Low-energy buildings and power electronics control for energy management and storage

P. T. Krein
Grainger Center for Electric Machinery and
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign

Here is an overview.

- This tutorial is a *power electronics* view of advanced buildings.
- While the designs are set up by architects, structural engineers, and engineers with relatively traditional backgrounds, the implementation is with advanced power electronics.

Power electronics is the key implementer of low-energy ideas.

- Heating, ventilation, and air conditioning (HVAC) systems get their controls through electric motor drives and electric valves.
- Lighting systems cannot have proper controls without power electronics.
- Any automated management of safety systems, elevators, water management, and building use requires modern power electronics.

What is the difference between a green building and a low-energy building?

- Green buildings emphasize materials and environmental management.
- Examples:
  - Recycled material used in construction
  - Products from renewable resources
  - Sustainable-practice woods and other materials
  - Waste and water management
  - Indigenous landscaping

What is the difference between a green building and a low-energy building?

- Low-energy buildings emphasize limited energy intensity (low use per square meter) and limited total energy consumption
- Examples:
  - Active lighting control
  - Daylight harvesting
  - Insulating glass
  - Thorough seals
  - Heat pumps

Not the same thing!

- Considerations for *green* and for *energy* actually have little overlap.
- Even though most people seeking green buildings also want low energy, the design and cost aspects are not the same.
- Since the overlap is limited, the design issues do not trade off. It is possible to create a building that is *both* green and consumes low energy.

Ref: http://www.epa.gov/greenbuilding/pubs/faqs.htm

How is "zero net energy" defined for buildings?

- Zero net definitions span a wide range:
  - Self-sufficient building, able to operate without external energy connections.
  - Zero net structure energy use, for which the building itself produces as much energy per year as consumed.
  - Zero net site energy use, for which the "greater building site" produces as much energy per year as consumed.

How is “zero net energy” defined for buildings?

- Zero net definitions span a wide range:
  - Zero net energy resource use, for which both site generation and purchased external renewable resources provide the supply.
  - Zero net emissions, in which renewable generation is sufficient to offset all sources of carbon emission over a year.
  - Zero net lifetime energy, in which renewable resources also offset energy associated with construction and construction materials.

What is required to achieve this?

- Low usage, high generation.
- Solar energy intensity is low enough that only modest structures can produce all their own energy needs.
- Many of the student-designed houses in the 2009 and 2011 Solar Decathlon competitions supply their own energy.

Many of these are zero net energy structures.

Larger buildings require additional site resources.

Lewis Center, Oberlin College, 1260 m^2 (achieved zero net in 2012)

http://thepragmaticsteward.files.wordpress.com

Research Service Facility, U.S. National Renewable Energy Lab, about 31000 m², and some of the surrounding solar resources.

Credit: Dennis Schroeder, NREL, photo 25859, May 2013

How do challenges differ between new construction and retrofitting?

- New construction offers new technology.
- Increasing energy costs, publicity opportunities, and emerging best practices contribute to possible success.
- Retrofits imposes extensive additional constraints:
  - Building envelope
  - Structural limitations
  - Operation issues – does the building need to function during retrofits?

New construction has its own limitations.

- Tradeoffs between first cost and life cycle cost.
- Most U.S. commercial building projects are not owner occupied.
- Limited incentives for green construction and low energy – costs and benefits are often separated.
- Sites themselves are constrained, and utilities have little incentive to provide distributed renewable generation to assist.

Often the best examples are owner occupied.

- Sectors most likely to seek green and low-energy building certification include:
  - Education
  - Government
  - Large-scale industry sites
  - Residential in areas with especially high energy costs.

Learning from one-off projects.

- Most major commercial and education buildings really are one-off projects.
- Important to distinguish among
  - Architectural objectives
  - Engineering objectives
  - Occupant objectives
  - Green building and low energy objectives

www.predock.com

Wikipedia commons

All large buildings involve compromises among budget and scope.

- Green design and low energy involve compromises.
- As techniques mature, the compromises are less limiting.
- Green design costs only a little more.
- Low energy needs to emphasize human management.
- Conventional rules of thumb can be a barrier.

Electrical systems are complicated by including communications and other functions.

- Today, electrical includes:
  - Sensors
  - Fire and life safety systems
  - Wired networks
  - Wireless access points
  - Managing access to mobile networks
  - Active features (daylight interaction, color-chaging windows, …)
  - Audi-visual systems

How can we make more intelligent use of sensors?

- Various types of occupancy sensing devices and functions.
- Smoke detection and fire system integration.
- CO_2 and environment sensors.
- Windows and doors.
- Thermostats and other devices as "occupant preference" sensors.
- Timing and intelligent schedule interfaces.

How can capabilities of modern mechanical and HVAC systems be enhanced?

- "Local empowerment:" giving occupants local control with minimal disruption to others.
- Best use of high-performance heat pumps and chillers.
- Consideration of use cases:
  - HVAC impact on acoustic environment
  - Process cooling loops
  - Local vs. building-wide access to certain services

Modularity is a powerful concept.

Water management brings complications with new opportunities.

- Are there added values to:
  - Cisterns or other storage
  - Gray water
  - Local treatment
  - Active storm management
  - Separate waste streams for processes and chemicals
- Each extra water system brings its own costs.
- The benefits depend on detailed patterns of use.
- Local laws and regulations determine which special systems will be used.

For green and low energy buildings, how can the various responsibilities support the best final result?

- Architects must embrace the objectives, but in a way that avoids cost escalation.
- Engineers must be experts on *system interaction* and not just subsystems.
- Construction teams must be detail-oriented and good at completely finishing to requirements. 80-20 rules are the enemy of advanced buildings.
- Users must be highly engaged.

Pitfalls: what can go wrong early?

- Architects are often tempted to "design to budget" rather than "design to function."
- Engineers may try to work with interesting technologies that are hard to implement.
- Construction teams may plan based on rules of thumb or general experience with less consideration for uniqueness.
- Users might assume that others will take care of details.

Building scale and limitation aspects

- Residential, as in Solar Decathlon, can achieve structure-based net-zero energy.
- Compromises include wall thickness, expensive appliances, and simple roof lines.

It is hard to scale up in high-activity buildings.

- Above 1000 m^2, supplements to rooftop solar may be needed except for vast one-floor structures.
- Exceptions include large-area low-density applications such as large single-story retail and convention centers.
- High-rise buildings can be expected to require off-structure solar energy.

Low-energy design needs to have a careful, data-driven basis.

- One of the most important issues is to make a link between project costs (first costs) and lifecycle costs.
- When budgets drive projects and operating costs cannot be taken into account, innovation can be stifled.

The work needs to start with benchmarking.

- In the U.S., ASHRAE 90.1 is an accepted starting point.
- American Society of Heating, Refrigeration, and Air Conditioning Engineers, Energy Standard for Buildings Except Low-Rise Residential buildings.
- Another benchmark is energy usage intensity (EUI)
  - This averages about 30 W/m^2 for education buildings.
  - About triple this for hospitals.

What about building energy use?

- In the U.S. (2010), 41% of primary energy went to residential and commercial buildings, 31% to industry, and 28% to transportation.
- There is a paradox: reduced building energy use is likely to maintain the same fraction.
- A more helpful measure is energy use per square meter. Can this reduce?

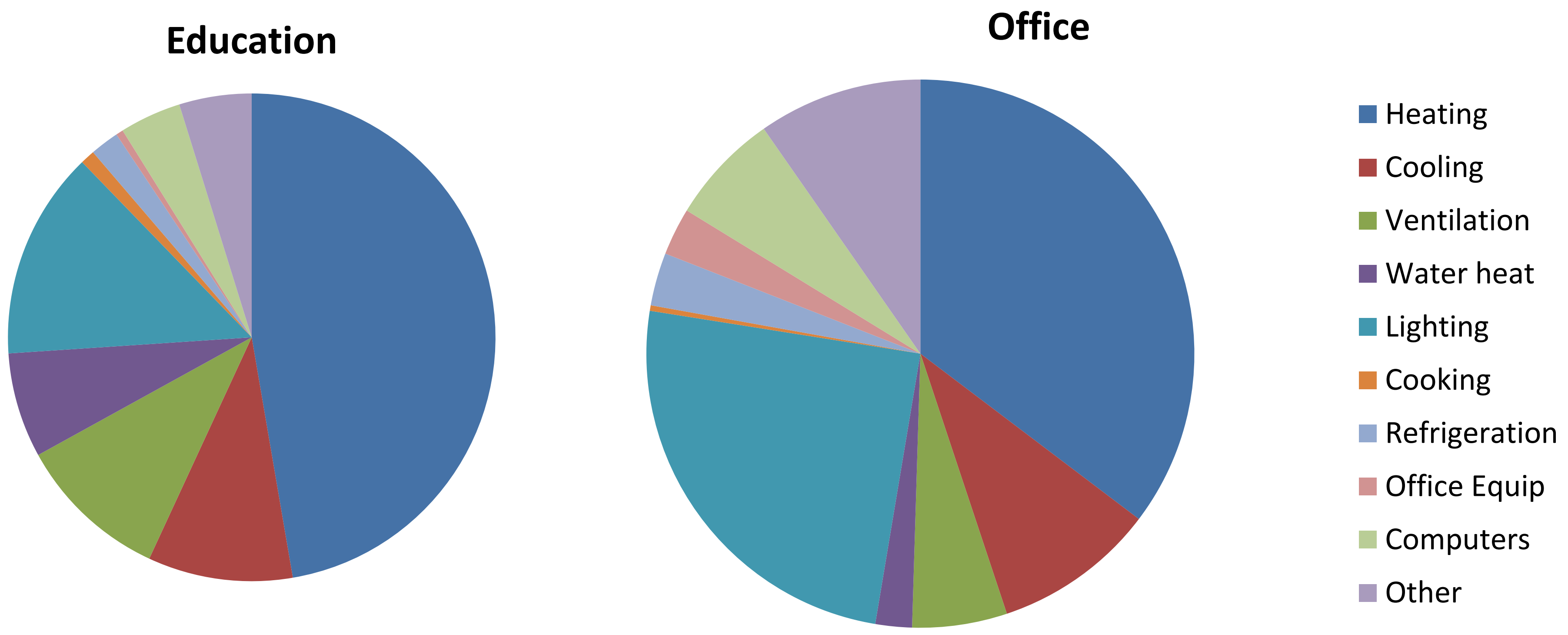
Ref: Buildings Energy Data Book, U. S. Dept. of Energy
http://buildingsdatabook.eren.doe.gov/ChapterIntro1.aspx

Here are some sample EUI benchmarks.

- Chicago: large office building, new construction, reference EUI is about 16 W/m^2 measured over a year.
- Chicago: secondary school, 28 W/m^2.
- Compare to US average, 34 W/m^2.

- U.S. new construction hospital 54 W/m^2.

Energy usage, 2003 survey results.



Energy Planning

- Gather stakeholders.
- Find willing advisors.
- Explore possibilities without premature limits.

Both qualitative and quantitative evaluation are needed.

- Is a particular idea consistent with project objectives?
- Does it help meet green design and energy goals?
- Will it add value to the end result?

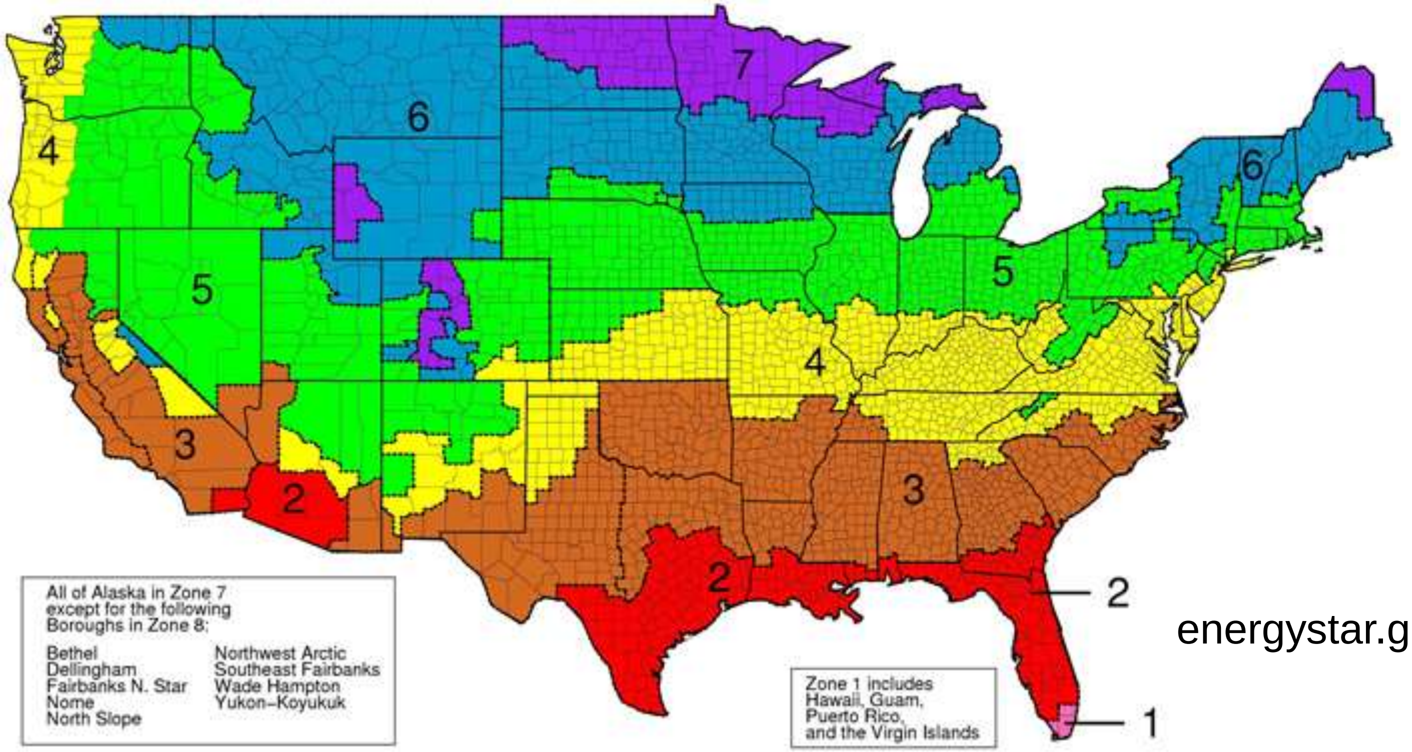
- First cost vs. life cost
- Example:
  - 25 year life cycle, including O&M and all expected costs.
  - Compare to first cost and evaluate.

Every highly efficient large building is likely to be a one-off design, so location matters.

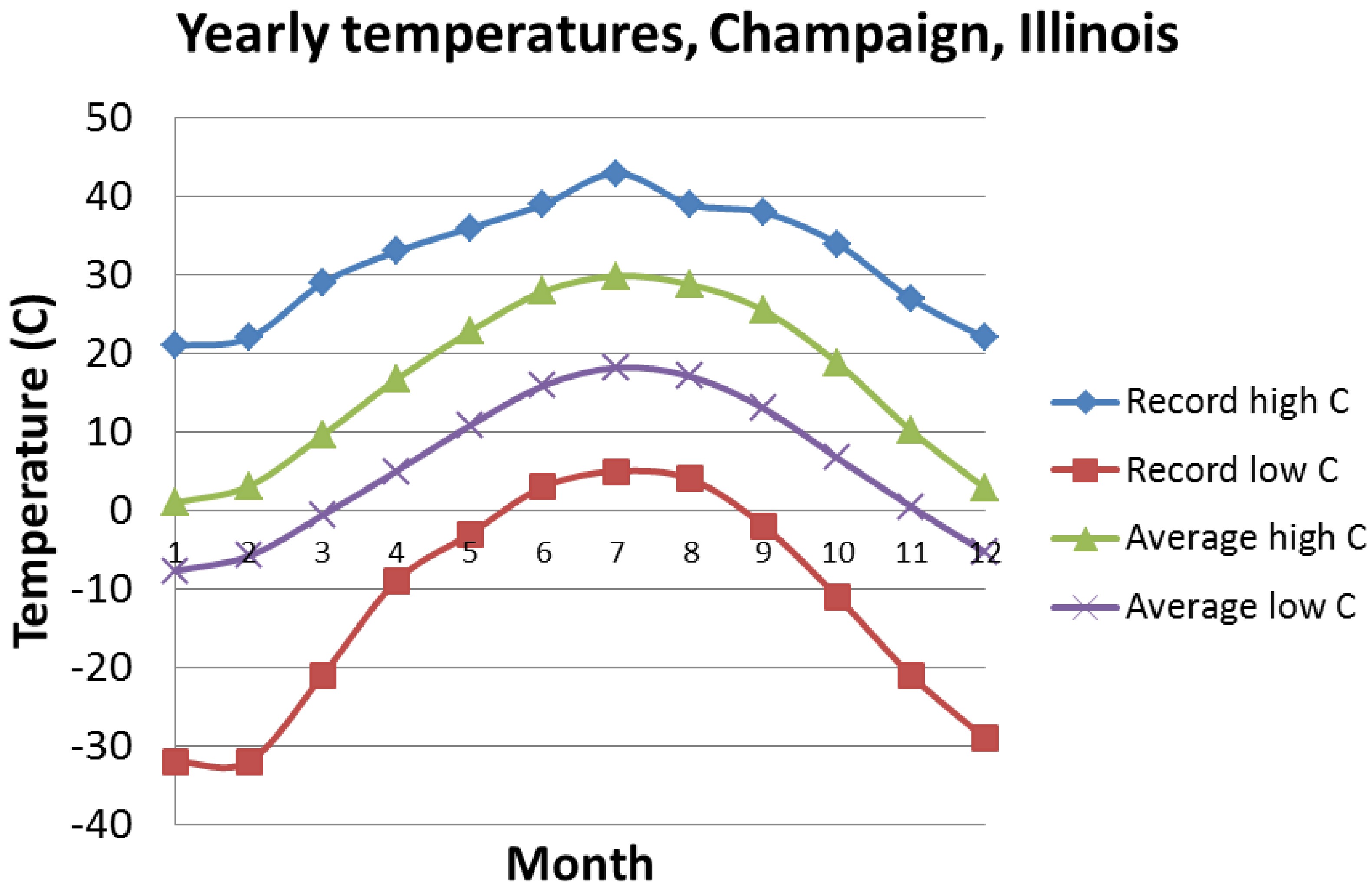
- Climate characteristics
- Water considerations
- Energy source possibilities
- Site characteristics
- Leverage with various attributes and features.

Climate dominates HVAC design.

- Zone-based designs are typical.
- Seasonal extremes must substantial in continental areas far from coast.



energystar.gov


Yearly temperatures, Champaign, Illinois
Temperature (C)
50
40
30
20
10
0
-10
-20
-30
-40
1
2
3
4
5
6
7
8
9
10
11
12
Month
Record high C
Record low C
Average high C
Average low C

Climate: "all in" site

- Average annual rainfall 41".
- Rain intensity can exceed 4"/h at times.
- Average annual snowfall 23". Maximum single storm reaches 18".
- Dynamic temperature changes of ~10°C/h (18°F/h) are not unusual.
- Wind loads include potential tornadoes.
- Flat terrain brings drainage challenges.

A few basic terms help define climate requirements.

- Heating degree days:
  - The product of thermal impact and time duration estimated when a building needs to be heated.
  - Relative to a base temperature (such as 18°C) above which no heat is required.
  - My base location: about 3200 K-days
- Cooling degree days:
  - Product of thermal impact and duration when a building needs to be cooled, relative to 18°C.
  - My base location: about 600 K-days

Water system issues

- Drainage management, snow loads
- Exterior slopes and flows
- Permeable pavement
- Water table
- Storm water retention or reuse
- Freeze-thaw cycles
- Landscape needs and point irrigation
- Gray water

Energy source issues

- Wind
- Solar
- Water (flow or tidal)
- Geothermal
- CHP
- Others?

Designs can leverage multiple attributes.

- District heating or cooling.
- Active daylight management vs. lighting.
- Parking structures and solar or wind power.
- Other passive solar attributes.
- Pre-heat or pre-cool.

Preparing and evaluating model results.

- “Rule of thumb” models either impose a nominal energy usage intensity or assign energy use based on “resident” occupants and outlet counts.
- Energy balance models attempt to predict occupant counts and timing, assign impact of doors opening and closing, and estimate traffic patterns.

Other types of models.

- Emulation models draw data from similar buildings and systems.
- Data fitting models are useful in retrofit situations.
- "EnergyPlus" model from the U.S. Department of Energy, comprehensive combination of building systems and features.

B. Griffith, N. Long, P. Torcellini, R. Judkoff, D. Crawley, J. Ryan, "Methodology for modeling building energy performance across the commercial sector," Technical report NREL/TP-550-41956, National Renewable Energy Laboratory, march 2008.

So far, models have had limited value for new construction.

- For retrofitting, it is possible to enforce data fits based on physical models and a few parameters.
- For new construction, energy balance models are only partial, and plug loads are especially difficult.
- Important to supplement with any available data from the same community.

Try to enhance models with data.

- Our most substantial example: clean room usage.
- Others types of instructional laboratories are also intensive energy users.
- It has been estimated that precise occupancy counts could allow adaptive HVAC and reduce consumption by 30%.
- How do entrances, exits, and traffic patterns affect energy?

Many low-energy attributes interact and need to be considered as a *system*.

- A high-performance building envelope changes the constraints on HVAC design.
- If users require open windows, the HVAC systems must not work against them.
- Dark spaces (such as laser labs) also tend to be places of more intense plug loads and heat generation.
- Areas of highest use identified and linked to traffic patterns.

Here are some examples of low-energy attributes and methods.

- User-oriented usage and energy management.
  - Task lighting
  - Local thermostat control
  - Occupancy sensors for lights and thermostats
  - Occupancy closed-loop HVAC operation
  - Activity schedules for control presets
- Match up needs
  - Meet acoustic objectives in various spaces.
  - Daylight emphasis in places where it adds value.

Some more specific examples can be considered.

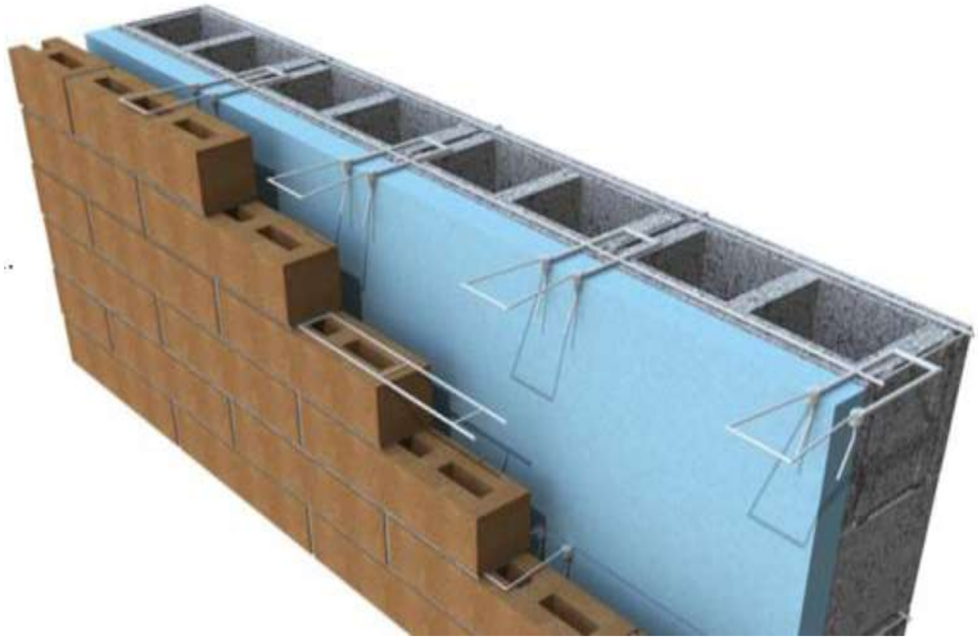
- Passive solar attributes.
- Trade off envelope performance, HVAC performance, and user requirements.
- Lighting choices.
- Spaces with large-scale functional changes, such as classrooms not used during summer.
- Integration of storage.

What about the building envelope?

- High-performance walls at R-30 and above.
- Windows, double-pane approaches R-2.5, triple-pane approaches R-3.5.
- "Perfect" seals are essential.
- Doors can compromise envelope performance quickly.
- Revolving doors or vestibules are intended to limit air infiltration.

Some examples.

- Brick over rigid insulation and steel studs, R-18 is typical.
- Block over filled-cavity cinder blocks, R-18 is also typical.
- Rainscreen cladding with rigid insulation, R-30 is typical.



oldcastlemasonry.com

HVAC and lighting dominate energy use.

- Computers are catching up as a major item.
- Many users do not recognize that *all* office equipment and computers are pure heat load into a building.
- A 100 W computer has the same energy impact as a 100 W cooking appliance – except that the computer is more likely to be on constantly.

What about HVAC types?

- Air-based examples include
  - High pressure low volume air systems
  - Low pressure high volume air systems
  - Displacement air systems
- Water-based examples include
  - Radiant walls and surfaces
  - Steam-based radiators and fin tubes
  - Hot-water based radiators and fin tubes
  - Chilled beams

The HVAC trend has been separation.

- Systems that maintain separate operation for:
  - Heating
  - Cooling
  - Ventilation
  - Humidity control
  - Water heating

tend to offer easier energy optimization.

Climate challenges can complicate the picture quickly.

- Some climates have multiple days that require *both* cooling degree-days and heating degree-days.
- The systems must interact correctly.
- Open windows can quickly compromise humidity control at the wrong times of year.

Another HVAC trend is better heat exchange and economizers.

- Make sure energy stays in the building – avoid extra energy to heat or cool exterior air.
- Use exterior air as a primary resource when temperature differences are low.
- Try to manage equipment heat rejection in ways that reduce other energy requirements.

Heat exchange is important.

Energy recovery wheel – heat exchanger

- Given energy to heat or cool air, it is essential to transfer heat between outside fresh air and building air as part of the ventilation process.

What are the opportunities?

- HVAC
  - Typical 30% reduction based on dynamic adjustment, occupancy sensing, and careful balancing.
  - Implementation with power electronics drives is essential.
- Lighting
  - Typical 35% reduction from T12 magnetic ballast to T8 power electronic ballast.
  - Typical 60% reduction from T12 to T5.
  - Projected to reach 80% reduction from T12 with solid-state lamps.

Displacement ventilation saves about 20% of energy.

- Low-pressure air enters at floor level.
- In a tall room, the lowest occupied space is kept comfortable.
- The incoming air is fresh and prevents contaminant buildup in the occupied space.
- Substantial reduction in energy use.

S. D. Hamilton, K. W. Roth, J. Brodrick, "Displacement ventilation," *ASHRAE Journal*, vol. 46, no. 9, pp. 56-58, Sept. 2004.

Lighting and dynamic management.

- Any lighting technology should coordinate well with daylight and actual use.
- Light intensity at the task point is important to consider.
- Solid-state lighting is especially helpful because the intensity can be adjusted from 0-100%, and rapidly.
- User management is important, especially in multi-use spaces.

It is important not to make the controls *too* dynamic.

- Human vision is well adapted to passing clouds and other natural dynamic effects on light level.
- It is possible to use dynamic controls to set a fixed illumination level at a specific task spot.
- This can lead to discomfort – background flicker and other effects even if a work surface is uniform.

Dynamic lighting control is a big energy saver.

- Lights can adapt open-loop based on time of day, or can be set to two or three fixed levels depending on window lighting.
- Typical office buildings should see 20% reduction or more in lighting energy from daylight interaction strategies.

Occupancy sensors have limitations.

- Many sensors require movement, and may toggle on and off in office spaces.
- If sensitivity is too high, HVAC action can interact with sensors.
- Heat load and CO_2 sensing.

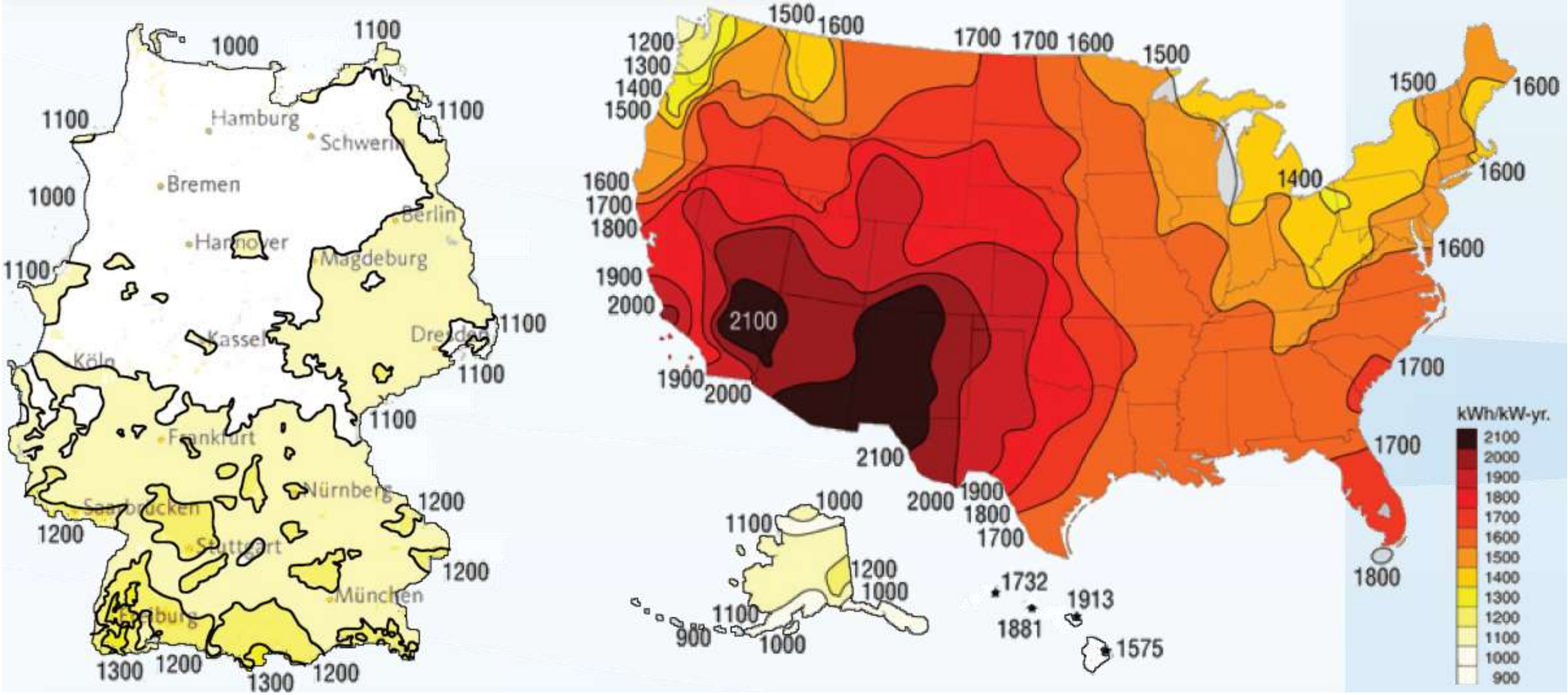
Ground interactive heat pump systems can reduce energy substantially.

- Now often called “geothermal,” these systems do not harvest energy from the earth.
- The function is to use the earth as a near-isothermal heat sink. At latitude 40°, the temperature below about 7 m is fixed at about 10°C.
- Horizontal or vertical pipe fields can be used to treat the earth as a “cold plate.”
- Heat pump allows heating and cooling.

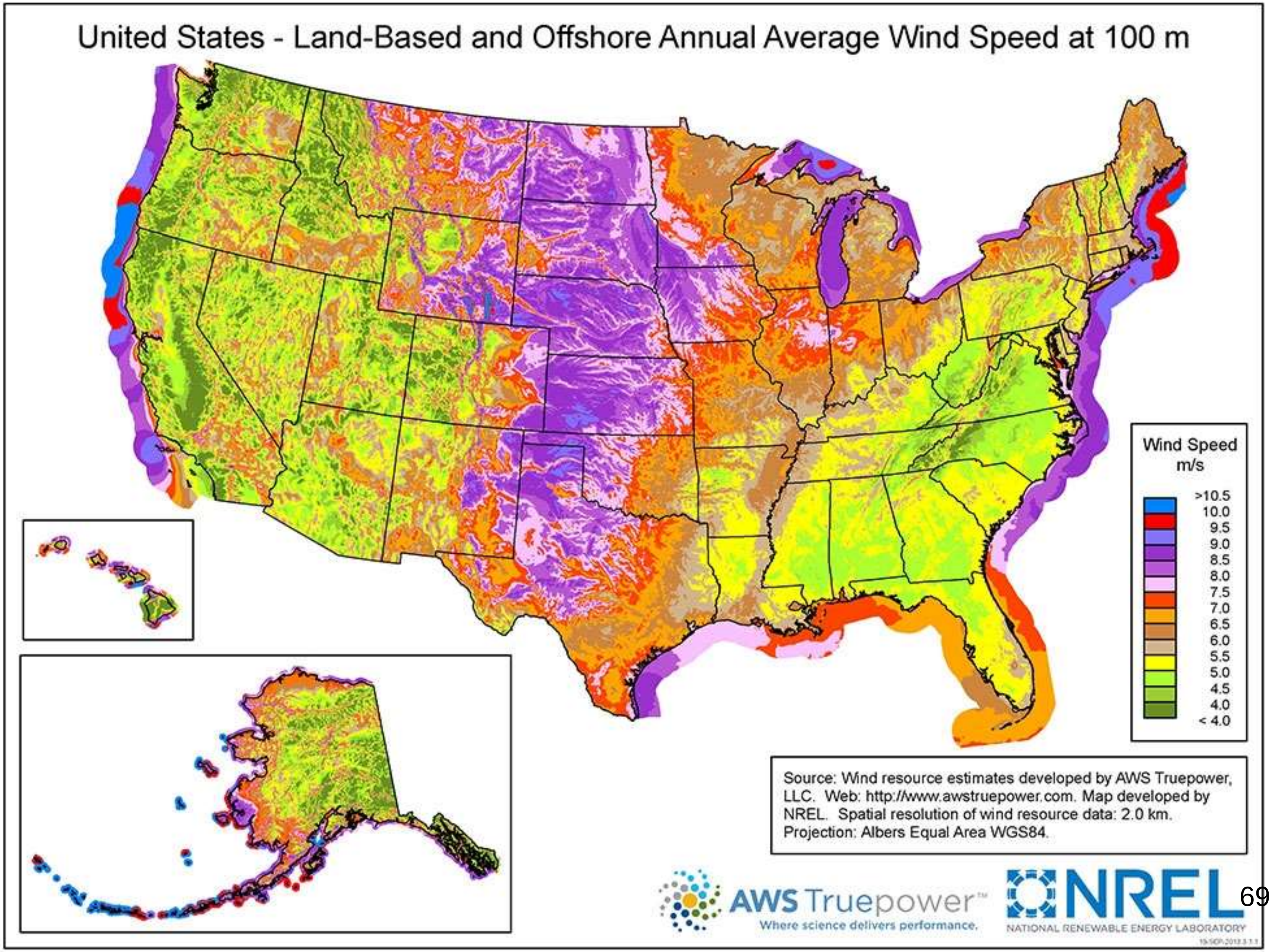
This comes at a cost.

- The first cost is substantial – only a little less per watt of capacity than the cost of installing solar panels.
- An alternative is district heating or cooling in which building heat pumps exchange energy with a much larger water-based system.

What about solar and wind resources?



From Solar Energy Industries Association, "U.S. Solar Industry – Year in Review, 2007"


United States - Land-Based and Offshore Annual Average Wind Speed at 100 m
Wind Speed m/s
>10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
< 4.0
Source: Wind resource estimates developed by AWS Truepower, LLC. Web: http://www.awstruepower.com. Map developed by NREL. Spatial resolution of wind resource data: 2.0 km. Projection: Albers Equal Area WGS84.
AWS Truepower
Where science delivers performance.
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Analysis needs to include both qualitative and quantitative evaluation.

- Qualitative work must consider those approaches most likely to be of value.
- Quantitative work here is based on EnergyPlus, along with our own information about life cycle aspects.

Qualitative examples.

QUALITATIVE ANALYSIS

CHILLED BEAMS

PROS
Reduce cooling transport energy
Reduce fan sizes
Lower reheat energy
Reduce peak electrical load
Reduce floor to floor height
Introduce white noise

CONS
Increase risk of condensation
Eliminate operable windows
Increase noise level
Raise chilled water connection charge

GEOTHERMAL

PROS
Reduce building energy costs
Reduce chilled water connection charge
Reduce steam consumption

CONS
Lose central CW distribution redundancy
Increase maintenance
Increase noise level
Increase area required for well field

LED LIGHTING

PROS
Increase lamp life
Decrease dimming turn down
Increase dimming efficiency
Increase lighting efficiency
increase task light performance

CONS
Increase cost
Reduce available design information
Reduce experience
Reduce fixture options

WIND GENERATION

PROS
Create on-site electrical generation
Reduce electrical usage
Create research potential

CONS
Impact architectural aesthetic
Extend payback
Conduct wind study to determine output
Increase noise level
Increase vibration
Introduce danger to birds

Checking the chilled-beam cooling system.

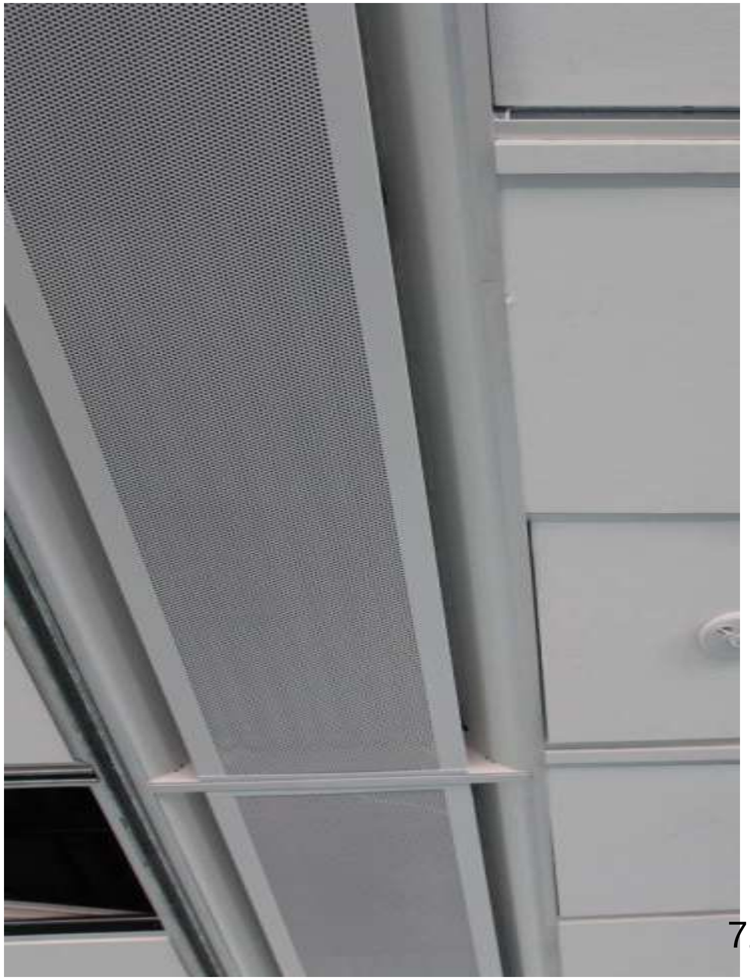
CHILLED BEAMS

PROS

Reduce cooling transport energy
Reduce fan sizes
Lower reheat energy
Reduce peak electrical load
Reduce floor to floor height
Introduce white noise

CONS

Increase risk of condensation
Eliminate operable windows
Increase noise level
Raise chilled water connection charge



Ground source heat pumps.

GEOTHERMAL

PROS

Reduce building energy costs
Reduce chilled water connection charge
Reduce steam consumption

CONS

Lose central CW distribution redundancy
Increase maintenance
Increase noise level
Increase area required for well field

Solid-state lighting.

LED LIGHTING

PROS

Increase lamp life
Decrease dimming turn down
Increase dimming efficiency
Increase lighting efficiency
increase task light performance

CONS

Increase cost
Reduce available design information
Reduce experience
Reduce fixture options

Is wind mounted on the structure viable?

WIND GENERATION

PROS

Create on-site electrical generation
Reduce electrical usage
Create research potential

CONS

Impact architectural aesthetic
Extend payback
Conduct wind study to determine output
Increase noise level
Increase vibration
Introduce danger to birds

Here are a few quantitative examples.

QUANTITATIVE ANALYSIS

STRATEGY	% ENERGY SAVINGS	ADDED 1ST COST	25-YEAR LCC SAVINGS
IMPROVED ENVELOPE (WALLS AND ROOF)	5%-6%	$150,000	$105,000
PASSIVE SOLAR DESIGN	2%-3%	$102,000	($19,000)
CHILLED BEAM COOLING SYSTEM	10%-11%	$31,000	$1,066,000
ENERGY RECOVERY WHEELS	10%-11%	($256,000)	$602,000
DISPLACEMENT VENTILATION	3%-4%	$188,000	$63,000
CONDENSER WATER HR WITH NET METERING	23%-27%	$417,000	$704,000
AIR SIDE ECONOMIZER	4%-5%	$110,000	$76,000
WATER SIDE ECONOMIZER / RECLAIM HEAT	1%-2%	$154,000	($131,000)
VENTILATION OCCUPANCY SENSORS	2%-3%	$24,000	$190,000
PREMIUM EFFICIENT MOTORS	0.2%	$6,000	$11,000
SOLAR HEATING (WATER OR AIR)	1.5%	$24,000	($42,000)
GEOTHERMAL	18%	$2,027,000	($570,000)
NATURAL VENTILATION	1%	$129,000	($33,000)

*cost savings

Many were considered, few were chosen.

QUANTITATIVE ANALYSIS

STRATEGY	% ENERGY SAVINGS	ADDED 1ST COST	25-YEAR LCC SAVINGS
IMPROVED ENVELOPE (WALLS & ROOF)	5%-6%	$150,000	$105,000
PASSIVE SOLAR DESIGN	2%-3%	$102,000	($19,000)
CHILLED BEAM COOLING SYSTEM	10%-11%	$31,000	$1,066,000
ENERGY RECOVERY WHEELS	10%-11%	($256,000)	$602,000
DISPLACEMENT VENTILATION	3%-4%	$188,000	$63,000
CONDENSER WATER HR WITH NET METERING	23%-27%	$417,000	$704,000
AIR SIDE ECONOMIZER	4%-5%	$110,000	$76,000
WATER SIDE ECONOMIZER / RECLAIM HEAT	1%-2%	$154,000	($131,000)
VENTILATION OCCUPANCY SENSORS	2%-3%	$24,000	$190,000
PREMIUM EFFICIENT MOTORS	0.2%	$6,000	$11,000
SOLAR HEATING (WATER OR AIR)	1.5%	$24,000	($42,000)
GEOTHERMAL	18%	$2,027,000	($570,000)
NATURAL VENTILATION	1%	$129,000	($33,000)

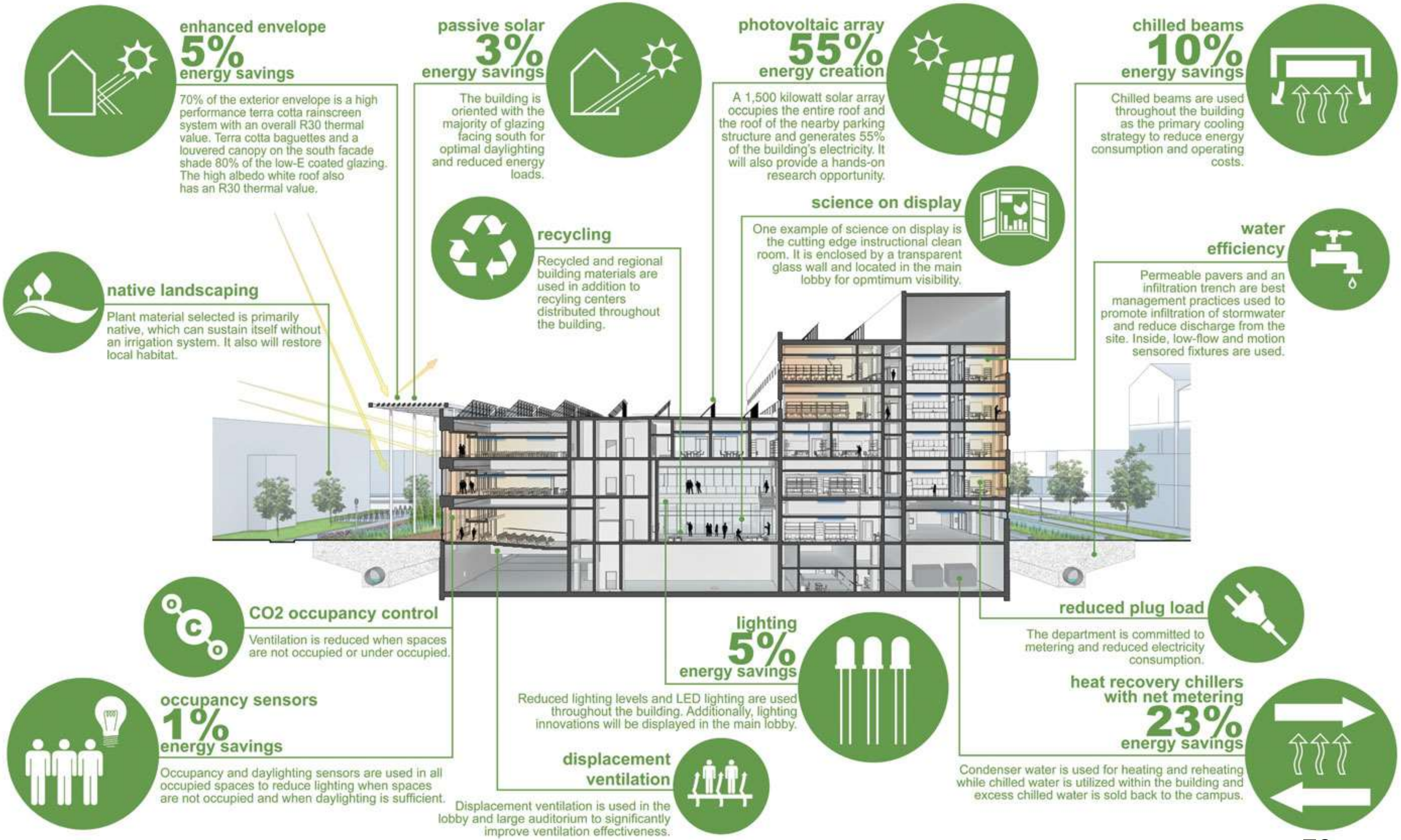
*chosen strategies

Some are in direct conflict.

CHILLED BEAM COOLING SYSTEM
10%-11% ENERGY SAVINGS
$31,000 ADDITIONAL 1ST COST
$1,066,000 25-YEAR SAVINGS

NATURAL VENTILATION
1% ENERGY SAVINGS
$129,000 ADDITIONAL 1ST COST
($33,000) 25-YEAR ADDITIONAL COST

Energy Reduction



Where would electronic drives be found in the large-scale subsystems?

- HVAC
  - Universal in primary HVAC to operate energy recovery wheels, operate fans and compressors, control pressure settings.
  - Universal in secondary HVAC for larger valve and damper actuators
  - Integration with the full building automation system is critical.

Where else are they found?

- Water systems and water management.
  - Pumps and pressure controls.
  - Sump pumps and storm water management.
  - Larger valves.
  - Deionization system pumps and actuators.
  - Sewer lifting for low levels.
- Elevators
  - Traction
  - Doors
  - Ventilation

There are more.

- Process cooling pumps.
- Heat recovery chiller compressors.
- Door openers.
- Fume hoods.
- Machine tools.
- Clean room equipment.
- Appliances.

For HVAC, drives are essential.

- Modern HVAC systems require accurate speed or torque control.
- Example: energy recovery wheel speed is related to temperature difference, ventilation volume requirements, and building loads.
- Energy reduction potential is large when drives can serve these loads.
- Constant volts per hertz drives are adequate.

One important issue is wide-area lighting.

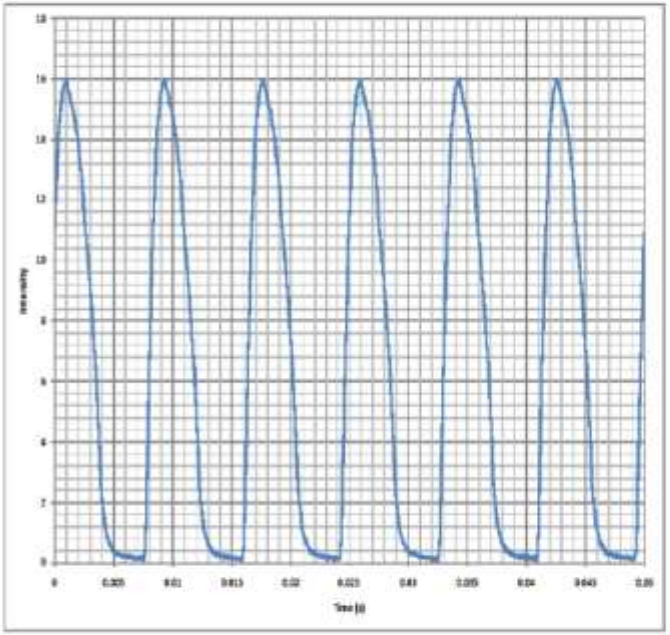
- Solid-state fixtures suitable for large rooms are just entering the market.
- In larger spaces, fluorescent still has an edge, in part because of form factors that work well with drop ceilings.
- Previously solid-state fixtures were limited to "down" lights.

Fluorescent lamps have control limits.

- Fluorescent lighting has nonlinear behavior.
- Hard to implement a complete full-range dimming function.
- The characteristics change with time as well.
- Even so, not hard to set multiple discrete levels.

Solid-state lighting offers broader control capability.

- Linear behavior in current over most of the range.
- Some companies advocate ac operation, but LEDs *flash* at double the line frequency in this operating mode.
- Single-phase filtering is vital.



Typical ac drive LED flicker.
Source: Kevin Willmorth Lumenique, LLC

What about daylight harvesting?

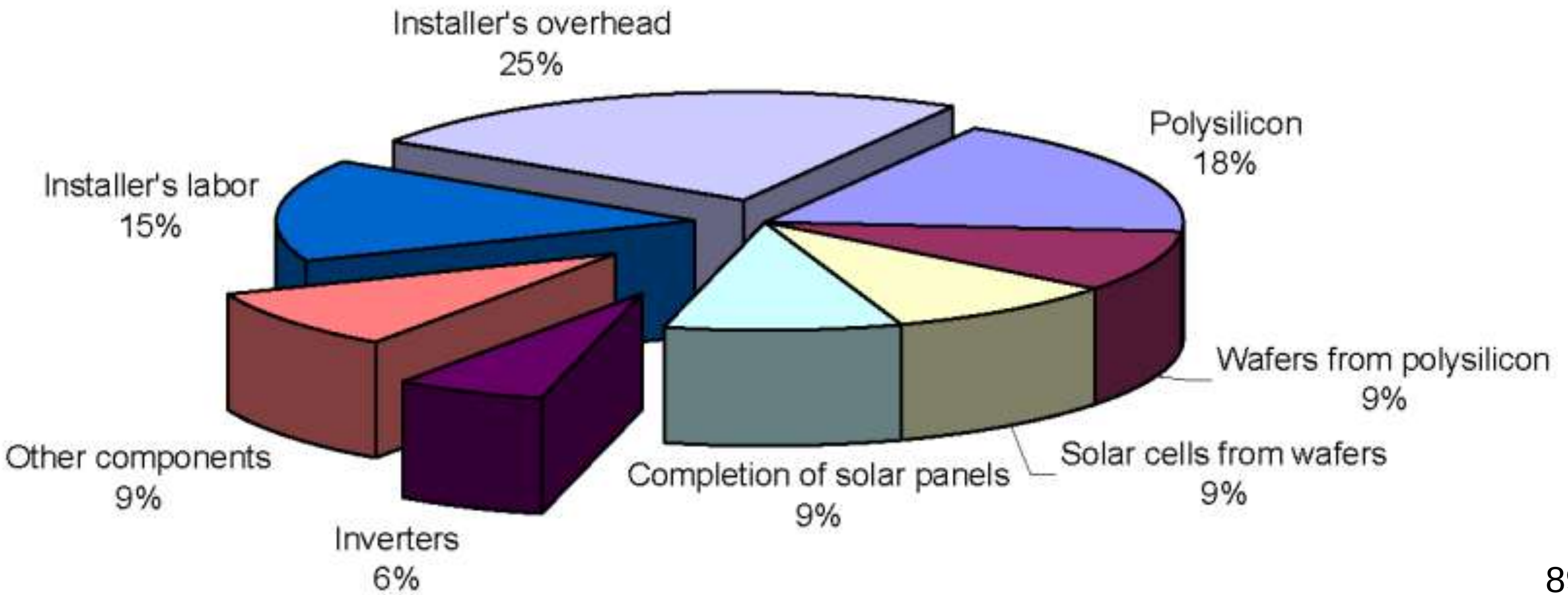
- When the right sensors are available, task and room brightness can be adjusted continuously.
- Since people are accustomed to cloud intermittency, it is important not to react too quickly.
- Color control is an interesting aspect as well – match the color change of sunlight over the course of a day.

The renewable energy emphasis is on solar.

- Grid interconnection must meet standards and codes.
- Wind complicates building integration issues.
- Still difficult to do standalone systems.

Costs have been dropping dramatically.

- A retail U.S. system in 2008 cost about $9 per peak watt before subsidies.
  - Roughly 1/3 cells, 1/3 mounting, 1/3 inverters and panel packaging.
  - Will anything need repair?

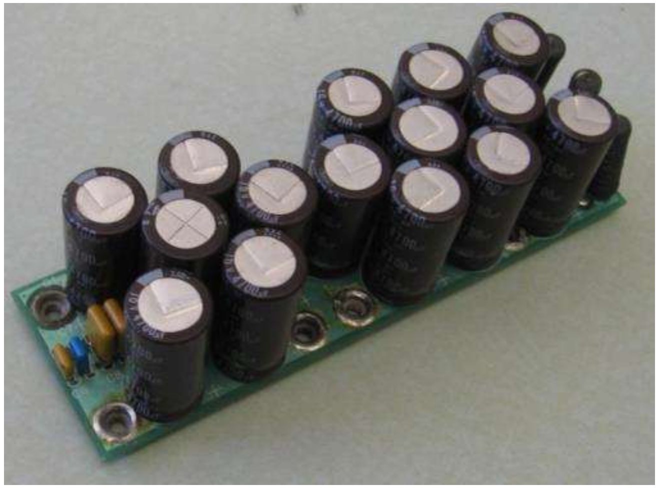


Costs have been dropping dramatically.

- Today, retail systems are below $3 per watt.
  - Roughly 30% cells and packaging, 15% inverters and panel packaging, the rest in installation and labor.
- Commercial systems are lower
  - Soon reaching $2 per watt for the most experienced installers.

High-reliability power electronics is a key enabler for the reduction.

- An inverter that meets grid interconnection standards (e.g. IEEE 1547) is an absolute requirement.
- Conventional inverters have been a weak link for reliability, especially in single-phase systems.

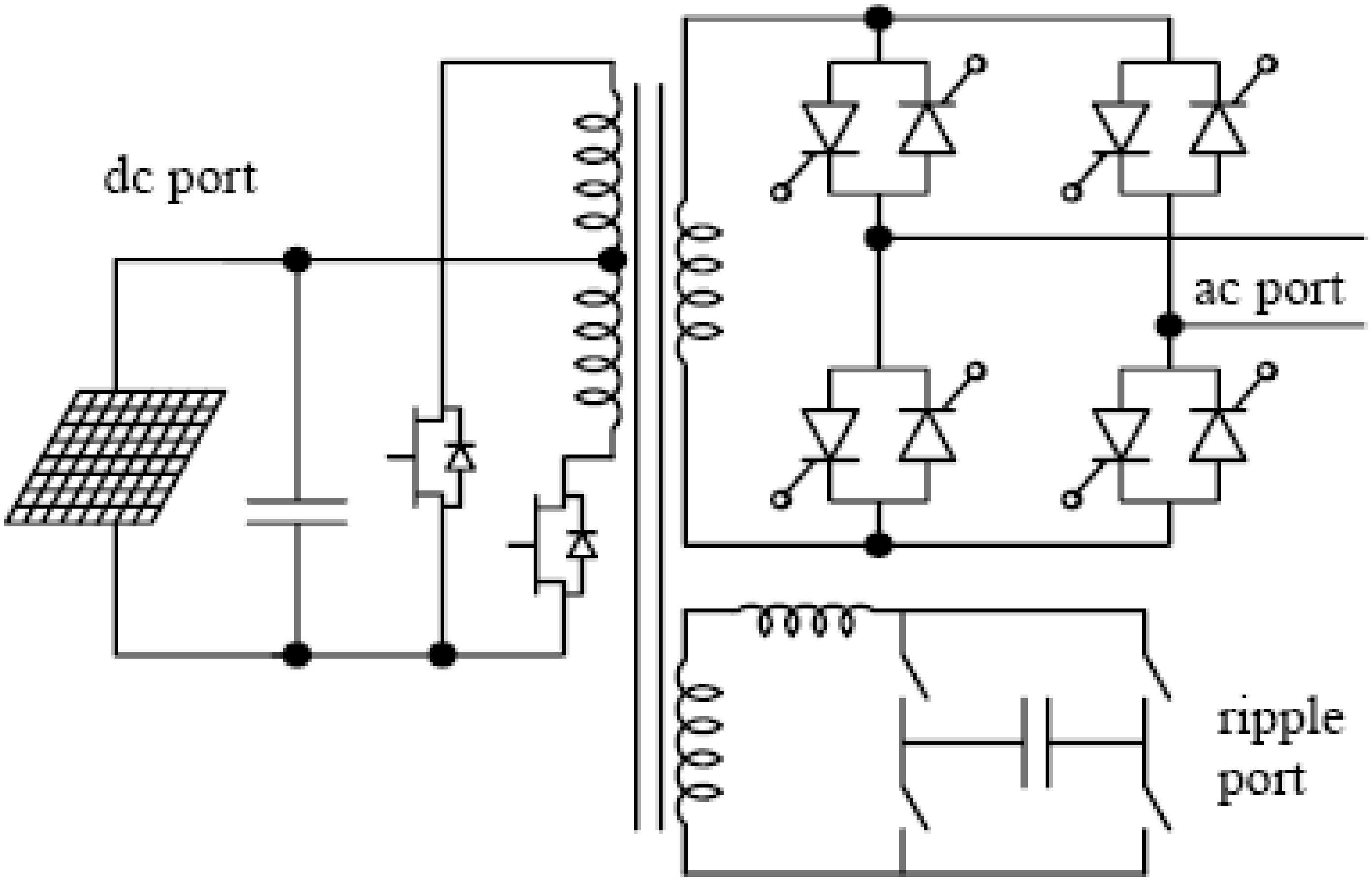


The power electronics should last as long as a solar panel.

- Power electronics is a major cost reduction driver.
  - Match panel life
  - Match warranty
  - Facilitate installation
  - Improve energy delivery
- Integrated ac PV panel:
  - Plug and play solar
  - No dc protection or wiring
  - Each panel controlled to deliver maximum energy
  - Need to enable and support utility operations (not all do)

This active ac link topology is one example.

- Ac link with active filter port.



Typical inverters have mean time between failure less than 10 years.

- For a useful solar power resource, must match panel capability
  - Eliminate electrolytic capacitors
  - Avoid delicate devices
  - Need reactive support
- New designs achieve MTBF above 100 years.

With ac panels, aiming is not an issue.

- Simpler structural issues.

PV power is ideal for rooftops.

- “Free space:” rooftop generation becoming routine
  - Generate electricity at the point of use
  - Capture energy that would increase building heat load
  - Easy mounting, controlled access

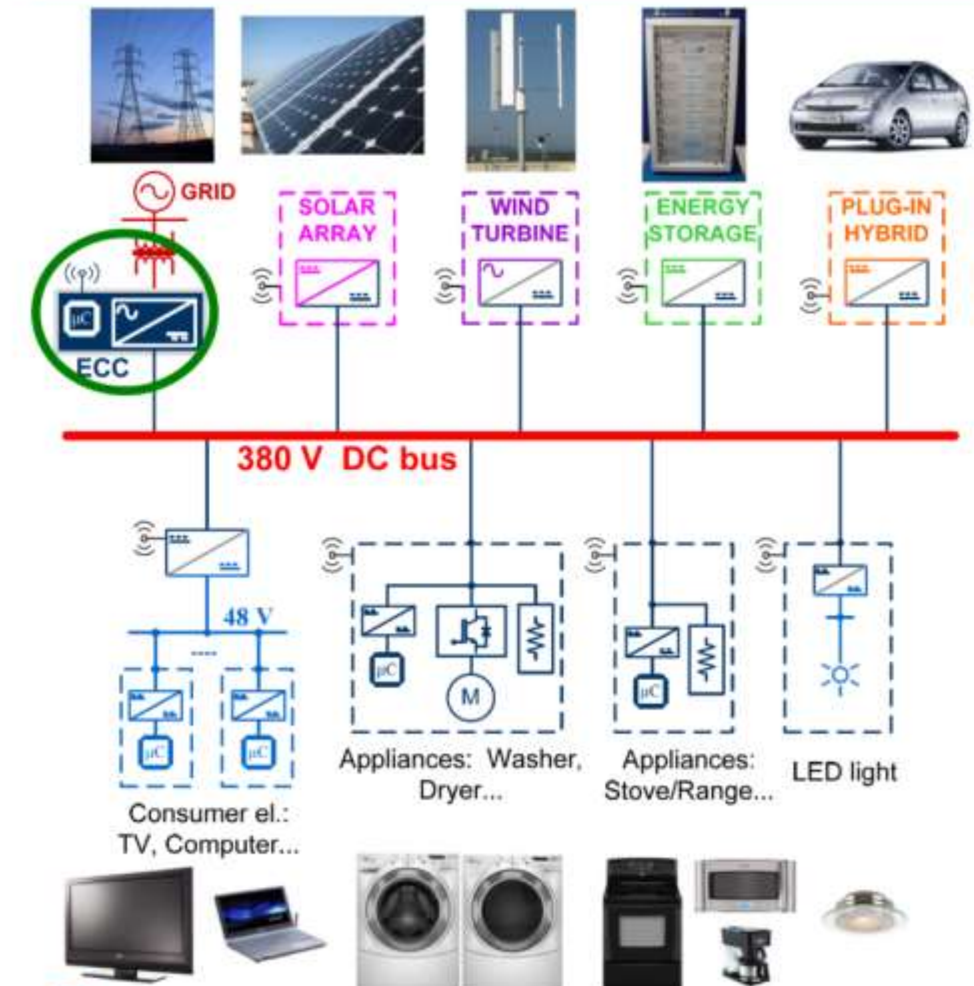
Walmart installation, California

www.greenpacks.org

What about dc distribution?

- In a high-performance building, most loads have rectifier front ends and can operate on dc.
- Why convert from ac to dc and then dc to dc?
- Direct dc supply.

Integration of Sources and Loads with DC Bus



Only the system net energy needs to be processed through the single grid-interface converter.

The grid-interface converter also works as the system energy control center (ECC) to manage the energy interaction between the dc system and utility.

Benefits:

- **Higher efficiency**
- **Lower cost**
- **More reliable**

D. Boroyevich, “Dc nanogrids for buildings with net-zero electric energy costs?” presented at *Workshop on Power Electronics and Electrical Challenges for Engineering Energy-Efficient Buildings,* March 2014.

Some solid-state lighting firms are advocating 24 V and 48 V distribution.

- This is *within* a room, such as an above-ceiling installation in a large space.
- Send power around from a single source with low voltage.
- Use low-voltage (wireless) controls to make adjustments.
- Safe and flexible.

At the bus level, higher voltages make sense.

- Various dc distribution methods resemble the original Edison ±150 V system.
- The 380 V system that is gaining users is often split to ±190 V for the same benefits as the Edison system.
- In this case, active power converters are needed for proper fault management.

An ac system has *fault detection* advantages.

- Traditional ac approach results in high fault currents.
- These are detected rapidly and cleared by circuit breakers.
- In effect, the detection and protection actions are integrated.

Fault management is harder in a dc system.

- Without current zero crossings, interruption can be challenging.
- Detect extreme currents, and then shut off the relevant power electronics.
- This can be successful, but now there are two separate steps.

Data centers are an element of many high-performance buildings.

New data center methods push the issues even harder.

- Can a data center operate with outside air, effectively with little or no HVAC?
- Can the temperature be allowed to climb?
- What about liquid heat exchange loops?
- Or even use the waste heat for other purposes if that is possible.

Any building with an internal data center faces special challenges in achieving low-energy goals.

- A similar argument can be made about cleanrooms, wet labs, or many other specialty applications.
- Integrated ways to harvest waste heat remain interesting.

Here is one storage concept.

- The supercomputer at Illinois operates as a state-of-the-art data center.

Cool water at night with cheap power (or during the day with excess solar) and cool the computers as needed.

- This tank stores about 30 MWh for every 1°C temperature change.
- Very difficult to scale batteries to this level.

A “virtual storage” concept for dynamics.

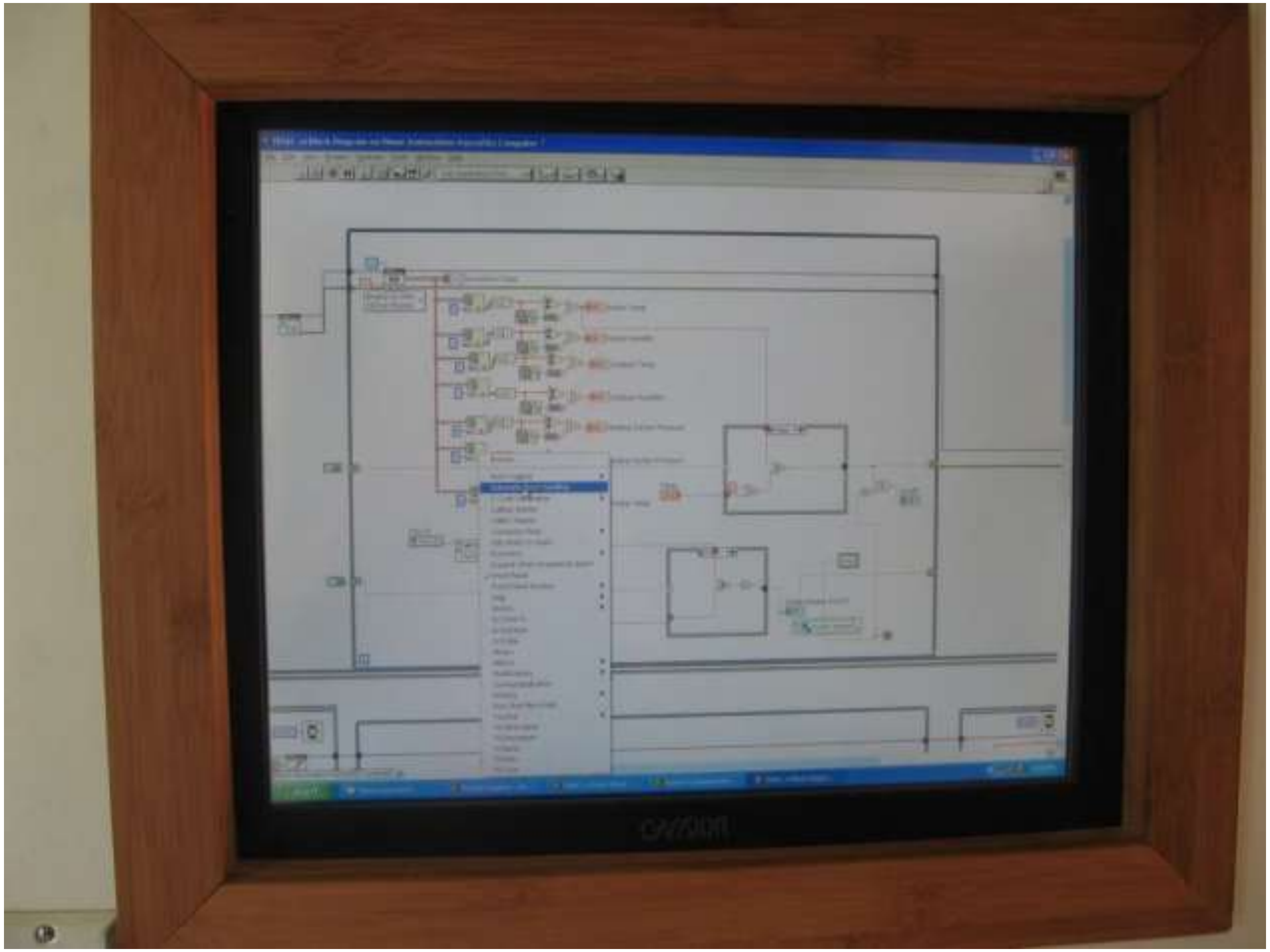
- A building has substantial thermal inertia, and response times of at least a few minutes.
- This implies that there is “fast bandwidth” to use provided long-term closed-loop behavior is not affected.
- Fast adjustments to HVAC can partly offset stochastic solar generation or rapid load variation.

Solar Decathlon – build a house that operates solely on sunlight.

This can be done for single dwellings.

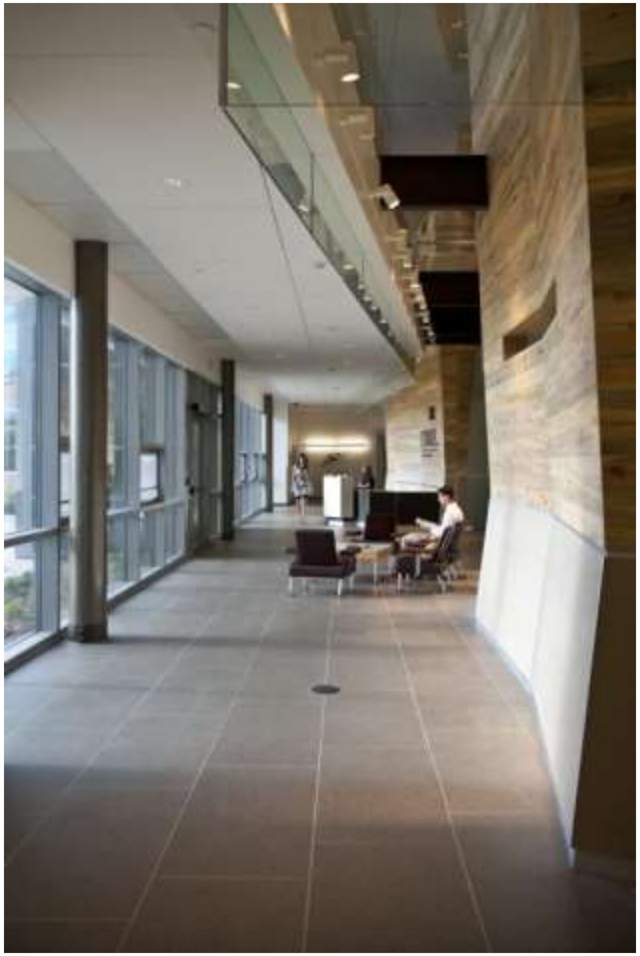
Full function interior.

Monitors show full operation, and this house produces about 30% more energy than it consumes.



Research Support Facility, National Renewable Energy Lab, Golden, Colorado

RSF is the largest formal net-zero building in the U.S.



It has also achieved LEED Platinum certification.

- Extensive recycled content.
- Emphasis on renewable materials.
- Active control in the exterior glass.
- Has a small data center – high energy intensity.

Here are some of the major attributes.

- East-west orientation and narrow floor plate.
- Thermal storage: concrete in basement.
- Daylight harvesting.
- Radiant heating and cooling with water.
- Displacement ventilation.
- Solar resources.

Electrical and Computer Engineering Building at the University of Illinois.

Construction started January 2012

- The building opened August 25, 2014
- “Green field” site.

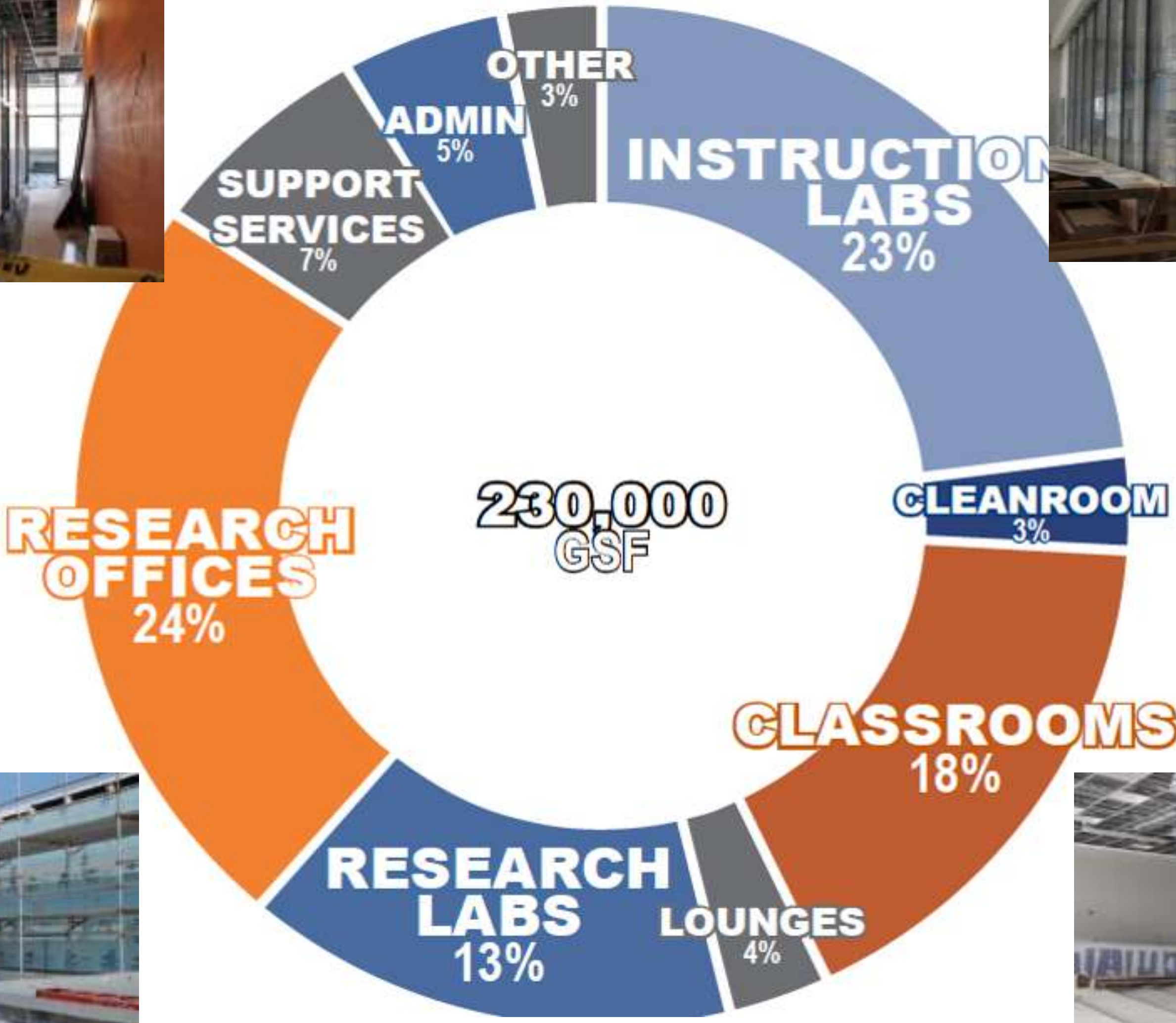
Collaborative spaces are all the rage, but it is less clear how designs are established.

- Not many evidence-based results are available and influential.
- In this case we did our own research.
- Example: "vertical traffic" is a big limiter.
- Example: Easy and tempting to silo by function.

Three fundamental objectives:

- Provide a *home* building for students
- Leverage activities on the north Engineering Quad
- Create one of the largest zero-net energy facilities

SPACE ALLOCATION



CONSTRUCTION

“All-in” student instructional spaces dominate the plan.

- About 24 instructional labs supporting about 30 lab courses
- Extensive services and student spaces
- Collaboration and group spaces
- Open projects lab

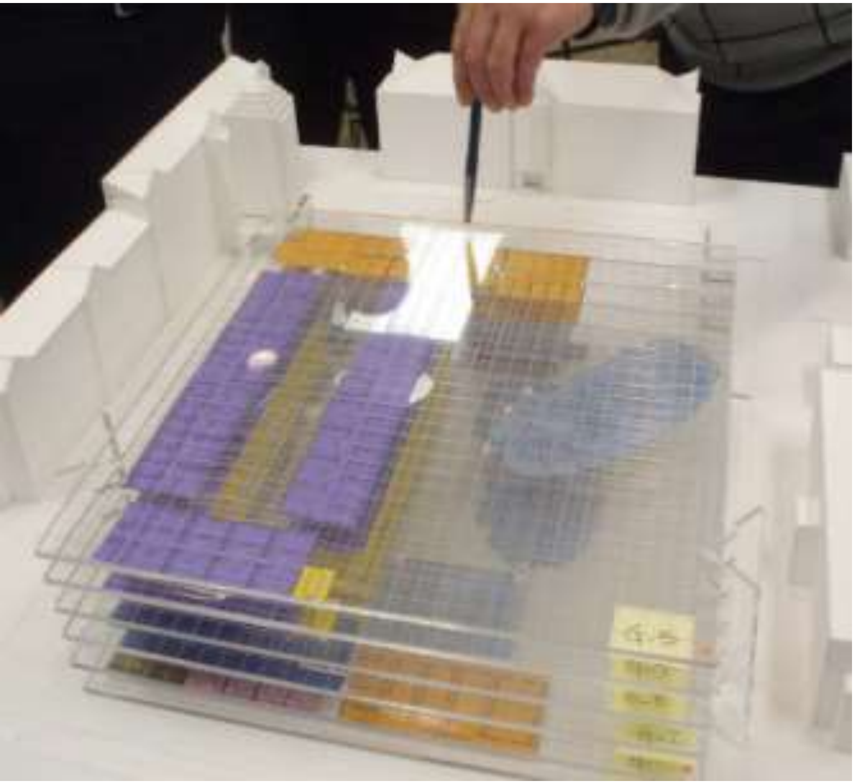
How big a project?

- An “inside-out” plan for 22,000 gross square meters and 11,000 net assignable square meters
- $95 million total project budget with 50 percent state support
  - Construction bid: $71.1 million, $300 per square foot.

Considerations assigned to the architects:

- Leverage proximity to existing facilities while providing missing extra functions
- LEED Platinum certification; targeting the most energy-efficient engineering building in the world
- Showcase Illinois innovations (LED, power electronics, advanced computing, others)

Many building projects start with outside appearance and work in.



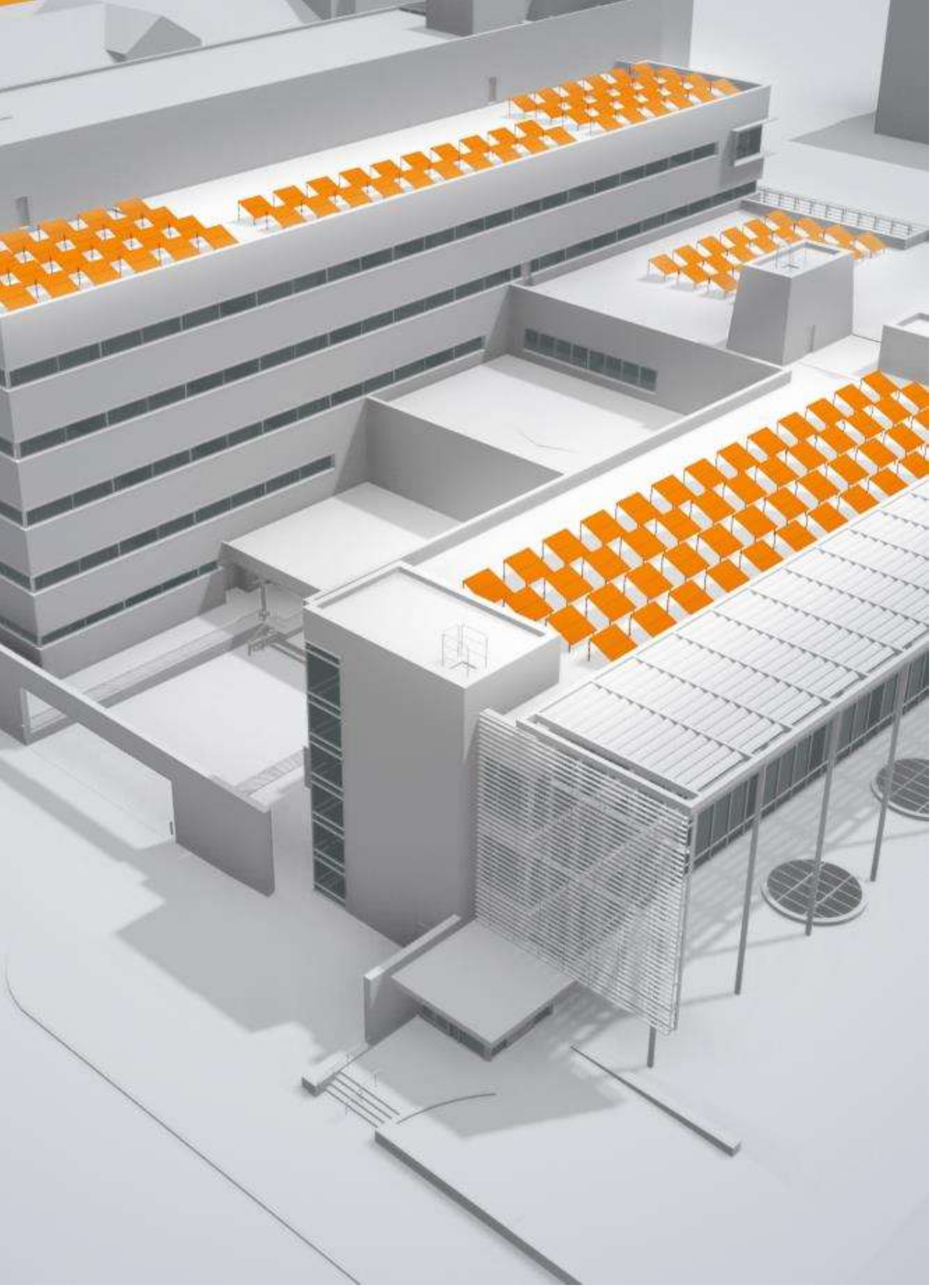
Contrast to many other architectural projects:

- Inside-out design
- Form follows function
- Emphasis on department *home*
- Energy efficiency

Low-energy features designed in:

- Lighting

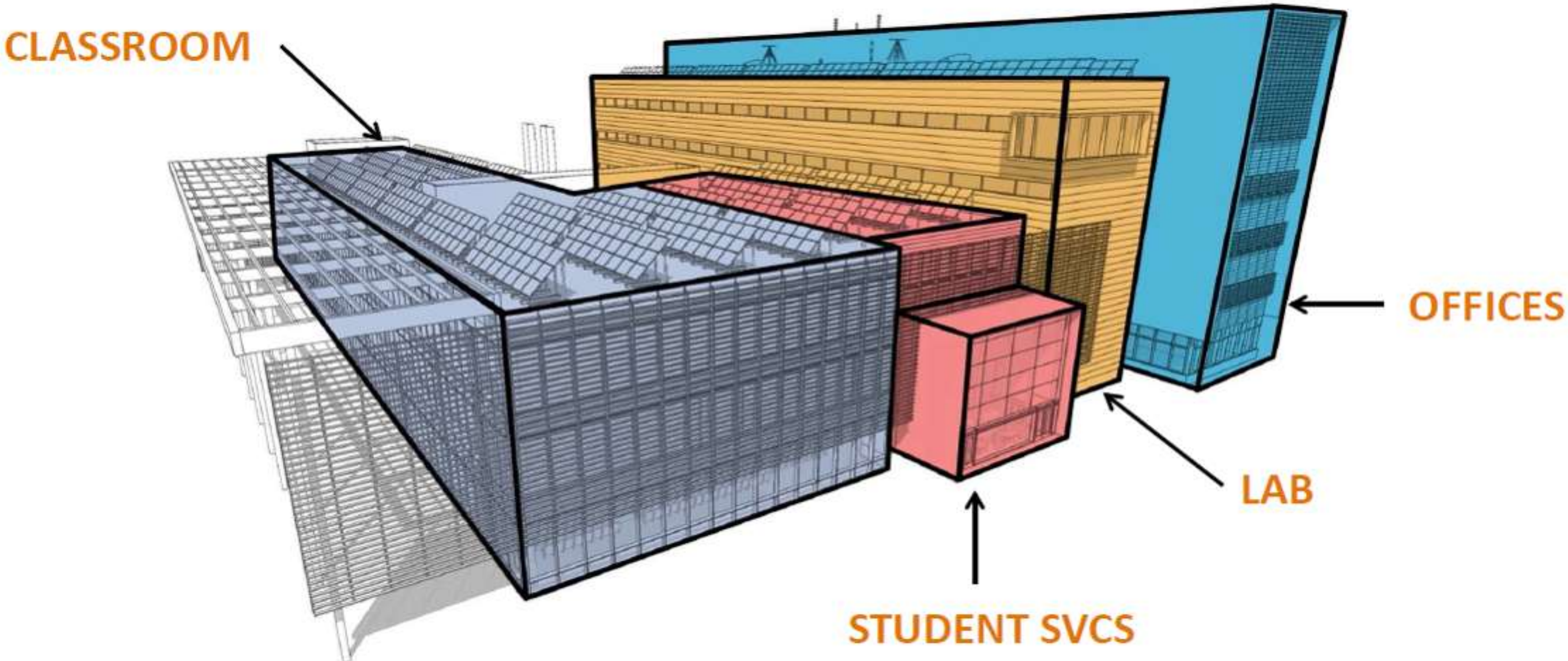
- HVAC
- Solar sources
- Energy management, etc.



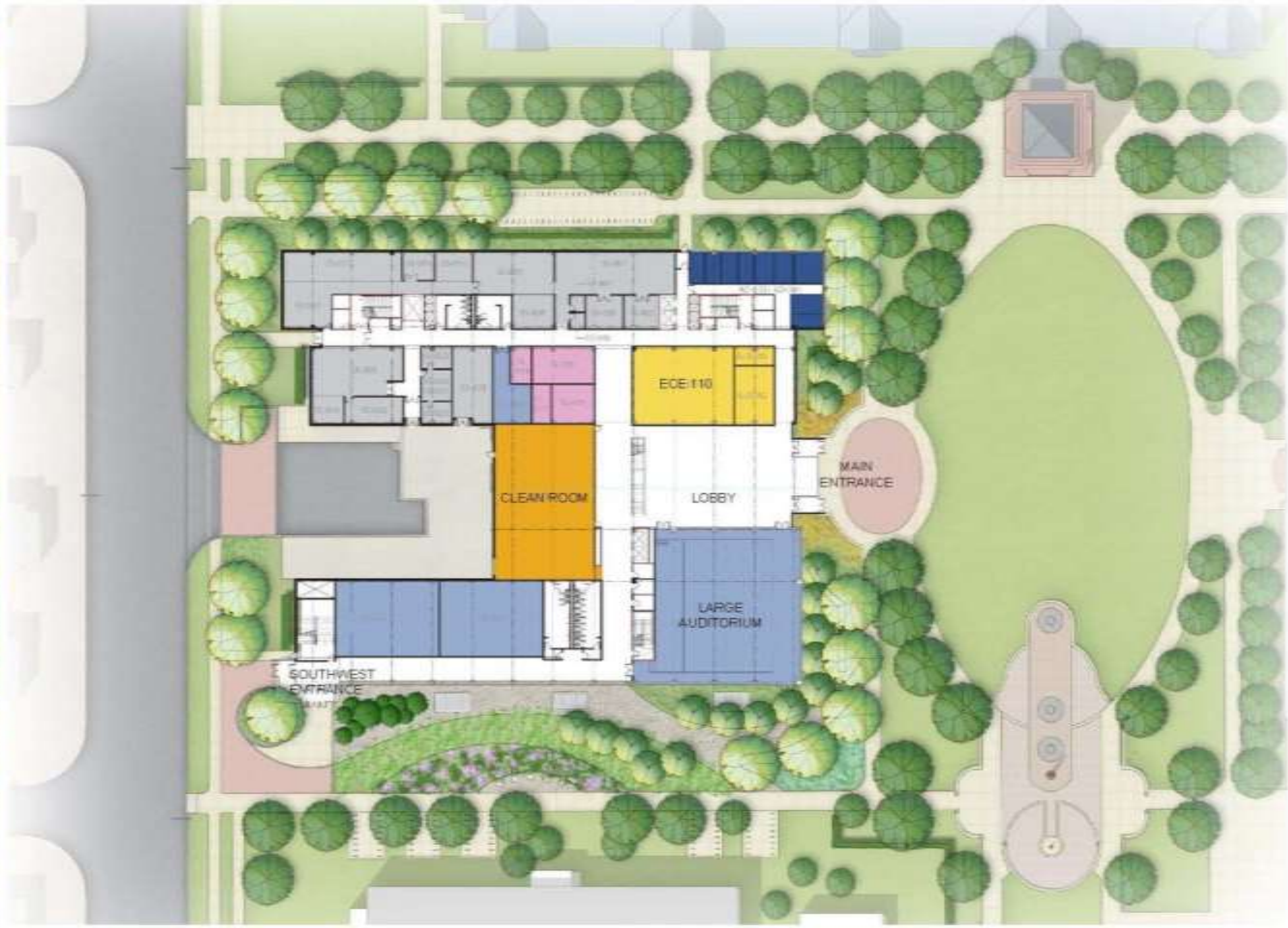
The solar installation will help us target net-zero energy.

- Projected for zero-net energy on an annual basis, including solar resources on parking structure
- Could become the second largest U.S. zero-net energy building

The layout emphasizes function and interaction.



Native landscaping enhances sustainability and reduces long-term costs.





CAUTION



How is low energy achieved?

BUILDING ENVELOPE

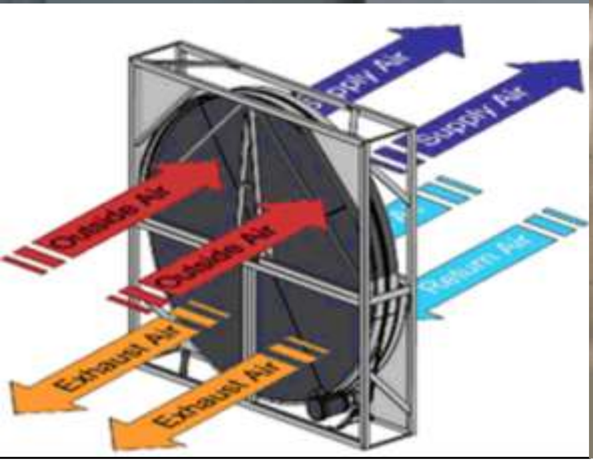
- R-30 curtain rain wall with terracotta facing
- Passive solar elements to minimize heat load
- Design takes advantage of natural light

Solid-state lighting dominates

- New solid-state LED lighting – about 80% of occupied spaces
- New plasma lighting
- High-grade fluorescent lighting
- Daylighting
- Higher efficiency multiplies benefits: less heat load

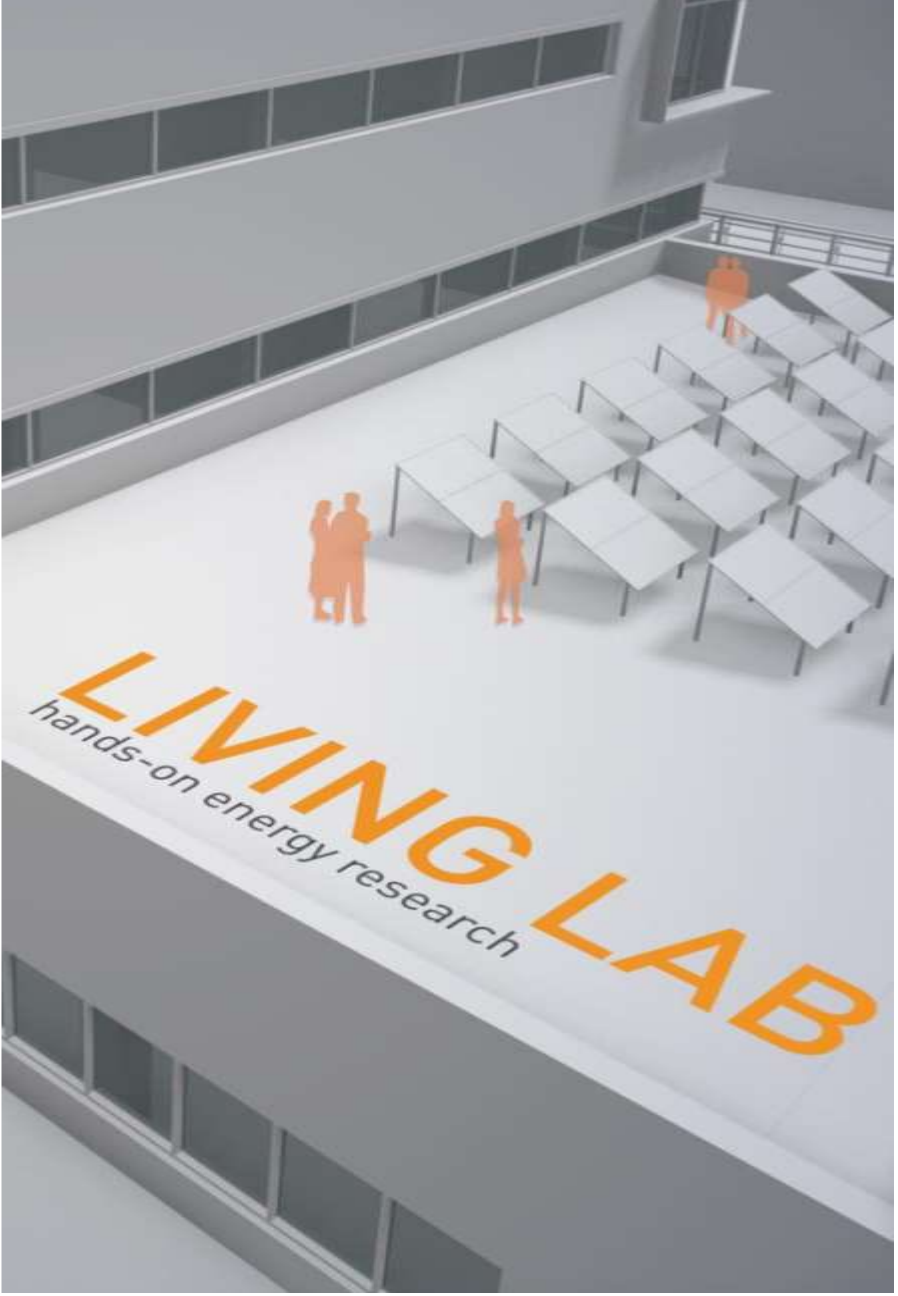
HEATING, VENTILATION, AIR CONDITIONING

- Chilled beams – water cooling system
- Energy recovery wheels
- Heat recovery chillers



SOLAR SYSTEMS

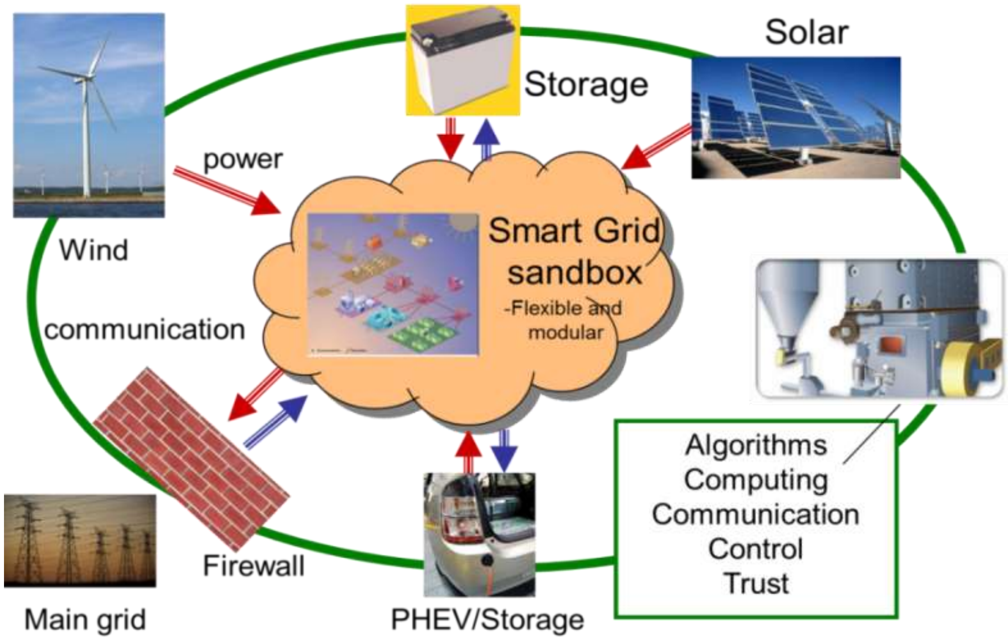
- 300 kW (peak) system on the building roof
- 1200 kW or more on north campus garage
- Integration with campus experimental microgrid



There are many other strategies.

- Sustainability laboratory
- Occupancy lighting sensors
- Premium efficiency electric motors
- EnergyStar appliances and equipment
- Plug-in vehicle ports
- User interfaces and extensive metering

The building serves as a living lab.



- Solar conversion and integration
- Energy tracking and user control
- Microgrids
- Smart grid aspects
- Low-energy buildings
- Occupant behavior