's sense during the ice age.

First Shelters



Public domain image courtesy of José-Manuel Benito on Wikipedia

Protect from wind and rain and trap the heat.

Roman *Domus*

Photo by Mary Harrsch on Flickr. License: CC BY-NC-SA.

Central heating, warm water, adequate rain protection.

Life was getting better, if you could afford it.

Medieval Living

Photo by Dunnock_D on Flickr. License CC BY-NC.

You need a lot of wood to keep that space somewhat comfortable during winter.

18th Century Colonial Housing

Building adapts to local climate. Deciduous trees on the south side for shading, small rooms to keep warm during winter.

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Full Climate Control

Photo by Lynn Betts, USDA Natural Resources Conservation Service. This image is in the public domain.

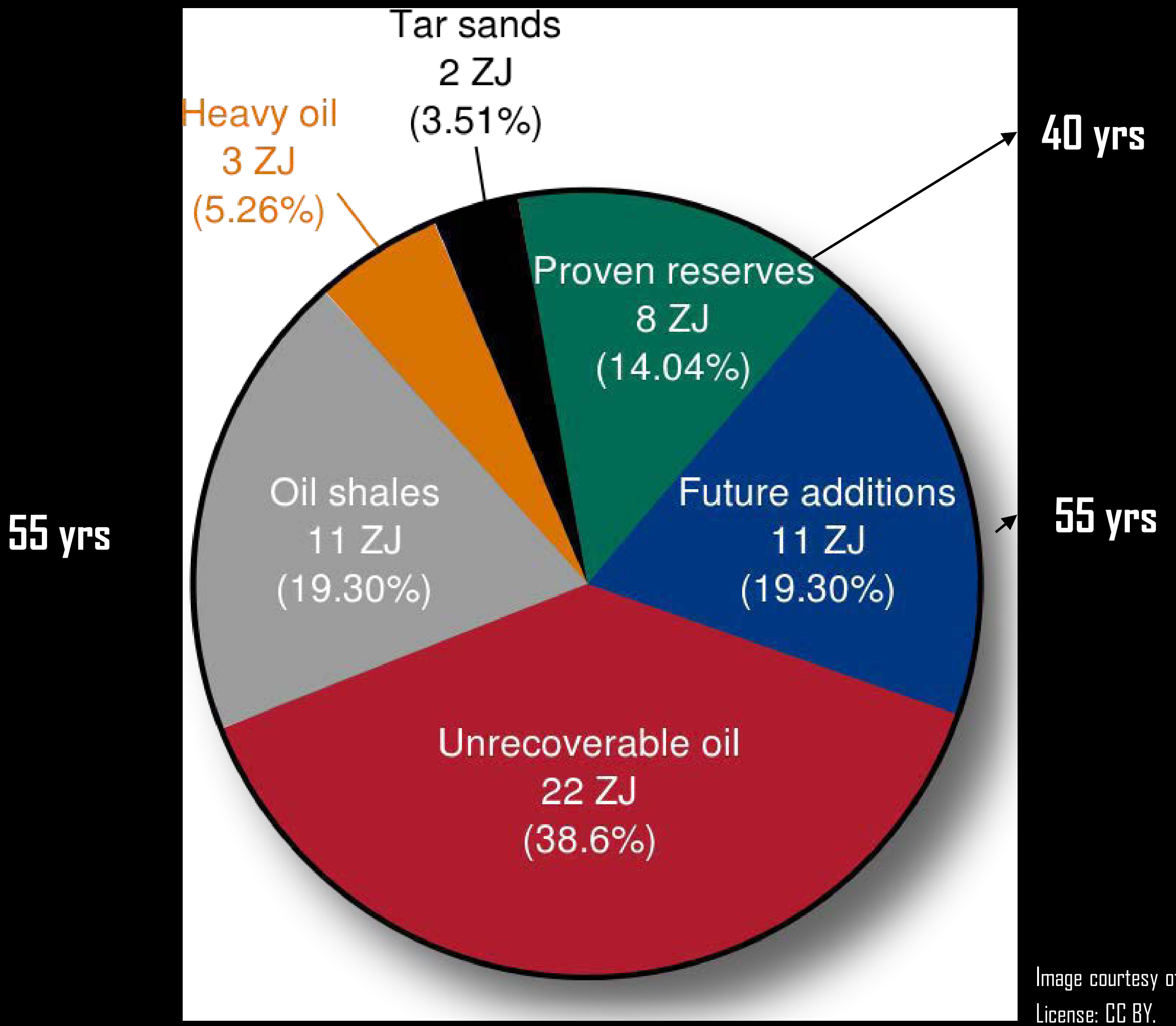
We can now separate building interiors from ambient climatic conditions. This photo could have been taken anywhere in the US and elsewhere.

Why resource-efficient?

Why Resource-Efficiency?

- Population Growth—see Thomas Malthus's *An Essay on the Principle of Population* (1798)
- Environmental Damage—see Rachel Carson's *Silent Spring* (1962)
- Limited Resources—see Meadows et al.'s *Limits to Growth* (1972)

Remaining Oil



- ~0.2 ZJ per year (32 billion barrels)

We are looking at 100 to 150 years of supply if demand stays stable.

Climate Change Milestones

1992 IPCC Report

Global mean surface air temperature has increased by 0.3 to 0.6° C over the last 100 years.... The size of this warming is … the same magnitude as natural climate variability. Thus the observed increase could be largely due to this natural variability; alternatively this variability and other human factors could have offset a still larger human-induced greenhouse warming.

2007 IPCC Report

Warming of the climate system is unequivocal. Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.

2014 IPCC Report

Global warming is here, human-caused, and probably already dangerous — and it's increasingly likely that the heating trend could be irreversible, a draft of a new international science report says.

2016 Paris Agreement (UNFCCC)

195 countries agreed to seek to limit global temperature increases in the 21st century to below 2 Degrees Celsius.

This class is directly contributing to goals 7, 11, and 13.

Energy Use in Buildings

What is Energy?

- The ability to do work.
- One cannot see energy.
- Energy manifests itself in different forms: Kinetic, thermal, gravitational, sound energy, light energy, elastic, electromagnetic, chemical, nuclear, and mass.

Energy Units for Electricity Use

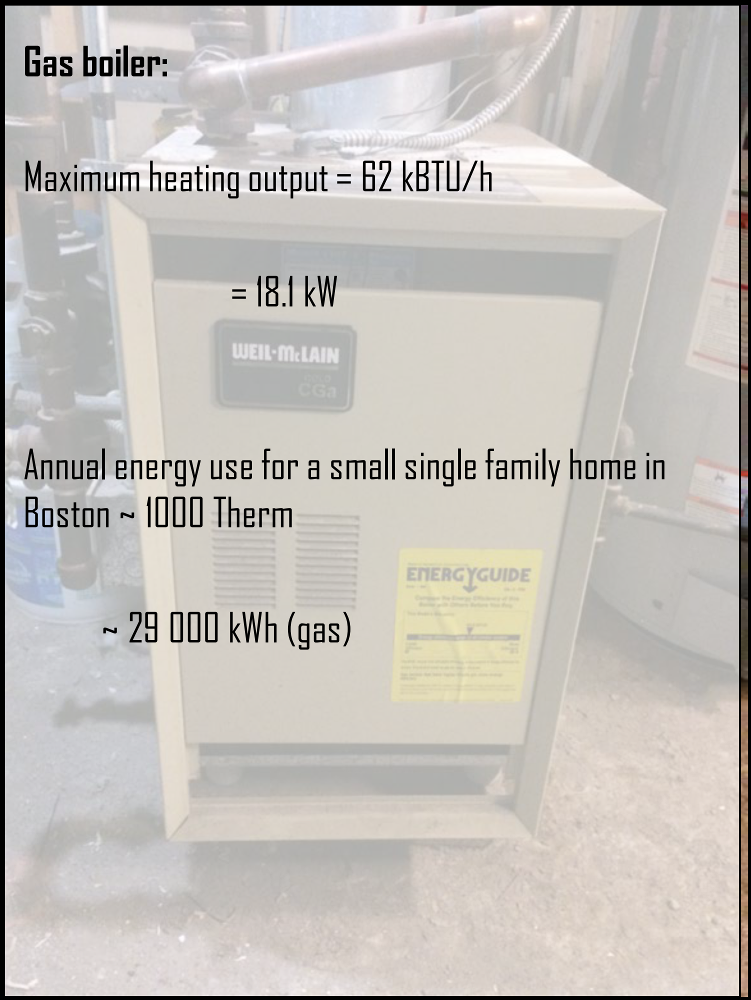
- 1 joule [J]: energy as work
- 1 kilowatt hour = kWh with 1 watt = 1 J /s
  = 1000 x J/s x 3600s = 3.600.000 J

Cell phone:	**Energy-Efficient Refrigerator:**
Battery size = 2900 mAh at ~3.8 V = 2.9 Ah x 3.8 V = 0. 011 kWh Annual energy use = 0.011 kWh x 365 d/1yr = 4 kWh/yr	Annual energy use = 150 kWh/yr

- A fridge constitutes one of the main energy uses in a living unit.
- However, electronic equipment adds up quickly. A heavily used laptop uses 150 kWh/yr. A desktop may use 600 kWh/yr.

Energy Units for Heating/Cooling

- 1 British Thermal Unit (BTU) = imperial unit, energy needed to cool or heat one pound of water by one degree Fahrenheit = 1 kBTU = 0. 293 Wh
- 1 Therm = 100 000 BTU



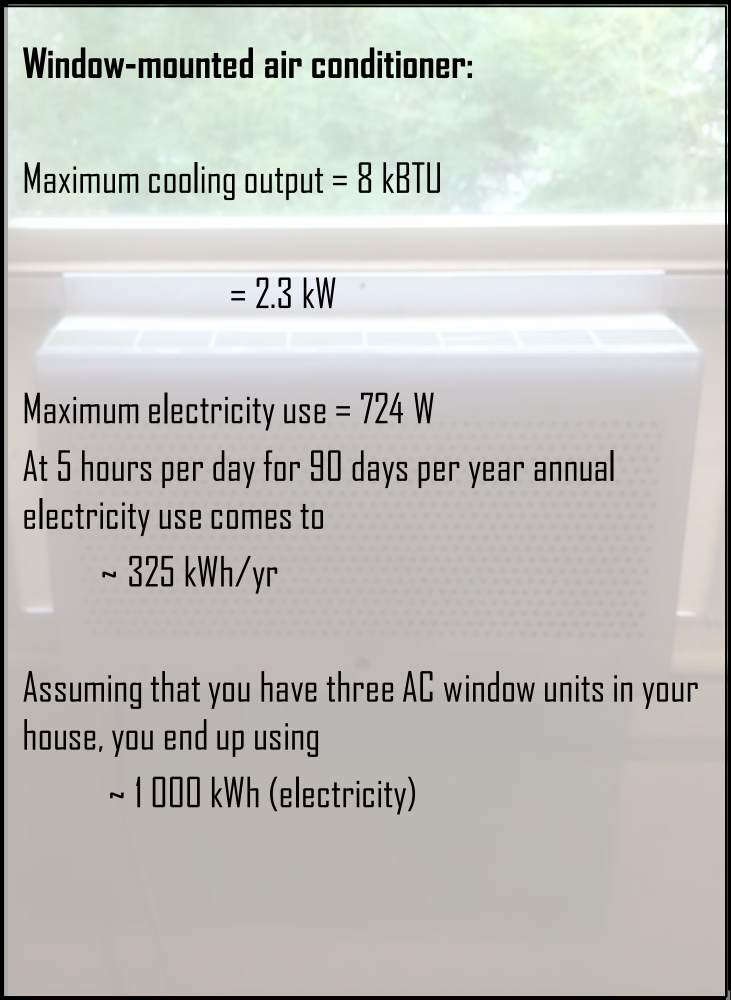
Gas boiler:

Maximum heating output = 62 kBTU/h

= 18.1 kW

Annual energy use for a small single family home in Boston ~ 1000 Therm

~ 29 000 kWh (gas)



Window-mounted air conditioner:

Maximum cooling output = 8 kBTU

= 2.3 kW

Maximum electricity use = 724 W

At 5 hours per day for 90 days per year annual electricity use comes to

~ 325 kWh/yr

Assuming that you have three AC window units in your house, you end up using

~ 1 000 kWh (electricity)

- The average US household uses 10 000 kWh of electricity per year.

Energy Units for Heating/Cooling

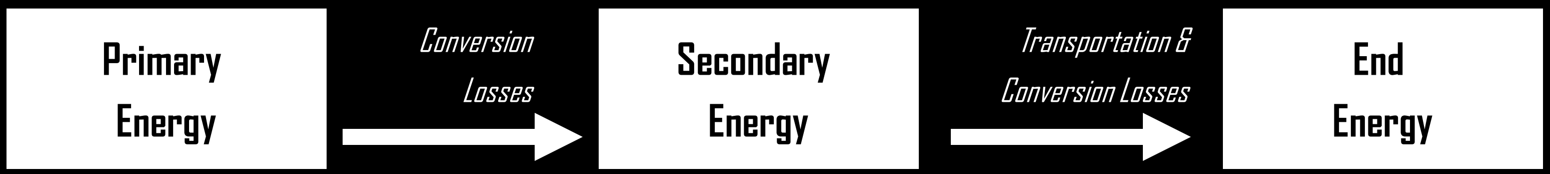
- Rule of thumb: The size of a heating and cooling unit depends on the size of the space to be cooled and very roughly corresponds to the following:

- Heating unit capacity (mild climate) = 30 BTU x floor area in feet

- Heating unit capacity (cold climate) = 60 BTU x floor area in feet

- Cooling unit capacity = 20 BTU x floor area in feet

Energy Conversion



- **Primary energy** is energy that has not been subjected to any conversion or transformation process. Primary energy is energy contained in raw fuels and any other forms of energy received by a system as input to the system.

- **Secondary energy** is energy being converted into more convenient forms of energy, such as electrical energy and cleaner fuels.

- **End Energy** is the energy delivered to a site to carry out work such as heating a house, running a fan, or lighting a room.

Table 7.5.3-1 CO_2e Emission Factors

Building Project **Energy Source**	**CO_2e** lb/kWh (kg/kWh)
Grid delivered electricity and other fuels not specified in this table	1.670 (0.758)
LPG or propane	0.602 (0.274)
Fuel oil (residual)	0.686 (0.312)
Fuel oil (distillate)	0.614 (0.279)
Coal (except lignite)	0.822 (0.373)
Coal (lignite)	1.287 (0.583)
Gasoline	0.681 (0.309)
Natural gas	0.510 (0.232)

- 10 000 kWh electricity = 7.6 ton CO_2e
- 29 000 kWh natural gas = 6.7 ton CO_2e
- Gas and electricity use have comparable environmental impact.

Energy Use Intensity (EUI)

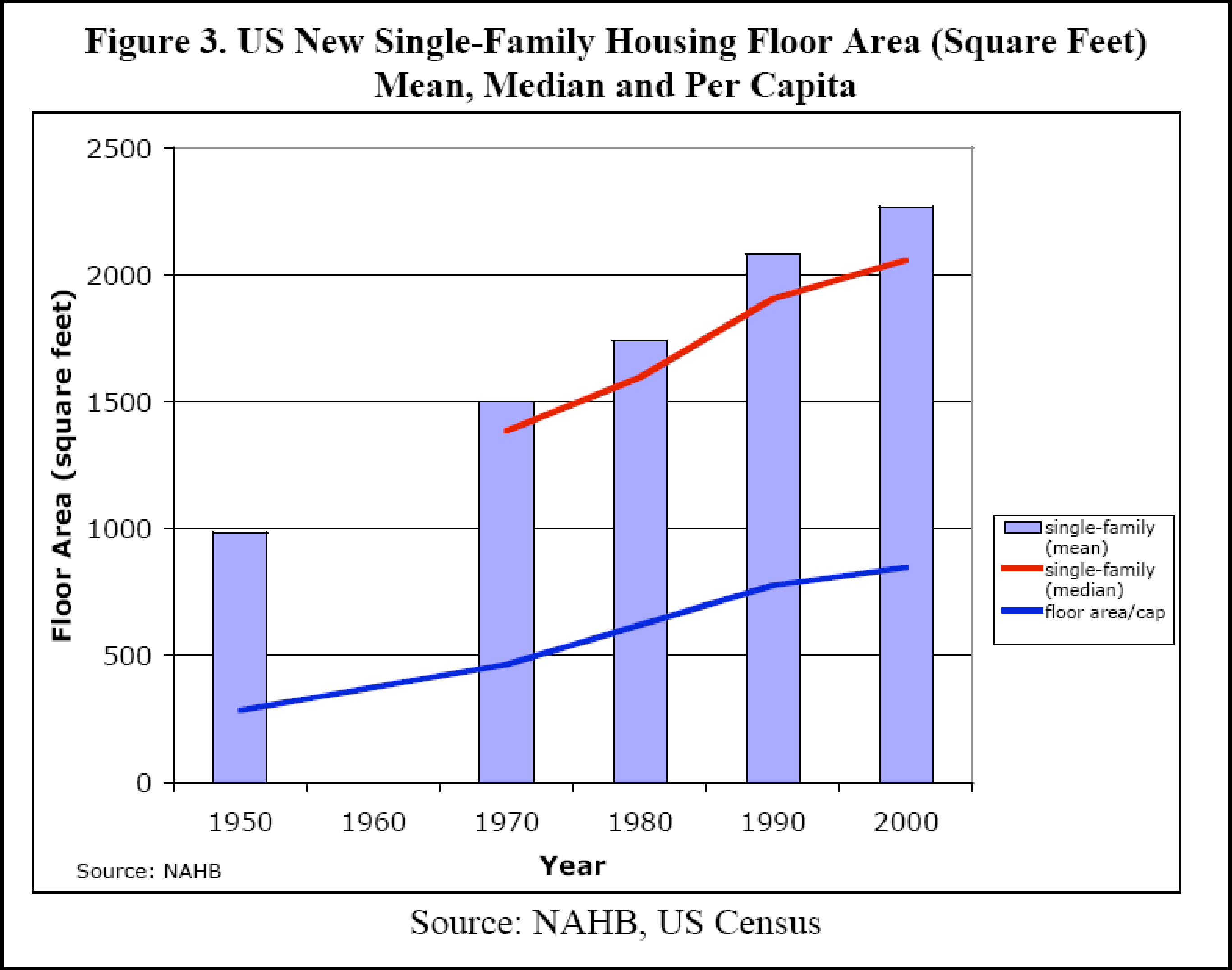
- Is a widely used performance metric to describe the energy performance of a building. It is defined as the annual site energy use of a building divided by its floor area. It is expressed in kWh/m^2yr or $kBTU/ft^2yr$ with 1 kWh/m^2yr = 317 BTU/ft^2yr

- When applied to a building that uses electricity and gas, adding energy use for gas and electricity is literally mixing "apples and oranges."

- By normalizing energy use by building size, the goal is to compare the energy performance of different buildings. This works best for buildings of comparable size, with similar programs and in related climates.

- EUI is a measure of how efficiently a space is thermally conditioned (heated and cooled) and lit. It is not a measure of the efficiency of the building program. In fact, having a spatially inefficient program with occupants and equipment spread over a larger area can reduce the EUI of a building.

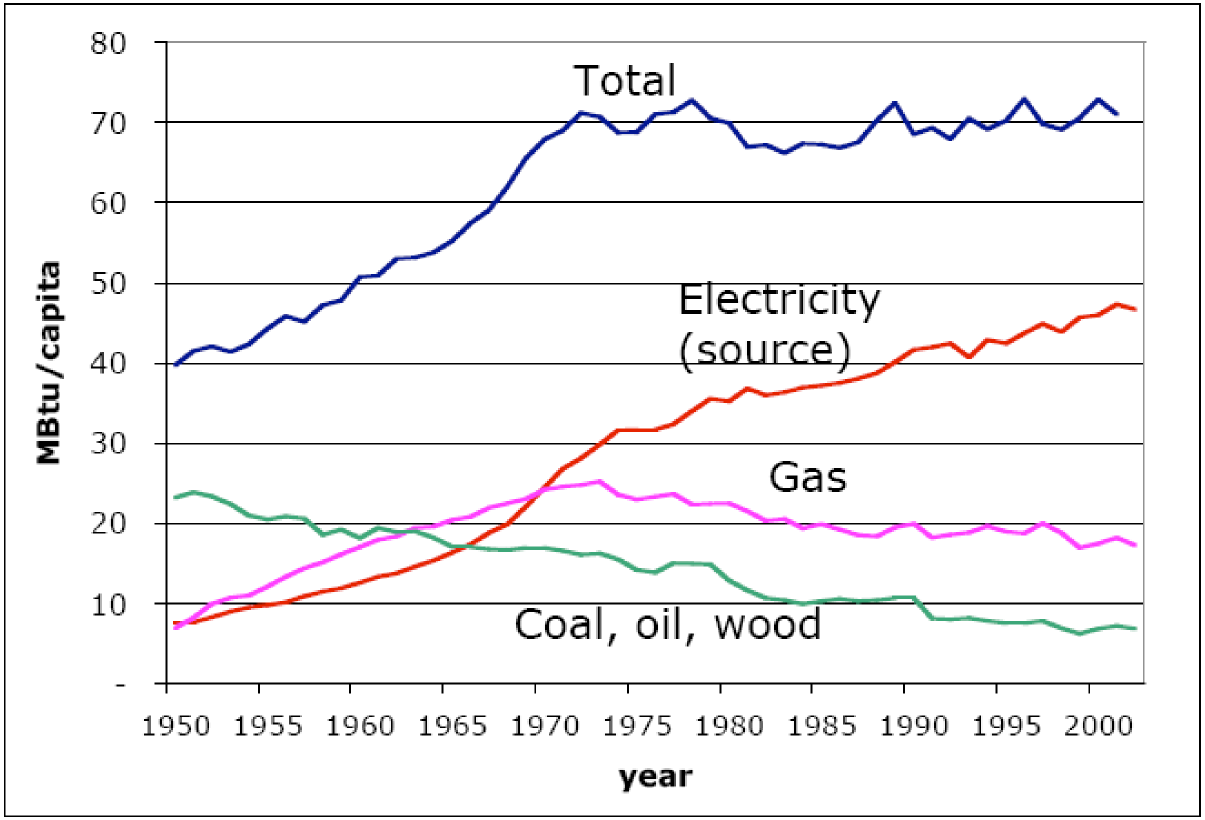
Floor Area of US Residential Buildings



SDLAB

Energy Use per Capita

Figure 2. US Residential Energy Use Per Capita, Total, Electricity [Source], Gas and Other (MBtu/cap)



Source: EIA 2003

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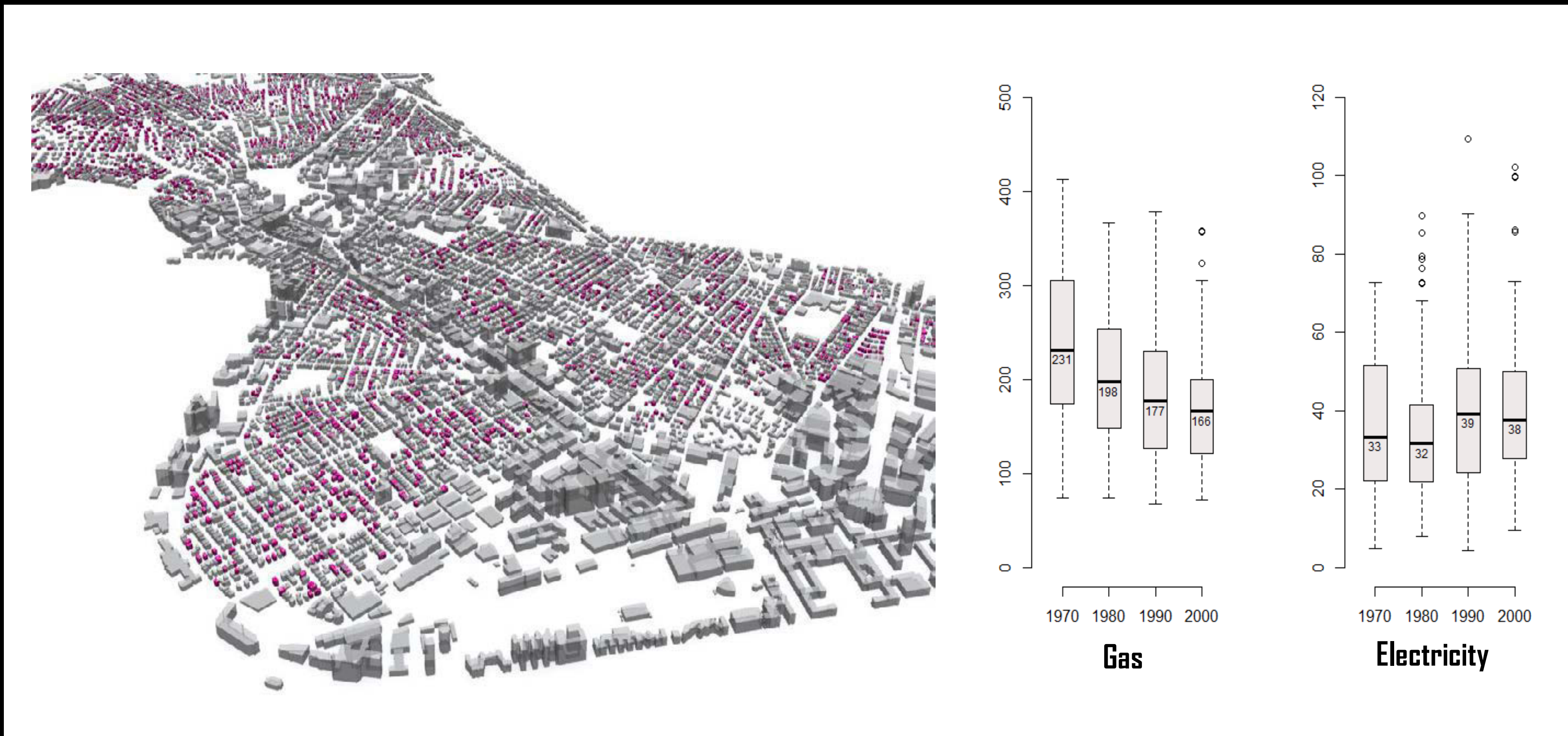
Building Energy Use by Age



Beyond Energy Use Intensity

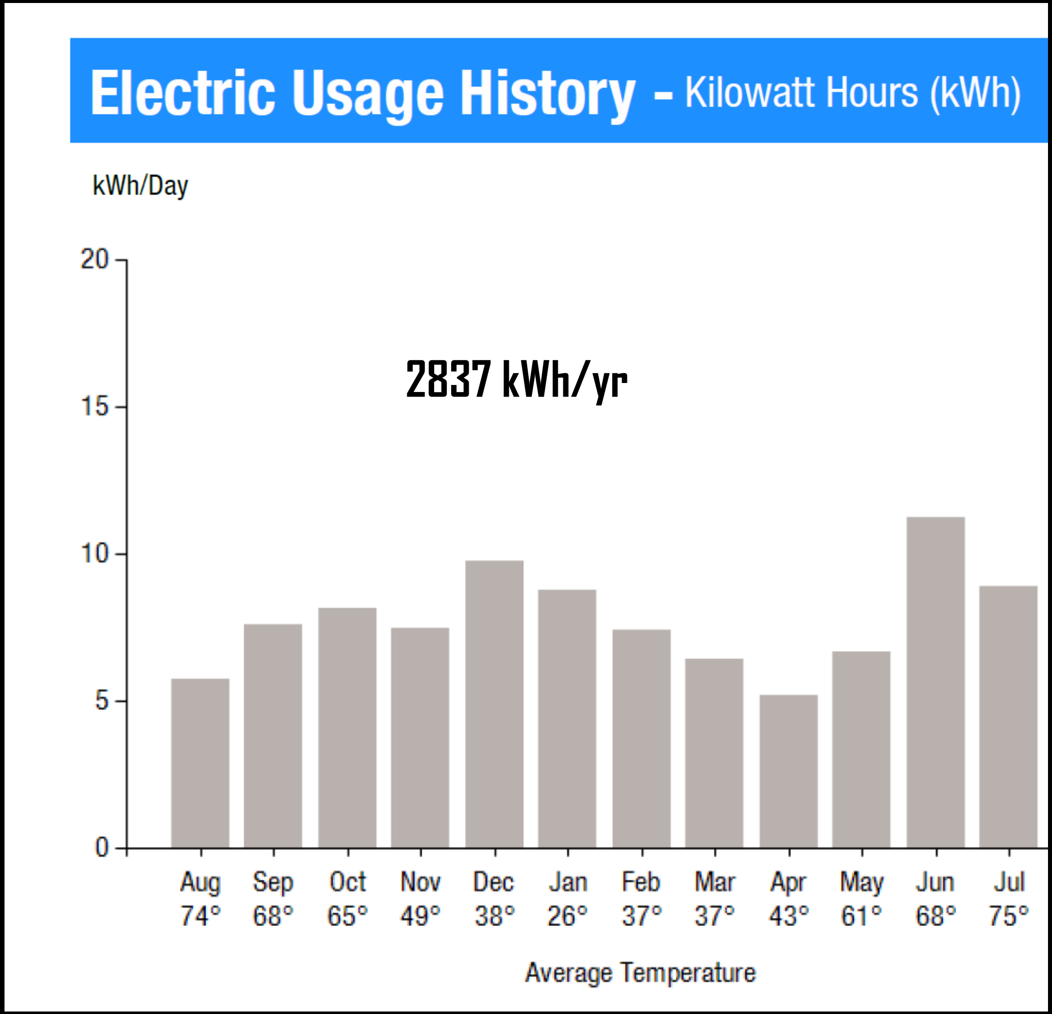
- For day-to-day decisions owners favor costs and/or maintenance costs per floor area to analyze buildings.

- To overcome some of the limitations of EUI, annual energy use for a space can be normalized by person hours used. This metric interprets a building as a service provider for comfortable space conditions (adequate temperature and lighting).

- The drawback of this metric is that it largely lies out of the control of the architect how a building is being used. Is a building design "bad" because occupants behave inefficiently?

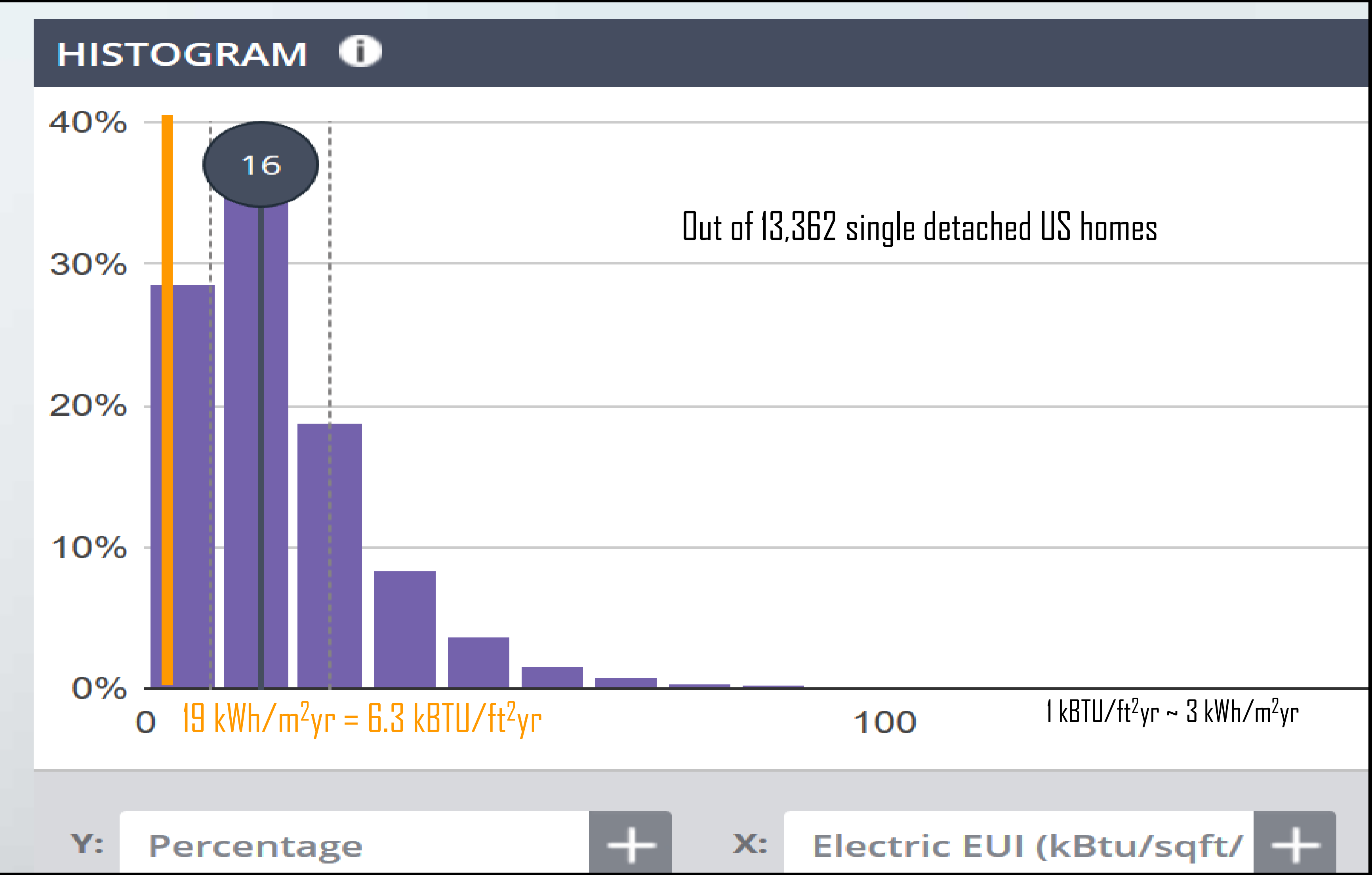
- On the other side, is a high EUI for an office building that is being used 24/7 an indication of poor performance?

Assignment 1: Your Past Energy Use

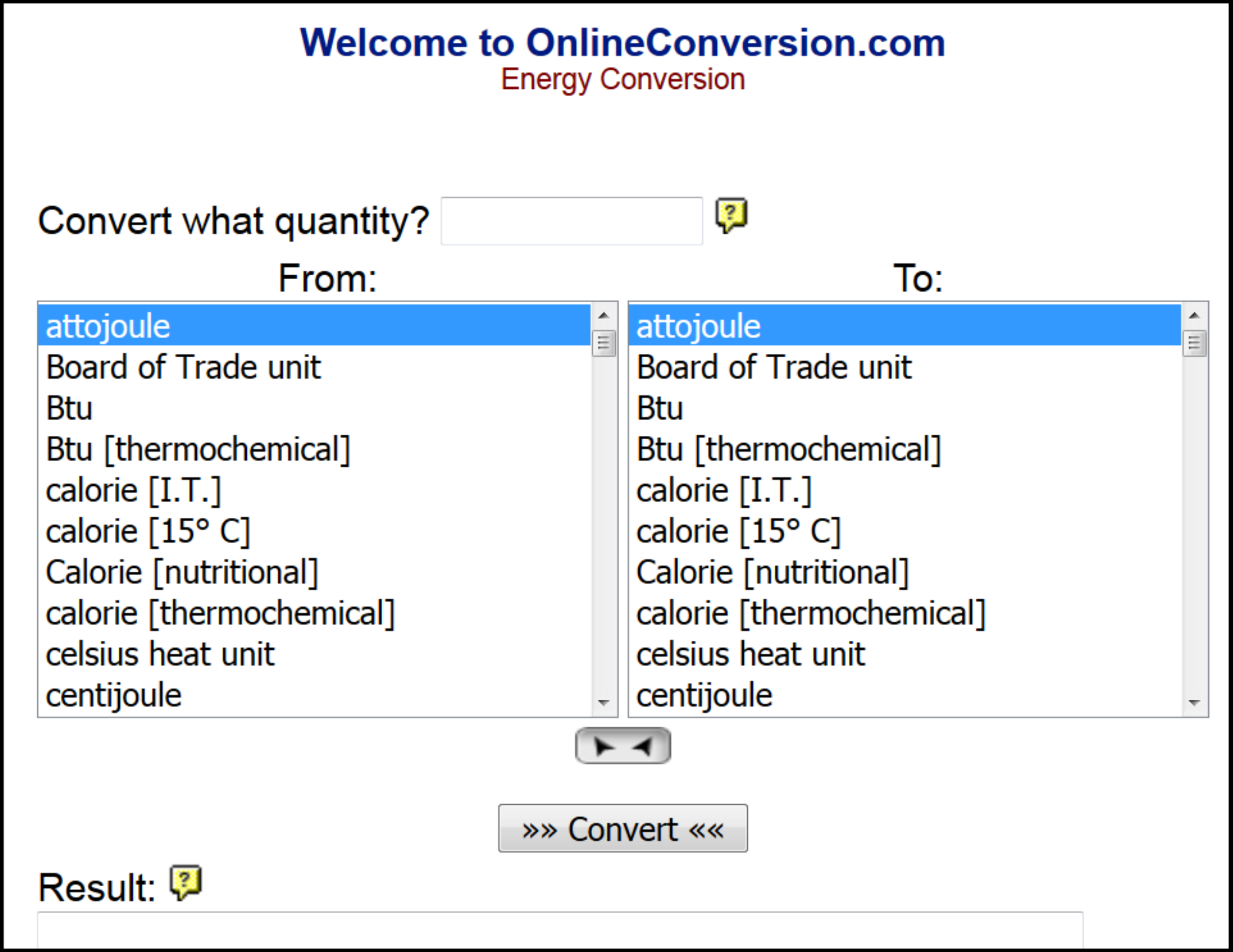


- 2837 kWh/yr / 150 m2 ~ 18.9 kWh/m^2 yr
- 2837 kWh/ yr / 4 person ~ 709 kWh/person year

Buildings Performance Database

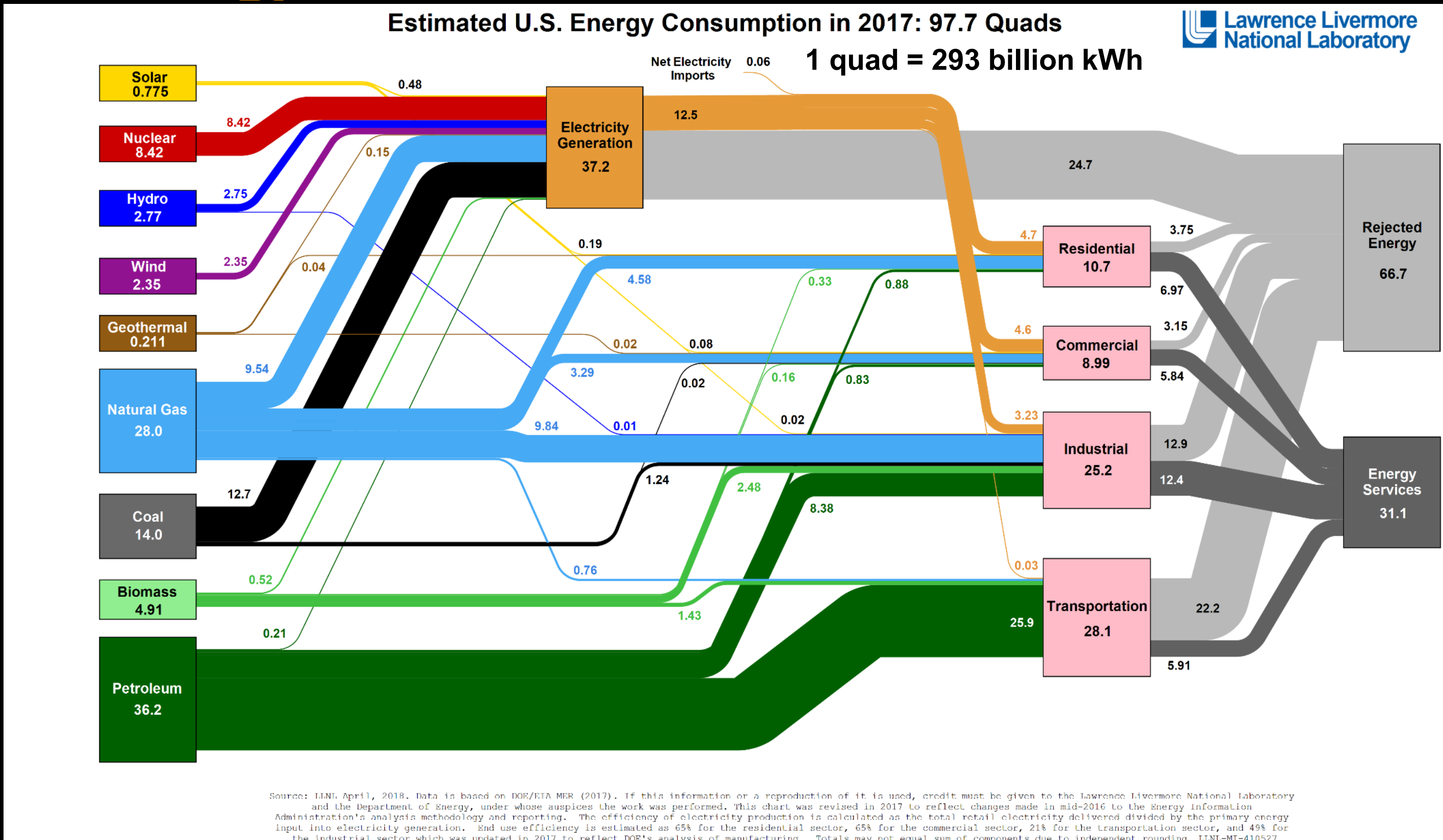


Handy Online Energy Converter



How does building energy use fit in the overall US energy infrastructure?

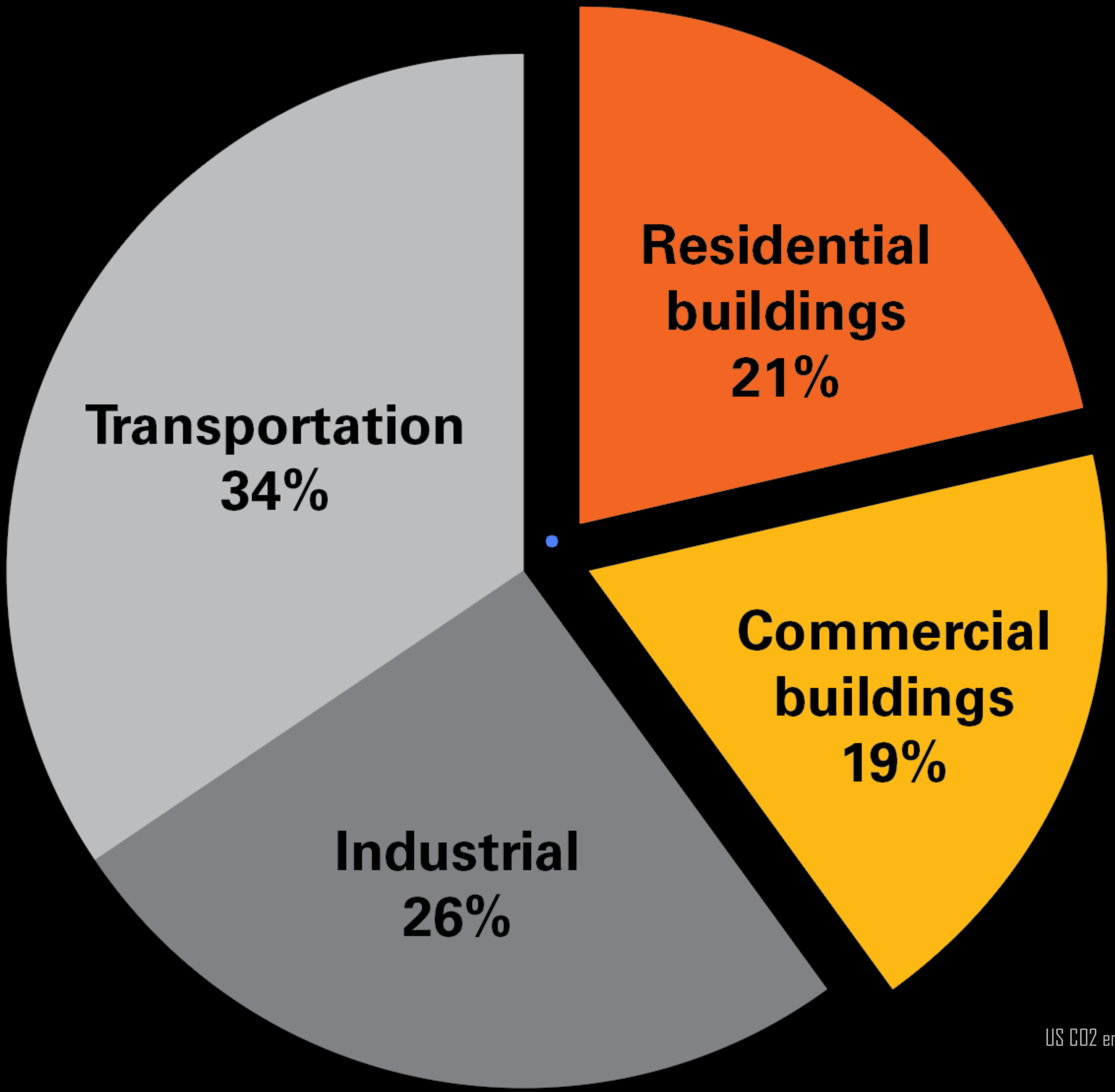
US Energy Flows 2017



Source: https://flowcharts.llnl.gov/content/assets/images/energy/us/Energy_US_2017.png. This image is in the public domain.

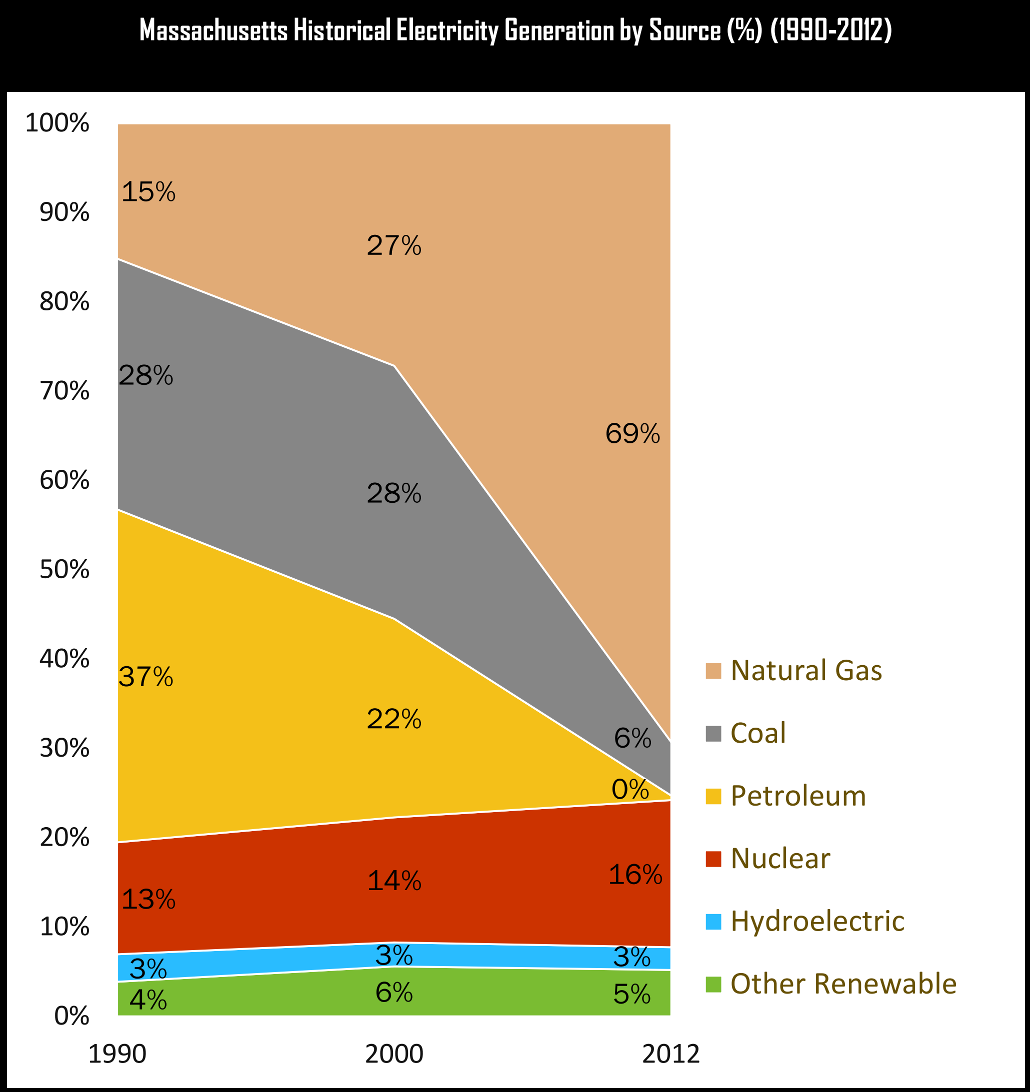
Electricity Use: 1/3 Industrial, 1/3 Residential, 1/3 Commercial

End Energy Use: 1/3 Transportation, 1/3 Industrial, **1/3 Buildings**



US CO2 emission by sector

Decarbonization of the Electric Grid



Graph based on data from http://www.eia.gov/state/?sid=MA.

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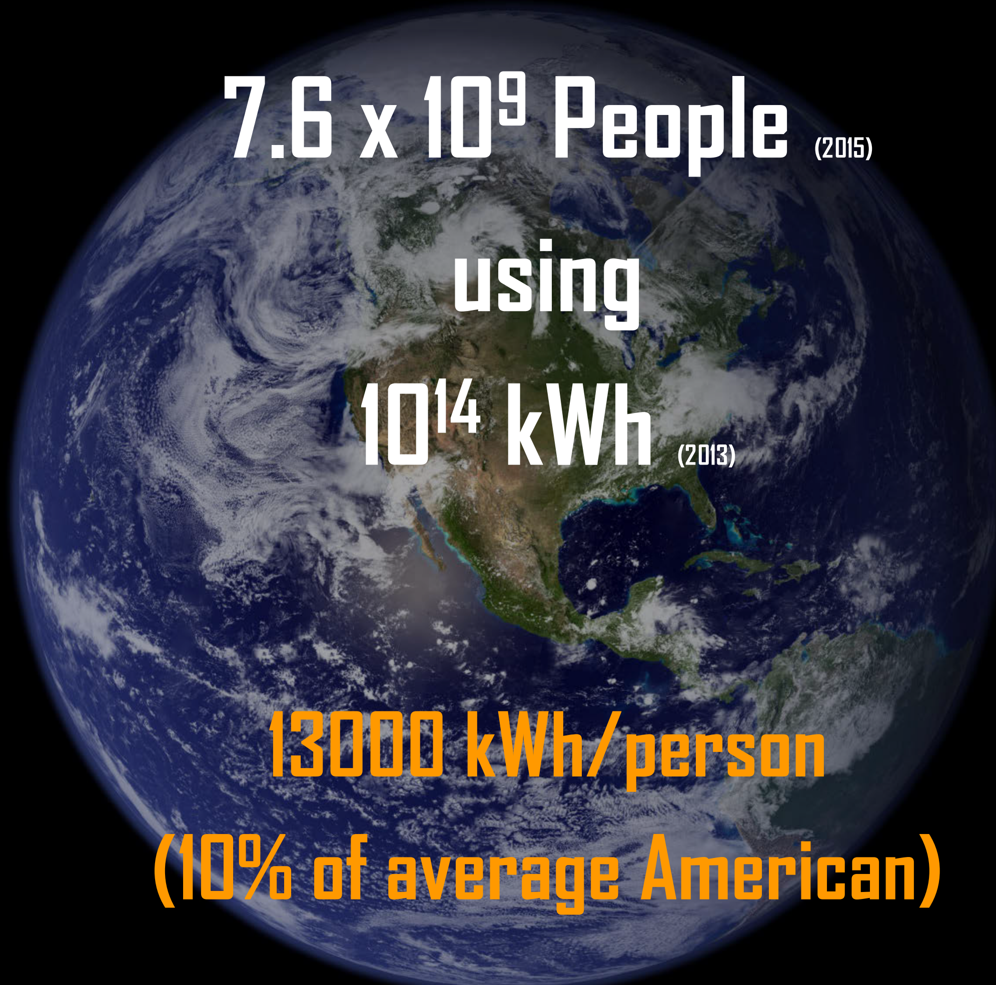
How do we compare to the rest of the world?

World Energy Use and Population



7.6×10^9 People (2015)

using

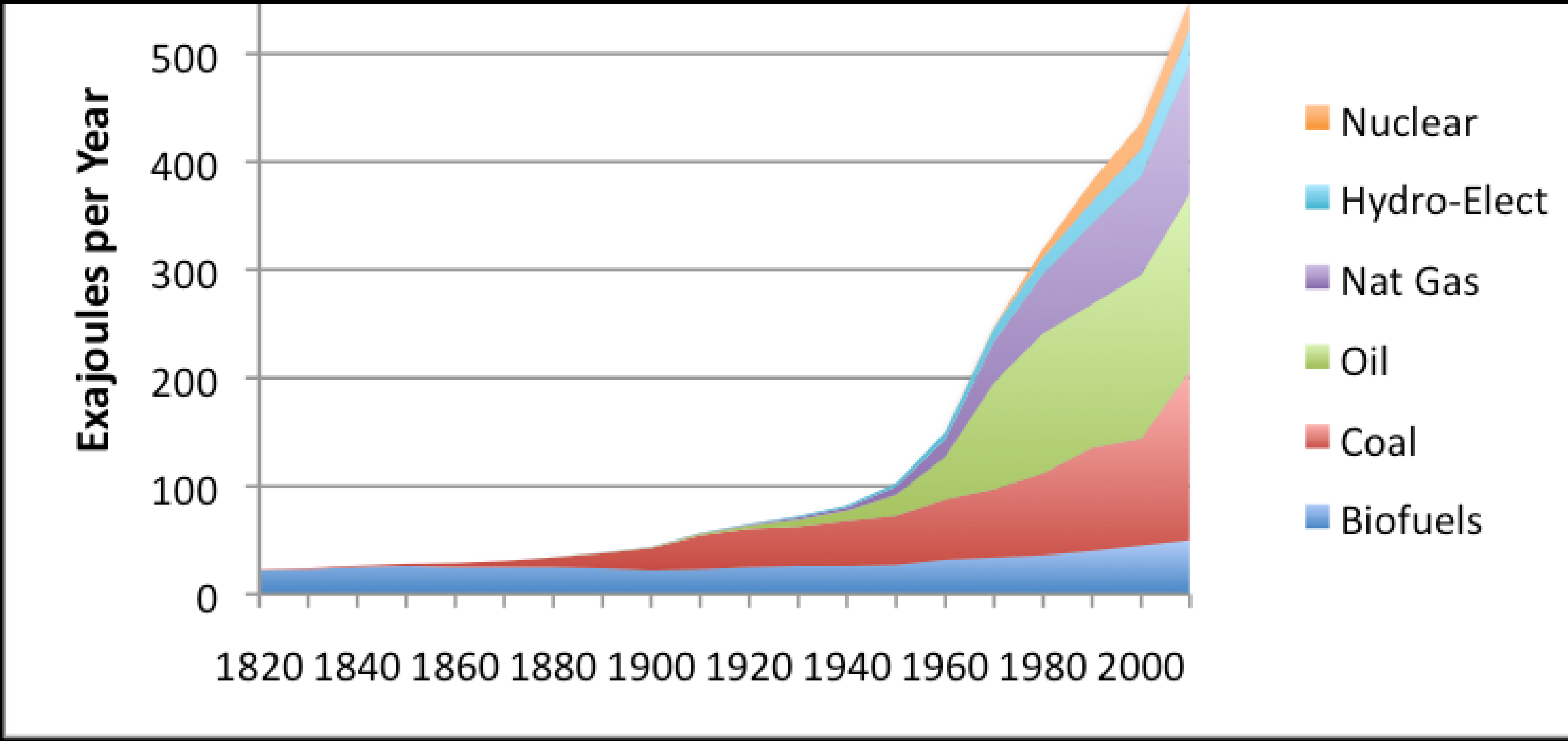
10^{14} kWh (2013)

13000 kWh/person

(10% of average American)

Public domain image courtesy of NASA Goddard Space Flight Center.

Where does our energy come from?



High Performance Buildings

Terminology
Sustainable – Green – Net Zero

❑ These are related but different terms to characterize the environmental performance of a building. When developing an environmental concept for a building, the design team should early on agree upon what type of building they aim to design.

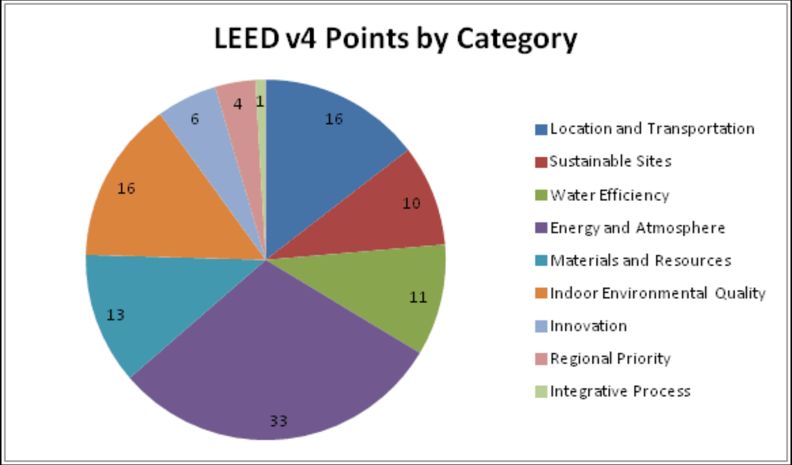
- Sustainable: most comprehensive as it addresses societal, economic, and environmental concerns.
- Green: includes operational energy use, embodied energy use, on site resource management, and occupancy well-being
- Net zero energy: concentrates on balanced use and generation of energy (differences exist as to whether energy has to be generated on-site or off-site and whether the cost for energy or primary energy should be considered. Embodied energy of the building structure is sometimes considered as well.)

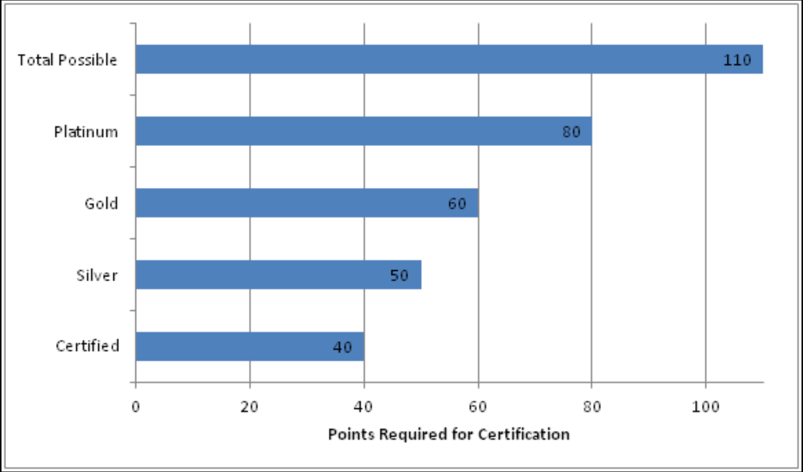
‘Green’ Building Design

Greenbuild 2011

- The ‘green’ building market has become a mass movement (Greenbuild ~30,000 visitors, Light+Building 180,000 visitors).

LEED – A Market Transformation Tool

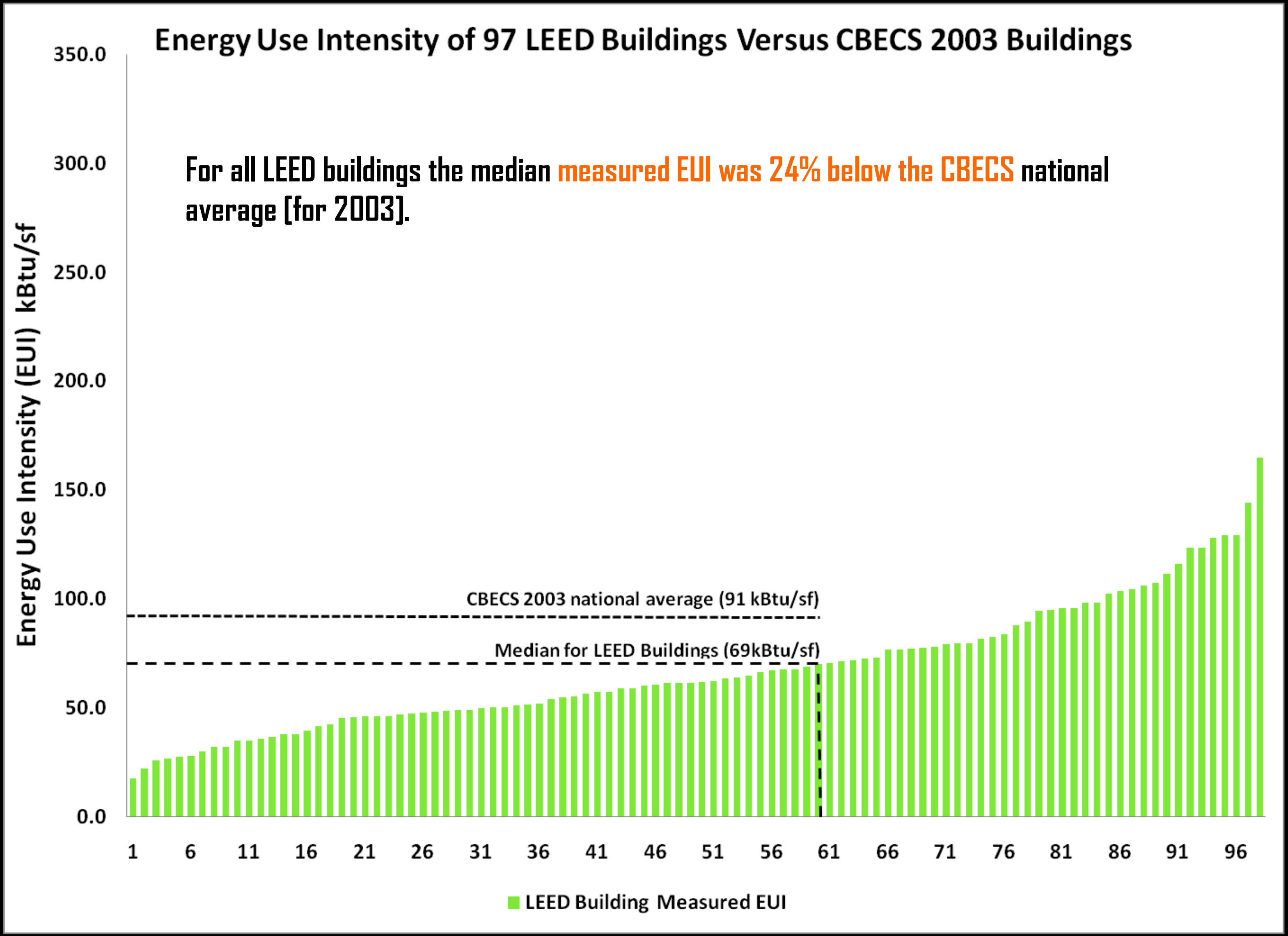




- LEED is a green building rating system.
- LEED stands for Leadership in Energy and Environmental Design.
- LEED operates at the building levels and addresses: Sustainable Sites, Water Efficiency, Energy & Atmosphere, Materials and Resources, and Indoor Environmental Quality.
- As of fall 2016, ~150,000 buildings were LEED registered and certified (106,000 homes, 33,500 commercial projects).
- LEED ratings come in Certified, Silver, Gold and Platinum.

Energy Performance of LEED Buildings

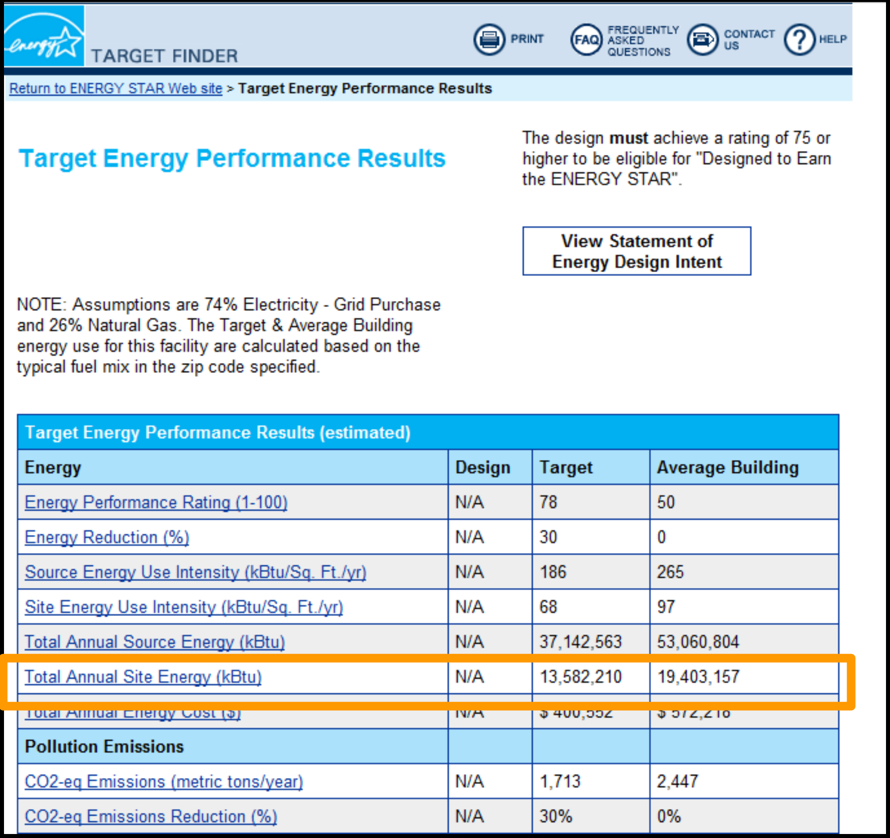
New Buildings Institute (NBI) Study (2008)



Graph based on data from www.gbci.org.
Note: 552 LEED-NC buildings were certified in 2006

Energy Star Target Finder

- ❑ A useful first step is to establish a meaningful baseline for energy use.
- ❑ The Energy Star Target Finder is based on the US Energy Information Administration's Commercial Building Energy Consumption Survey (CBECS).
- ❑ CBECS 2003: ~5000 commercial buildings across the US

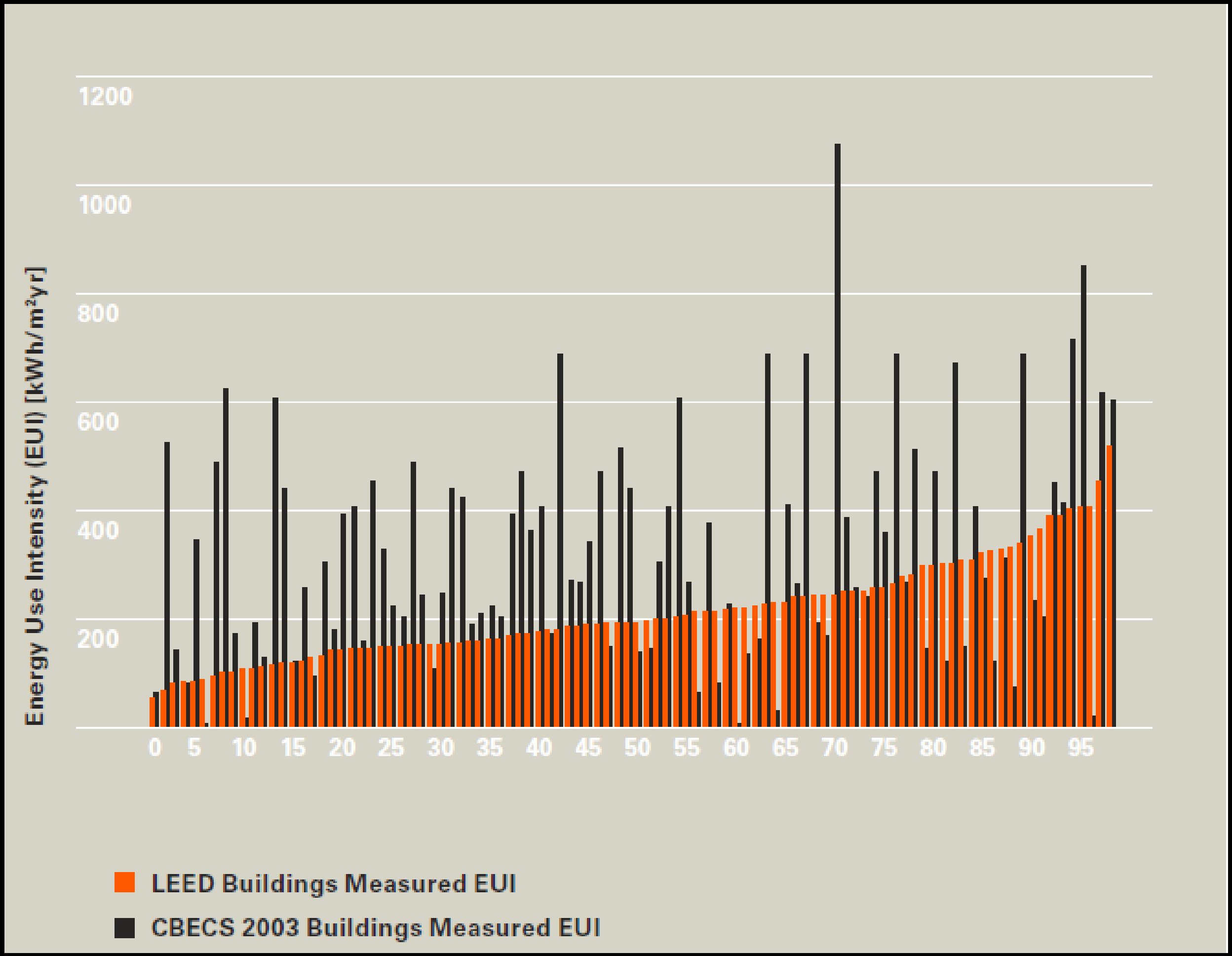


Target Energy Performance Results (estimated)			
Energy	**Design**	**Target**	**Average Building**
Energy Performance Rating (1-100)	N/A	78	50
Energy Reduction (%)	N/A	30	0
Source Energy Use Intensity (kBtu/Sq. Ft./yr)	N/A	186	265
Site Energy Use Intensity (kBtu/Sq. Ft./yr)	N/A	68	97
Total Annual Source Energy (kBtu)	N/A	37,142,563	53,060,804
Total Annual Site Energy (kBtu)	N/A	13,582,210	19,403,157
Total Annual Energy Cost ($)	N/A	$ 400,552	$ 572,218
Pollution Emissions			
CO2-eq Emissions (metric tons/year)	N/A	1,713	2,447
CO2-eq Emissions Reduction (%)	N/A	30%	0%

This image is in the public domain.

http://www.energystar.gov/buildings/service-providers/design/step-step-process/evaluate-target/epa%E2%80%99s-target-finder-calculator

Performance of LEED Buildings

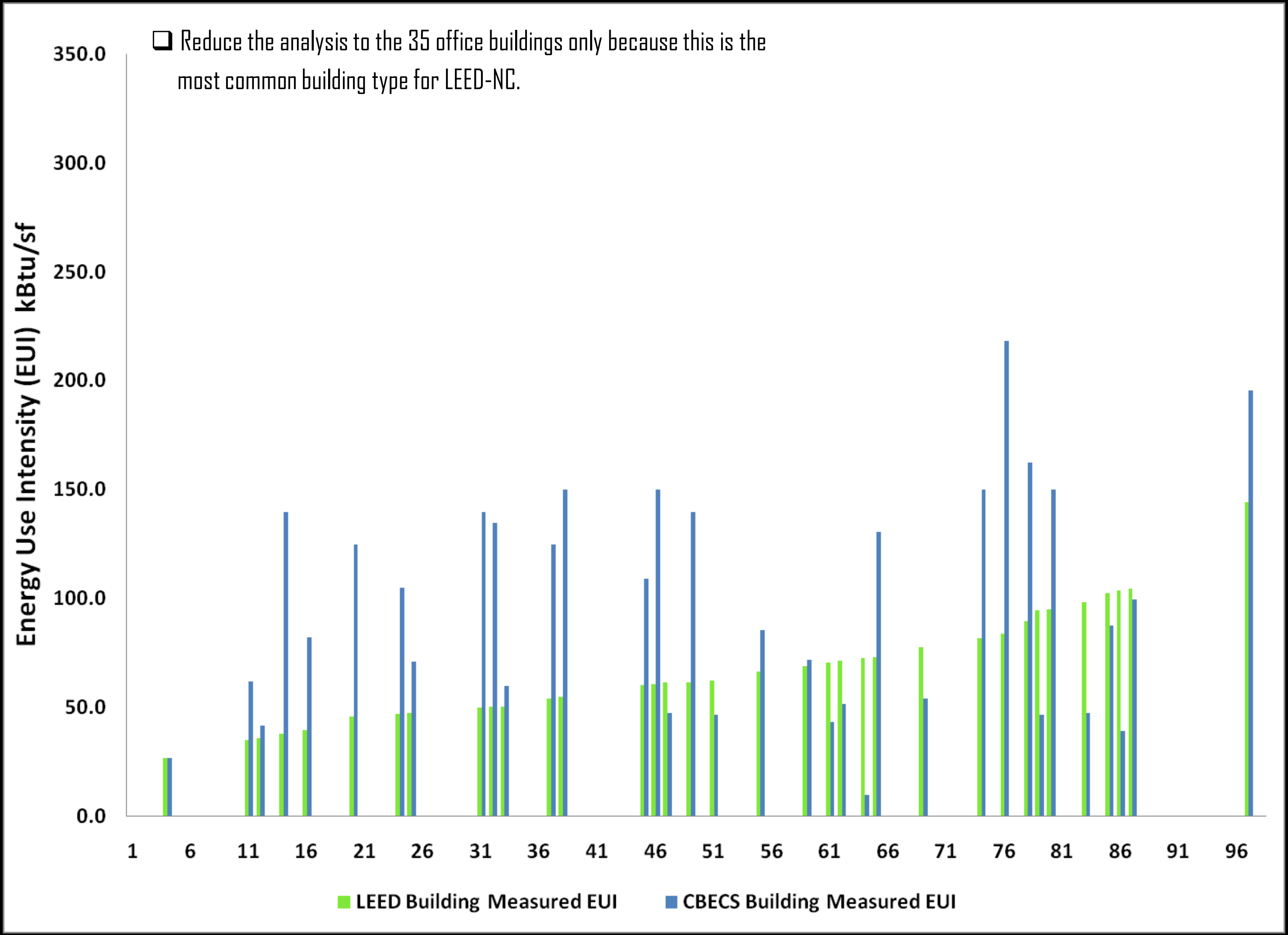


Graph based on LEED-NBI data, CBECS matching by Newsham et al, 2009

- LEED buildings have on average a 30% lower EUI (Energy Use Intensity).
- A third of LEED buildings had a higher EUI than their matched CBEC counterpart.

Energy Performance of LEED Buildings

DO LEED buildings save energy? Not Really …

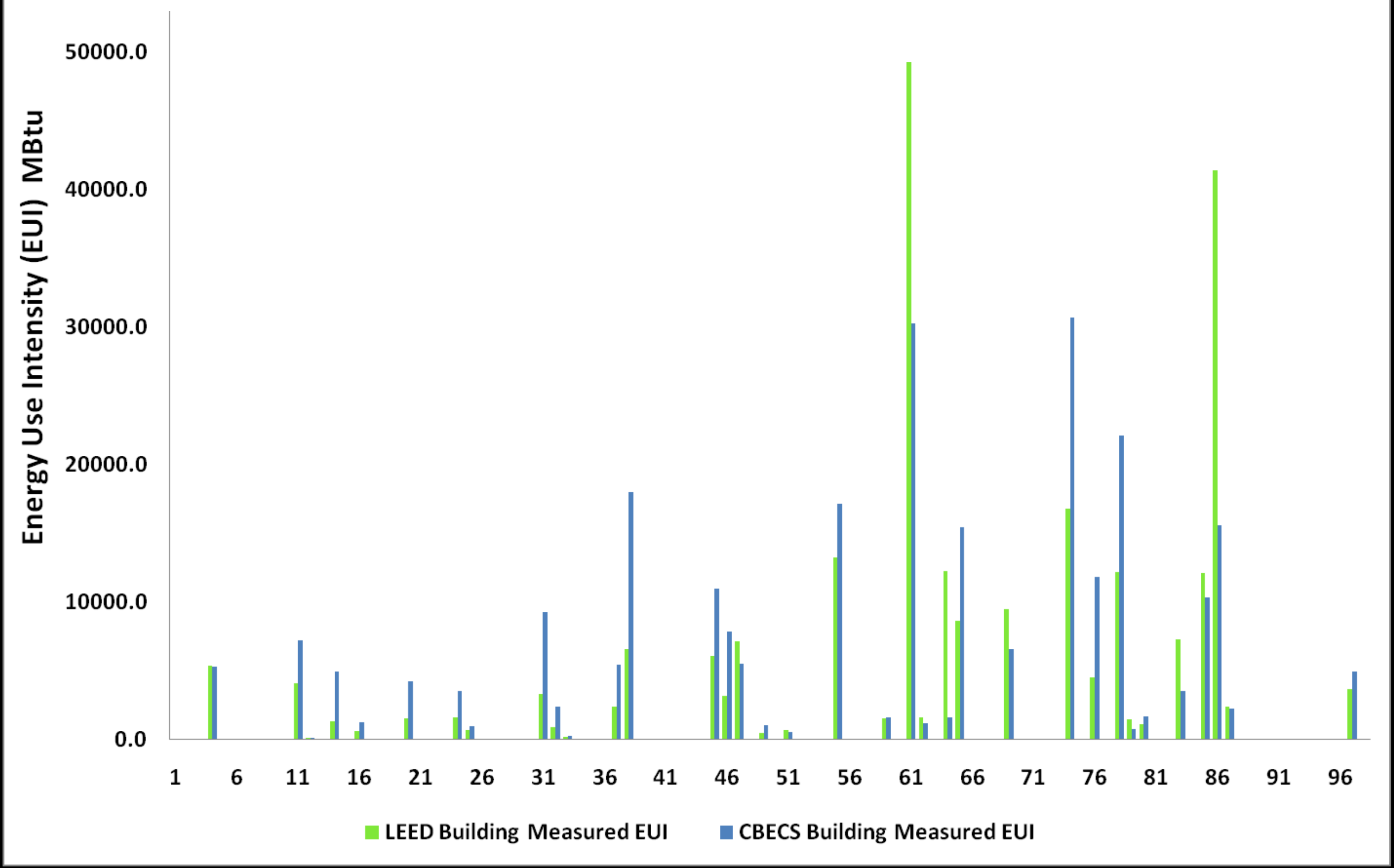


Paper: J H Scofield, "Do LEED-certified buildings save energy? Not really…," *Energy and Buildings*, Volume 41, Issue 12, December 2009, Pages 1386-1390

Energy Performance of LEED Buildings

DO LEED buildings save energy? Not Really …

- ❑ Multiply EUI with floor area for each building.
- ❑ Result: "35 LEED office buildings and Newsham's matching CBECS office buildings are statistically equivalent."



Paper: J H Scofield, "Do LEED-certified buildings save energy? Not really…" *Energy and Buildings,* Volume 41, Issue 12, December 2009, Pages 1386-1390

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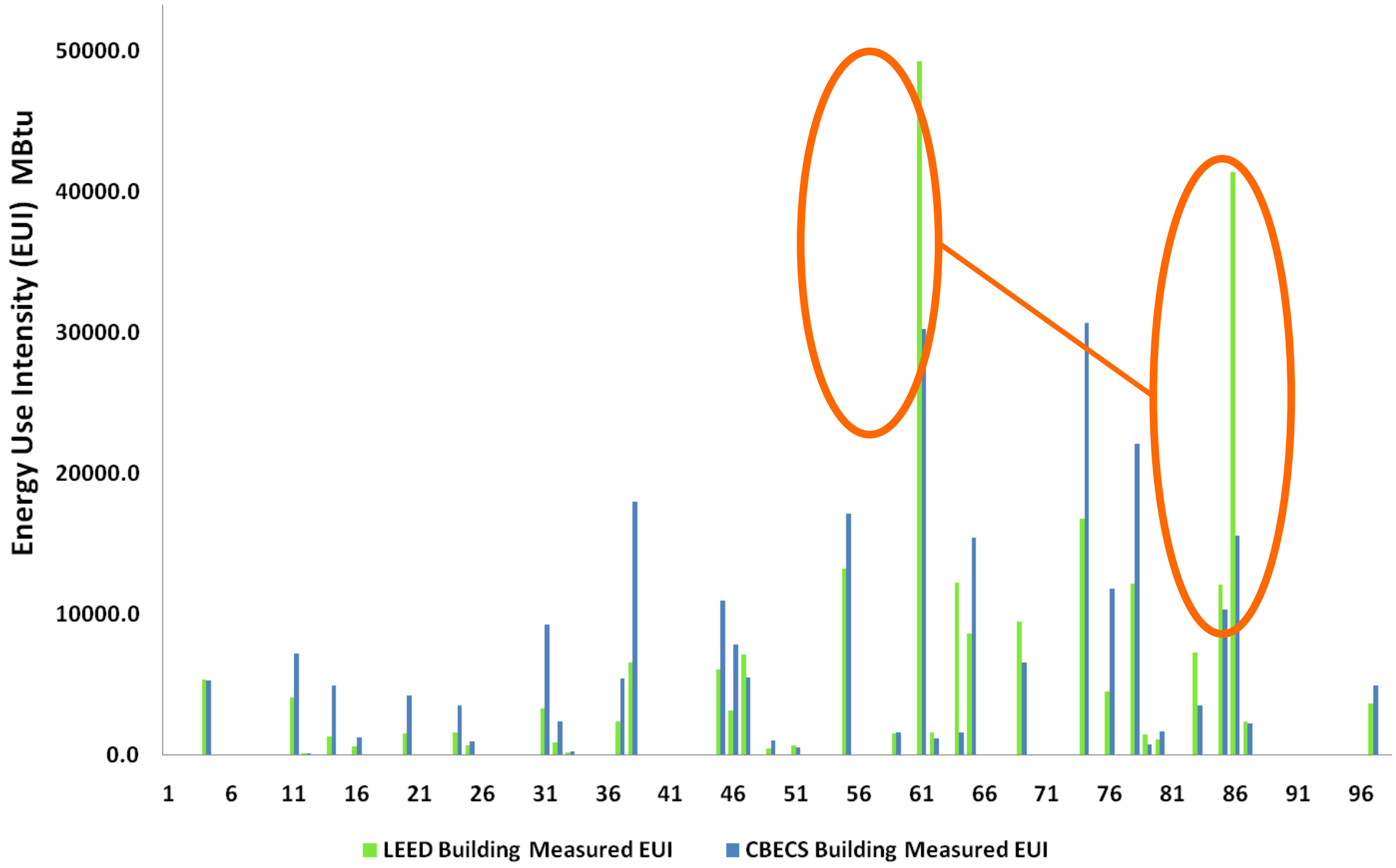
Energy Performance of LEED Buildings

DO LEED buildings save energy? Not really …

- ❑ Notice significance of two large buildings (700000 ft² and 400000 ft²).
- ❑ Are smaller LEED office buildings generally more energy-efficient than larger buildings? (Argument on the 'over-use' of PV in smaller buildings.)



Paper: J H Scofield, "Do LEED-certified buildings save energy? Not really…" *Energy and Buildings*, Volume 41, Issue 12, December 2009, Pages 1386-1390

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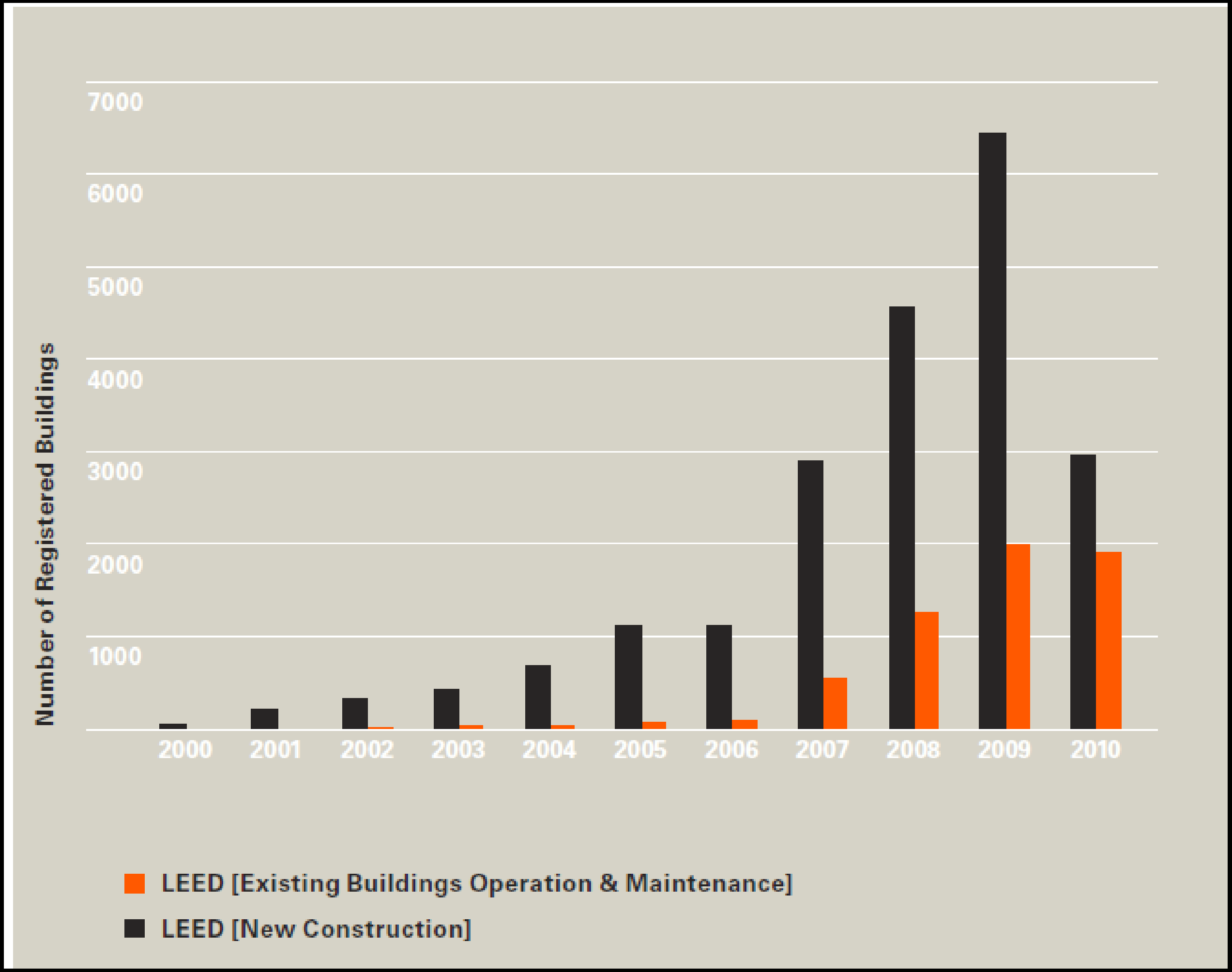
Trend for LEED-NC and LEED-EBOM



Graph based on USGBC data.

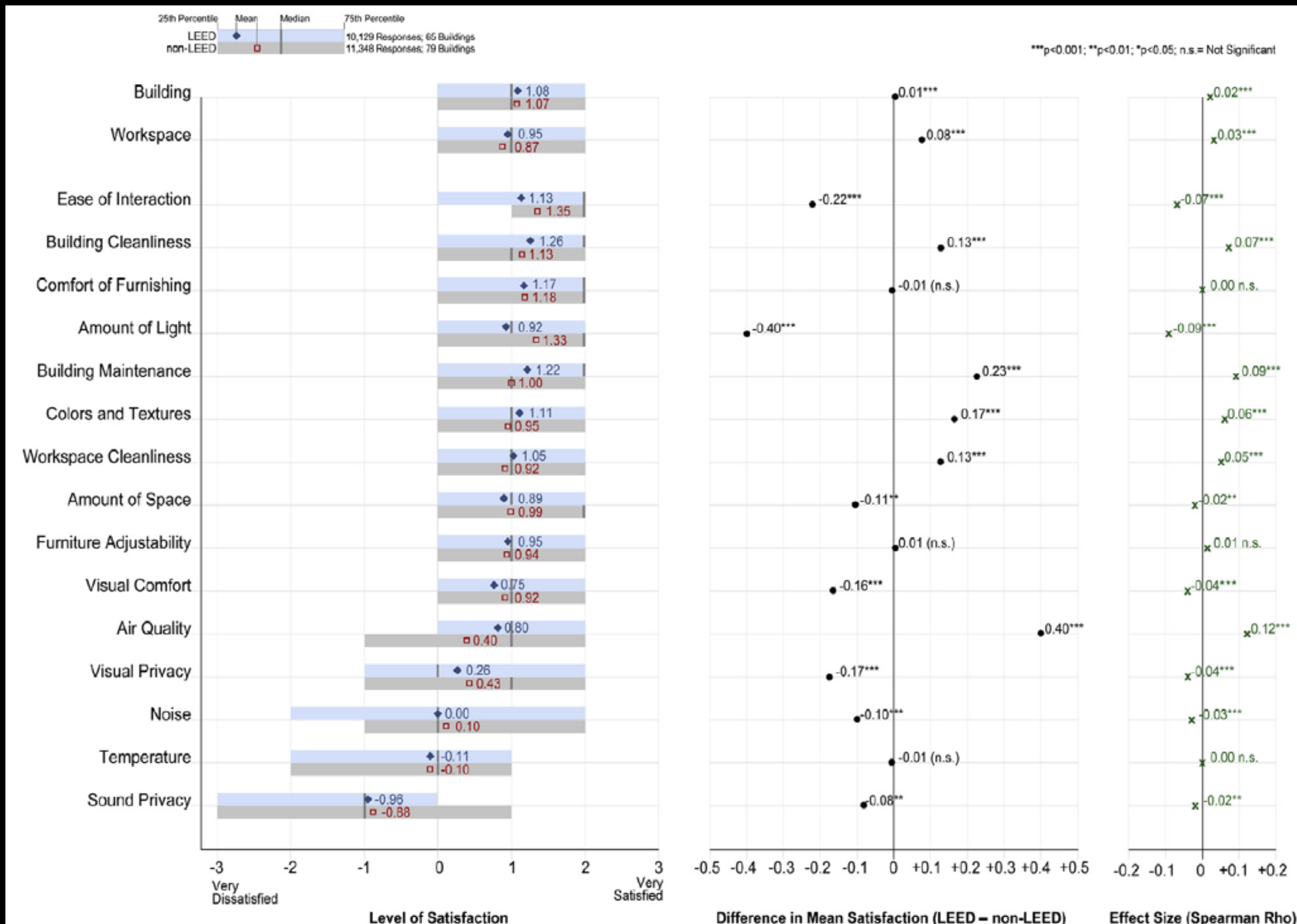
- Owners are learning that commissioning is key.

Environmental Satisfaction in LEED Buildings (2006)

Graph based on data from S. Abbaszadeh et al., 2006.

- Environmental satisfaction with lighting and acoustics in LEED buildings the same as in conventional buildings. Main complaint: "not enough daylight."
- In 2009, out of over 1200 buildings that were certified under LEED, 43% and 66% were awarded the daylighting and view credits, respectively.

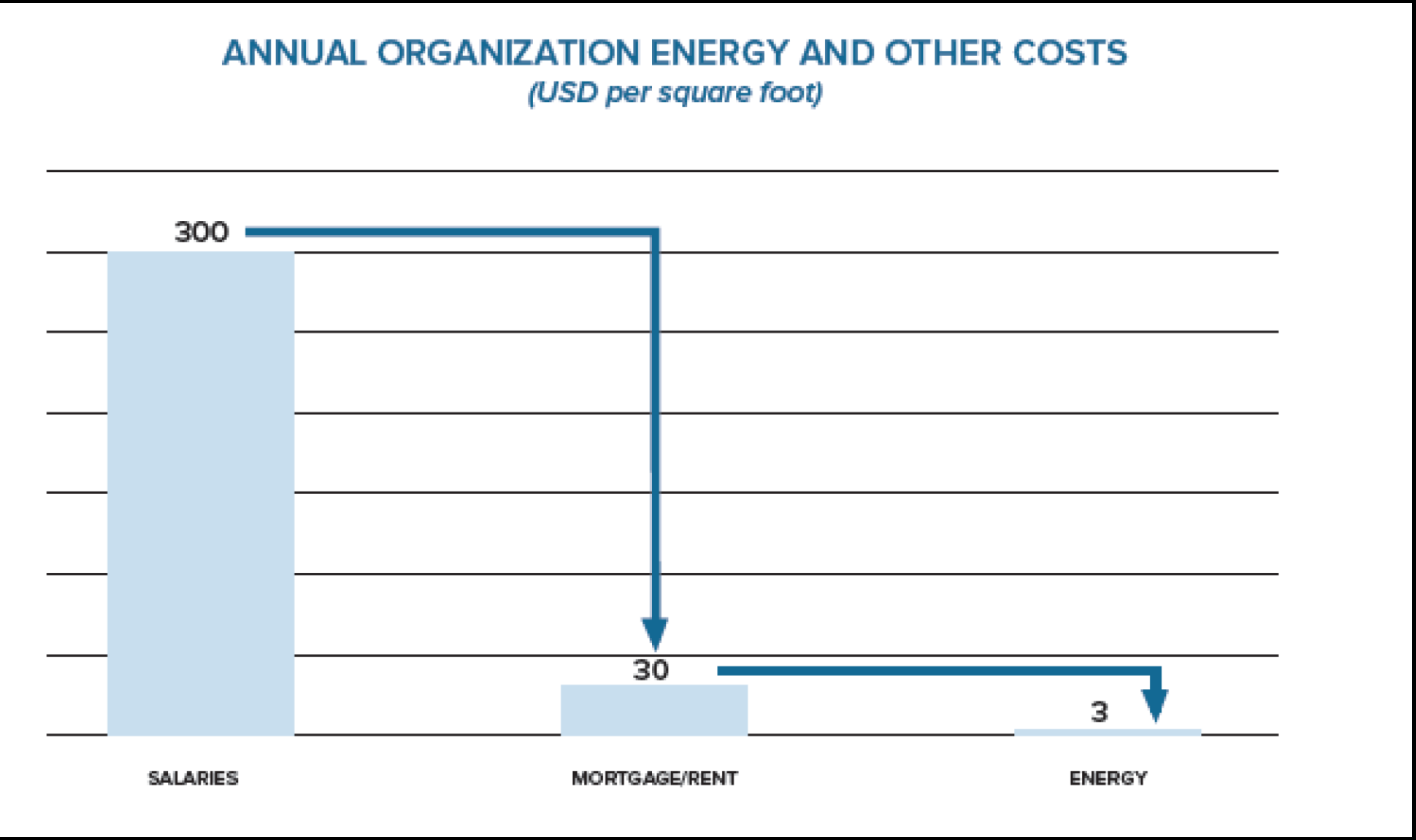
Environmental Satisfaction in LEED Buildings (2013)



S. Altomonte, S. Schiavon, 2013, "Occupant satisfaction in LEED and non-LEED certified buildings," *Building and Environment* 68, pp. 66-76. Courtesy of Elsevier, Inc., https://www.sciencedirect.com. Used with permission.

- Occupants of LEED certified buildings are equally satisfied with the building overall and with the workspace as occupants of non-LEED buildings are.
- Occupants of LEED buildings tend to be slightly more satisfied with the air quality and workspace cleanliness and less satisfied with the amount of light, visual privacy and amount of space than occupants of non-LEED buildings.

This is important because …



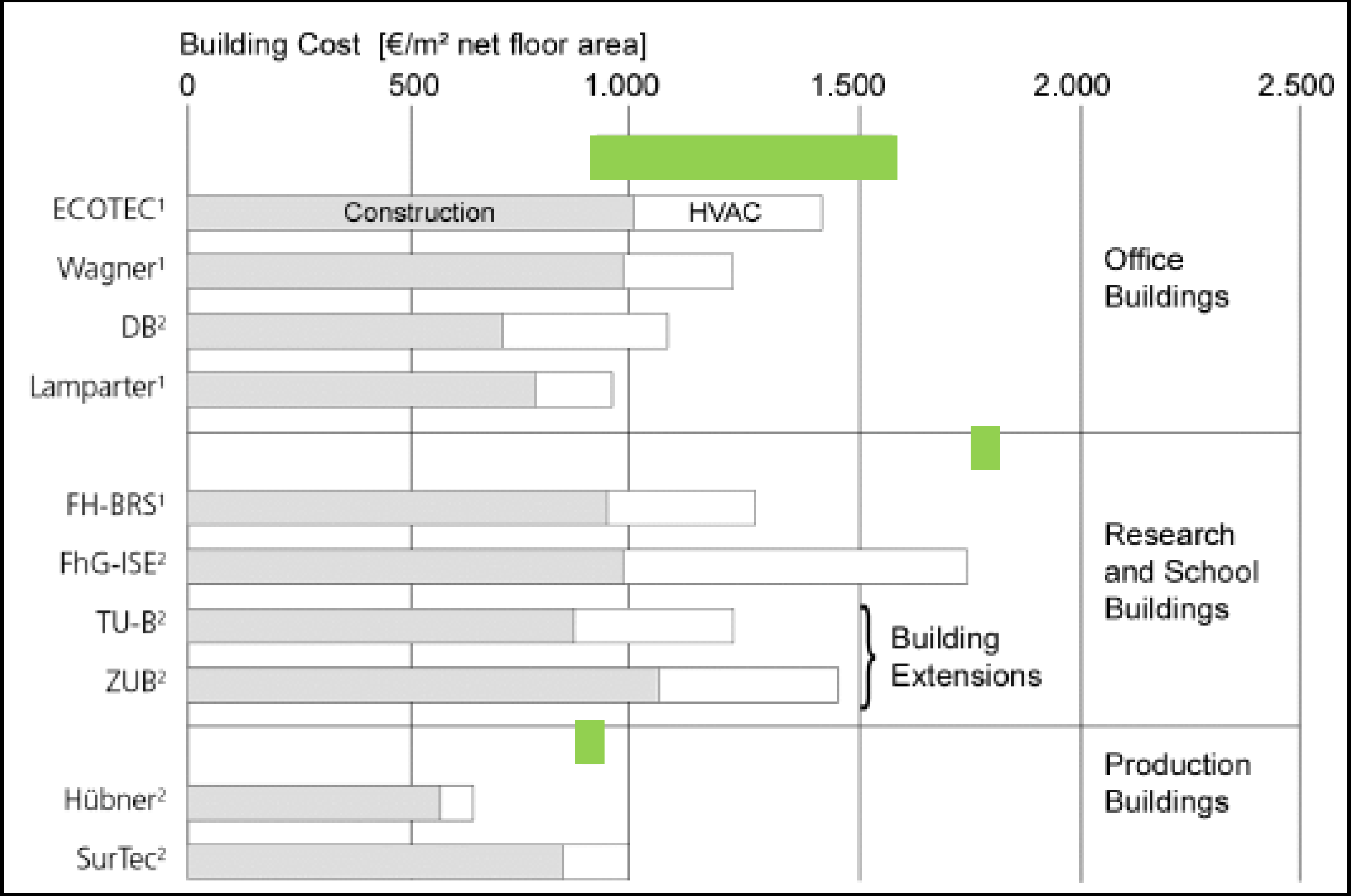
Financial Performance of LEED & Energy Star Buildings

"We find that buildings with a 'green rating' command rental rates that are roughly 3 percent higher per square foot than otherwise identical buildings – controlling for the quality and the specific location of office buildings. *Ceteris paribus,* premiums in effective rents are even higher – above 6 percent. Selling prices of green buildings are higher by about 16 percent.

Our analysis establishes that variations in the premium for green office buildings are systematically related to their energy-saving characteristics. For example, calculations show that a one dollar saving in energy costs from increased thermal efficiency yields roughly 18 dollars in the increased valuation of an Energy-Star certified building."

Eichholtz, Kok, Quigley 2009
http://www.ucei.berkeley.edu/PDF/csemwp192.pdf

Construction Costs for High Performance German Buildings

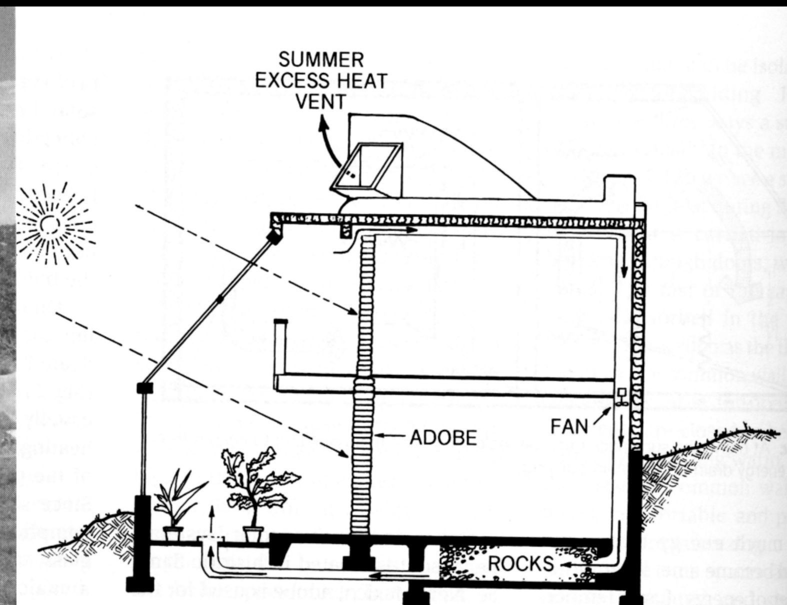


Costs for German reference buildings in 2000

Paper: Reinhart C F, Voss K, Wagner A, Löhnert G, "Lean buildings: Energy-efficient commercial buildings in Germany." Proceedings of the ACE[3] 2000 Summer Study on Energy Efficiency in Buildings 3 pp. 3.287-3.298, Pacific Grove, USA, August 2000.

Selected Examples

Solar Architecture (1978)



Two-story sunspace, thermal mass, Trombe wall, active air circulation system for thermal comfort, 83% solar heated.

Self-Sufficient Solar House Freiburg

- South-exposed half cylinder
- Air-to-ground heat exchanger
- Ventilation-heat-recovery
- Solar hot water
- Photovoltaics 4.2 kW_{peak}
- Transparent insulating panels
- Fuel cells and hydrogen tanks

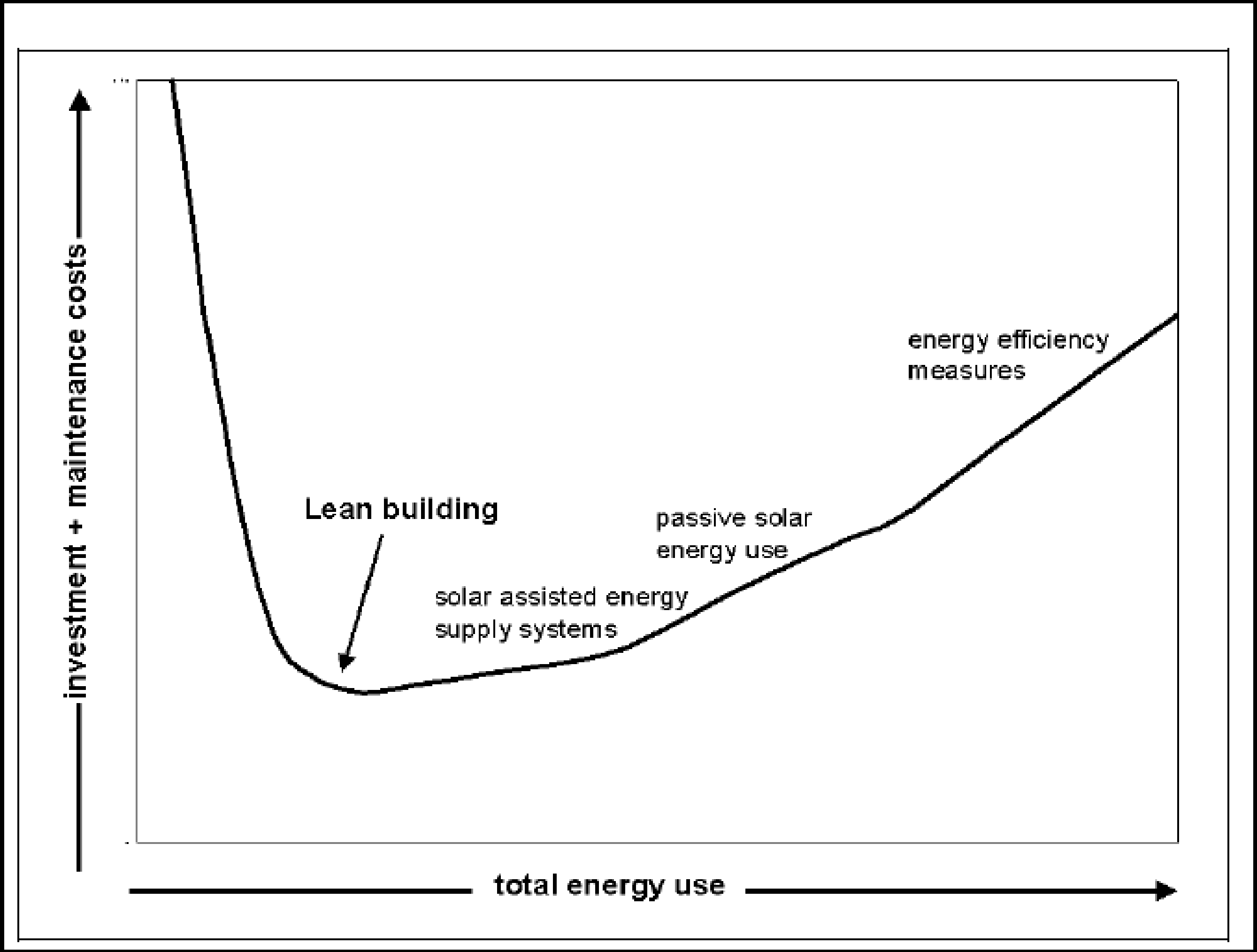
Self-sufficient solar house Freiburg, 1991
Architecture: Planerwerkstatt Hölken & Berghoff

Mixed reactions in the architectural community:

the building of the future … a building in the emergency room

Lean Building ('Schlankes Gebäude')

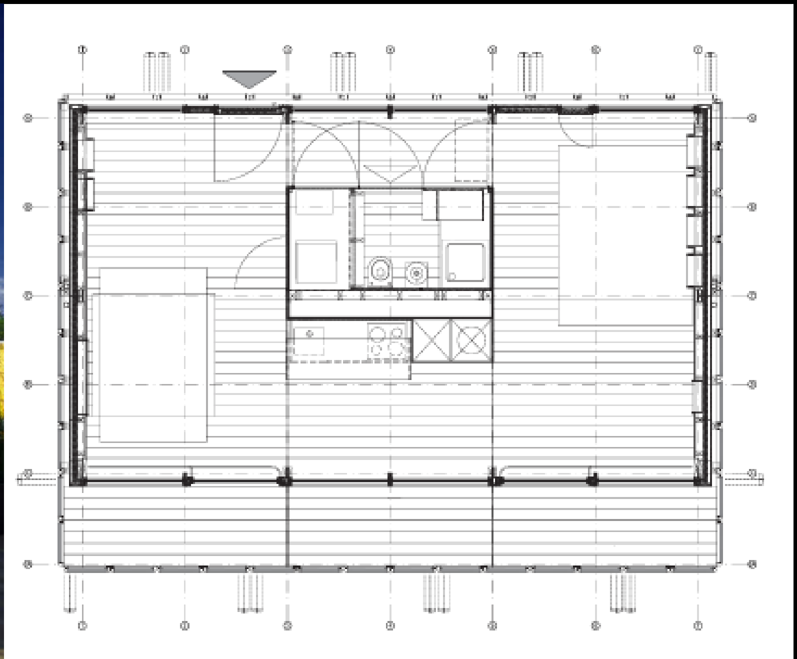
Reinhart, Voss, Wagner 2000)



Using the electric grid for energy storage.

Finding the 'sweet spot'.

Selected Solar Home (2007)



Solar Decathlon Winner 2007 (Team Germany)

"Made in Germany." Triple glazing, thermal mass through PCM, exterior wooden shutters, PV on the roof, integrated lighting system, clear architectural forms

Passive House

- ❑ Reduced heating demand 15 kWh/m² per year
- ❑ Tight building envelope (blower door $n_{50} < 0.6\ hr^{-1}$).
- ❑ Energy-efficient appliances and domestic hot water heating (total primary energy use for heating, hot water and electricity less than 120 kWh/m² per year.

Zero Net Energy Buildings

This is a Zero Net Energy Building

What does that mean?

ZEB

A ZEB is a non grid connected, energy efficient building matching its energy needs by on-site generation fully based on renewables.

Net ZEB

A Net ZEB is a grid connected, energy efficient building that balances its total annual energy needs by on-site or near-by generation and associated feed-in credits.

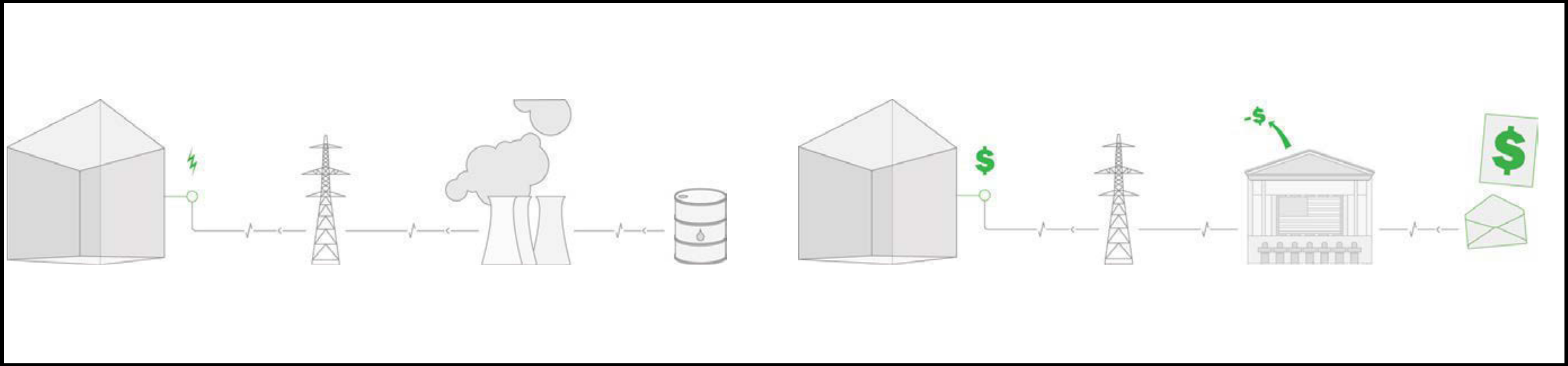
Net ZEC

A Net ZEC is a cluster of buildings fulfilling the net zero balance in total using the identical, local energy infrastructure. The cluster uses benefits from the economy of scale and levelling out the load and generation profiles of each building.

Zero Net Energy Building Definition

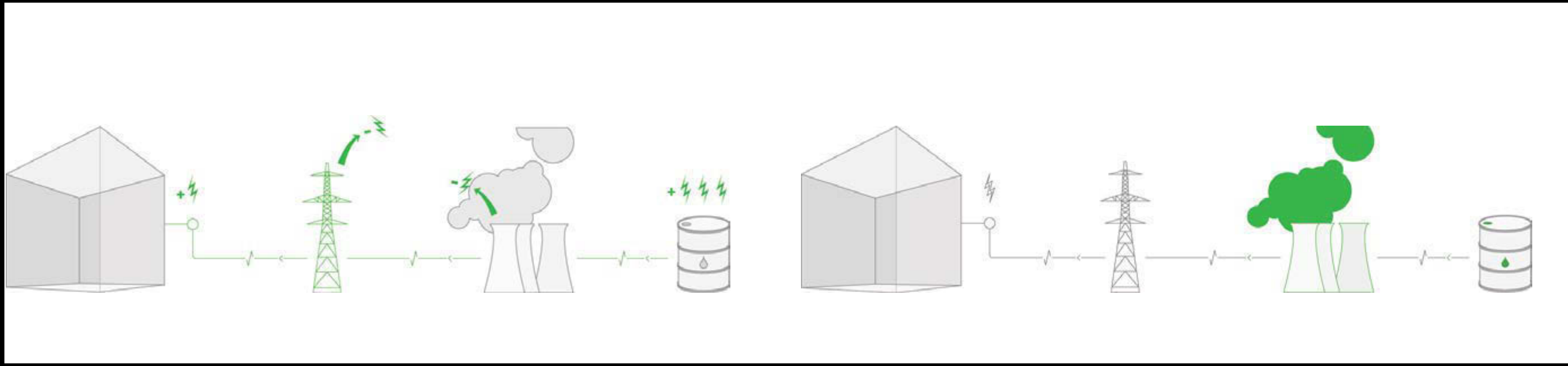
Net Zero Site Energy: produces as much as it uses

Net Zero Energy Costs: aims for an annual energy bill of $0



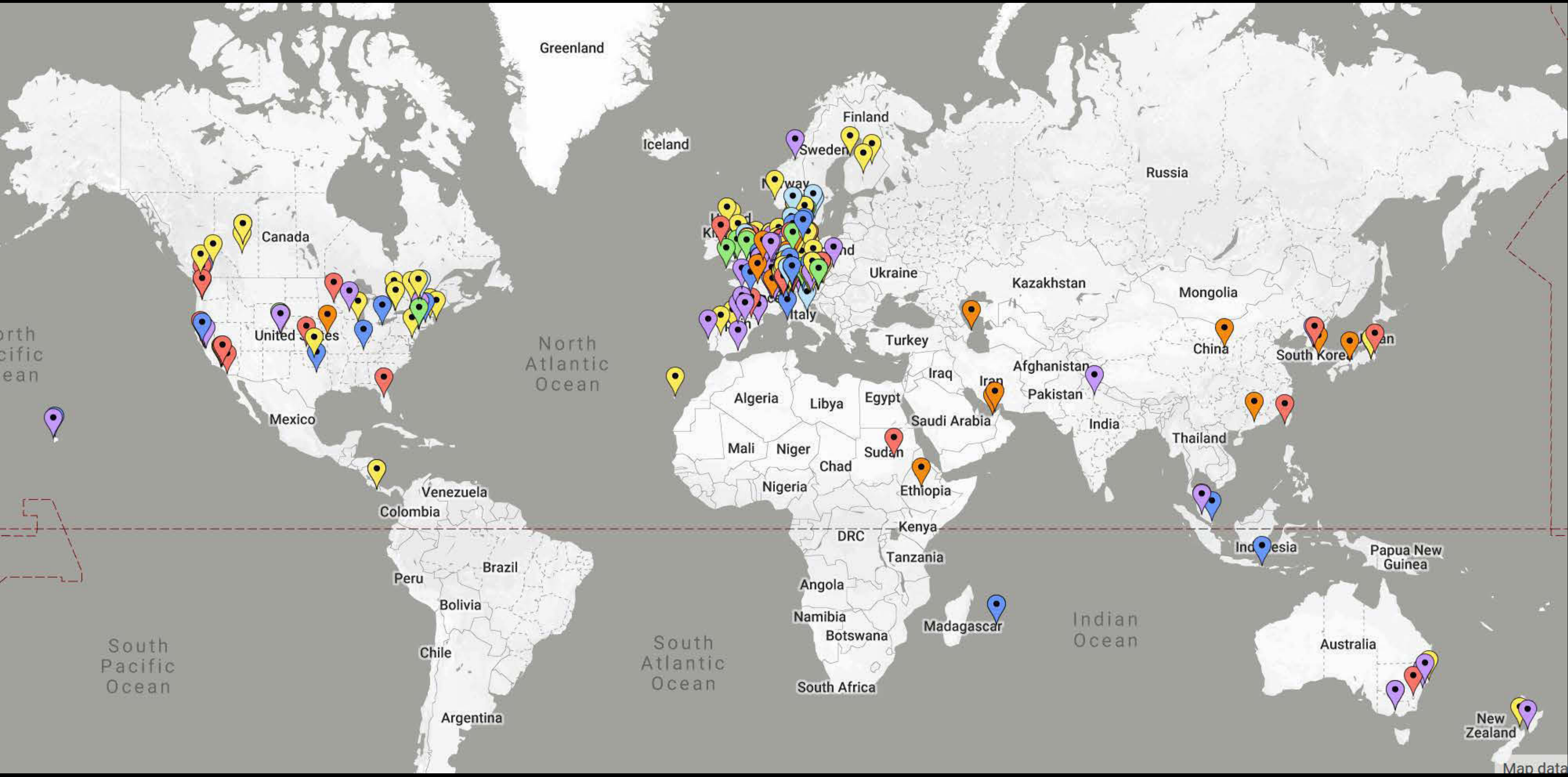
Net Zero Source Energy: produces as much as it uses at sources

Net Zero Energy Emission: aims for carbon neutral



MIT SDLAB

Net ZEBs in the world



- ❑ Database maintained until 2013

Examples

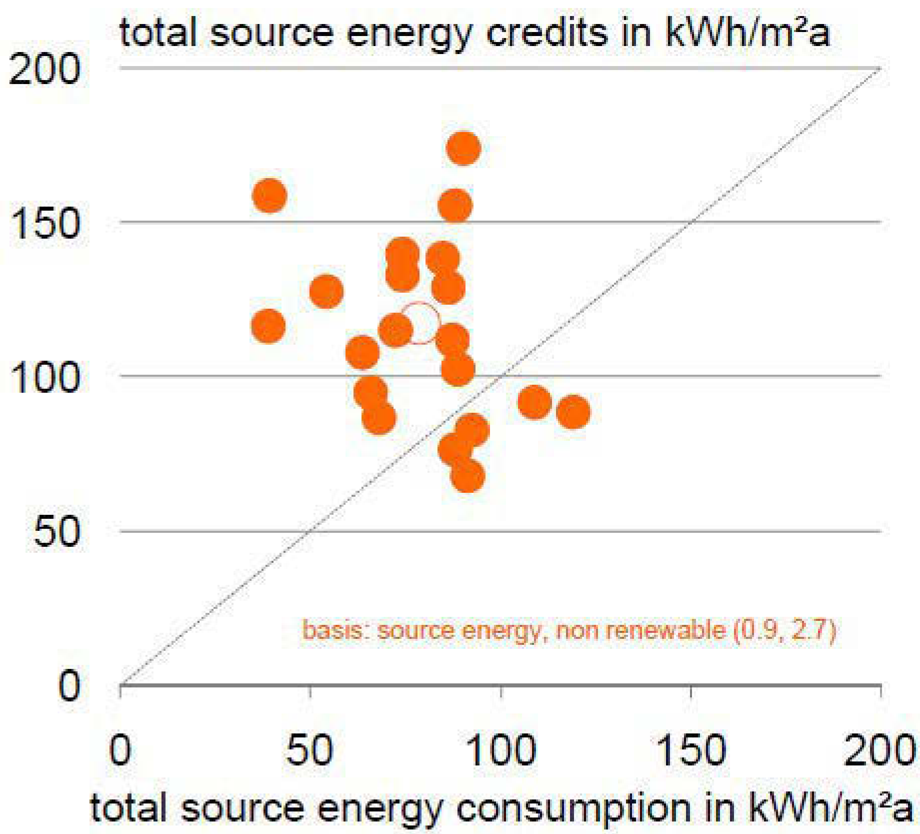
Energy Flex House, Denmark

Home for Life, Denmark

Truro Residence, MA

Aldo Leopold Legacy Center, Fairfield, WI

Plus Energy Houses



Slide courtesy of Karsten Voss. Used with permission.

Larger Examples

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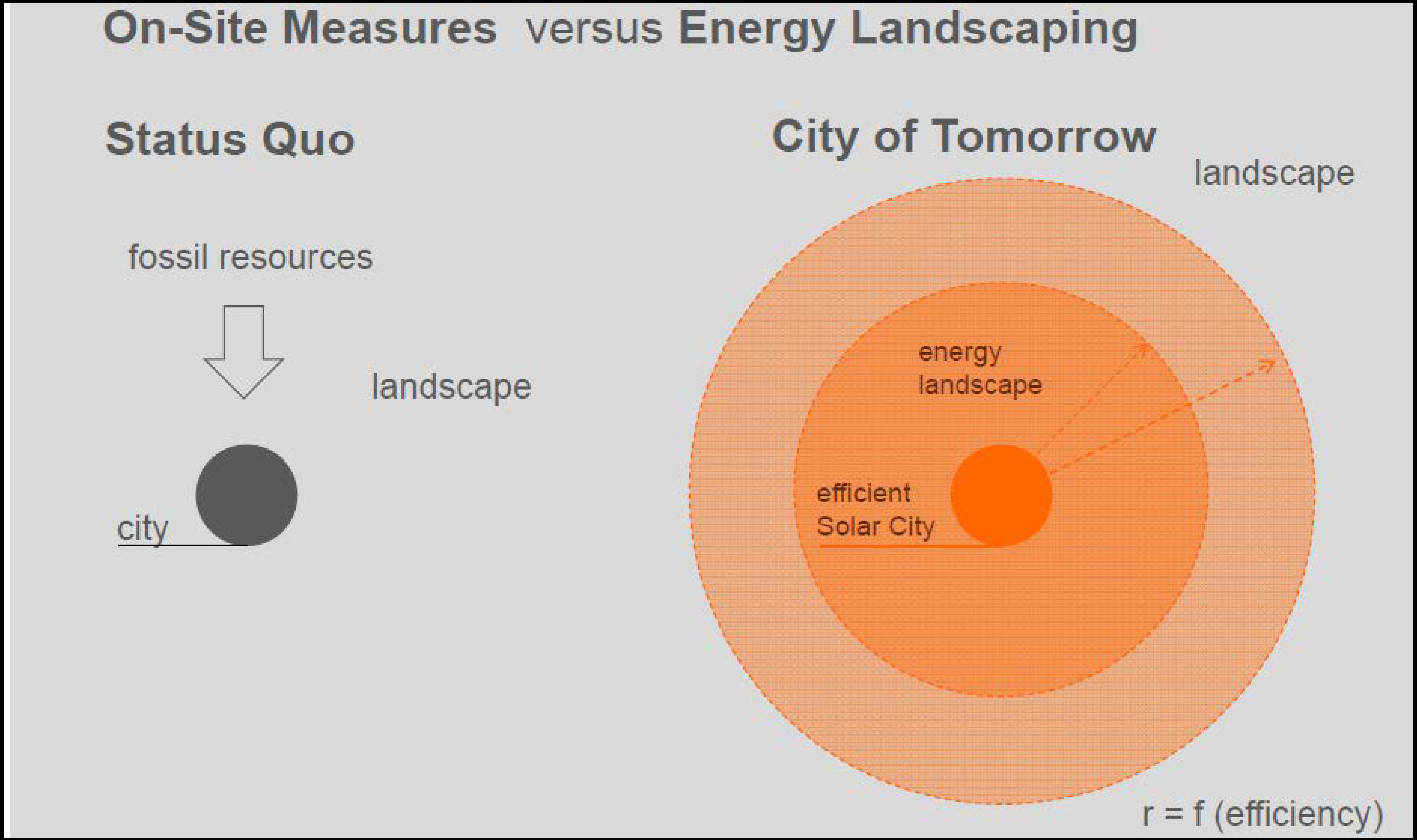
Highest Net ZEB in the world?

Net Zero Energy in Downtown Urban Districts?

Density and shading are unfavourable circumstances for individual buildings with equalized annual energy balance. Initial projects try to overcome the barriers with extreme building and solar module efficiency.

Slide courtesy of Karsten Voss. Used with permission.

A vision for future cities

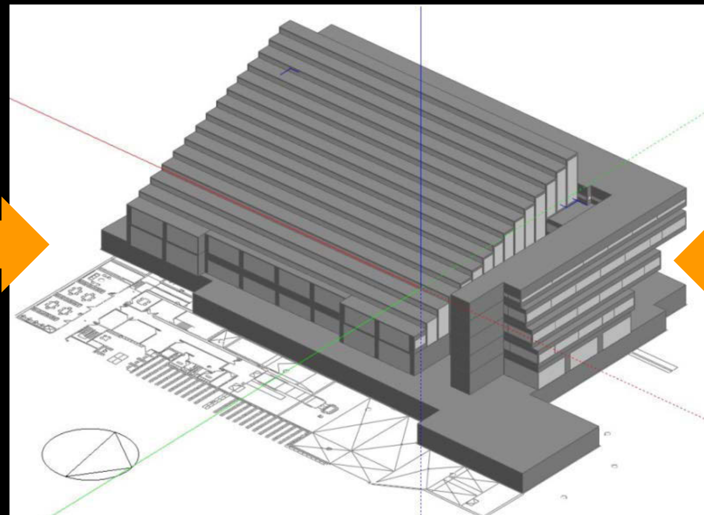


Slide courtesy of Karsten Voss. Used with permission.

Case Study Gund Hall

Case Study - Gund Hall

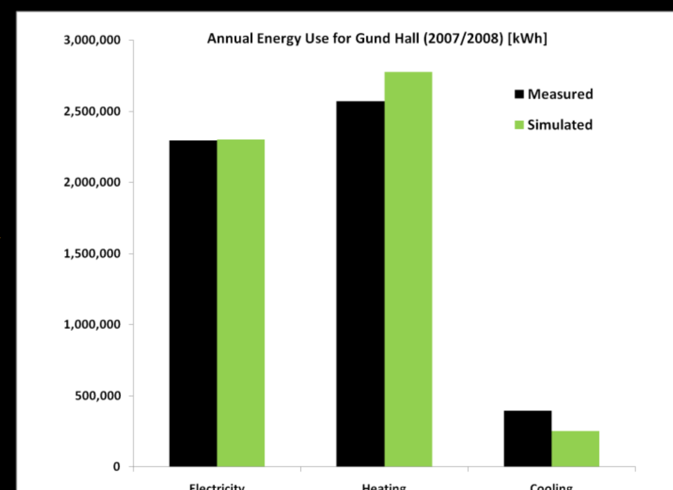
Collect weather data



Build an energy model

Survey occupant behavior

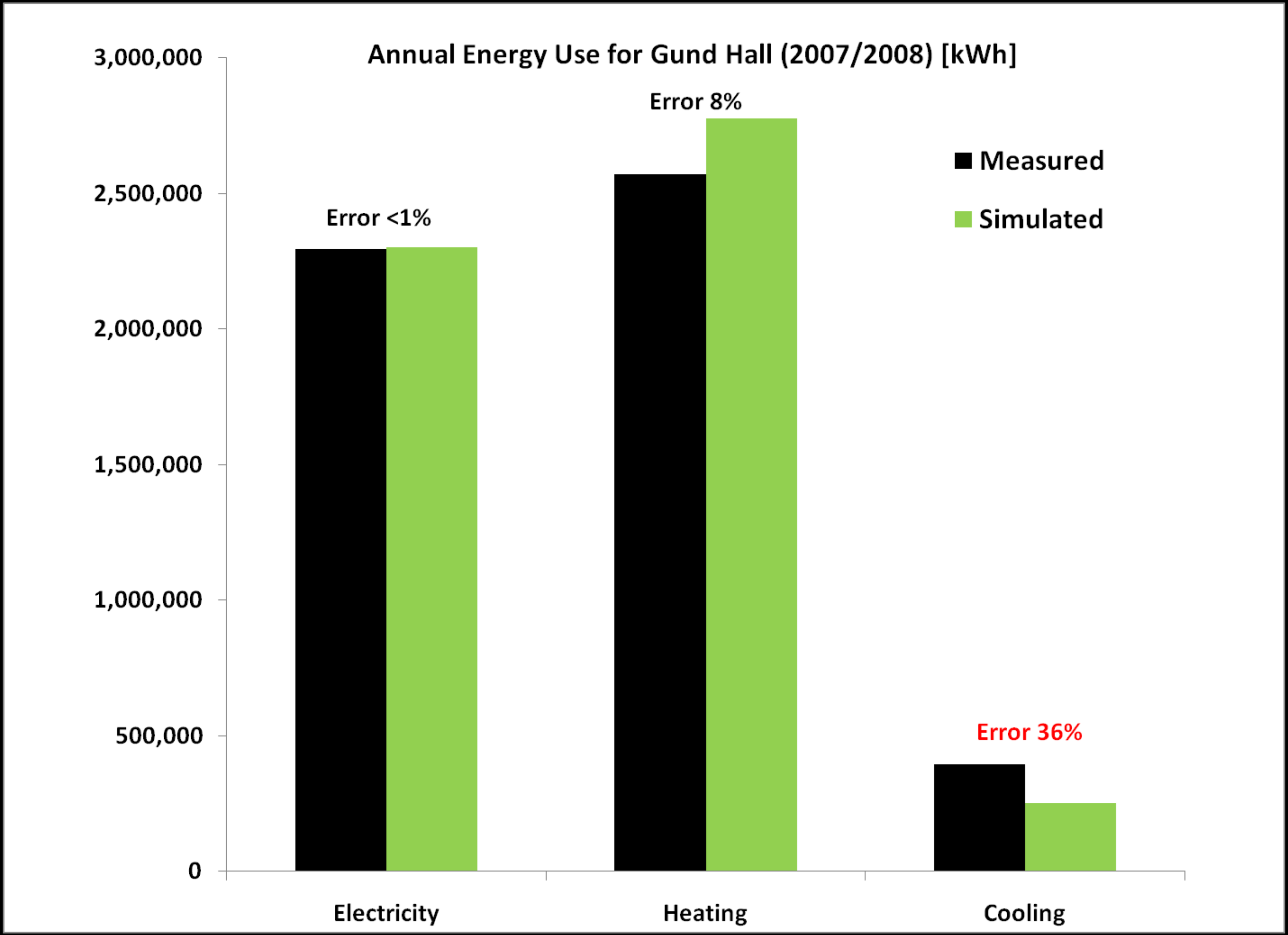
Measure Energy Use



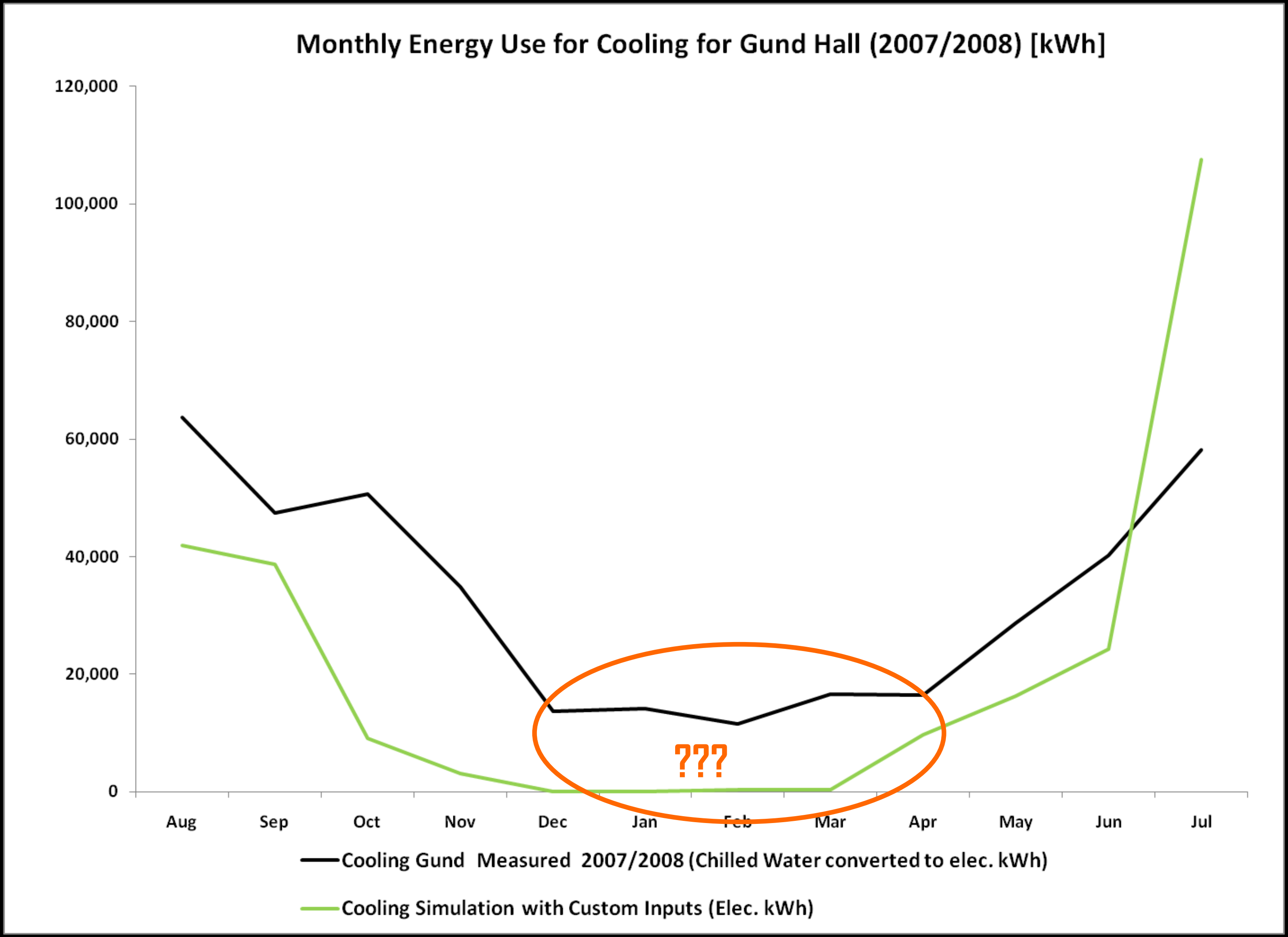
Predicted versus measured energy use

Paper: Wasilowski H A, Reinhart C F, "Modeling an existing building using customized weather data and internal load schedules as opposed to default assumptions - A Case Study," Proceedings of Building Simulation 2009, Glasgow, July 2009

Energy Use of Gund Hall: Measurement vs. Simulation



Monthly Energy Use for Cooling



- ❑ Cooling use in winter?

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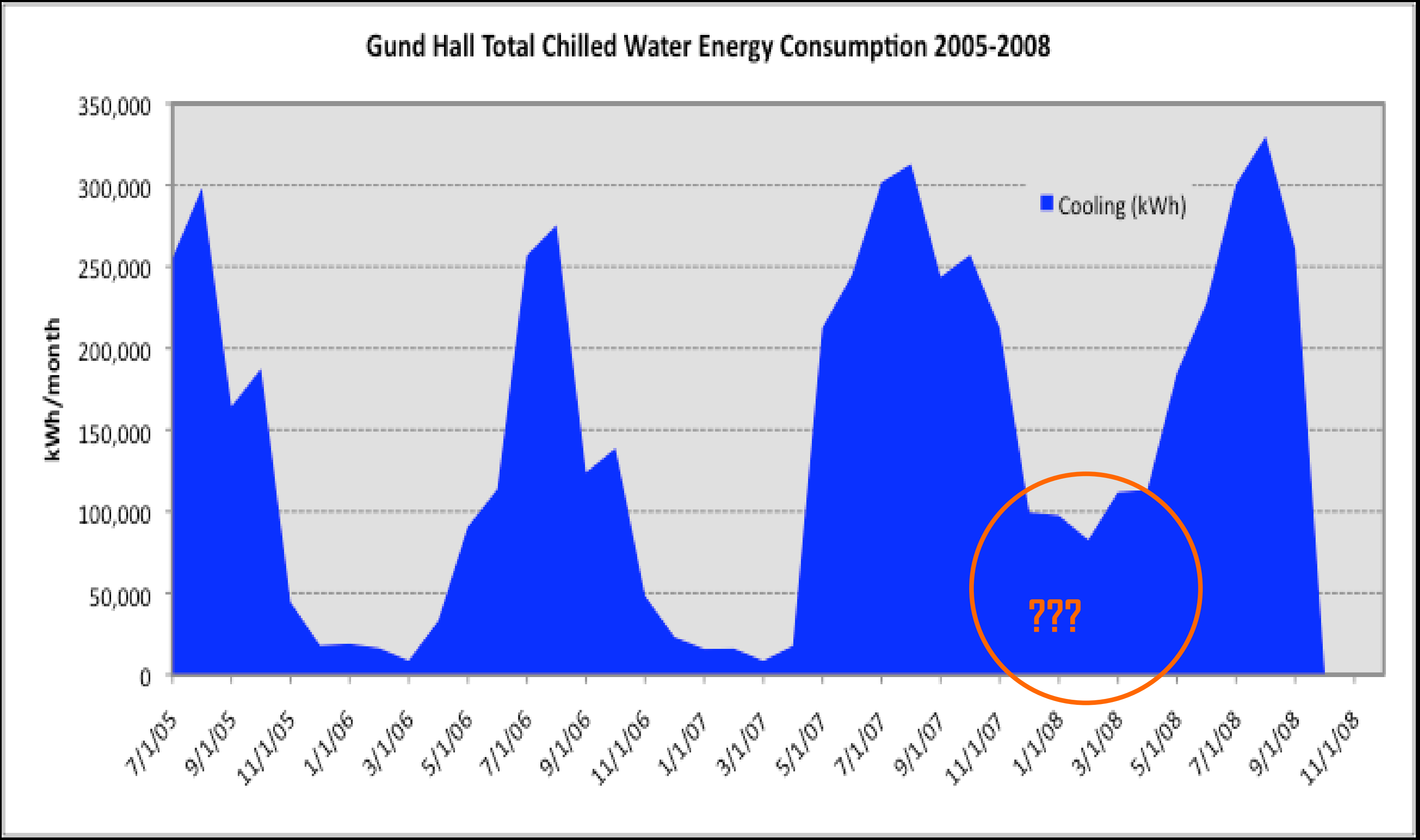
Historic Cooling Data for Gund Hall



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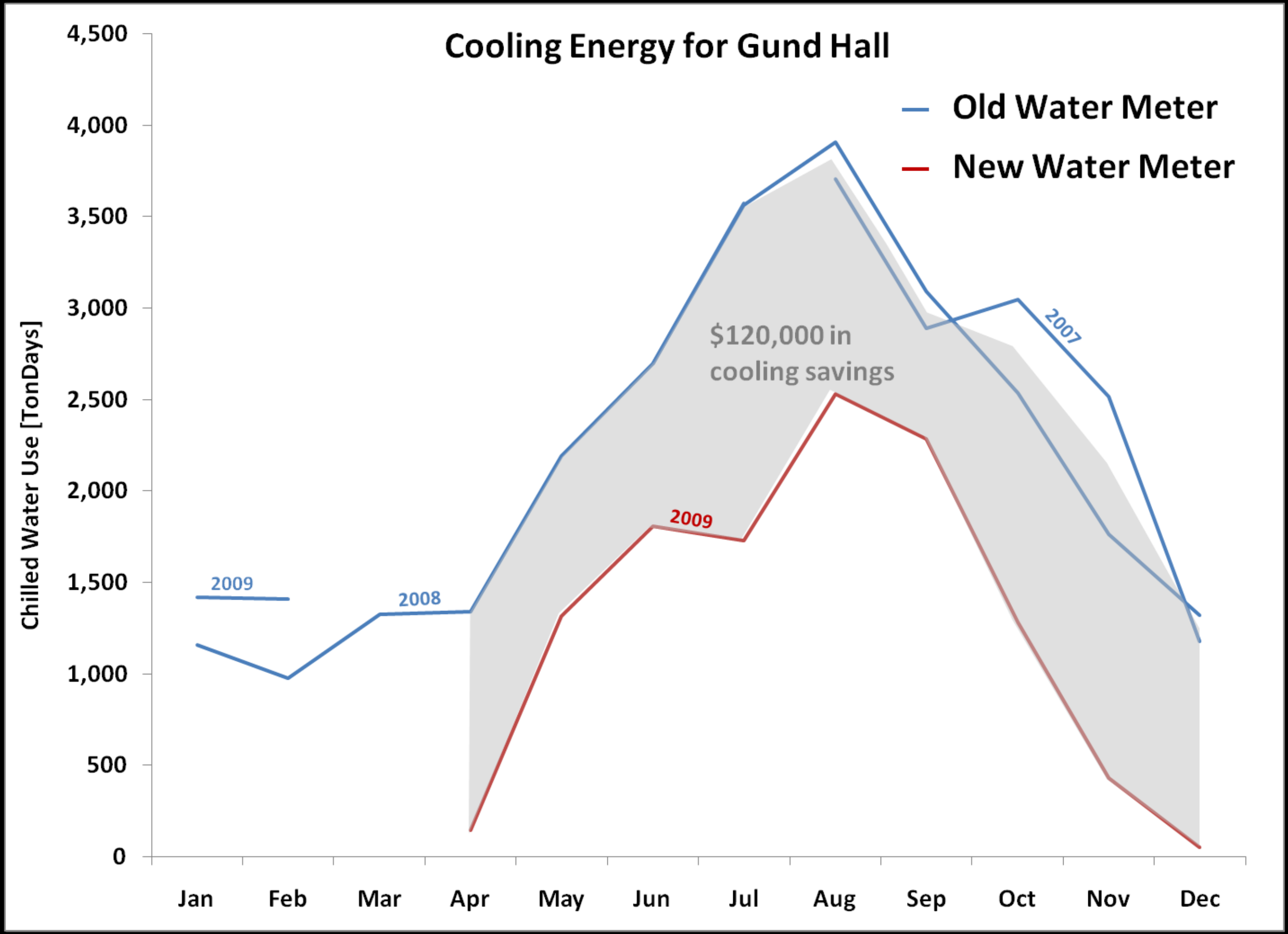
Monthly Energy Use for Cooling

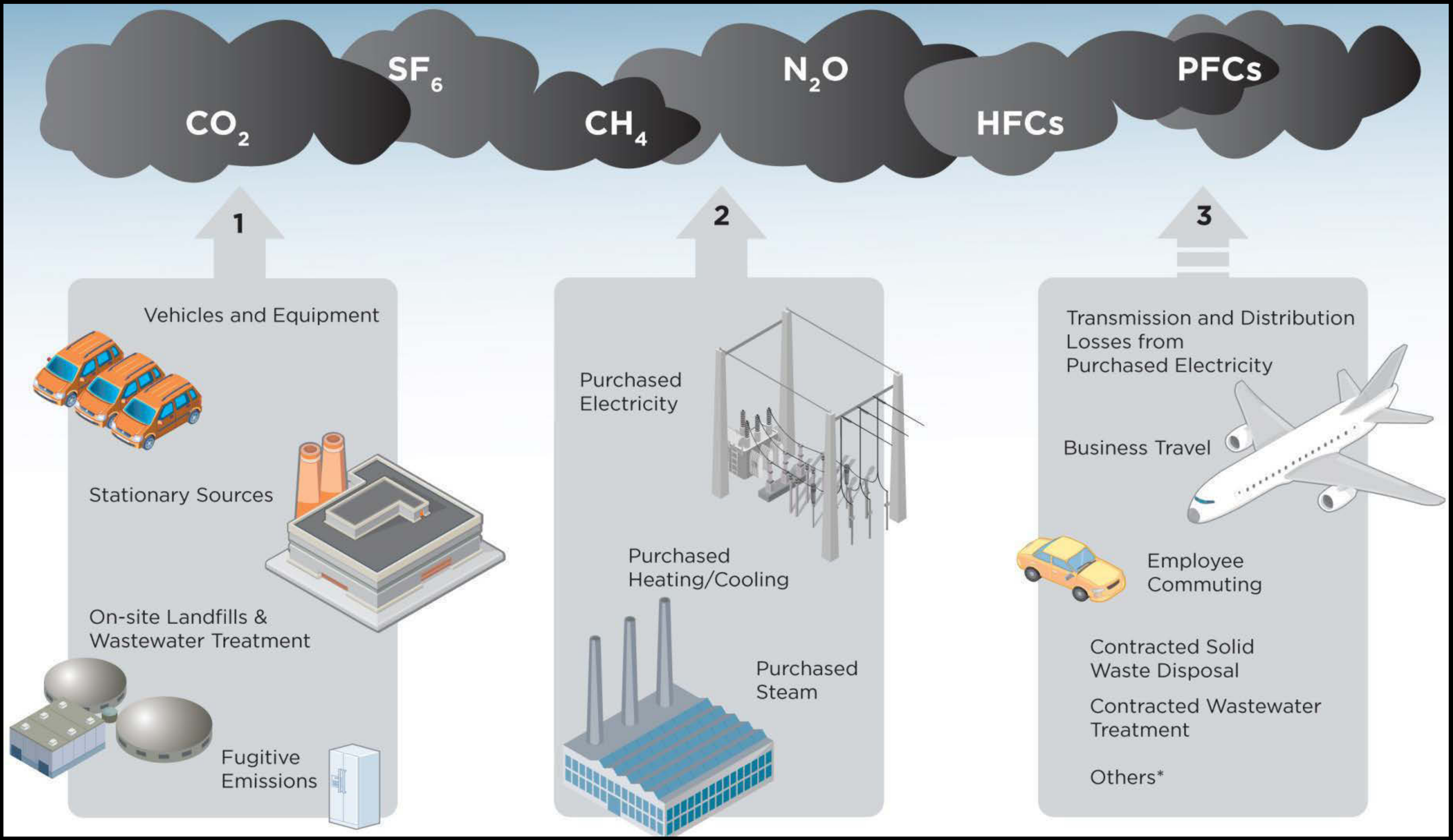


- Chilled water flow meter was replaced in March 2009.

MIT Campus Study

Scope and Carbon Emissions

Public domain image courtesy of US EPA.



Scope 1:

Greenhouse gas emissions from sources that are owned or controlled by Institute

Scope 2:

Greenhouse gas emissions resulting from the generation of electricity, heat, or steam purchased by the Institute

Scope 3:
Greenhouse gas emissions from sources not owned or directly controlled by the Institute but related to Institute activities

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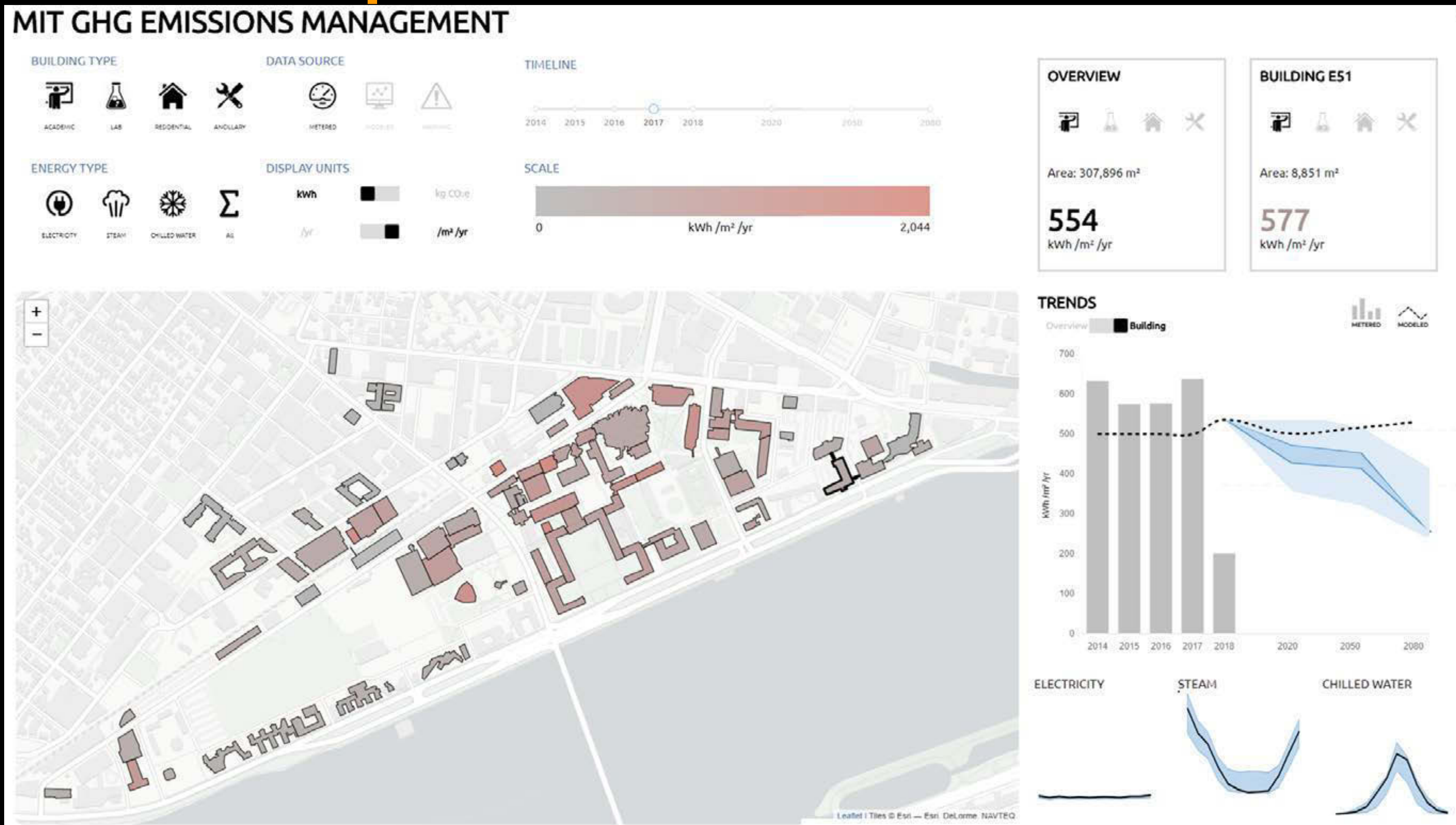
MIT Live Campus Model



https://web.mit.edu/CampusEnergyModel/www/

Paper: S Nagpal, J T Hanson, K Spencer, N Bhatia, C F Reinhart, “Auto-Calibrated Urban Building Energy Models as Continuous Commissioning and Planning Tools,” submitted to *Applied Energy*

Questions?