Lecture 03
Energy demand and buildings

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CIVIL-239: Engineering a sustainable built environment

24 September 2024

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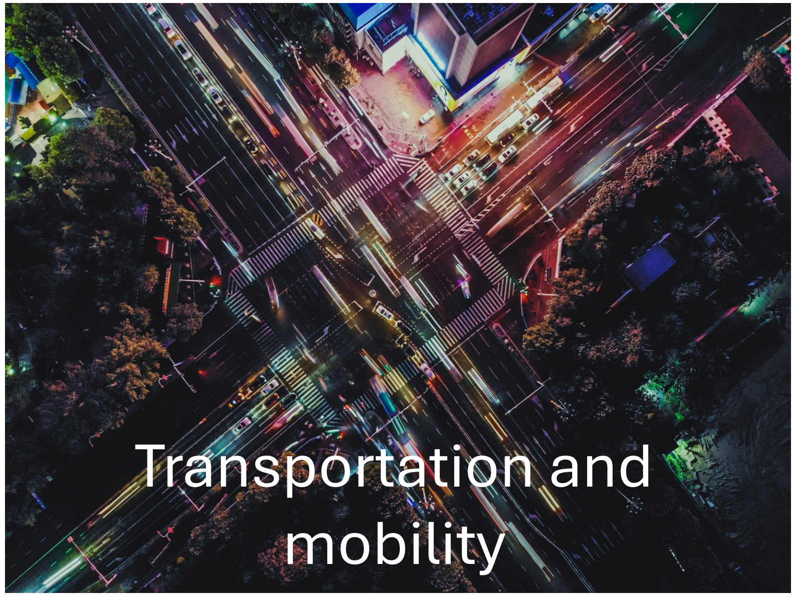
"We shape our buildings, and afterwords **our buildings shape us**"

– Winston Churchill

Week	Date	Course Content	Engineering knowledge and tools	Due
	Course introduction			
1	10-Sep	What is sustainability? Human, natural, and built systems in civil engineering	The role of the built environment in sustainability	
2	17-Sep	Sustainability indicators New economic thinking	The importance of data	
	Buildings and energy			
3	24-Sep	Energy demand: buildings and infrastructure	How design impacts energy demand; Energy and load calcs	Assignment 1
4	1-Oct	Energy supply: Renewables, the grid, and grid integration	Interface between the built environment and energy systems; time-series data analysis	
	Mobility and sustainability			
5	8-Oct	Transportation systems Autonomous vehicles	Link between transportation, energy, and health; systems thinking	Assignment 2
6	15-Oct	Sustainable urban design and active mobility Social systems	System dynamics	
7	22-Oct	No Class - Fall Break		
8	29-Oct	***Midterm exam***		Assignment 3

Subdisciplines of civil engineering



Outline

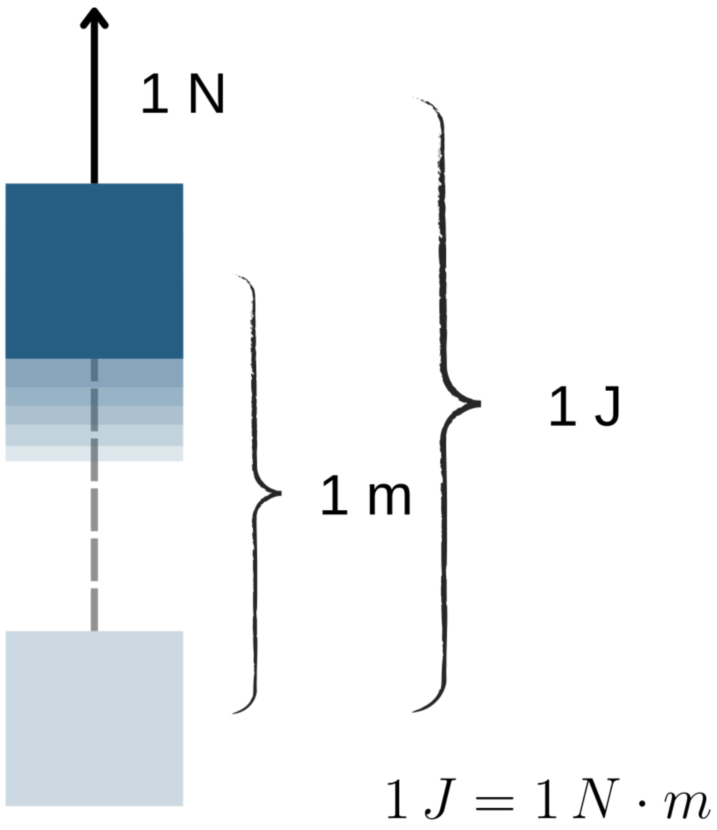
- Energy fundamentals
- Energy flows
- Fundamentals of building energy demand
- Strategies for improving building energy performance
- Case study

Housekeeping

- Assignment 1 due today
- Assignment 2 out today, due in 2 weeks
  - Focuses on buildings, energy consumption, and carbon emissions
- Late homework policy:
  - If late, –50% of grade
  - Updated on course information sheet

How do we talk about energy?

- Basic energy unit: Joule (SI unit of energy)
- 1 Joule = amount of work done when a force of 1N displaces a mass through a distance of 1m in the direction of the force
- Units: equivalent to $N \cdot m$ or $\frac{kg \cdot m^2}{s^2}$



Source: Wikimedia commons

How do we talk about energy?

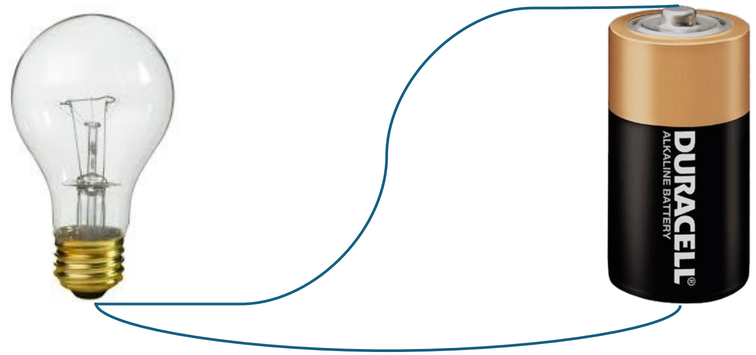
Energy = Power x Time

Power is energy transferred or converted per unit time
1 Watt = 1 Joule / second

Watt-hours (Wh) are another unit for energy

Power unit: watt (W)

Energy unit: watt-hour (Wh)



(60W light bulb)

(60W for 1 hour → 60Wh battery)

SI Prefixes

Commonly used units

Prefix	10^n	Symbol	Decimal equivalent
yotta	10^{24}	Y	1 000 000 000 000 000 000 000 000
zetta	10^{21}	Z	1 000 000 000 000 000 000 000
exa	10^{18}	E	1 000 000 000 000 000 000
peta	10^{15}	P	1 000 000 000 000 000
tera	10^{12}	T	1 000 000 000 000
giga	10^{9}	G	1 000 000 000
mega	10^{6}	M	1 000 000
kilo	10^{3}	k	1000
hecto	10^{2}	h	100
deca	10^{1}	da	10
	10^{0}		1
deci	10^{-1}	d	0.1
centi	10^{-2}	c	0.01
milli	10^{-3}	m	0.001
micro	10^{-6}	μ	0.000 001
nano	10^{-9}	n	0.000 000 001
pico	10^{-12}	p	0.000 000 000 001
femto	10^{-15}	f	0.000 000 000 000 001
atto	10^{-18}	a	0.000 000 000 000 000 001
zepto	10^{-21}	z	0.000 000 000 000 000 000 001
yocto	10^{-24}	y	0.000 000 000 000 000 000 000 001

Other energy and power units

- Oil equivalents:
  - 1 liter of oil contains ~ 10-11kWh
  - 1 ton of oil equivalent (toe) = 41.868 GJ = 11,630 kWh [defined by convention]
- British thermal units:
  - Used for heat energy
  - Energy required to raise 1 pound of water by 1ºF
  - 1Btu = 1,055 J = 0.293 Wh

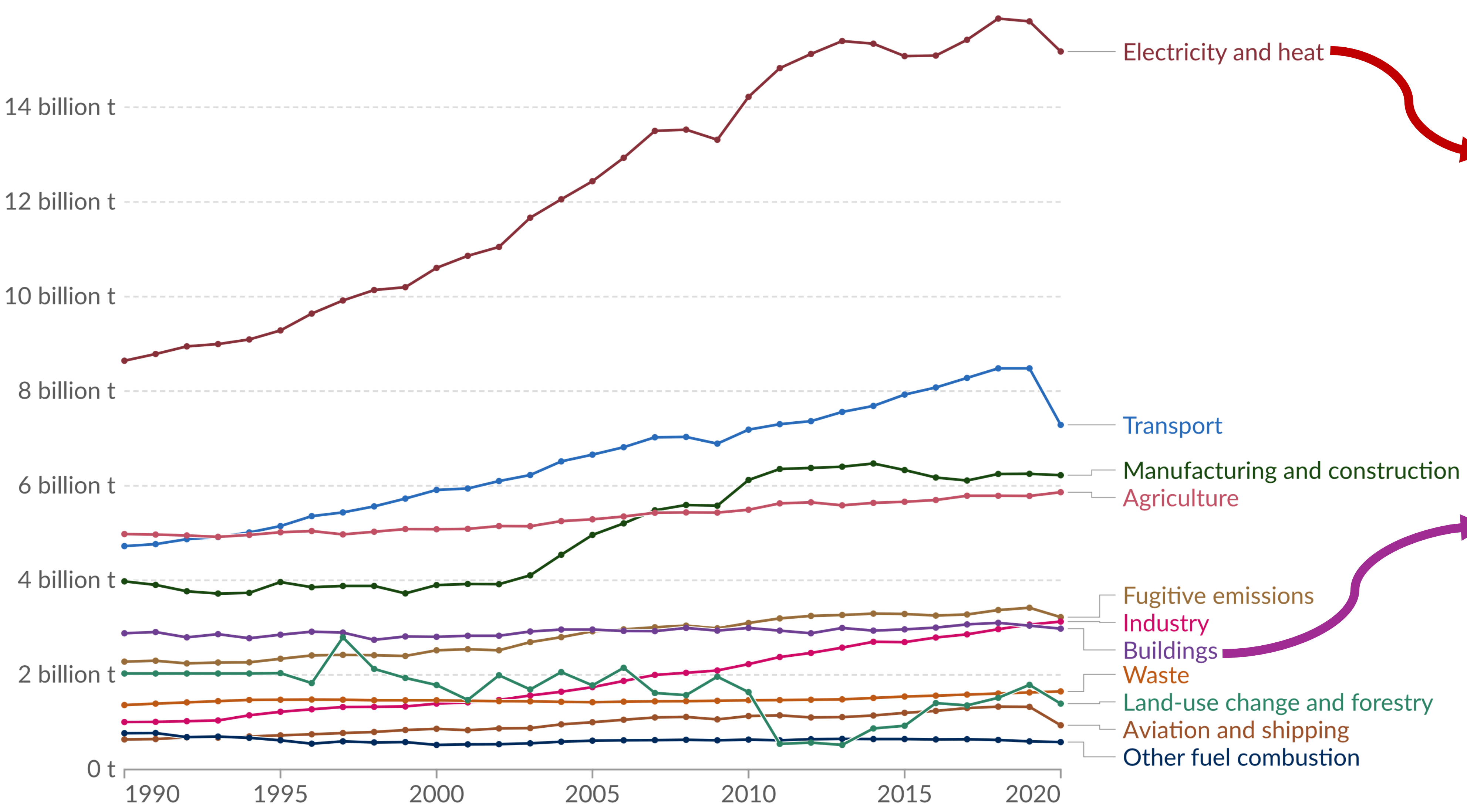
Energy in society

$4 * 10^7\ J$	$2 * 10^9\ J$	$2 * 10^{17}\ J$	$6 * 10^{20}\ J$	$5.5 * 10^{24}\ J$	$1.2 * 10^{34}\ J$
11 kWh	600 kWh	61.5 TWh	168’0000 TWh		
					
Combustion of $1m^3$of natural gas	$61l$ ordinary gasoline tank	Swiss annual electricity consumption in 2023	Total world annual primary energy consumption in 2022	Annual energy received by Earth’s surface from the Sun	Total yearly energy output of the Sun

Source: Christophe Ballif

Greenhouse gas emissions by sector, World

Greenhouse gas emissions[1] are measured in tonnes of carbon dioxide-equivalents[2] over a 100-year timescale.



Buildings responsible for a large % of electricity and heat consumption

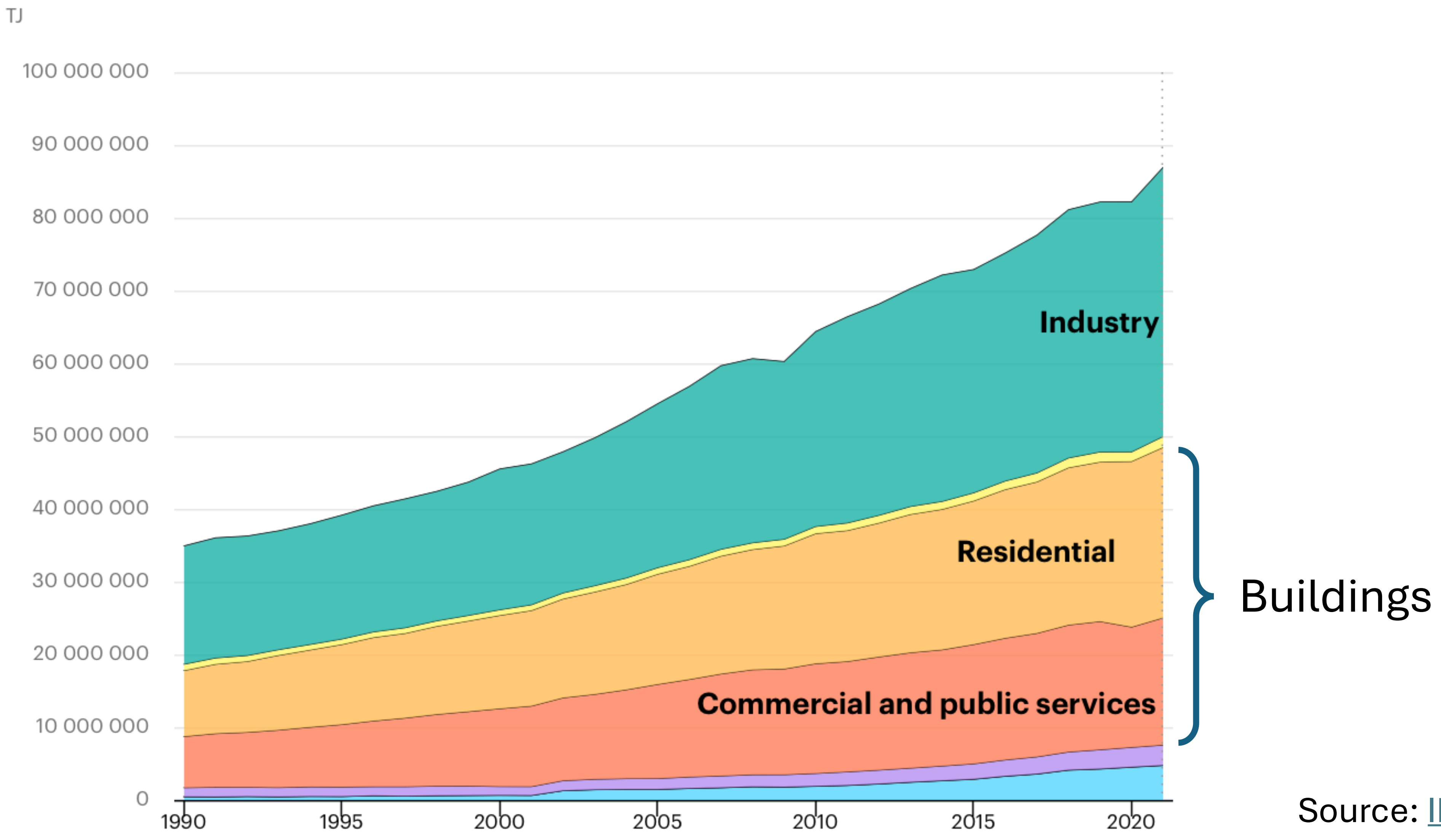
Building materials and construction processes

Data source: Climate Watch (2023)

OurWorldInData.org/co2-and-greenhouse-gas-emissions | CC BY

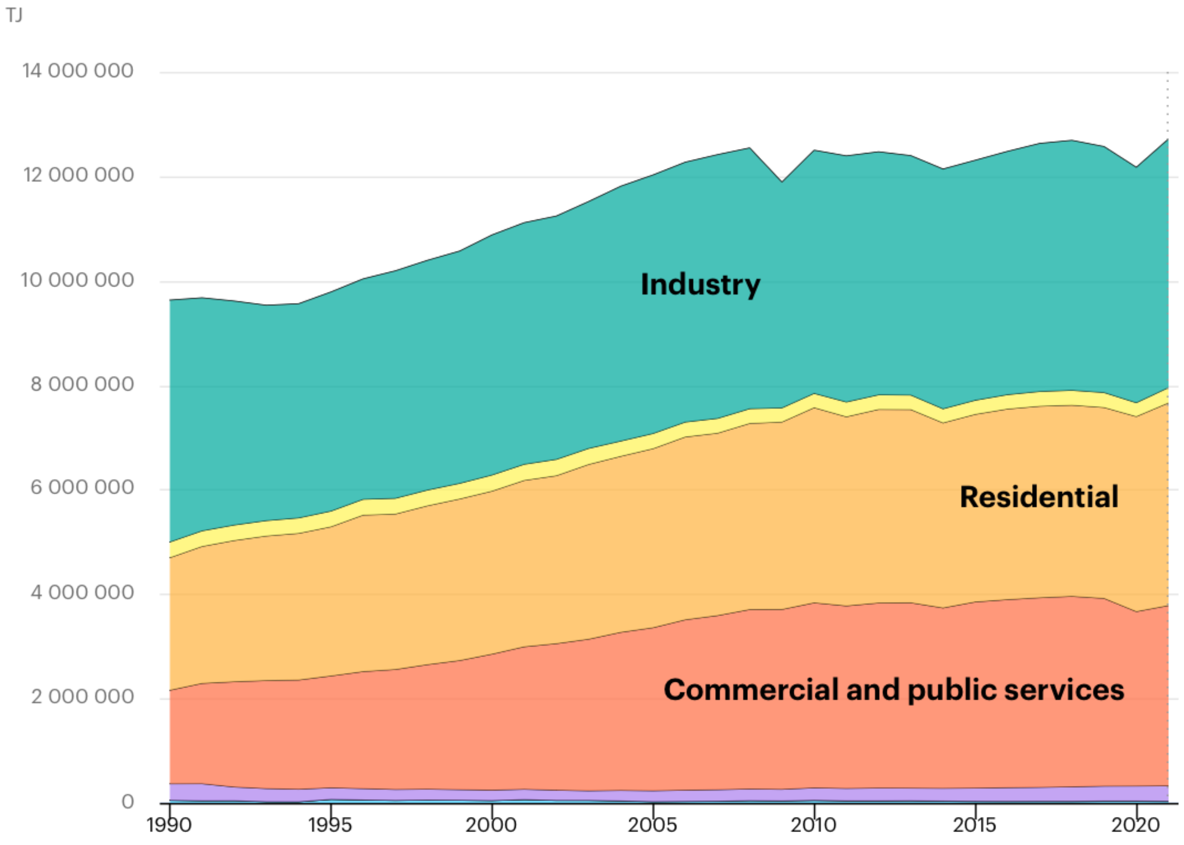
Note: Land-use change emissions can be negative.

Electricity consumption by sector, global

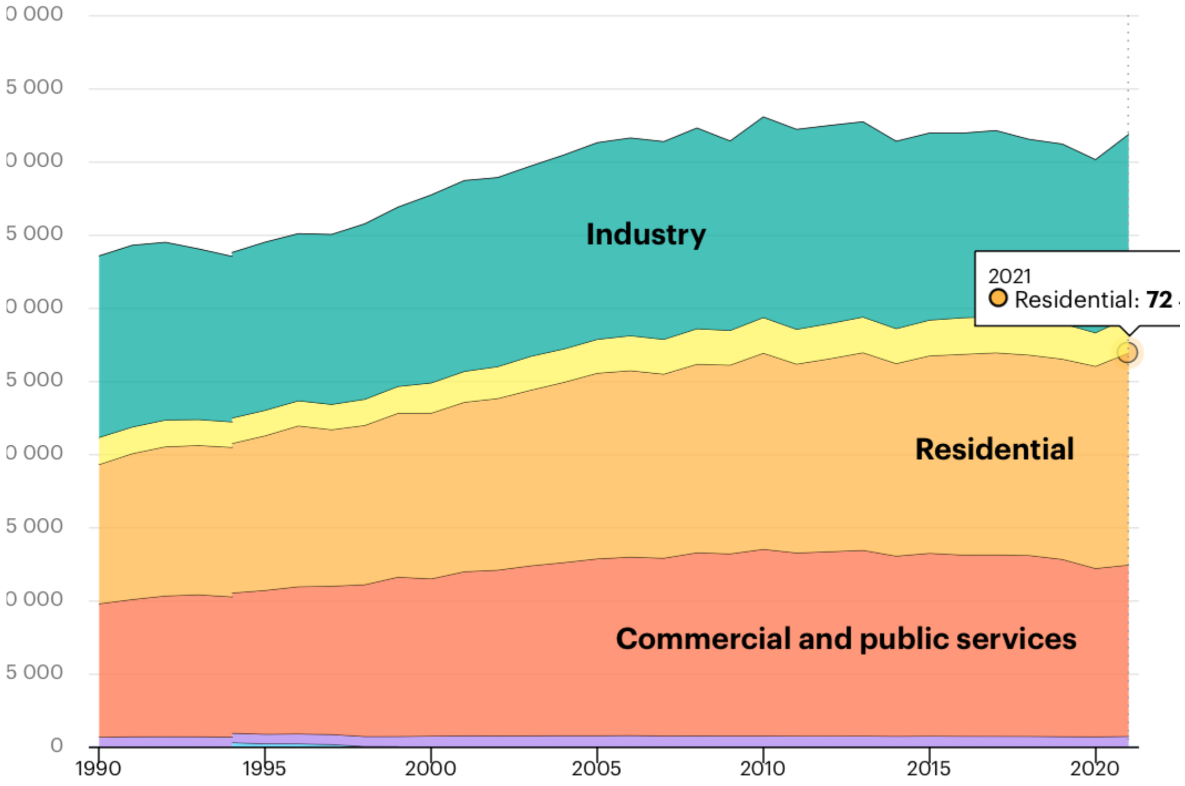


Source: [IEA]

Electricity consumption by sector, Europe



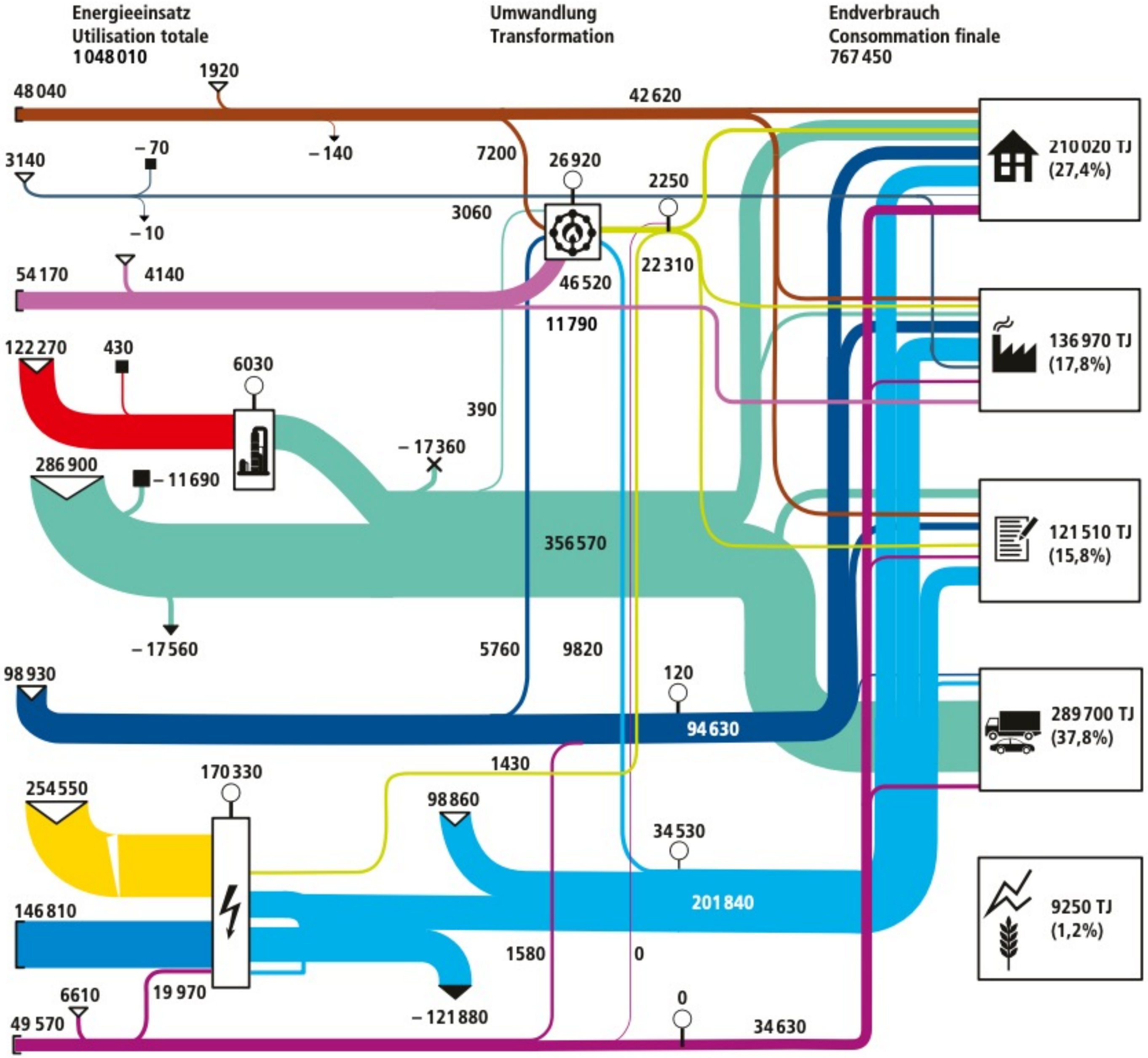
Electricity consumption by sector, Switzerland

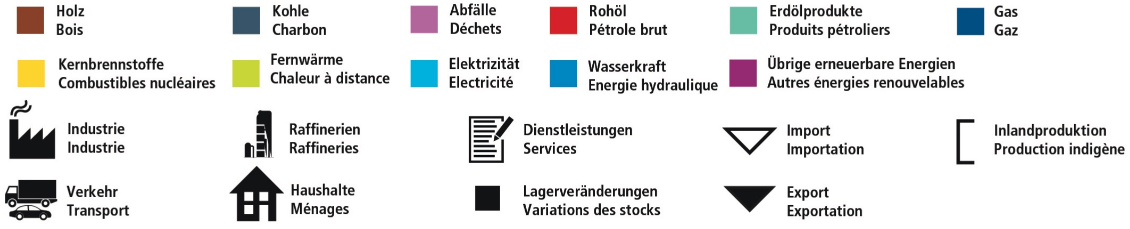


Industry · Transport · Residential · Commercial and public services · Agriculture / forestry · Fishing · Non-specified

Swiss energy flows

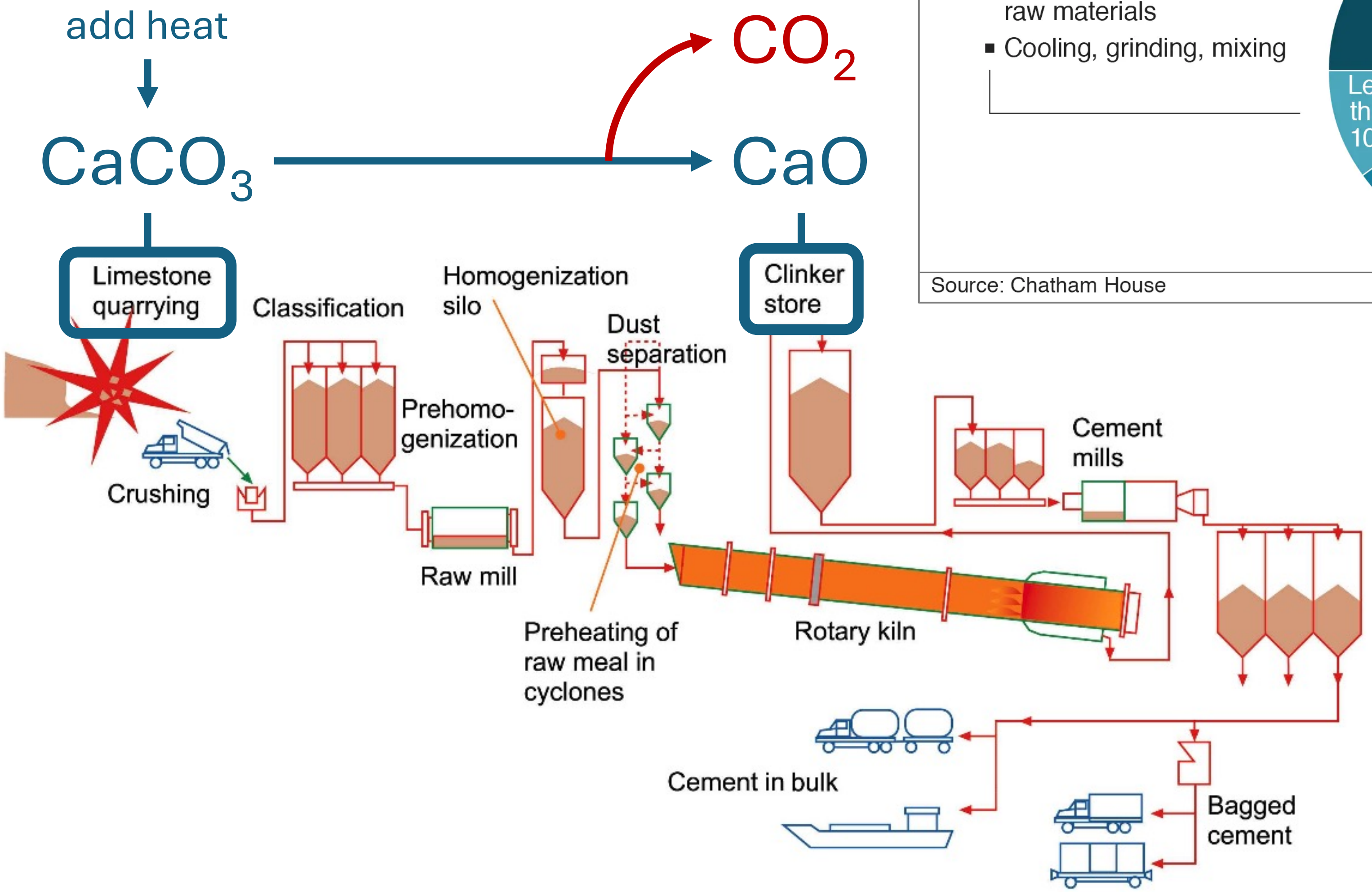
- Sankey diagram shows energy flows from source (e.g. oil, hydropower) to end use (e.g., buildings, transport)

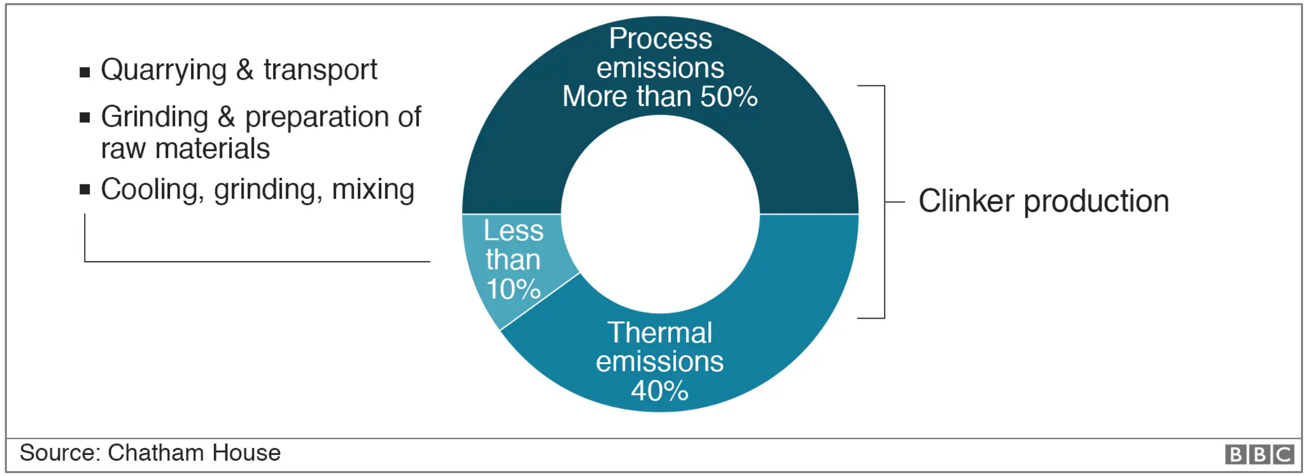




Source: SFOE

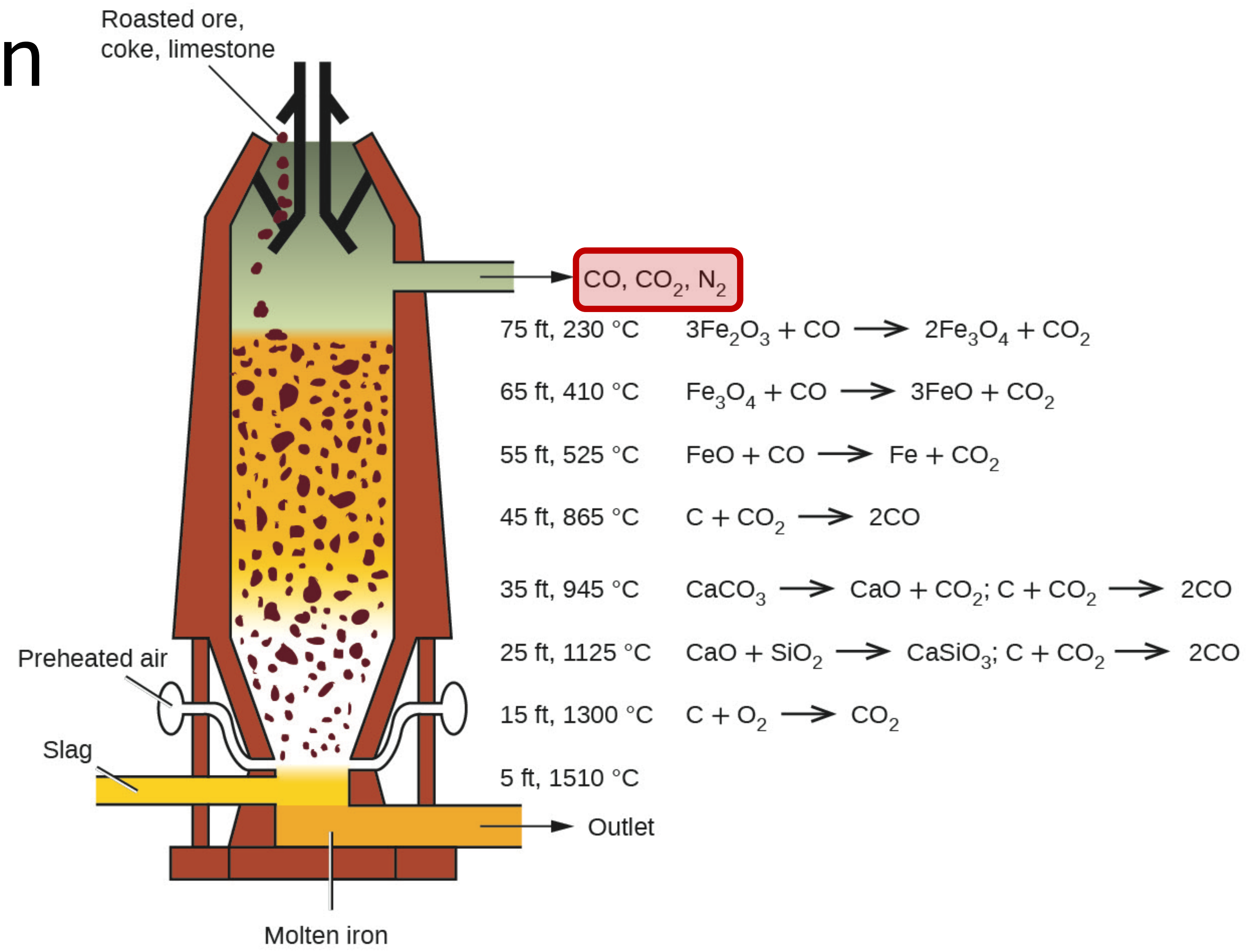
Cement production





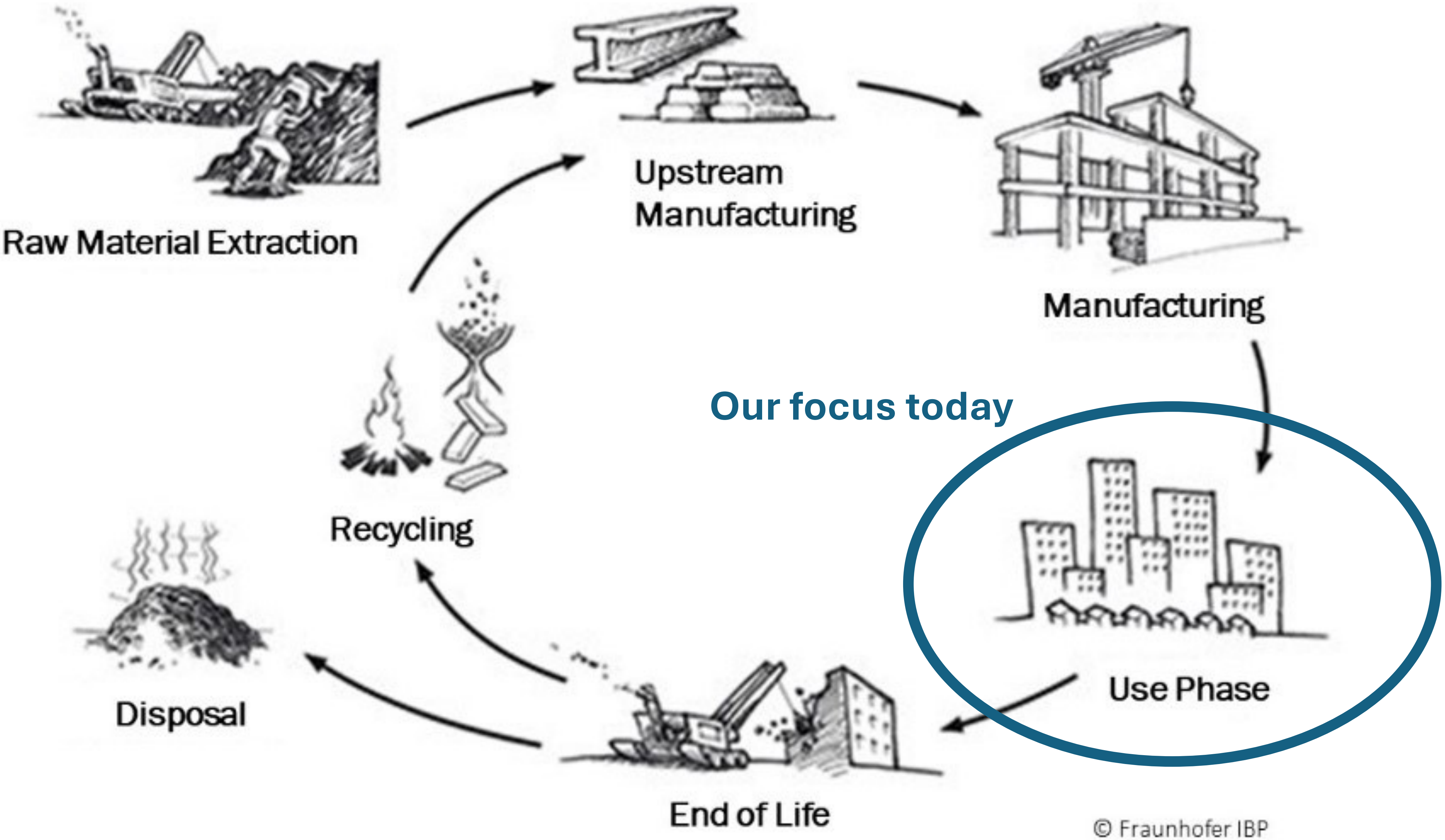
Steel production

- Production of steel also involves chemical processes that produce CO_2



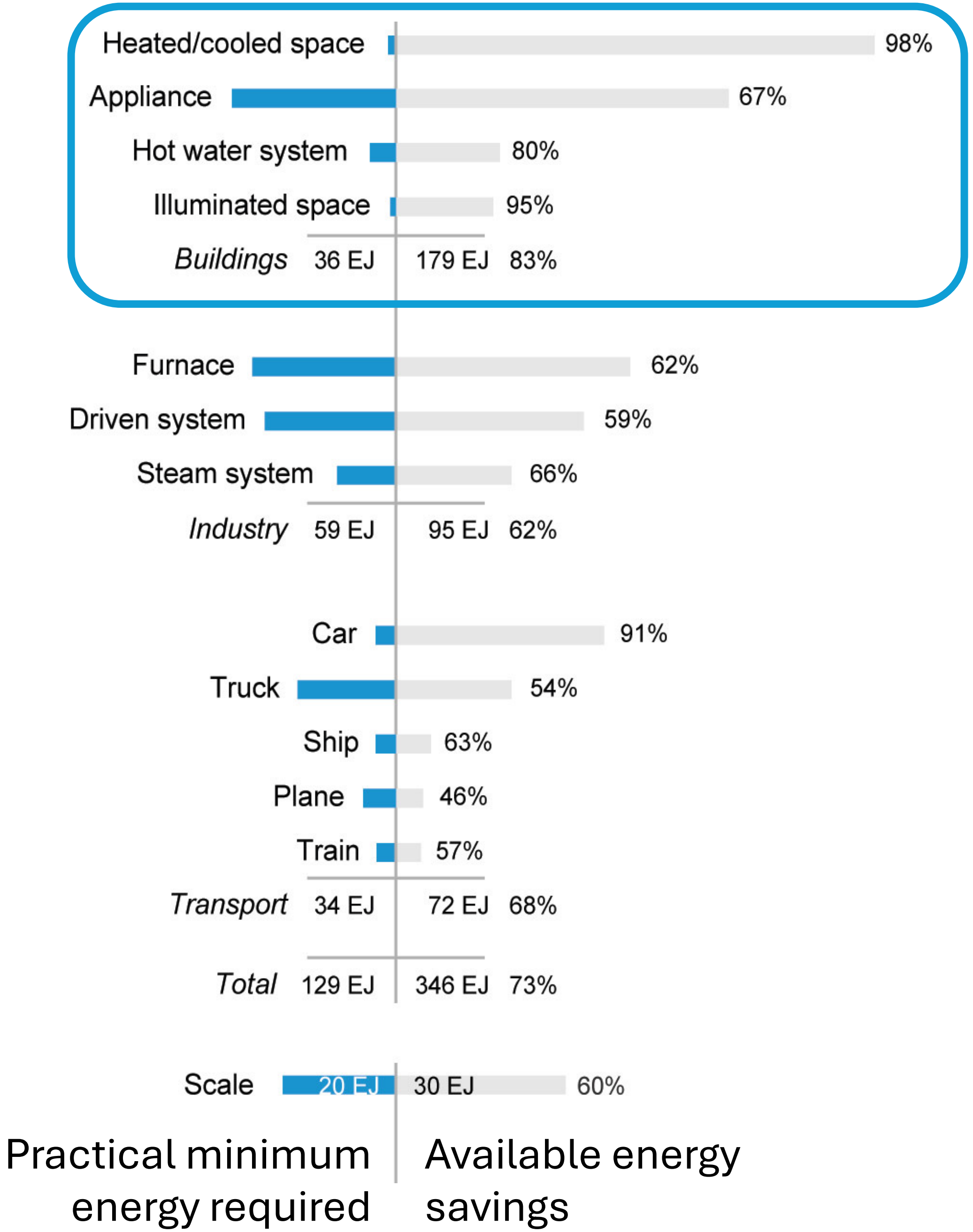
Source: Wikimedia commons

The Life Cycle of a Building



Energy and buildings: summary

- Total energy consumption of buildings
  - 34% of global energy demand, 37% of global CO_2 emissions (UN)
  - In cities, this can be much higher… 70% of NYC emissions
- This is mostly operational energy, but embodied energy is also important
  - Embodied: Energy required to produce materials
- Electricity
  - Especially in the developed world, buildings account for a large percentage of electricity consumption



Buildings

Largest opportunity for reduction

Cullen et al. *Environ. Sci. Technol.* 2011, 45, 4

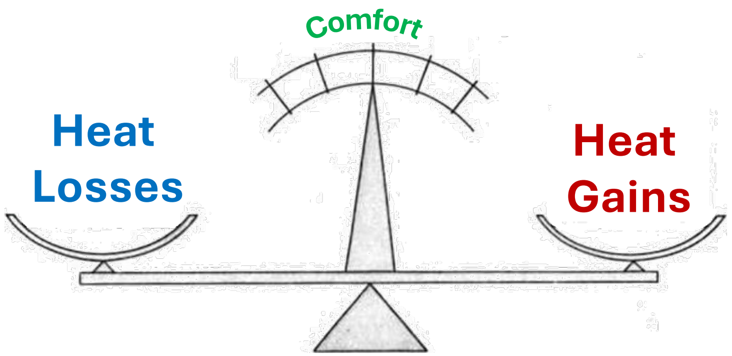
Fundamentals of building science

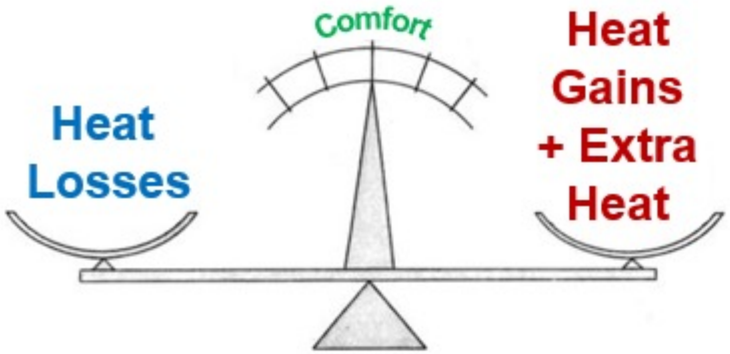
Energy **demand** in buildings

- Heating and cooling are driven by exterior conditions (weather and climate) along with internal conditions (internal heat gains, people)
- Lighting is driven by the need for visual comfort
- Plug loads are the various appliances that are used within buildings

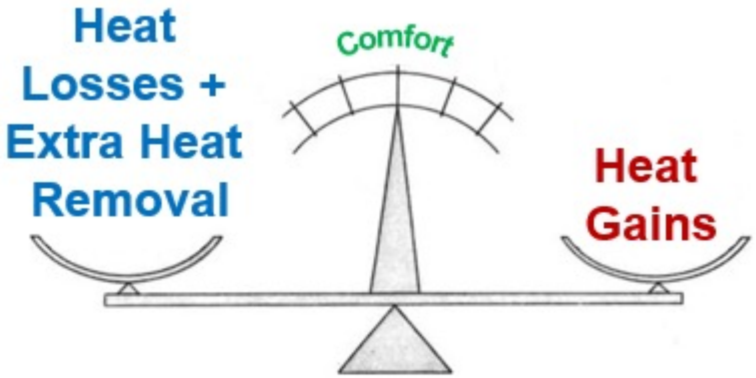
Heating and cooling demand

- **A comfortable indoor temperature** is *maintained* by *balanced* **heat losses** and **heat gains**
- **Heating** or **cooling** is needed when *they are imbalanced* and *extra* **heat addition** or **removal** is **necessary**





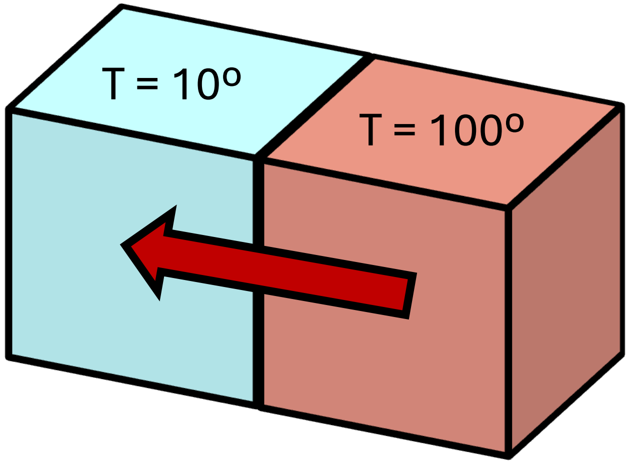
HEATING



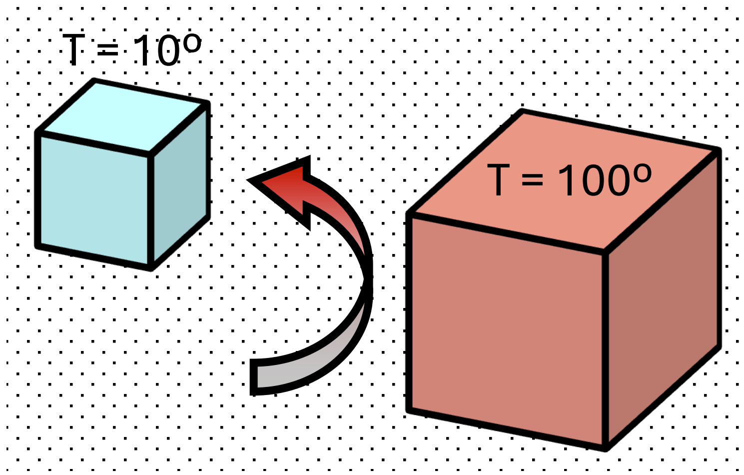
COOLING

Heat transfer

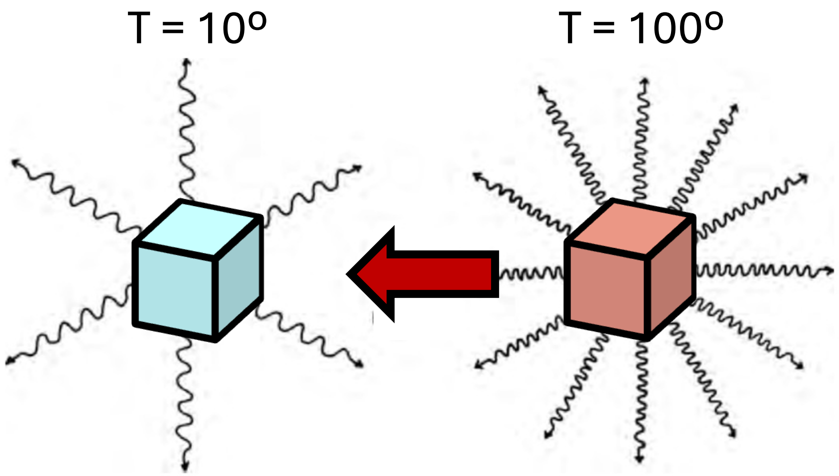
Three types of heat flow:



Conduction
(two surfaces in contact)

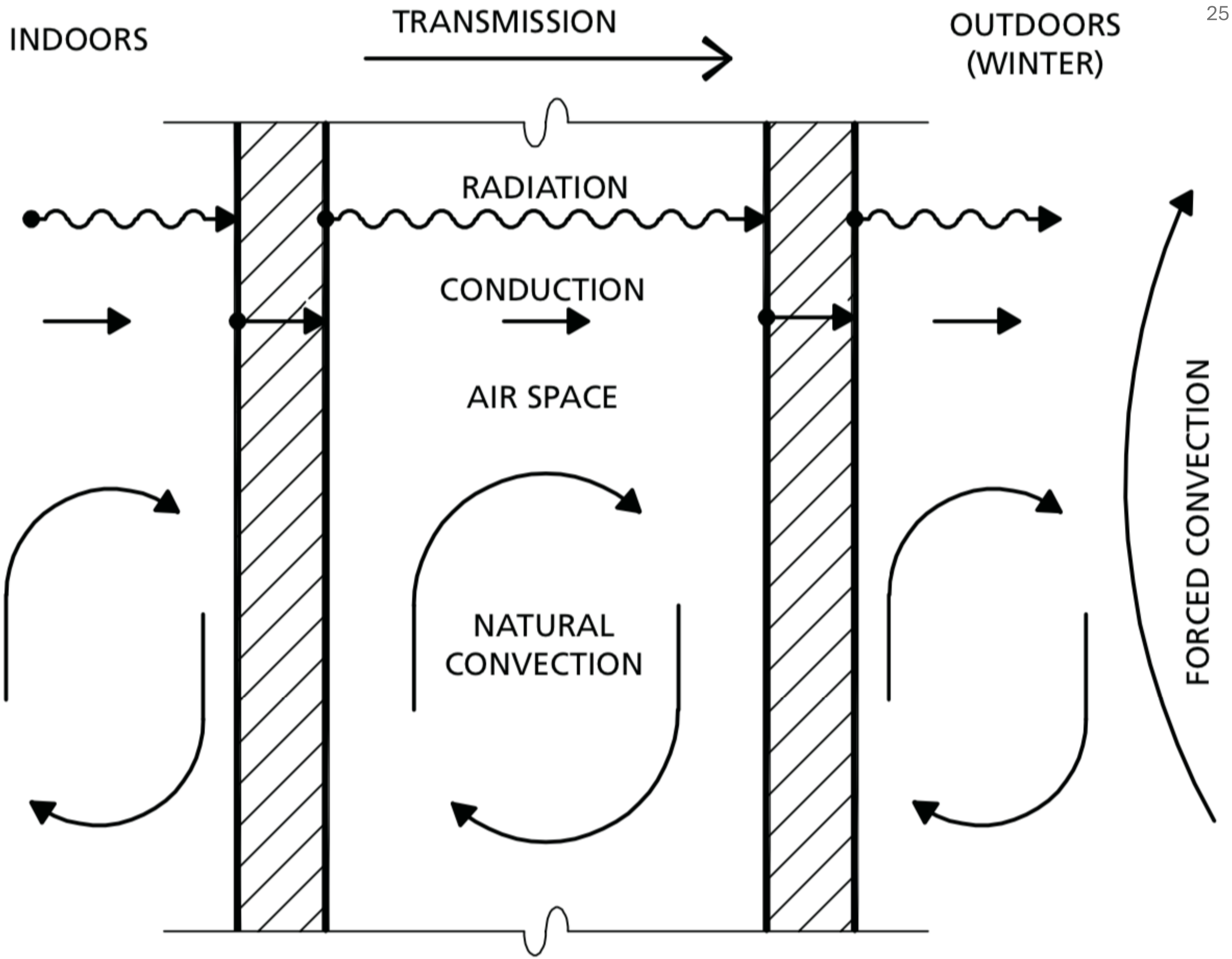


Convection
(heat moved through a fluid)



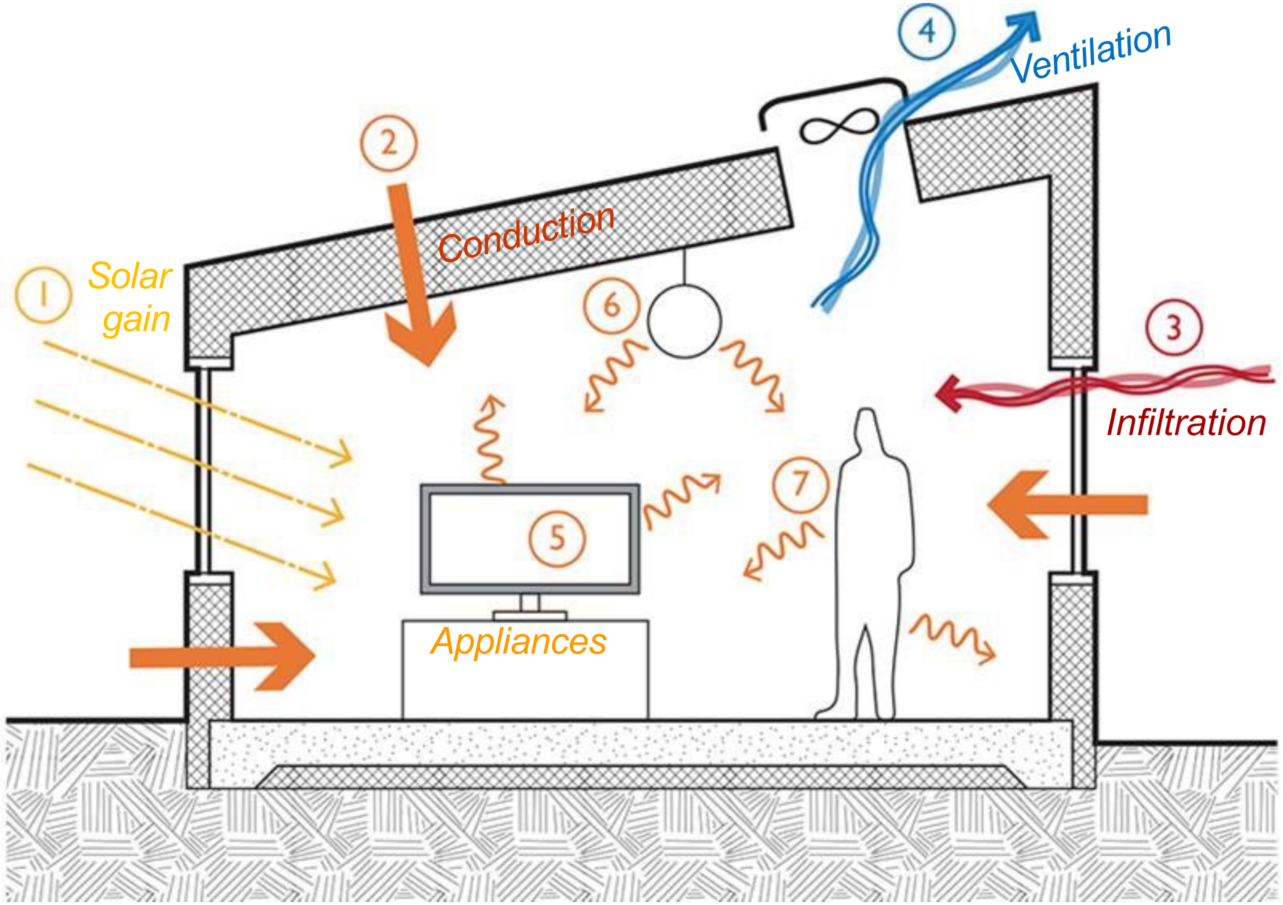
Radiation
(hotter masses radiate more)

Building heat flows



Building heat flows

- **Radiation**
  (incident solar radiation and all surfaces - lights, people, appliances, etc.)
- **Convection**
  (infiltration, ventilation, air flow over surfaces)
- **Conduction**
  (points of contact, building materials)



Source: https://sefaira.com

Energy load summary

- Heat Losses
  - Conduction at envelope
  - Infiltration at envelope
- Heat Gains
  - Conduction at envelope
  - Infiltration at envelope
  - Solar gain through glass
  - Lighting
  - Equipment
  - People

Passive design principles

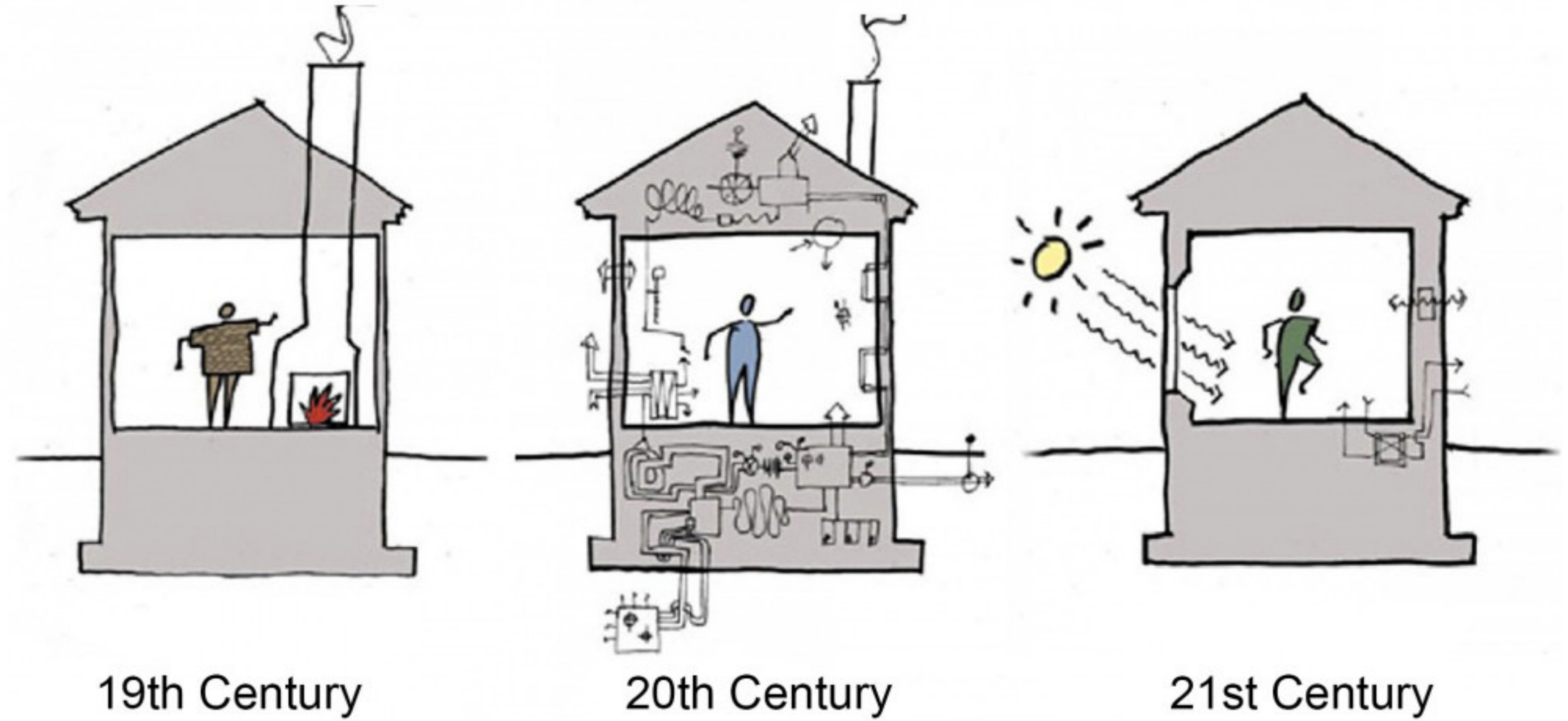


Image source: Albert, Righter and Tittmann Architects

If it's cold outside, how do we prevent heat loss?

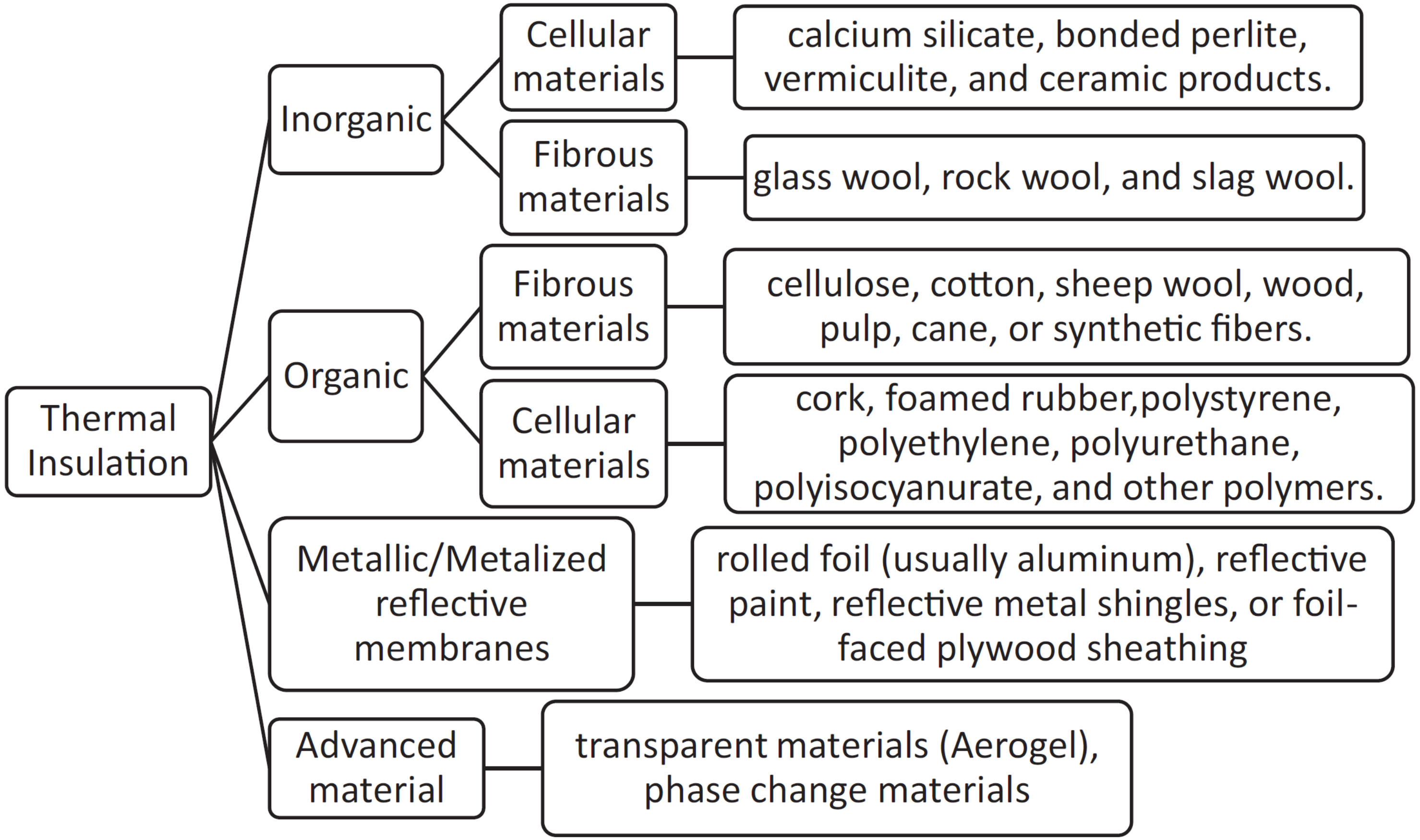
- Three modes:

U-factor
(heat loss factor)

$$\begin{aligned} \texttt{conduction} &= \texttt{area} \times U \times (\Delta T \times \texttt{time}) \\ \texttt{convection} &= \texttt{volume} \times N \times (\Delta T \times \texttt{time}) \\ \texttt{radiation} &= \texttt{area} \times \texttt{solar intensity} \end{aligned}$$

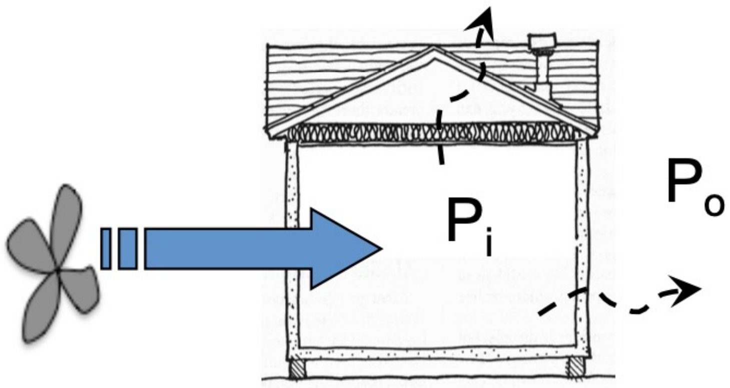
Air changes per hour
(infiltration/ventilation rate)

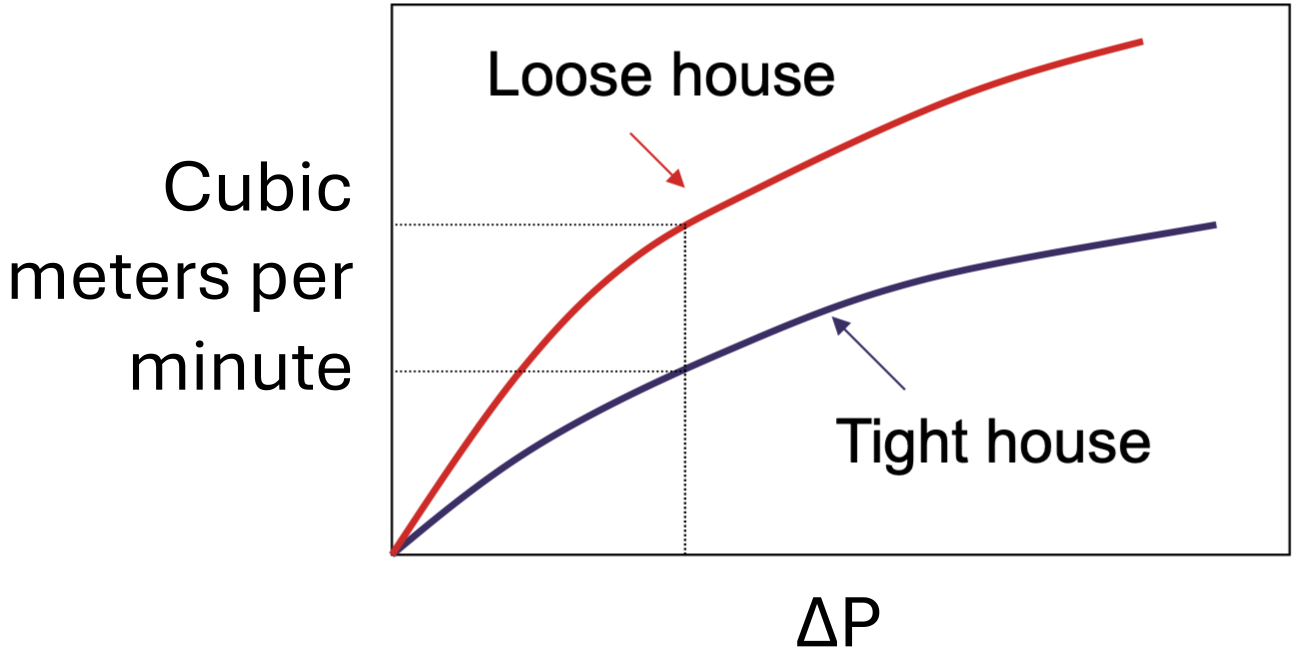
Improving conductive heat losses: insulation



Source: Sadineni et. al. (2011), Renewable and Sustainable Energy Reviews vol. 15

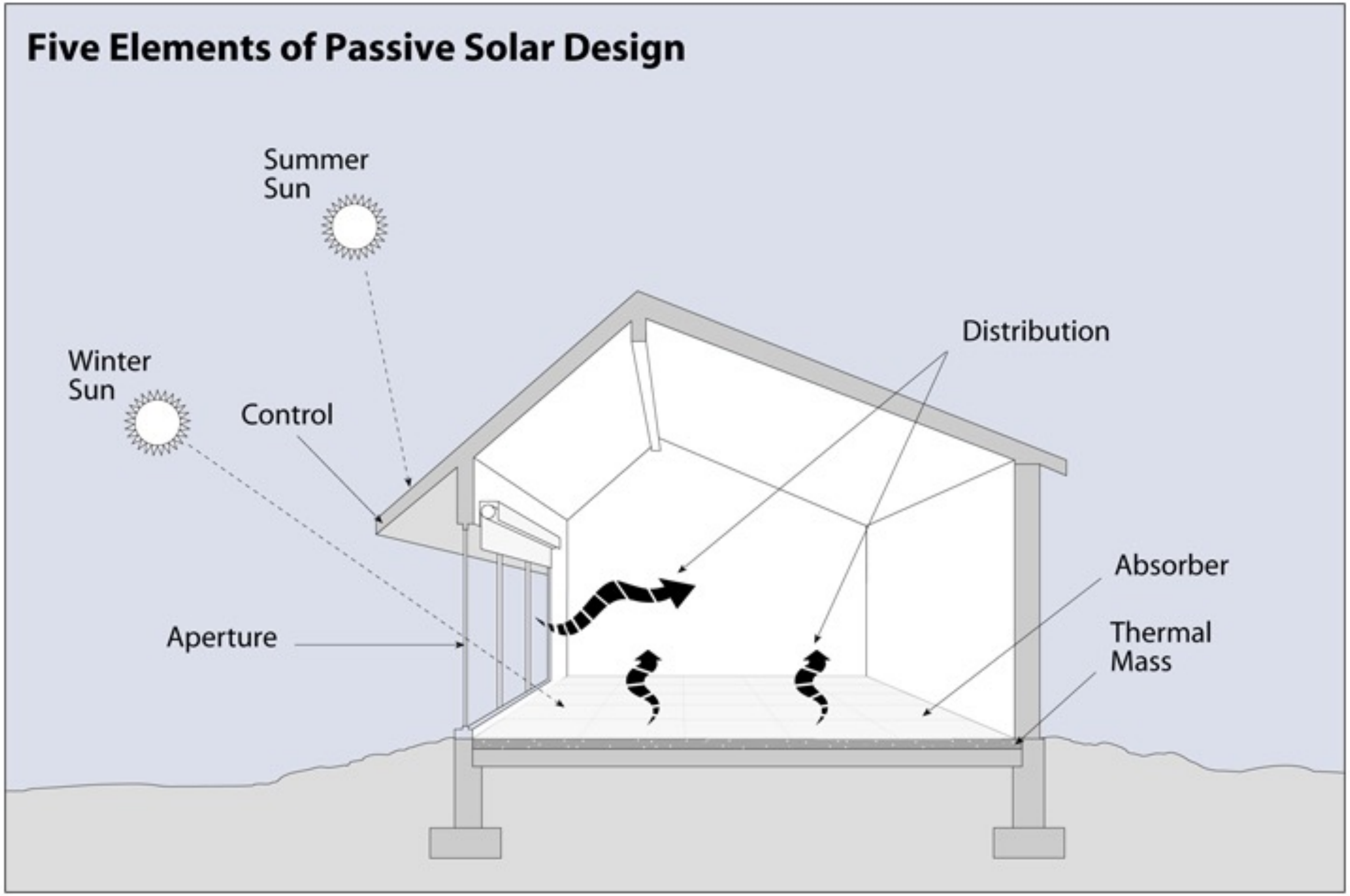
Improving convective heat losses





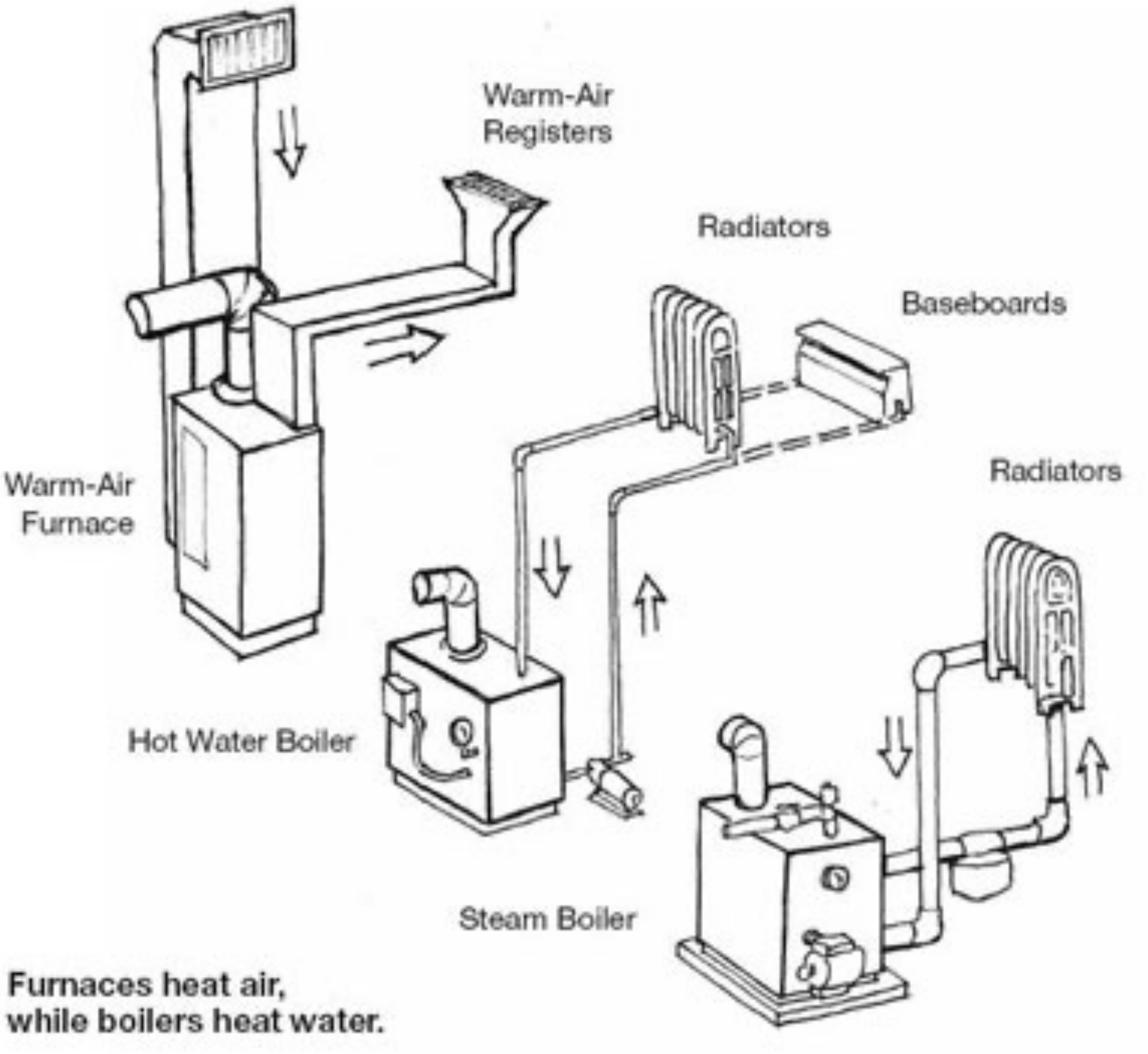
Source: Gil Masters

Passive heating systems



Active heating systems

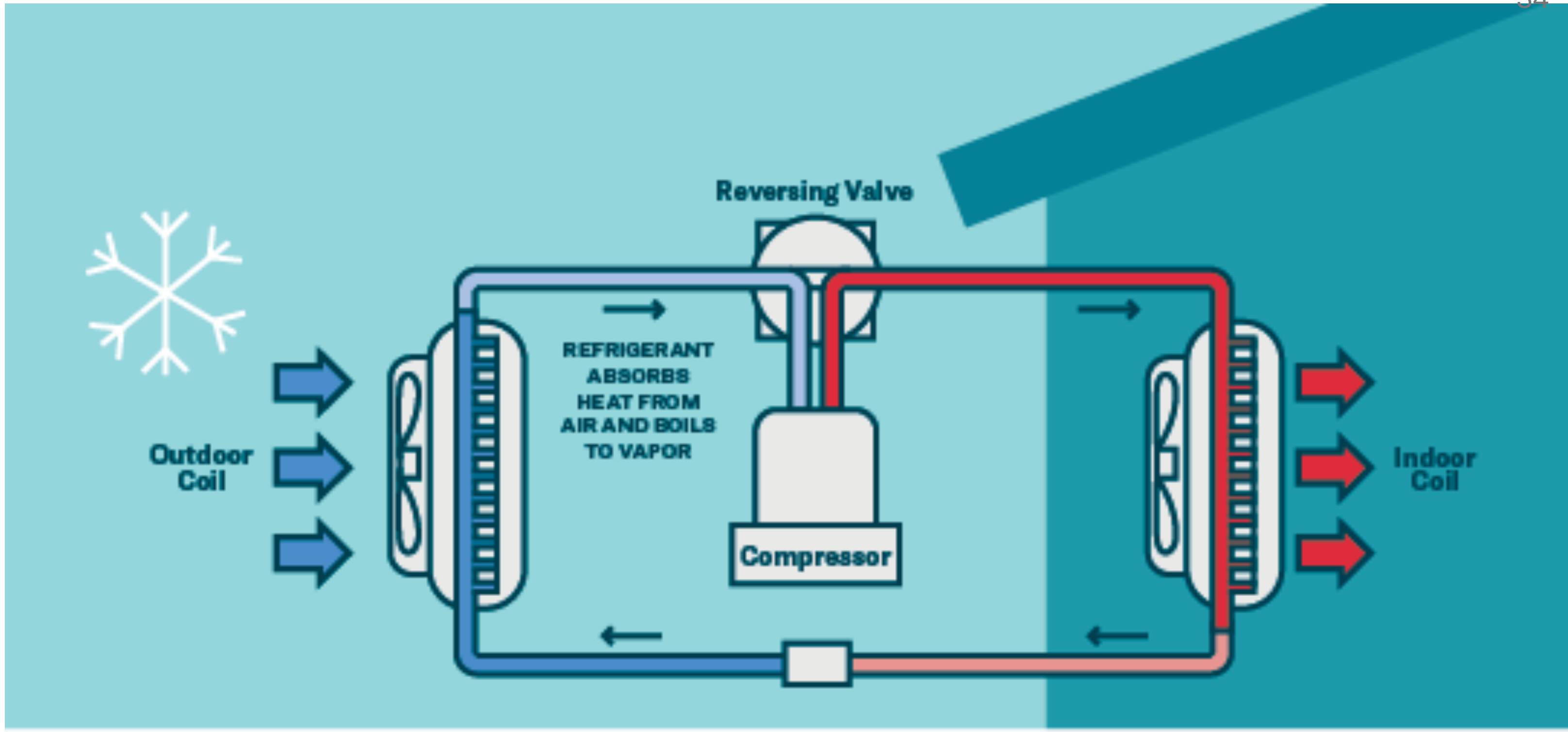
- Furnaces and boilers are common in residential buildings
- Most commonly they use natural gas or a form of heating oil
- These systems ***create*** heat



https://smarterhouse.org/heating-systems/types-heating-systems

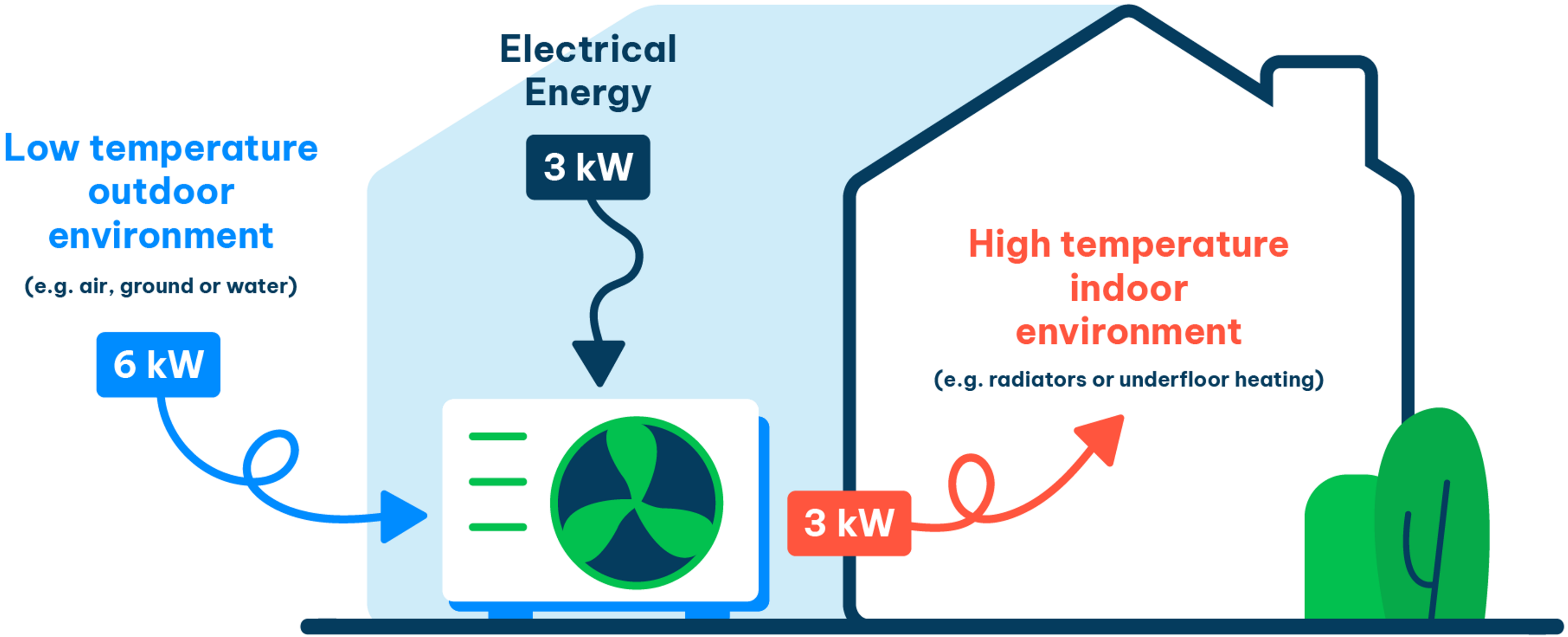
Active heating systems

- Air source heat pumps are becoming more common
- These systems ***move*** heat



Source: Sierra Club

Heat pumps ***move*** heat



Source: Stanford Building Decarbonization Learning Accelerator; The Eco Experts

How to measure performance?

- General coefficient of performance (COP) equation:

$$COP = \frac{Useful\ energy\ obtained}{Energy\ input}$$

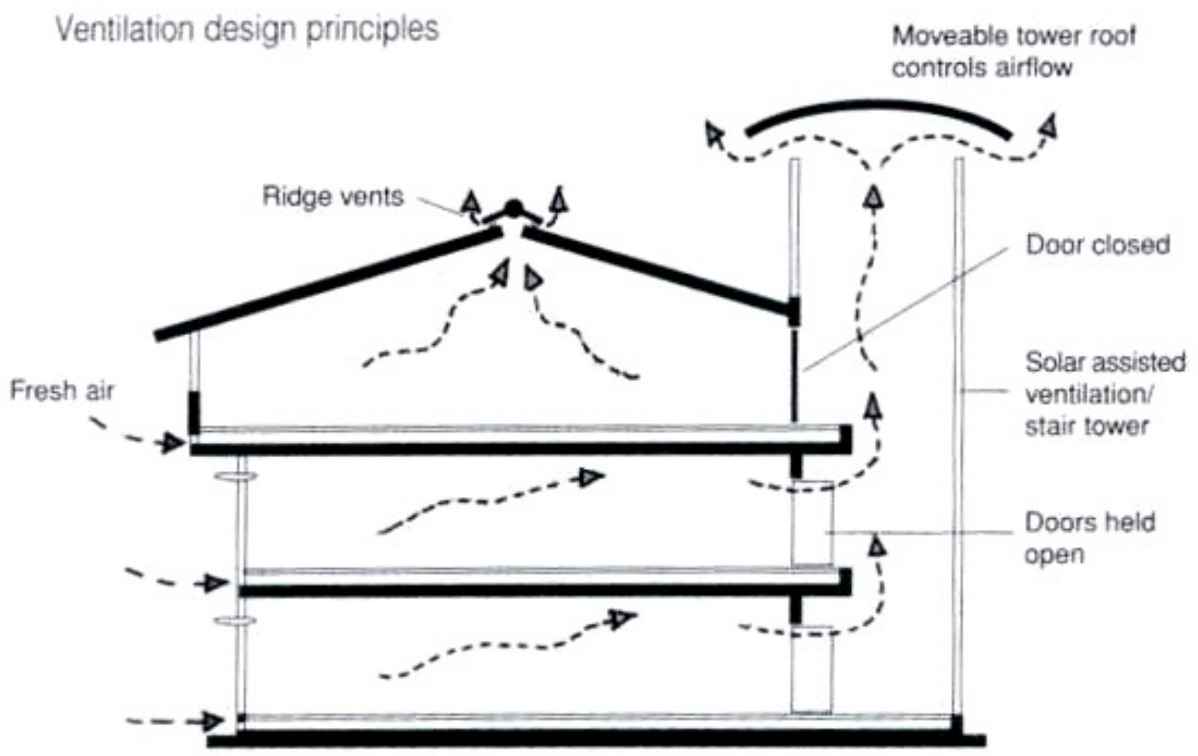
- Heat pumps use the COP as their indicator of performance
  - Theoretical maximum, obtained from first lay of thermodynamics (note: temperatures are in Kelvin)

$$COP_{max,heating} = \frac{T_H}{T_H - T_C}$$

- For furnaces, the coefficient of performance is also called the annual fuel efficiency rating (AFUE)

If it's hot outside, how do we prevent heat from entering the building?

- Limit heat gain through windows, walls, and roofs
- Use natural ventilation when it's cool enough outside (e.g. at night)
- Use free evaporative cooling when it's very dry



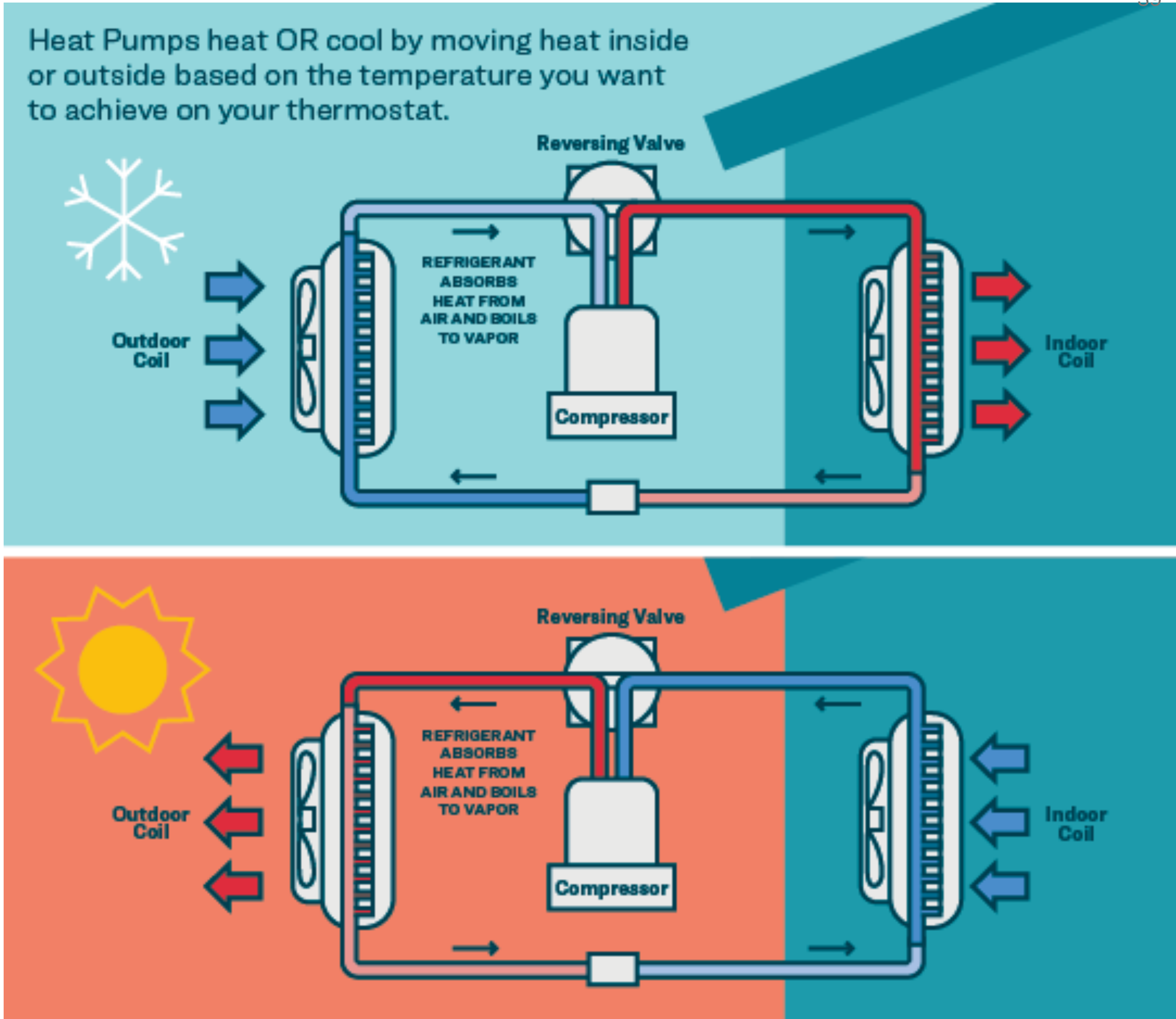
Passive cooling: evaporative cooling

- The amount of energy in air is a function of both its temperature and its moisture content
- If you have very dry air, and you add water to the air, the temperature will decrease due to conservation of energy

Active cooling systems

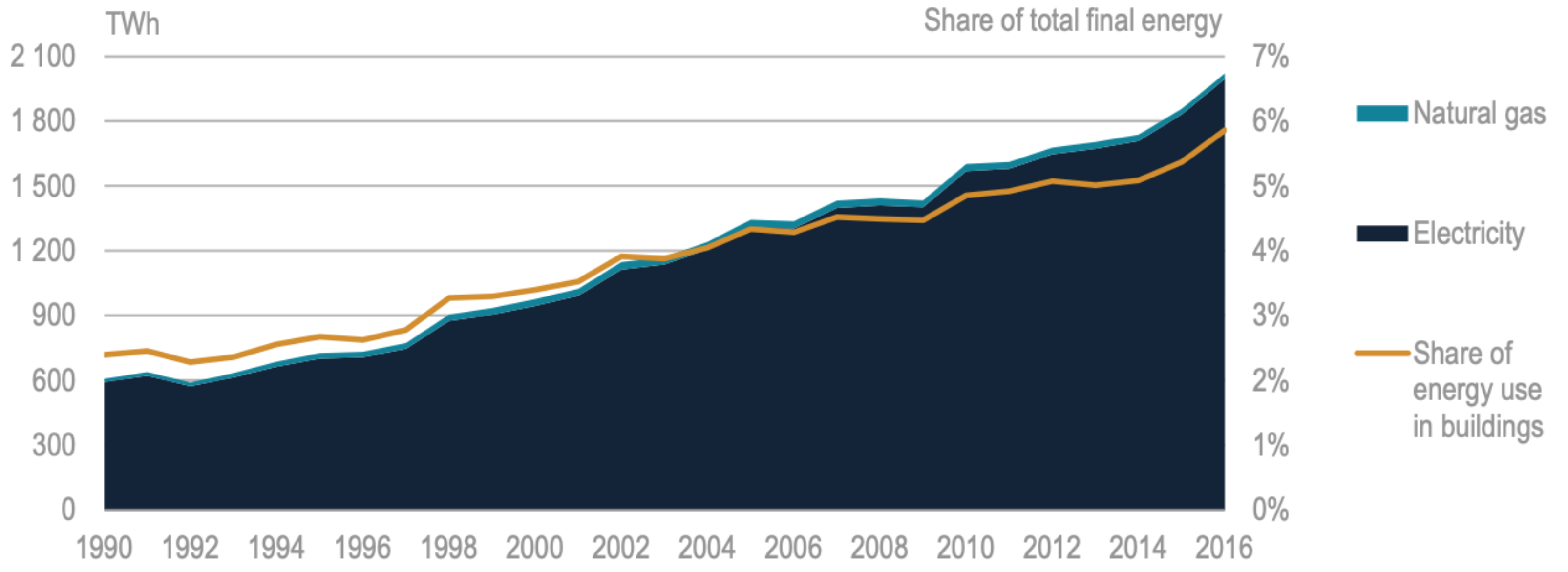
- Heat pumps can cool as well
  - You just reverse the system
- Air conditioners operate in the same way

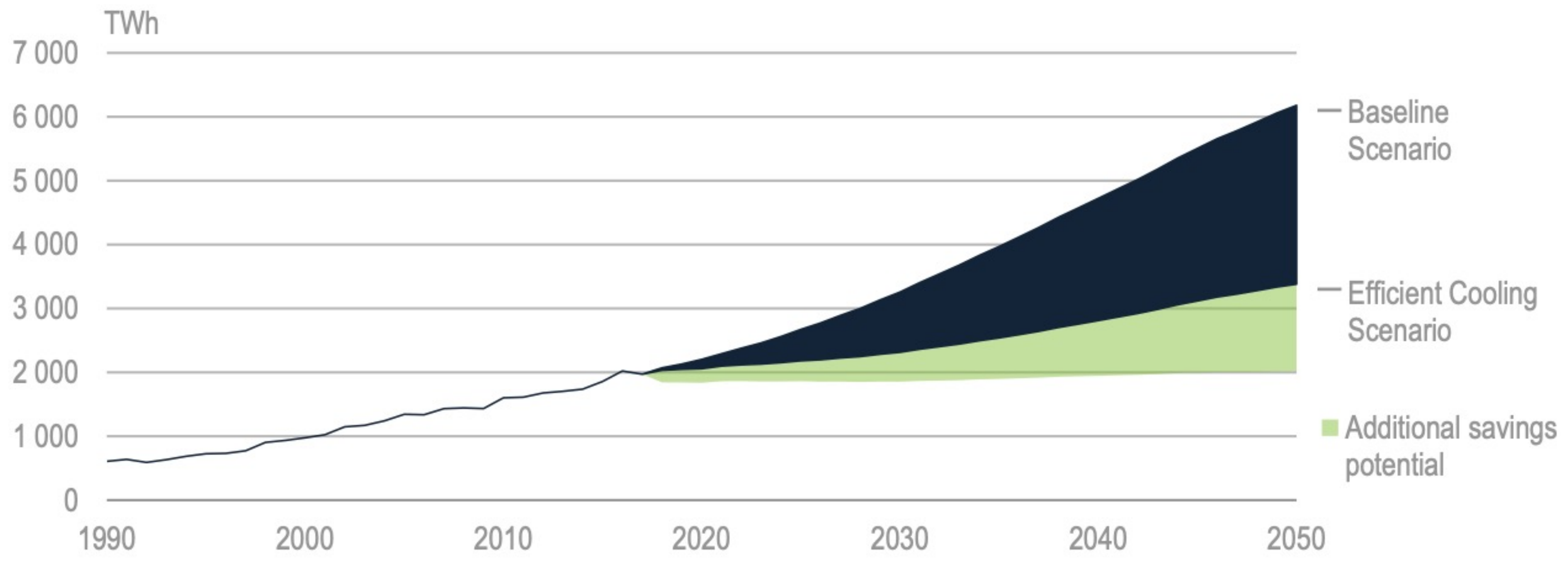
$$COP_{max,cooling} = \frac{T_C}{T_H - T_C}$$



The past and future of cooling

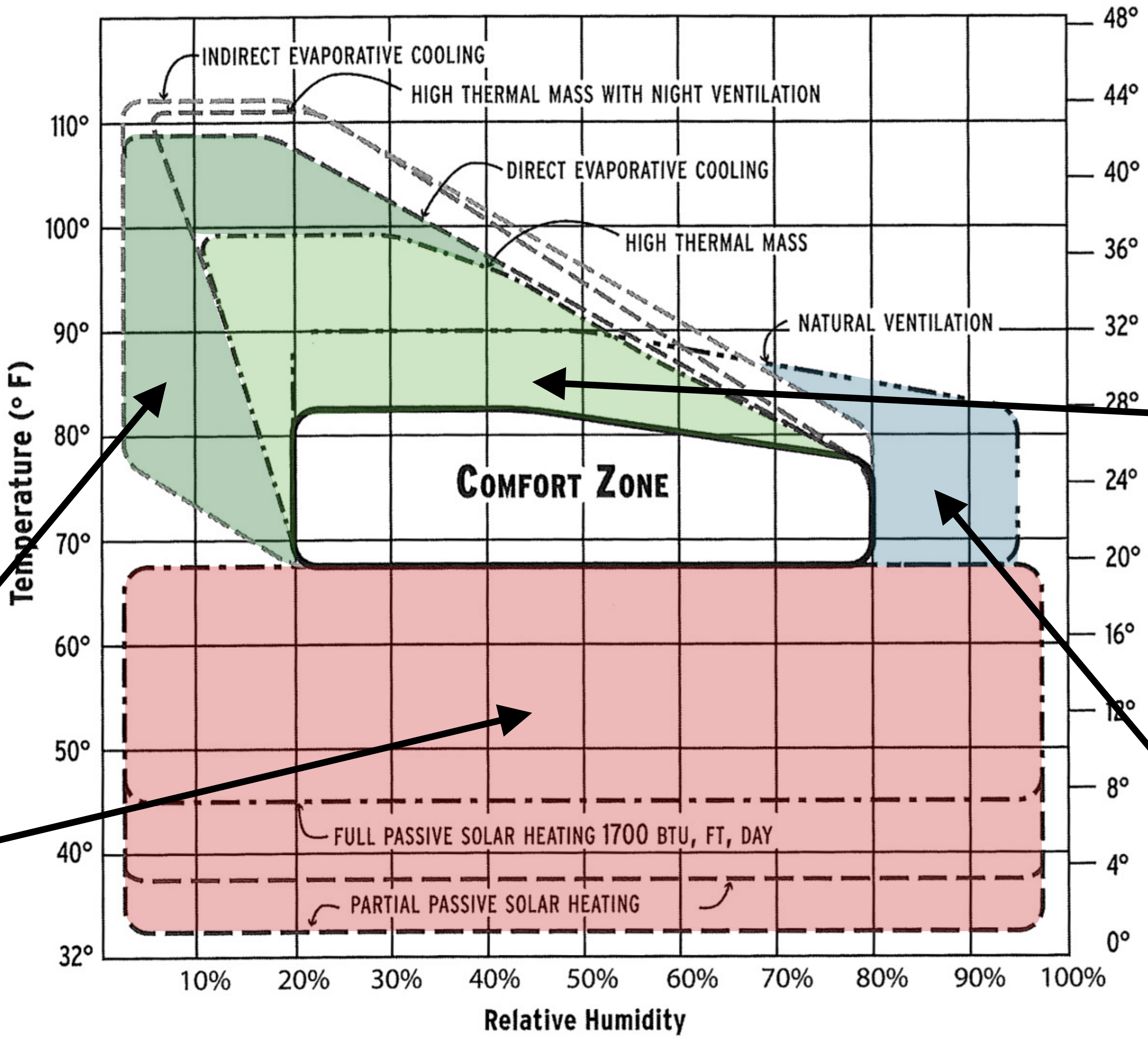
- Top graph: growth in cooling energy consumption
- Bottom graph: projected increase in cooling energy consumption in baseline and efficient scenarios
  - Baseline scenario: everyone who needs cooling gets it





Source: IEA

The Bioclimatic chart



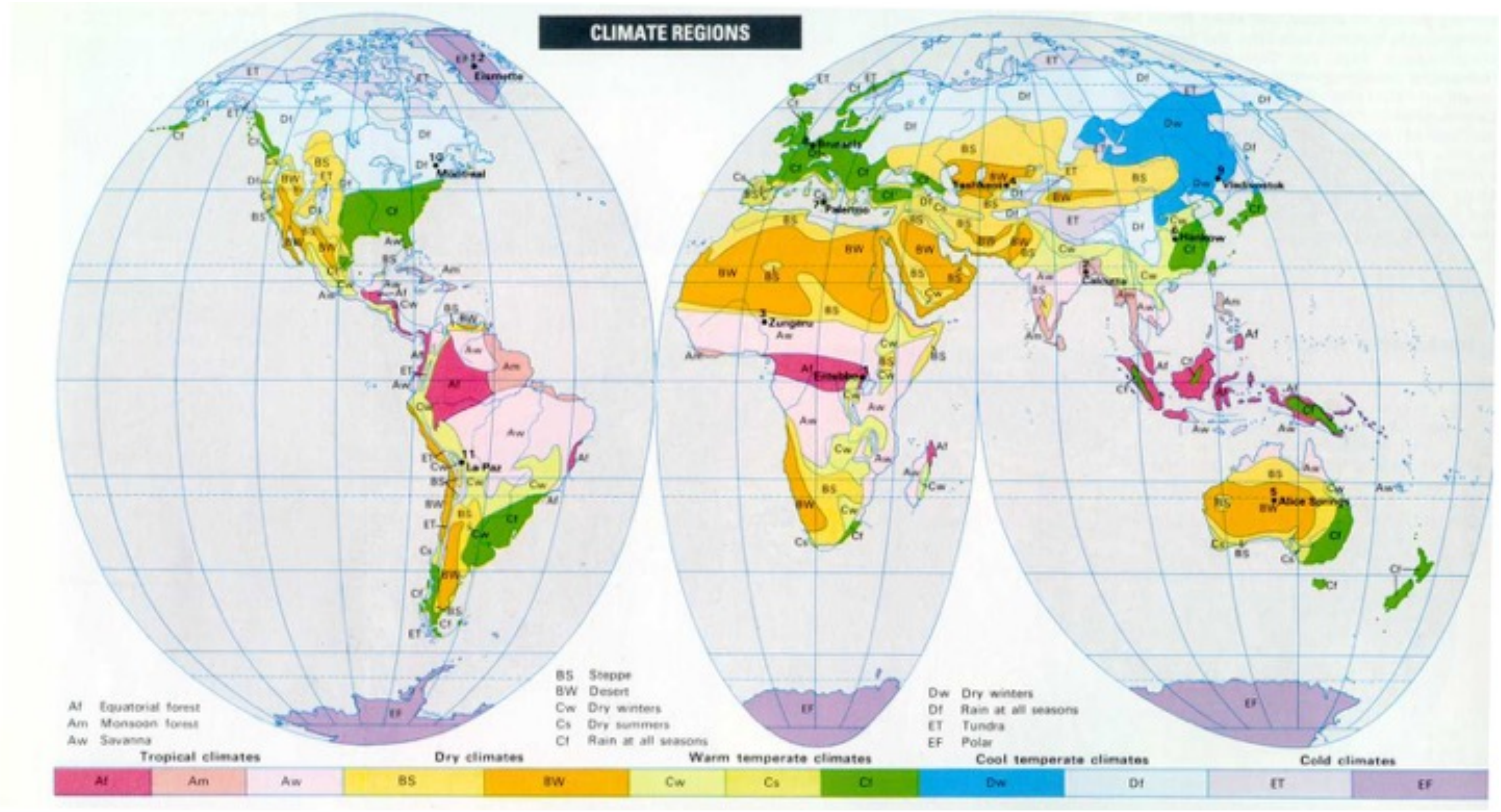
When hot and dry, provide direct evaporative cooling

When cold, add solar radiation

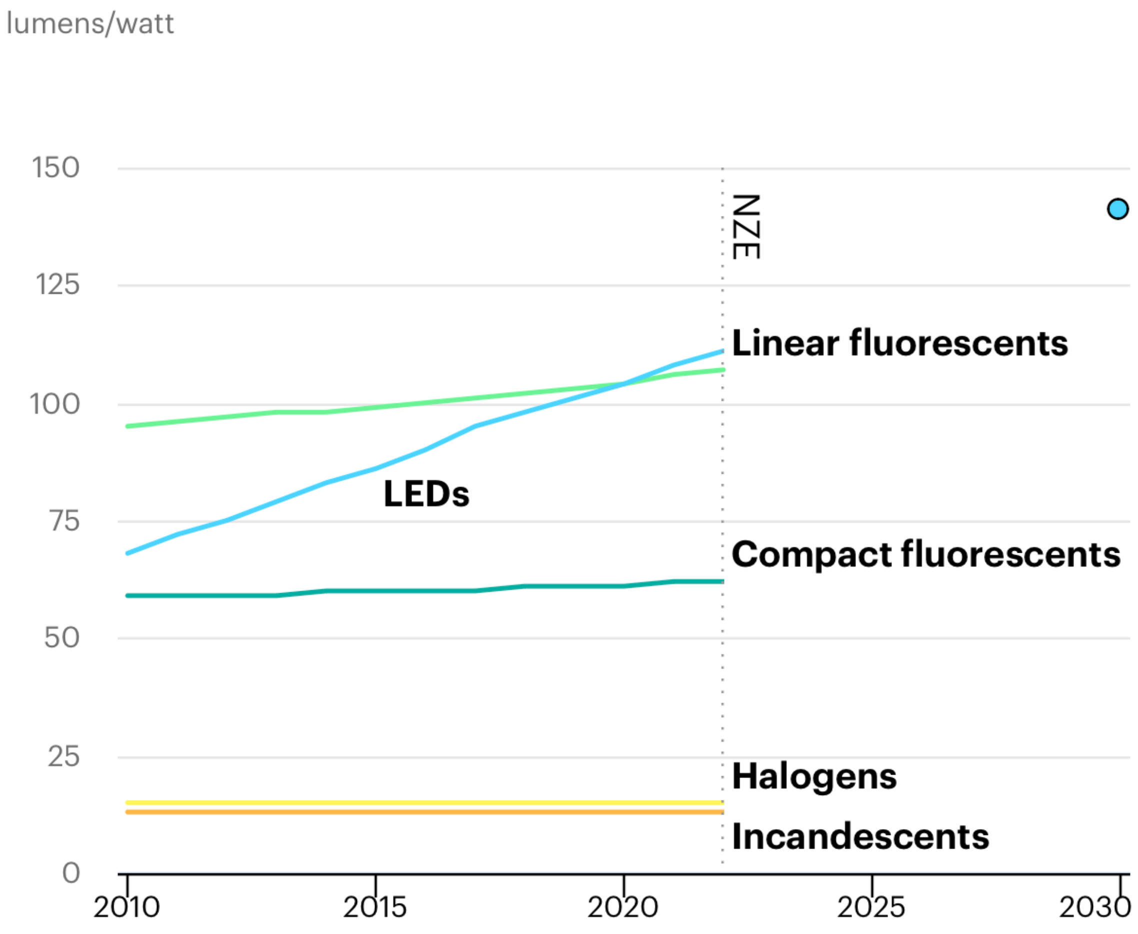
When hot, incorporate thermal mass

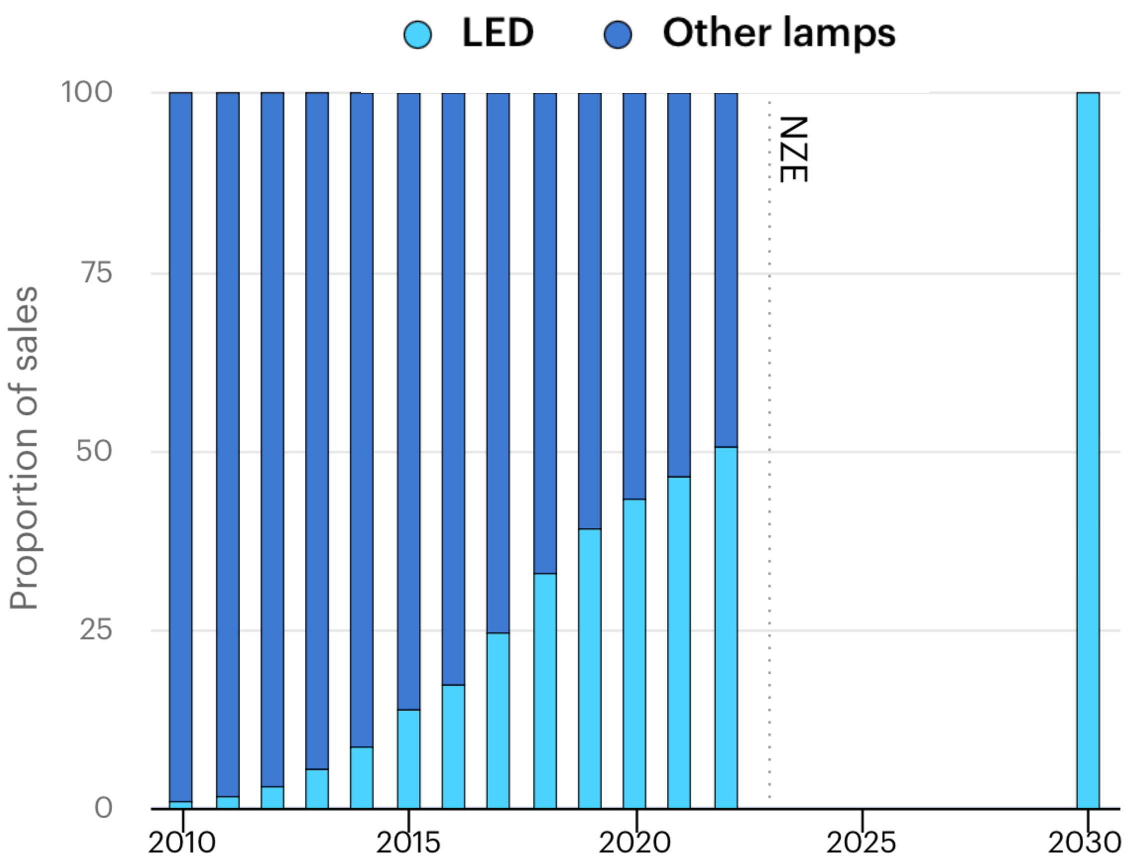
When hot or hot/humid, add air movement

Climate zones



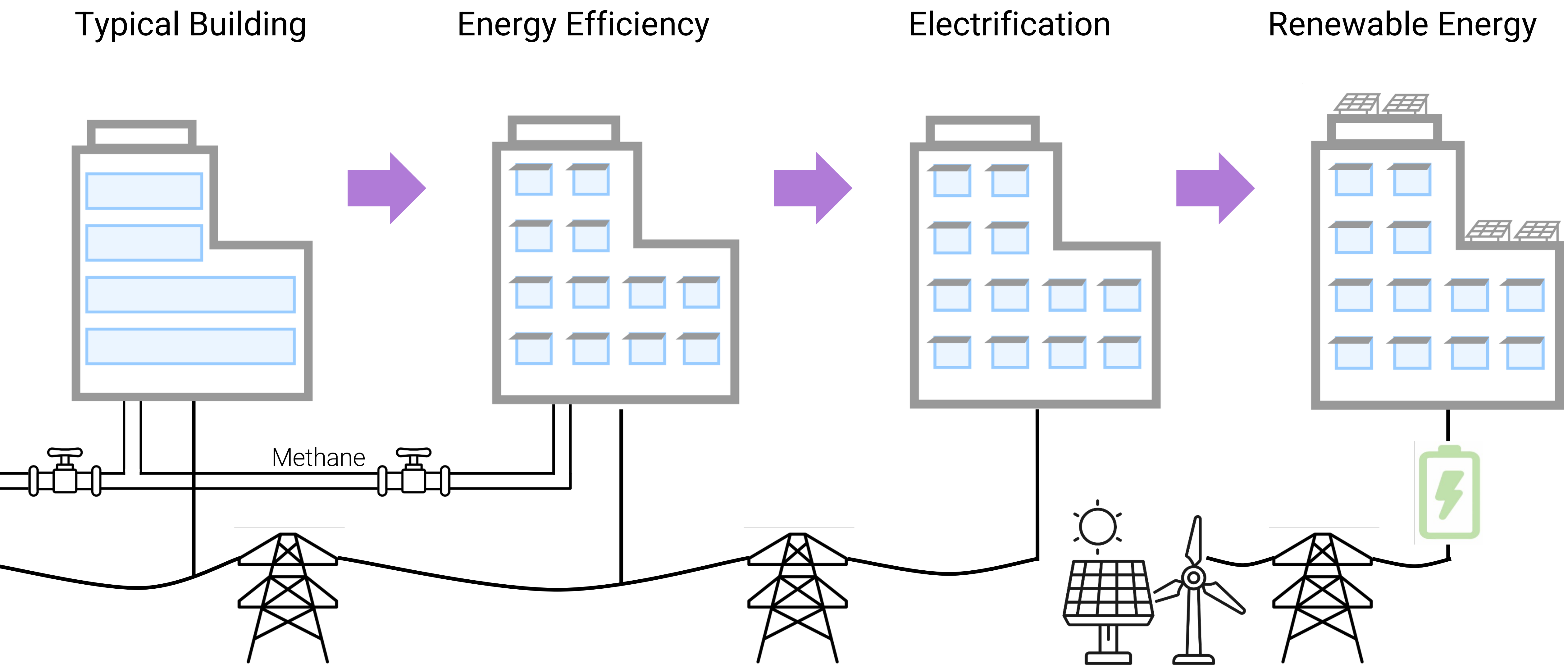
Supplying the other energy demands in buildings: lighting





Source: IEA

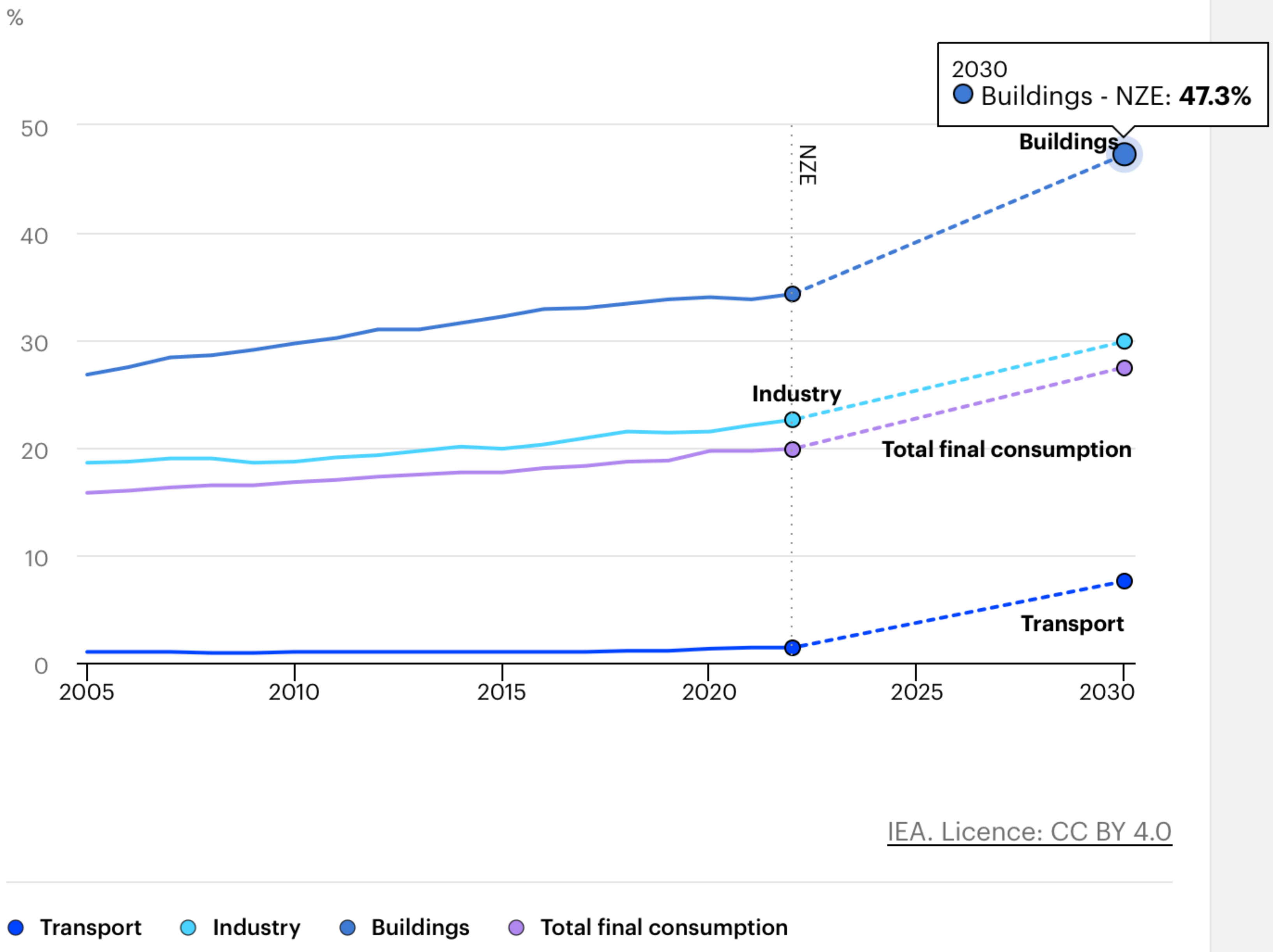
Design Path to Operational Decarbonization



Source: Stanford BDLA

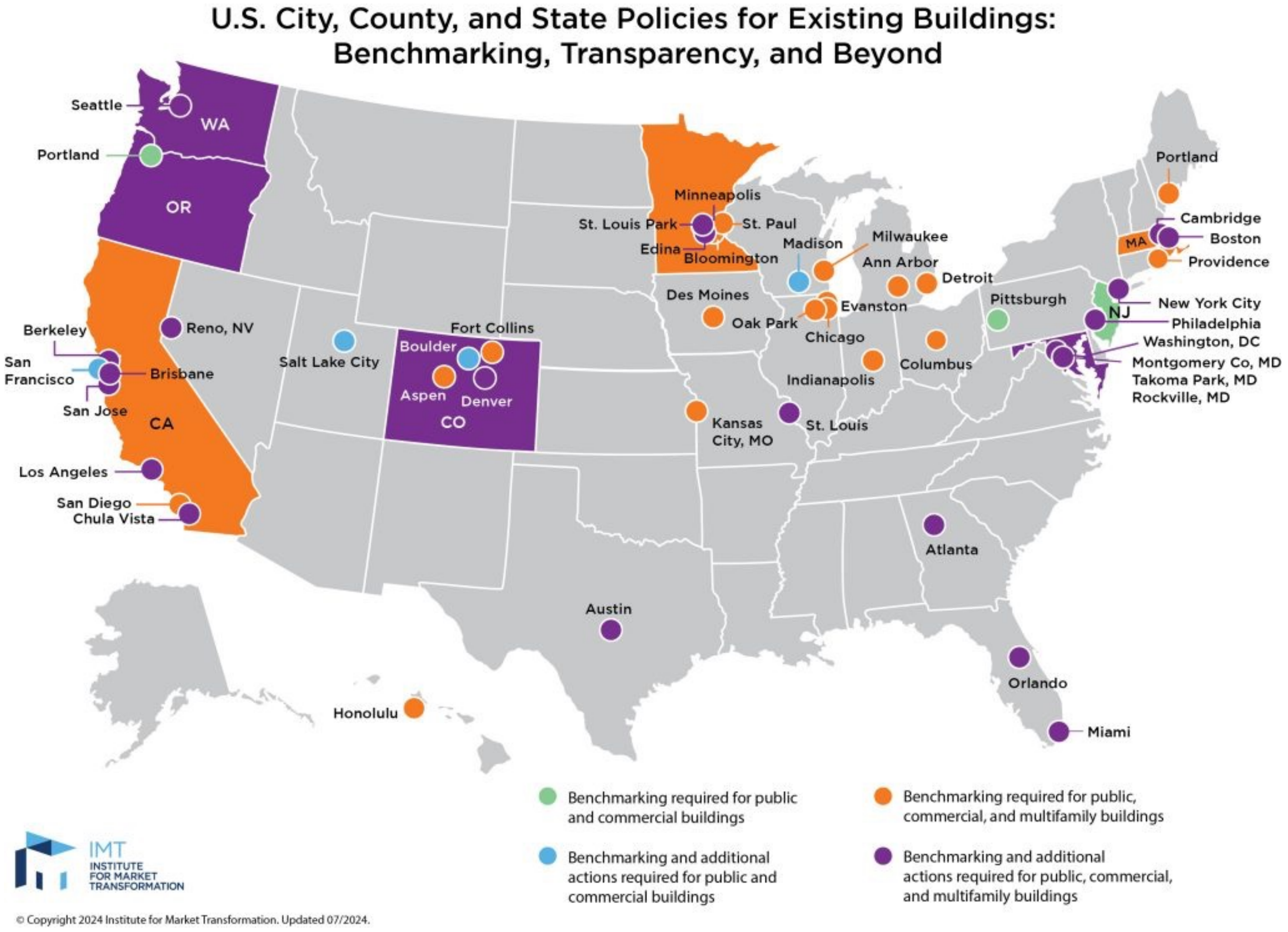
Electrification

- To reach net-zero energy, we need to electrify out buildings
- Buildings’ share of electricity demand is expected to rise with deployment of electric technologies (e.g. heat pumps)

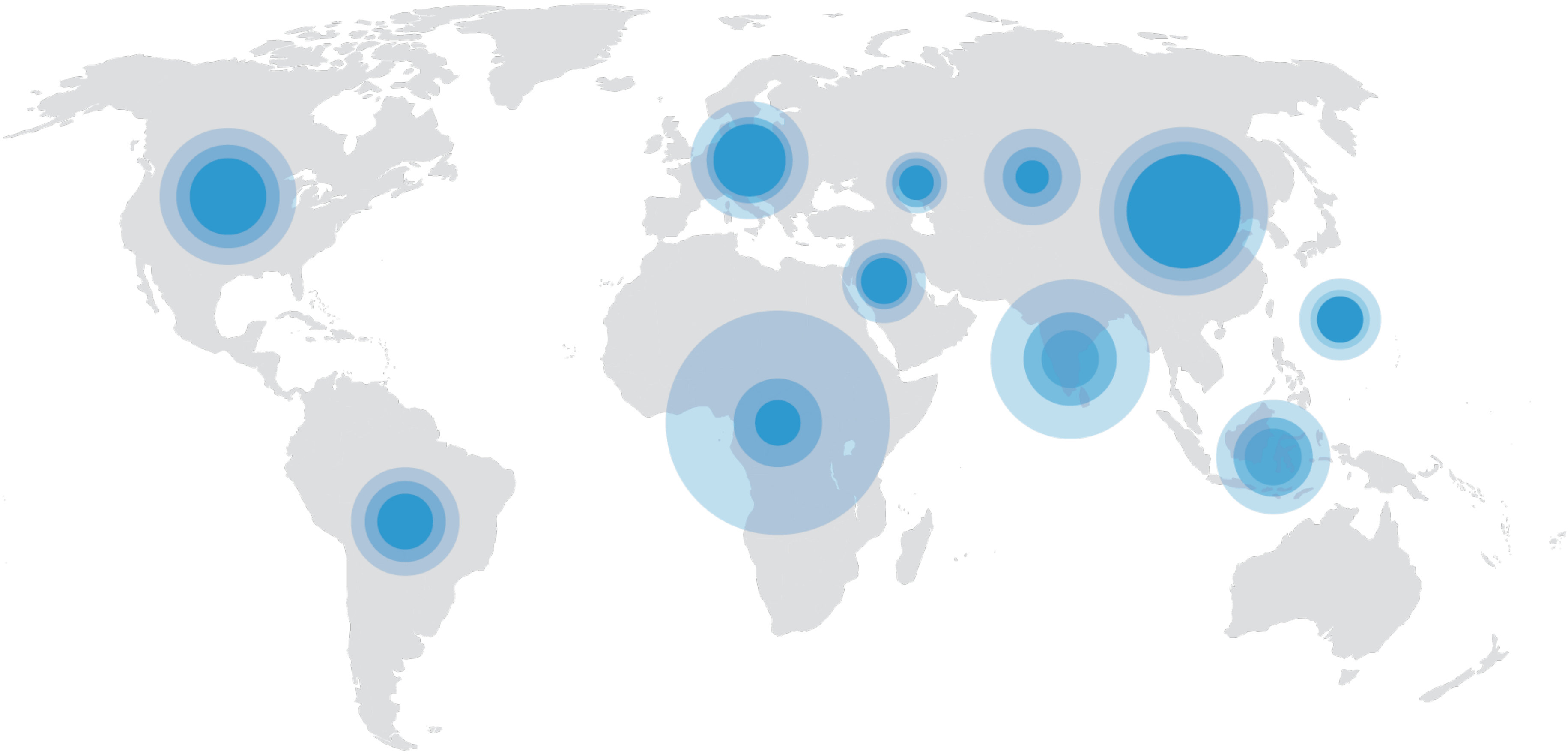


Benchmarking

- *You can't manage what you don't meaure*
- Benchmarking helps to identify which buildings are good targets for retrofits and efficiency upgrades



Global building floor area is expected to **double** by 2060.



Most of this will be concentrated in the developing world

Data Sources: Global ABC, Global Status Report 2017

The importance of smart operation

Source: MIT Open Courseware

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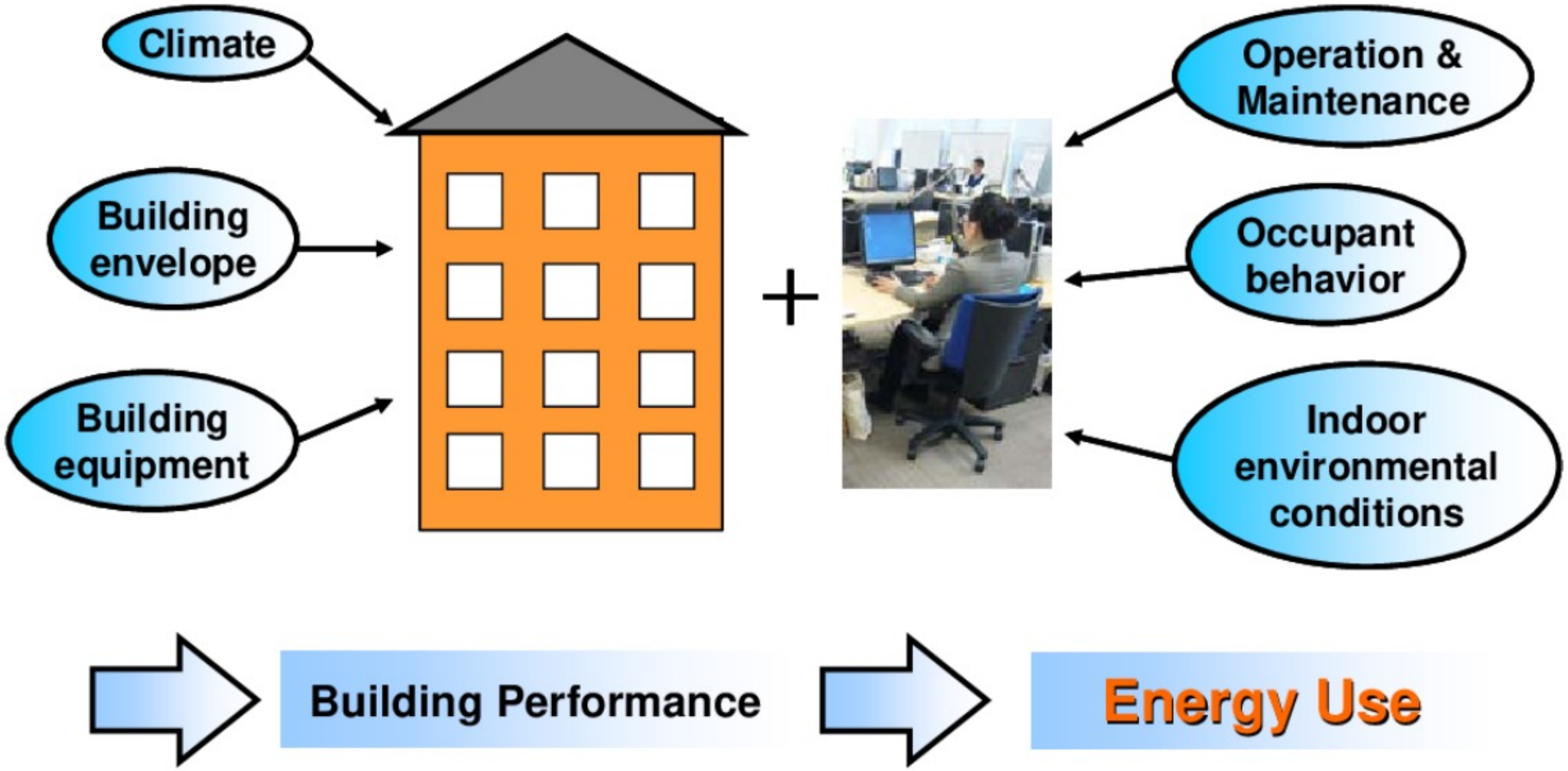
Source: MIT Open Courseware

The importance of smart operation

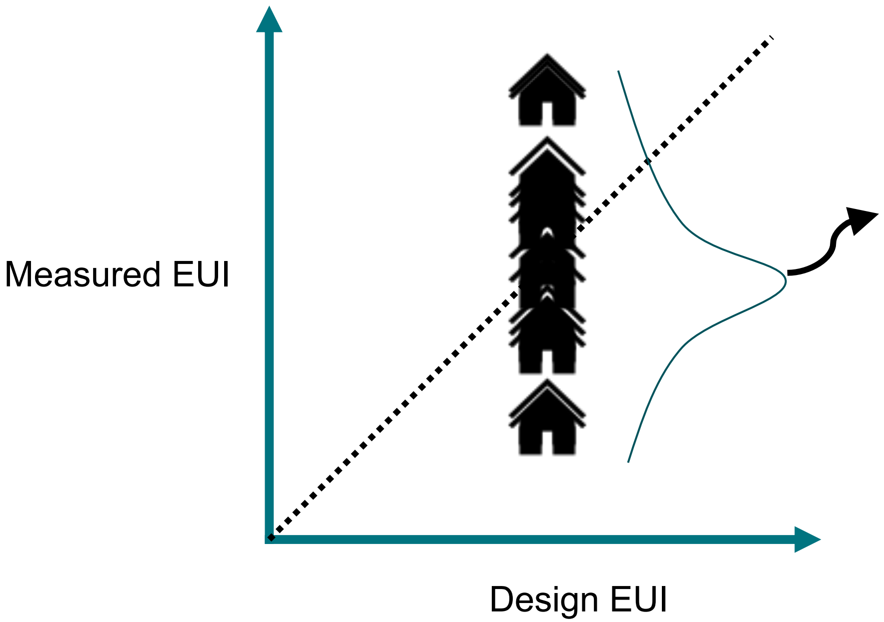
Source: MIT Open Courseware

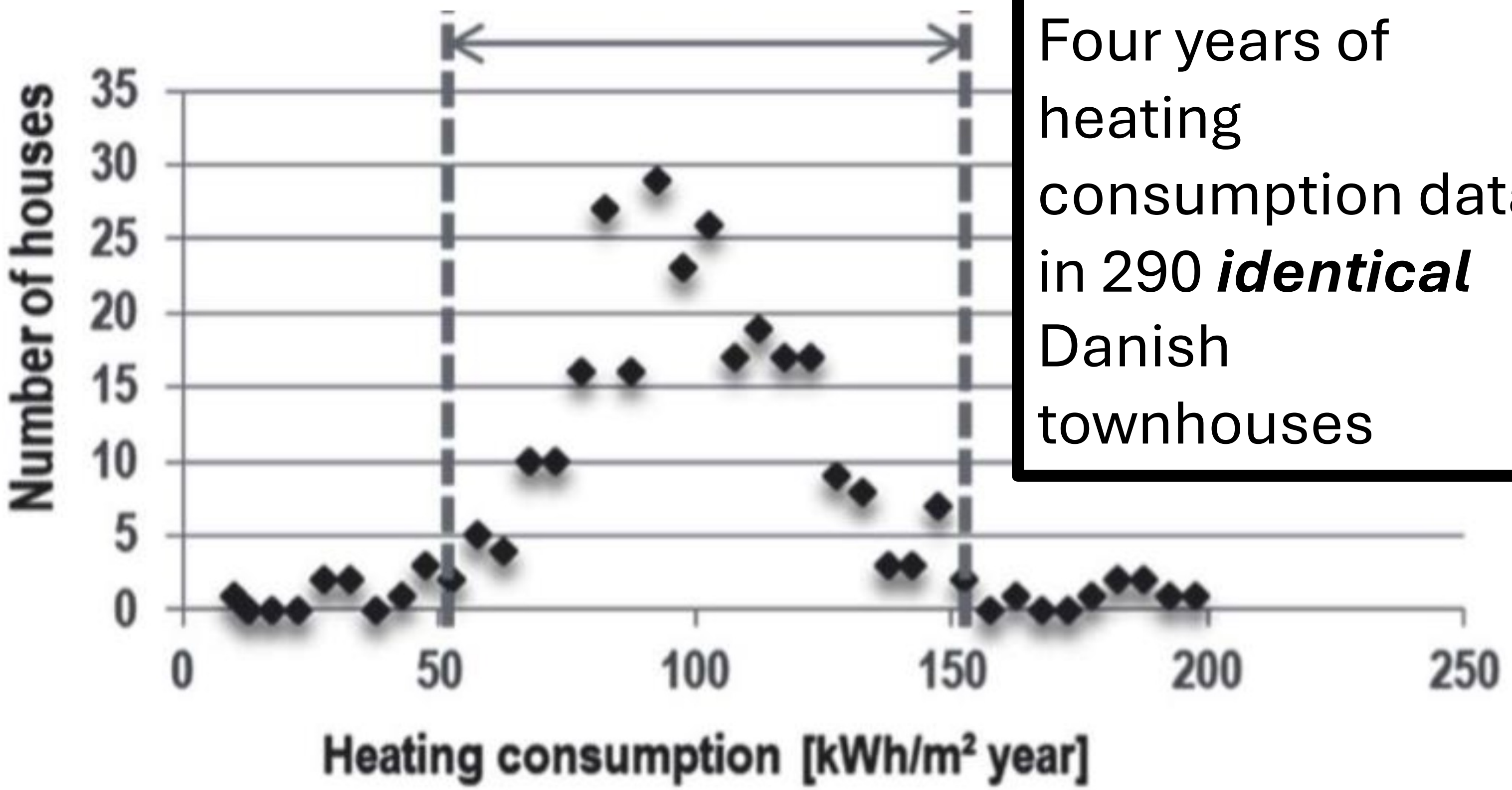
“Buildings don’t use energy, people do”



Source: IEA EBC Annex 53 Final Report

The importance of human behavior & operation





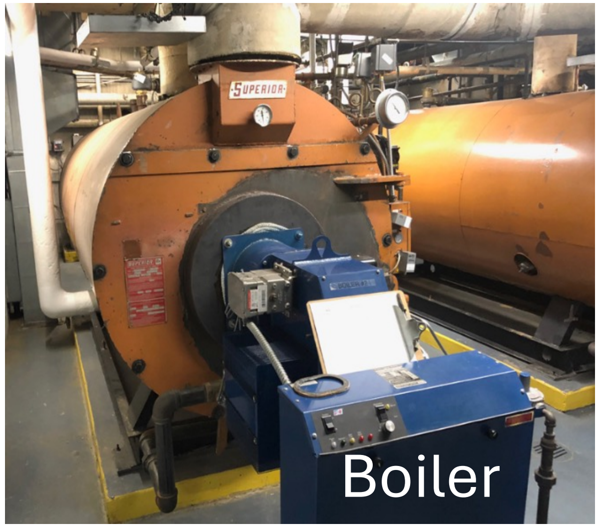
Four years of heating consumption data in 290 ***identical*** Danish townhouses

Case study: American Institute of Architects HQ

Source: Stanford BDLA

Case study: American Institute of Architects HQ

- Existing building:
  - Chillers provide cooling by chilling water, and the water was pumped through the building (electric)
  - Natural gas boilers provide steam for heating system and hot water for water use
  - Air handling units provide ventilation



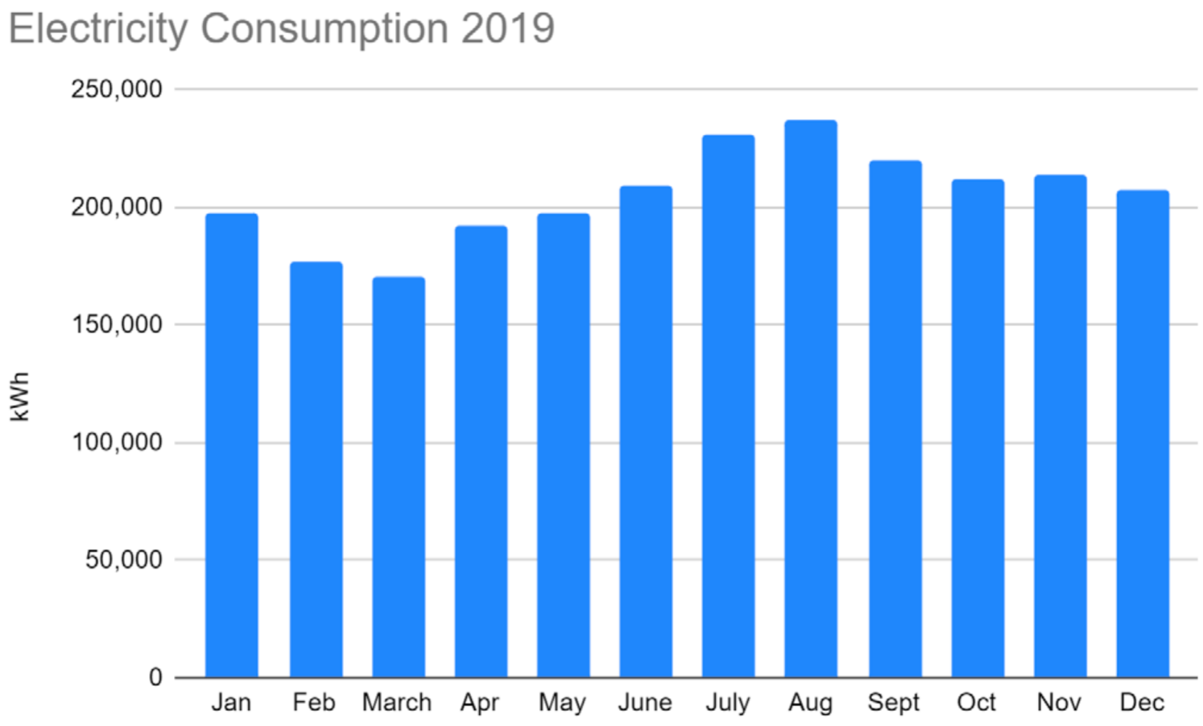
Boiler

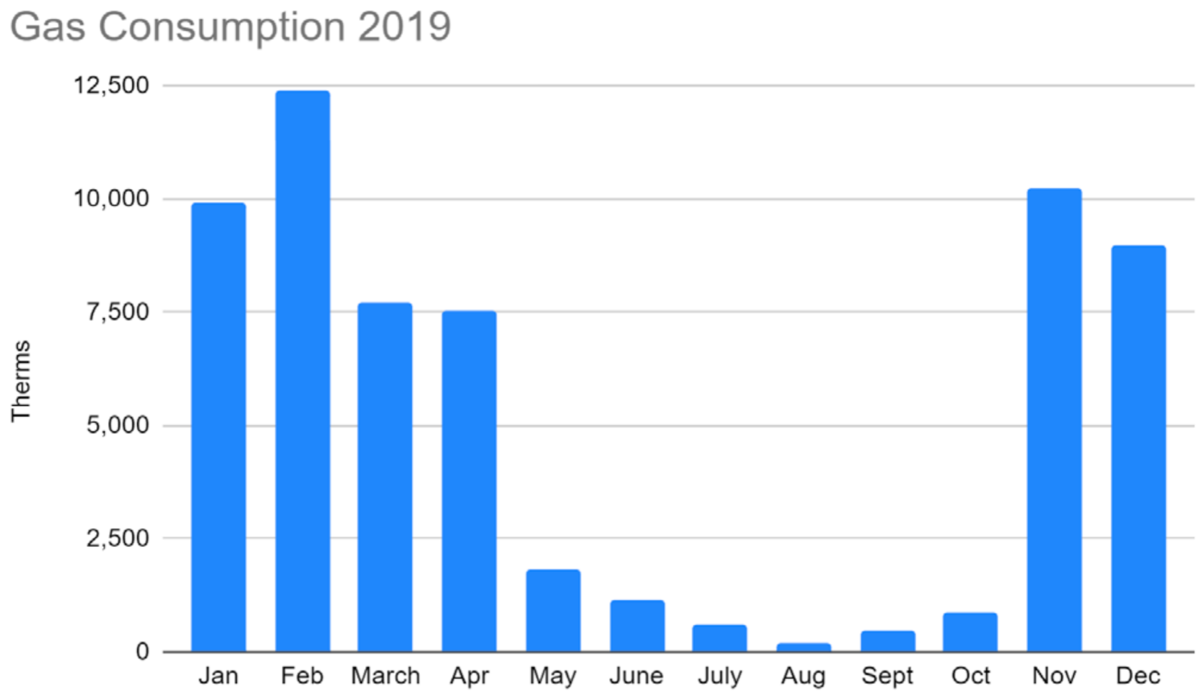

Air handling unit

Chiller

Source: Stanford BDLA

Case study: American Institute of Architects HQ

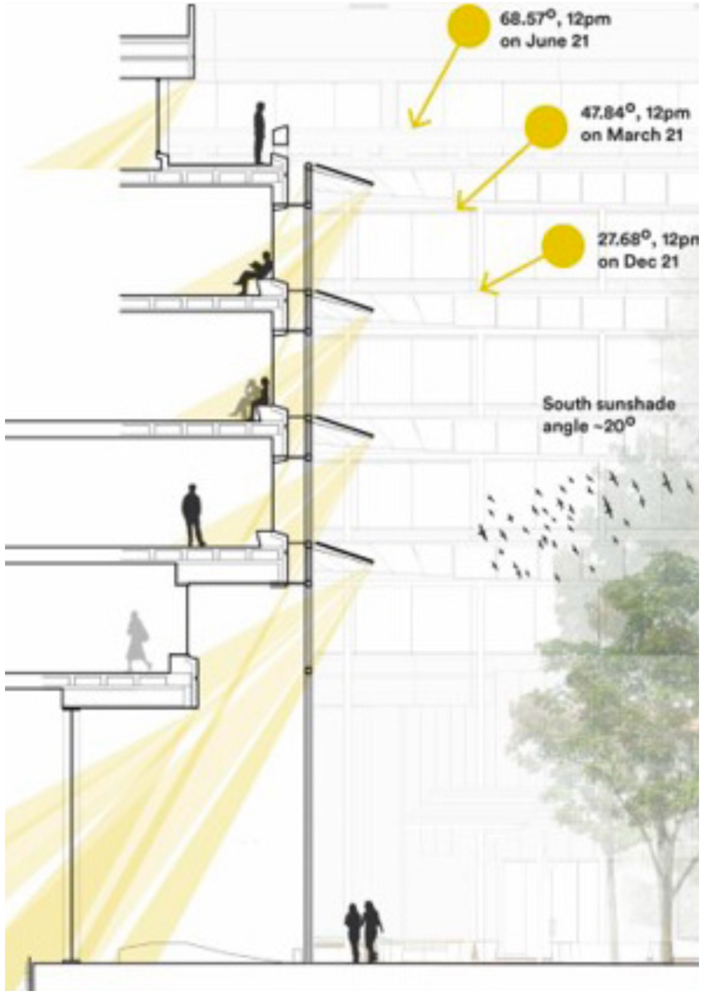




Source: Stanford BDLA

Case study: American Institute of Architects HQ

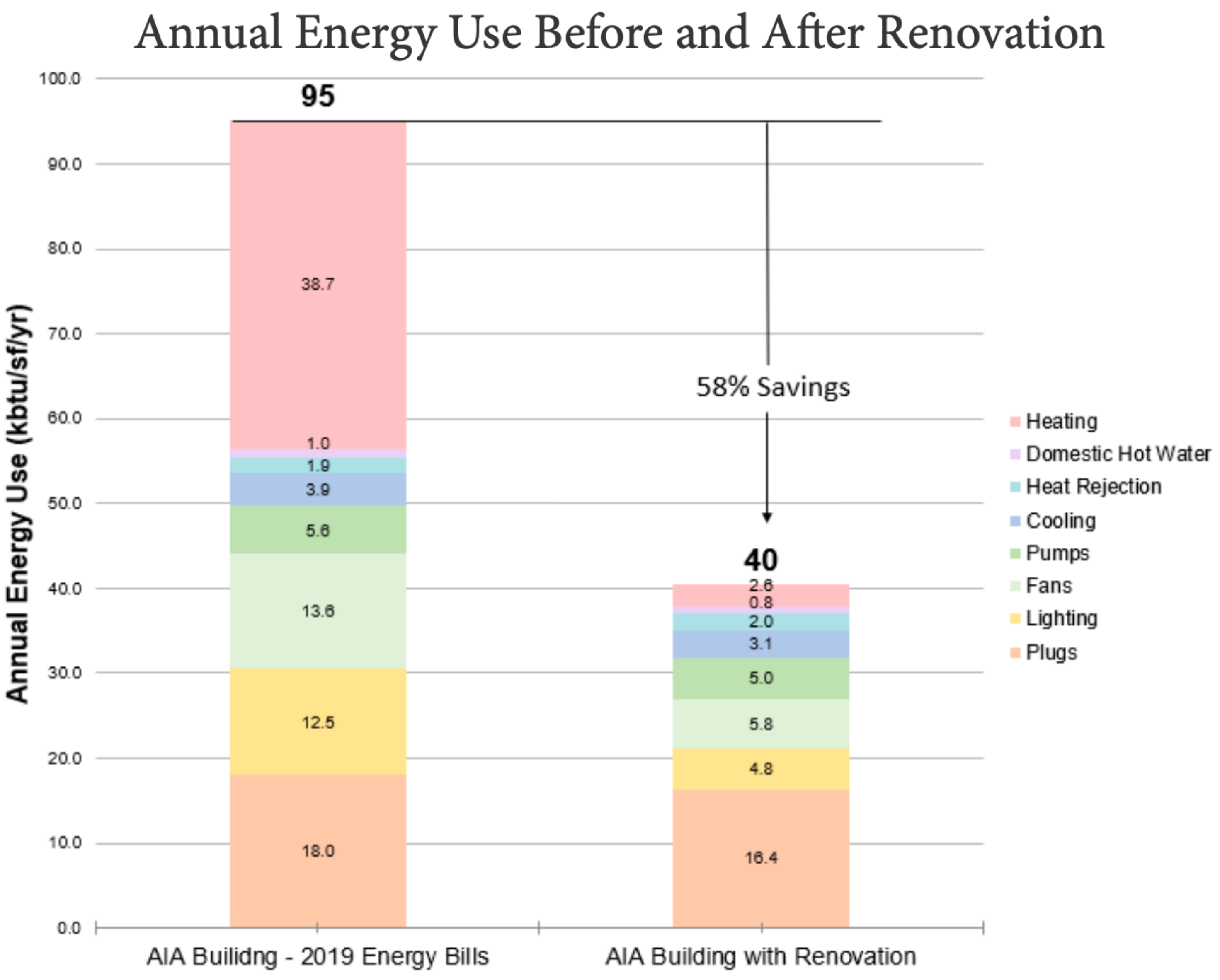
- Renovation strategies for efficiency:
  - Add solar shading (reduce heat gain)
  - Replace windows
  - Improve insulation
  - Replace lights with more efficient ones



Source: Stanford BDLA

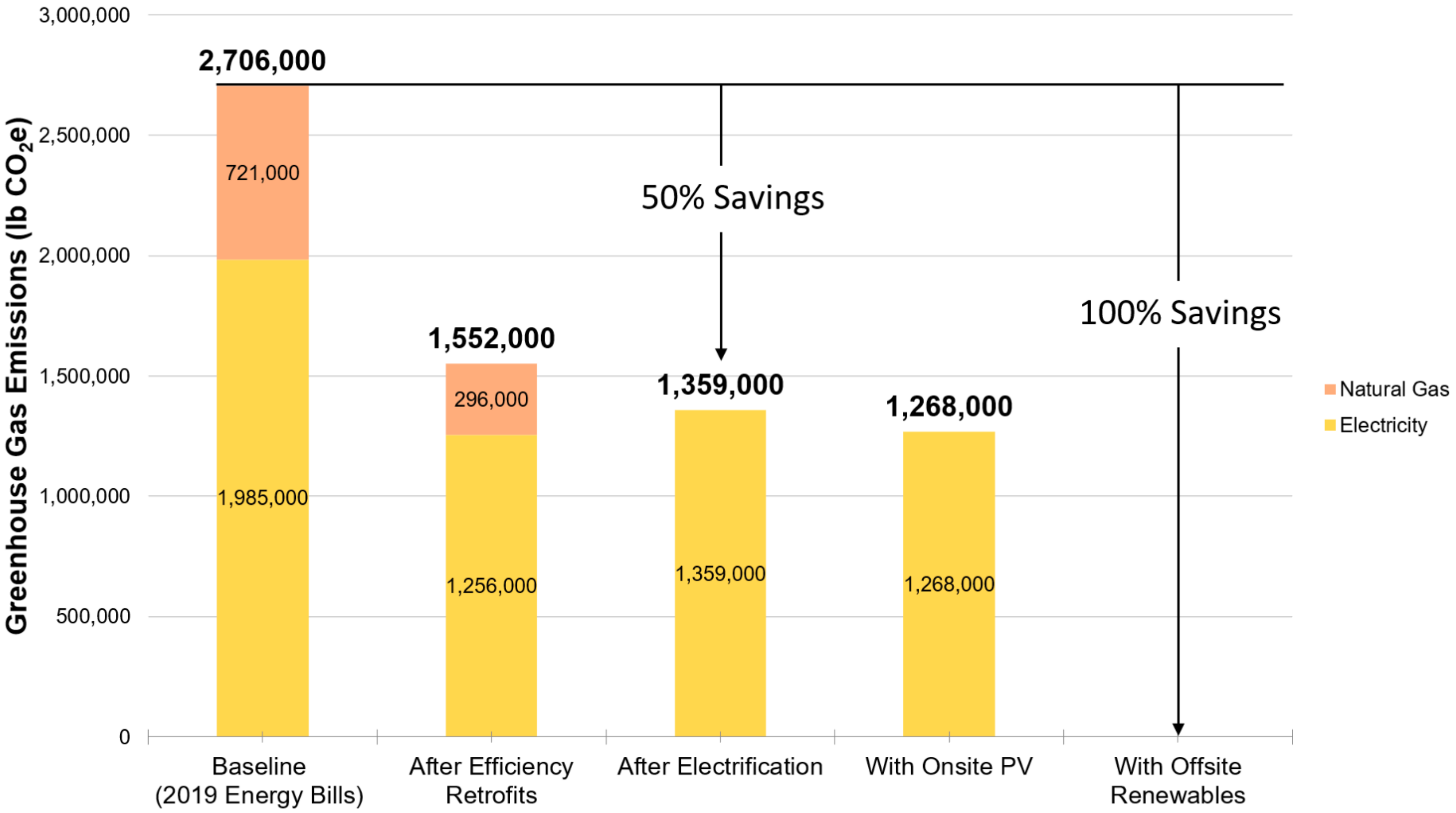
Case study: American Institute of Architects HQ

- Heating, ventilation and air conditioning (HVAC) renovation:
  - Replace boilers with air-source heat pumps for heating and cooling



Source: Stanford BDLA

Elimination of Annual Operational GHG Emission



Source: Stanford BDLA