

Lecture 03

Energy demand and buildings

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CIVIL-239: Engineering a sustainable
built environment

24 September 2025



“We shape our buildings,
and afterwards **our**
buildings shape us”

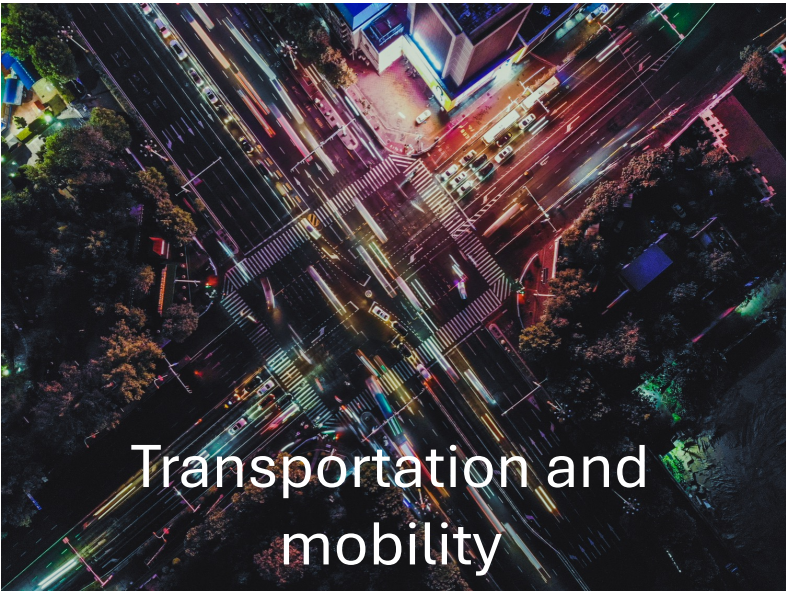
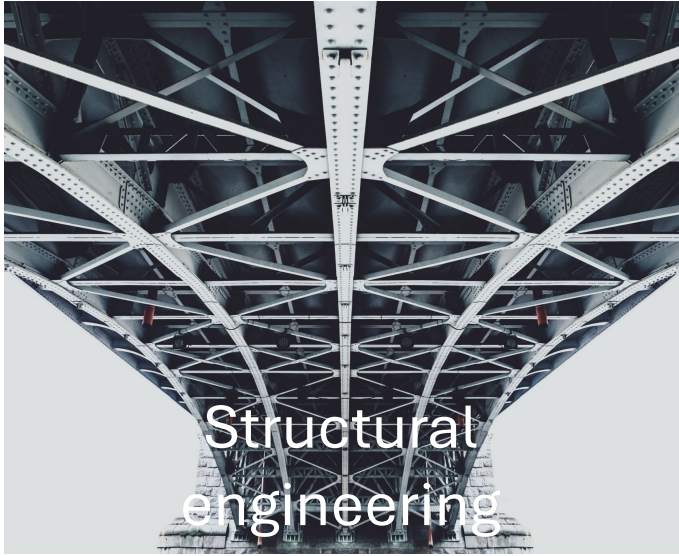
– Winston Churchill



Week	Date	Course Content	Engineering knowledge and tools	Due
Course introduction				
1	10-Sep	The climate crisis What is sustainability? Sustainability 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	Link between transportation and energy; 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 – CE 1 1		Assignment 3



Subdisciplines of civil engineering



Housekeeping

- Assignment 1 due today
- Assignment 2 out today, due in 2 weeks
 - Focuses on buildings, energy consumption, and carbon emissions



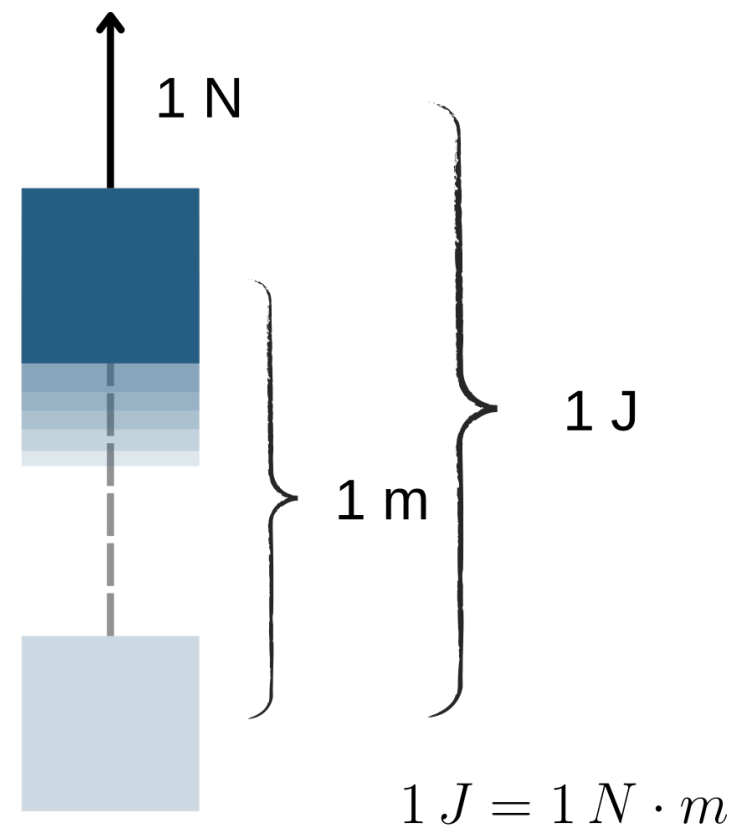
Outline

- Energy fundamentals
- Energy flows
- Fundamentals of building energy demand
- Refrigeration cycle and heat pumps
- Strategies for improving building energy performance
- Case study



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 $\frac{kg \cdot m^2}{s^2}$



How do we talk about energy?

$$\text{Energy} = \text{Power} \times \text{Time}$$

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

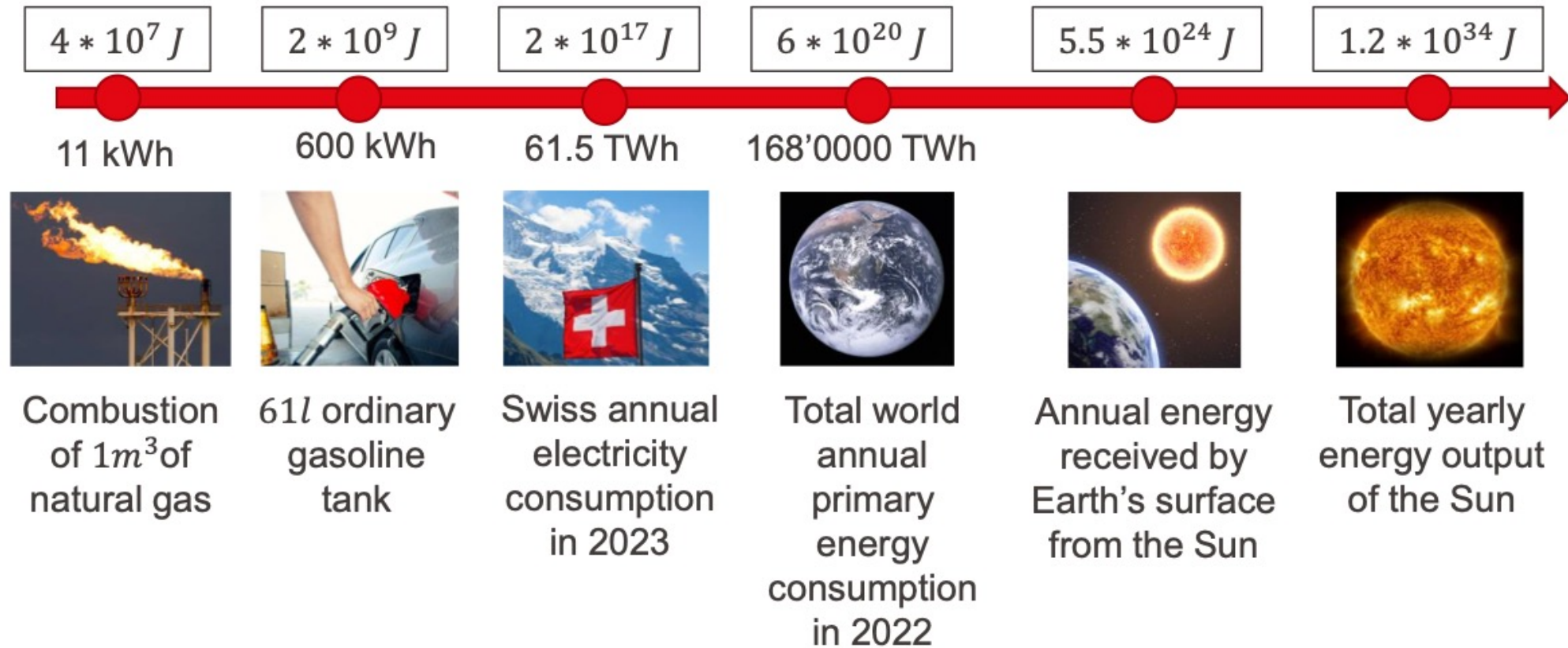


Other energy and power units

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



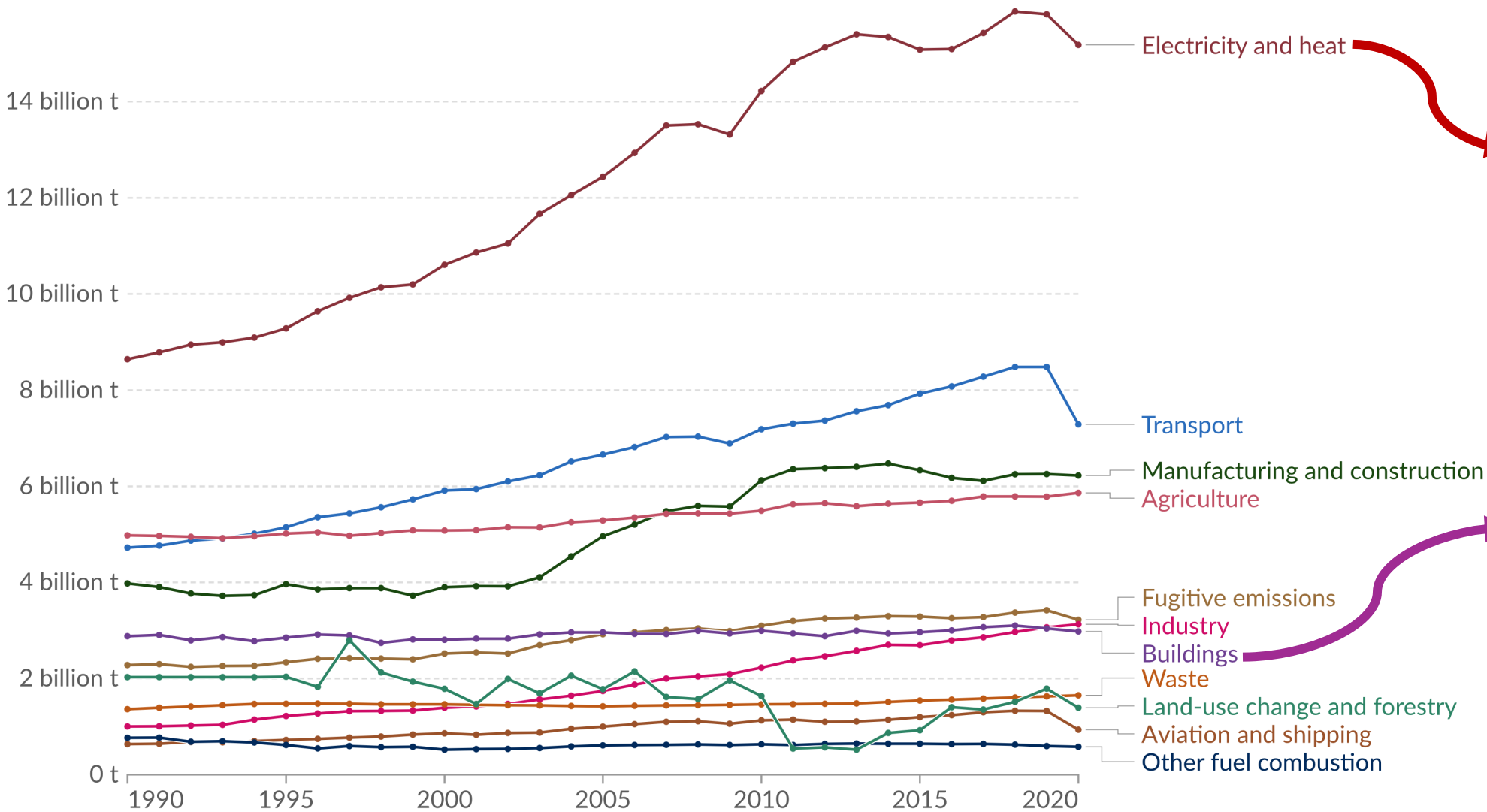
Energy in society



Greenhouse gas emissions by sector, World



Greenhouse gas emissions¹ are measured in tonnes of carbon dioxide-equivalents² over a 100-year timescale.



Buildings responsible for a large % of electricity and heat consumption

Building materials and construction processes

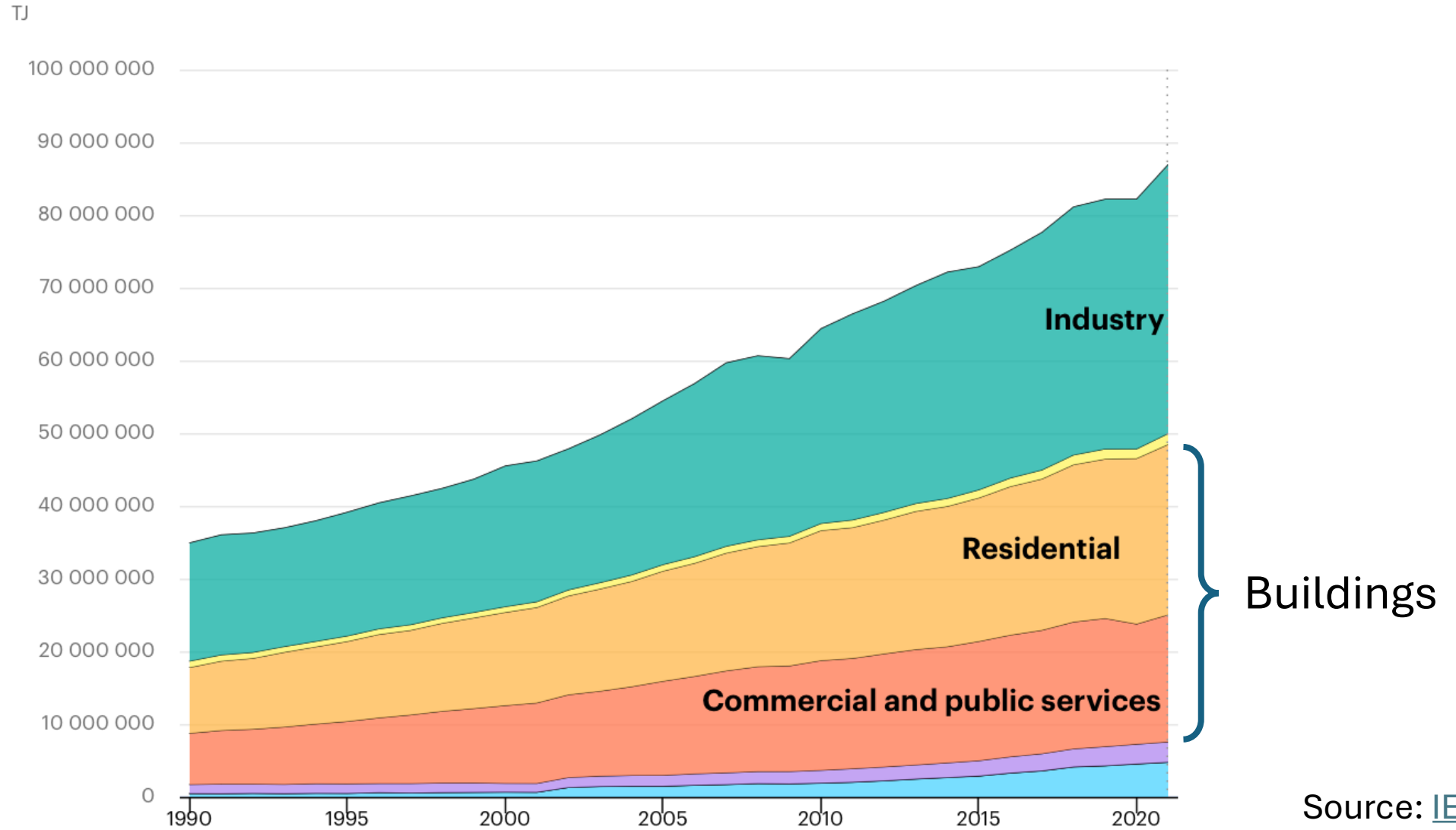
Data source: Climate Watch (2023)

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

Note: Land-use change emissions can be negative.



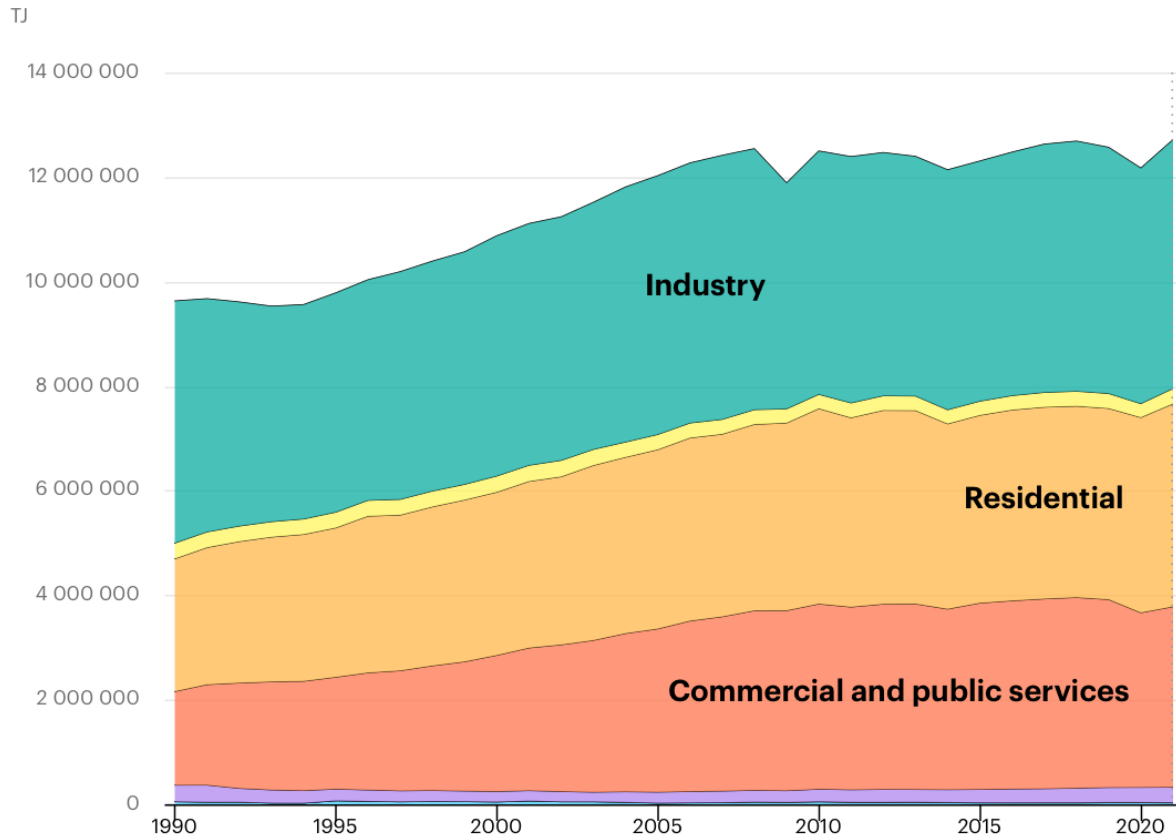
Electricity consumption by sector, global



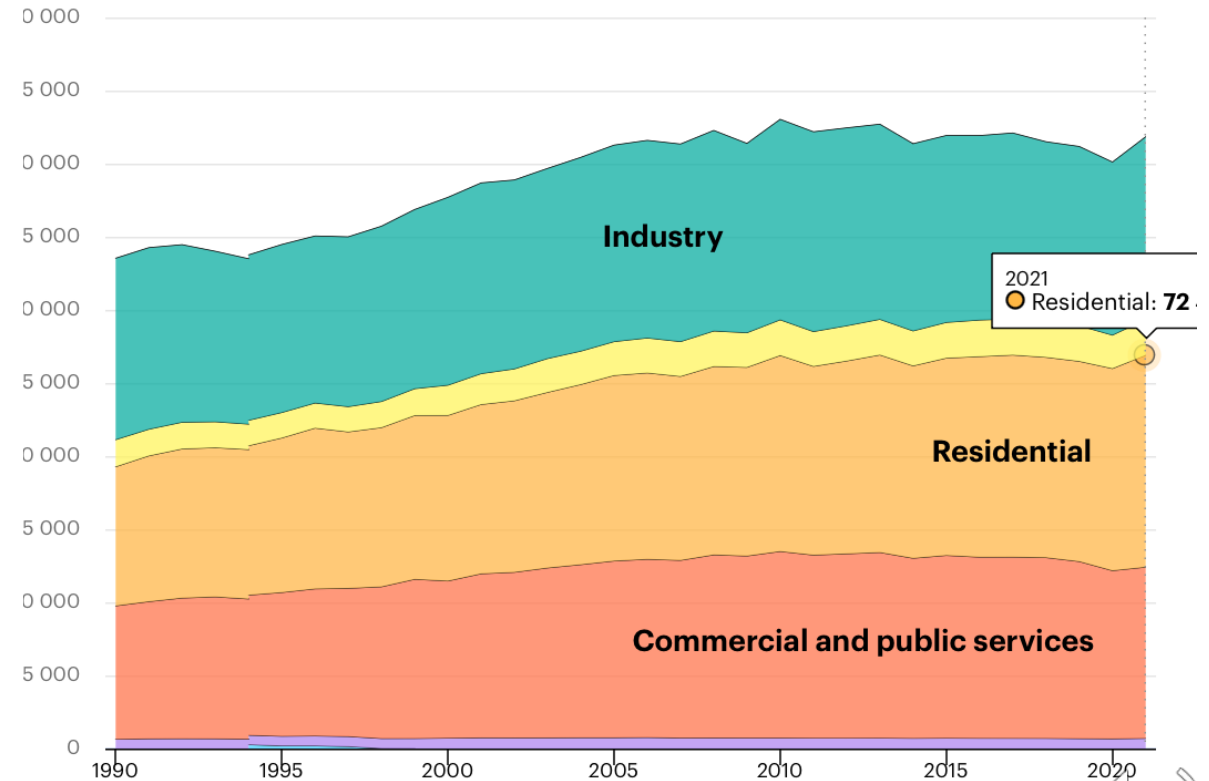
● Industry ● Transport ● Residential ● Commercial and public services ● Agriculture / forestry ● Fishing ● Non-specified



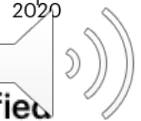
Electricity consumption by sector, Europe



Electricity consumption by sector, Switzerland

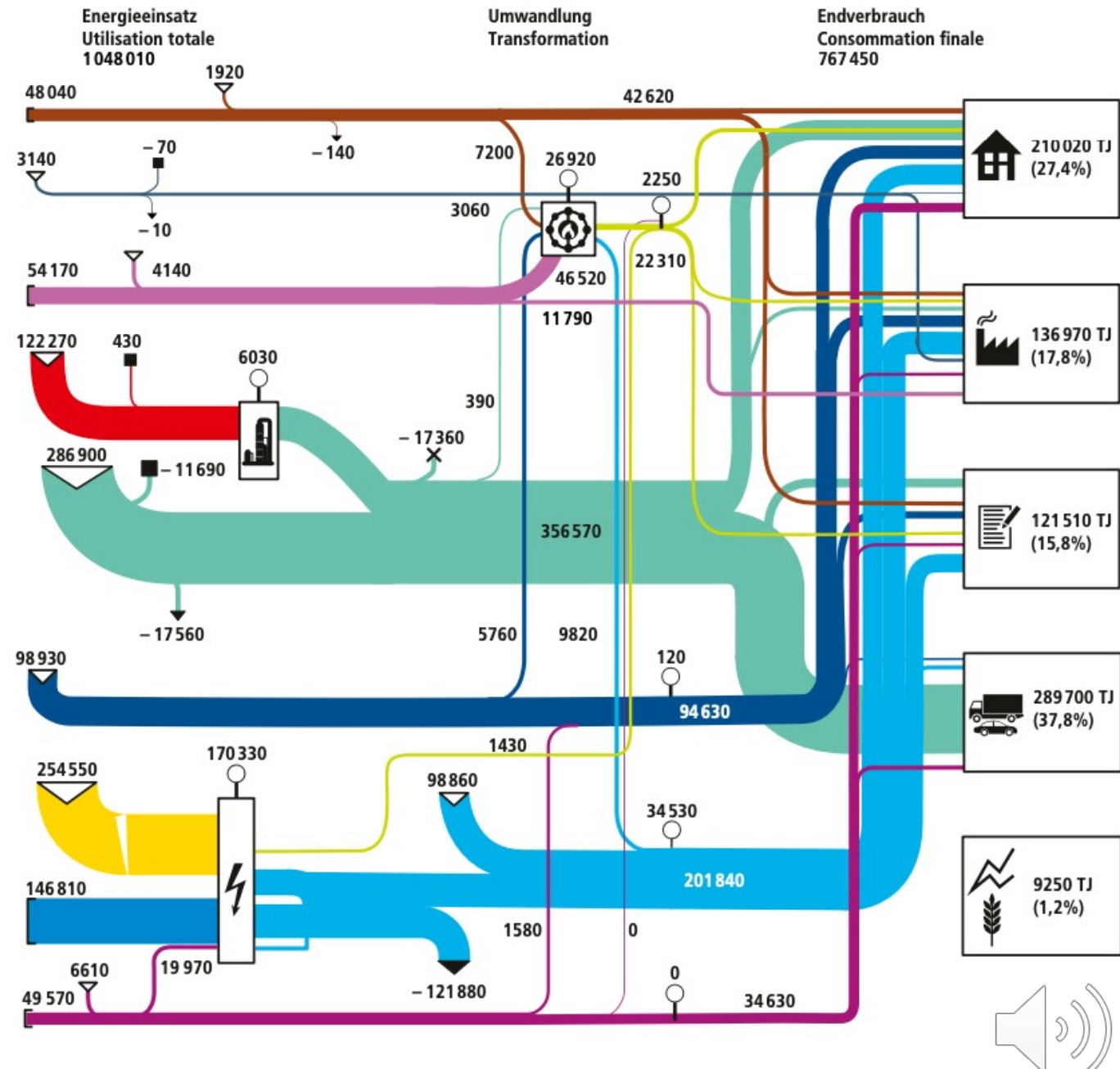


● Industry ● Transport ● Residential ● Commercial and public services ● Agriculture / forestry ● Fishing ● Non-specified



Swiss energy flows

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



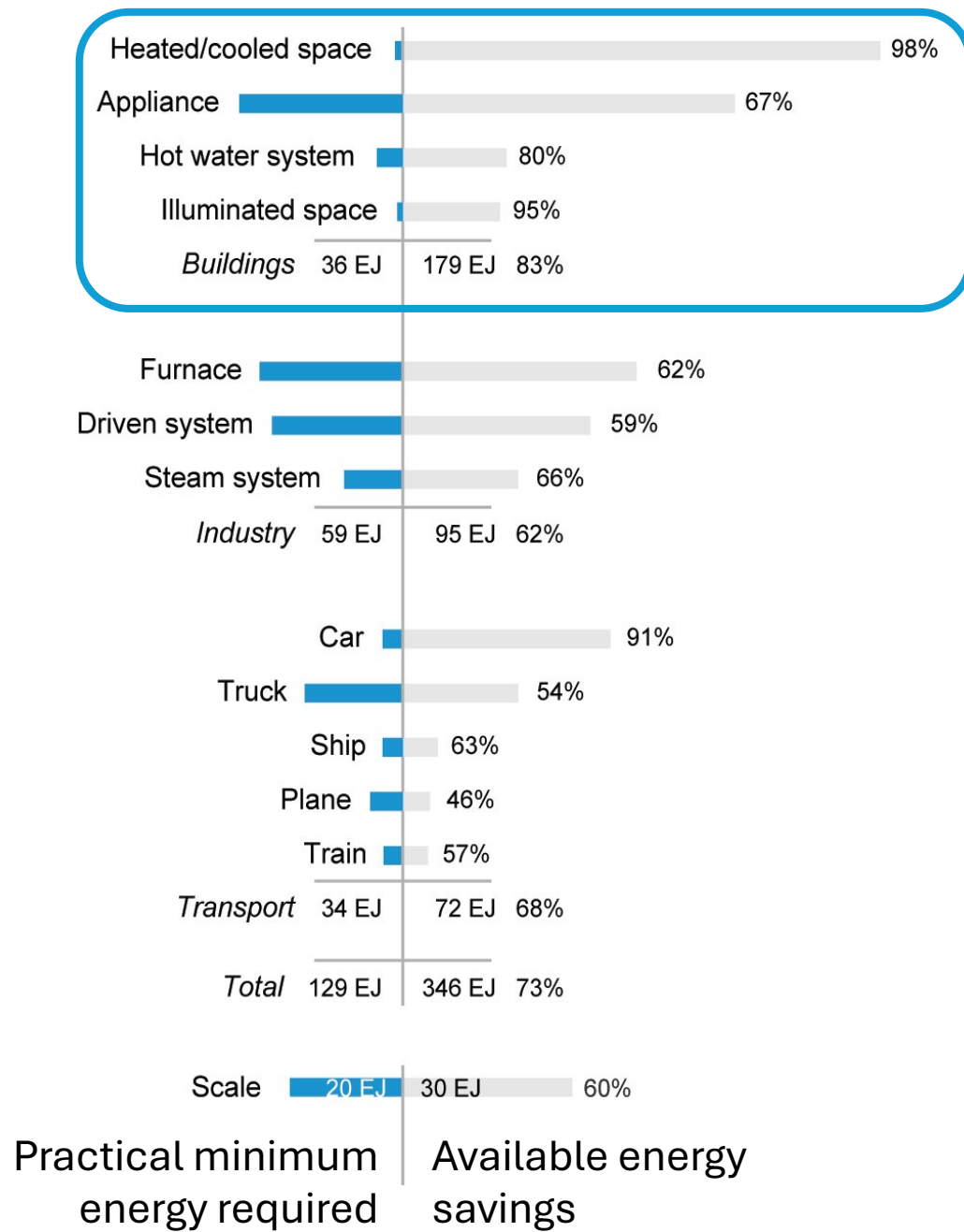
The Life Cycle of a Building



Energy and buildings: summary

- Total energy consumption of buildings
 - 34% of global energy demand, 37% of global CO2 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

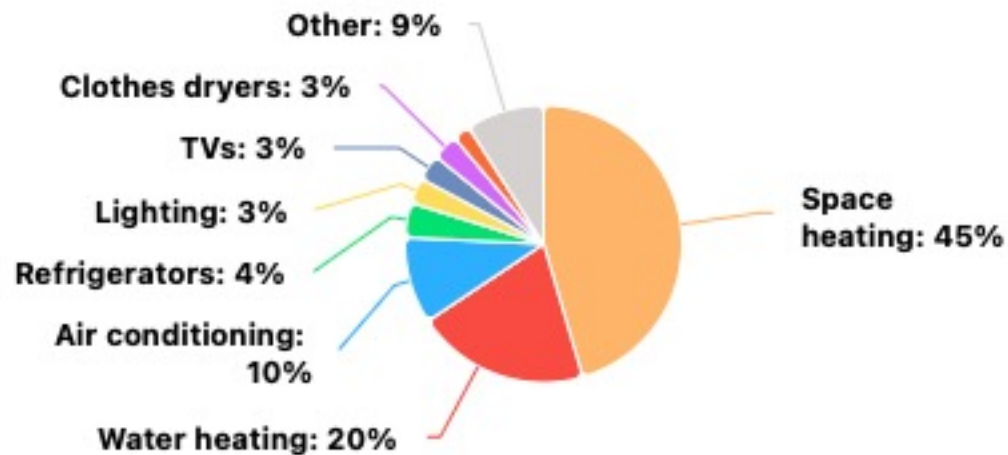


Fundamentals of building science

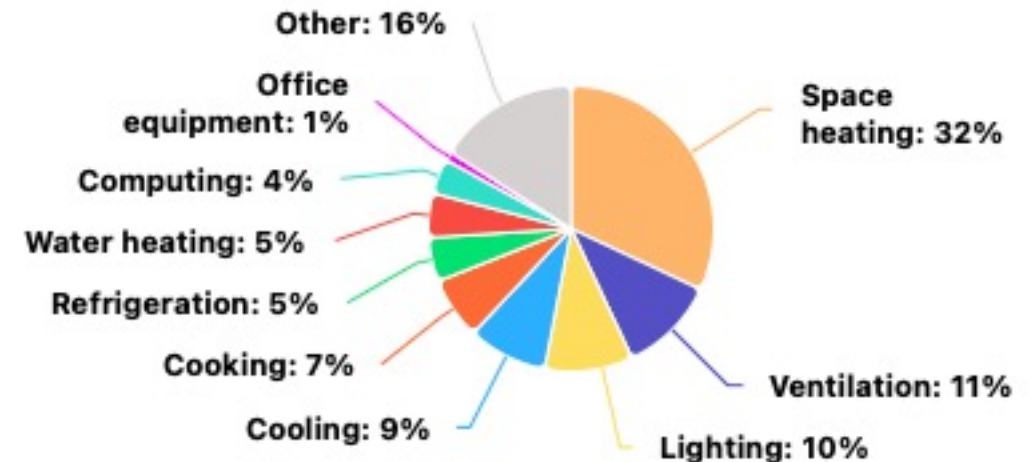


How buildings use energy

**Energy Consumption by End Use
(U.S. Residential Buildings)**

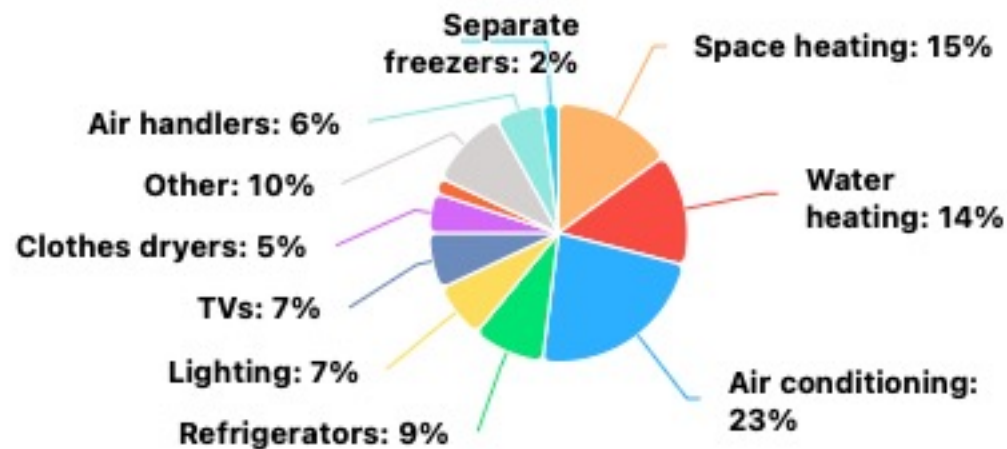


**Energy Consumption by End Use
(U.S. Commercial Buildings)**



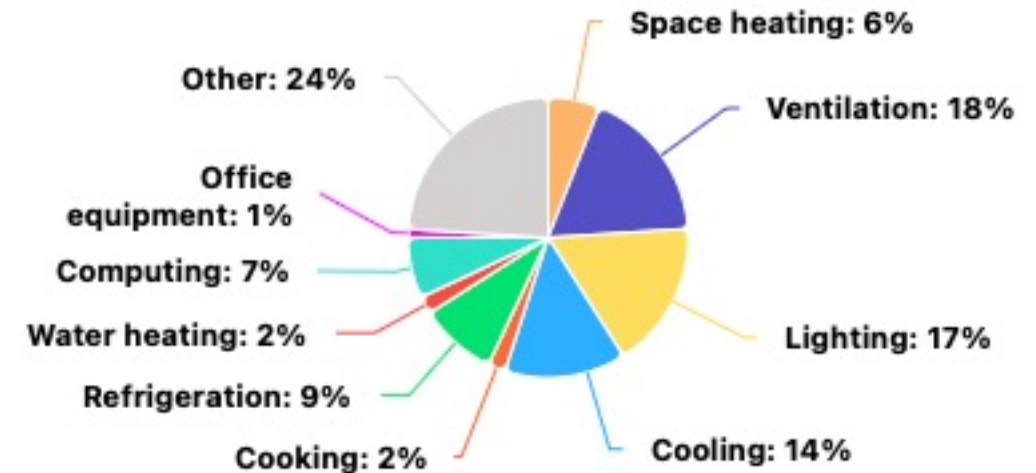
How buildings use electricity

**Electricity Consumption by End Use
(U.S. Residential Buildings)**



Electricity is 45% of energy consumption
in residential buildings

**Electricity Consumption by End Use
(U.S. Commercial Buildings)**



Electricity is 60% of energy consumption
in commercial buildings



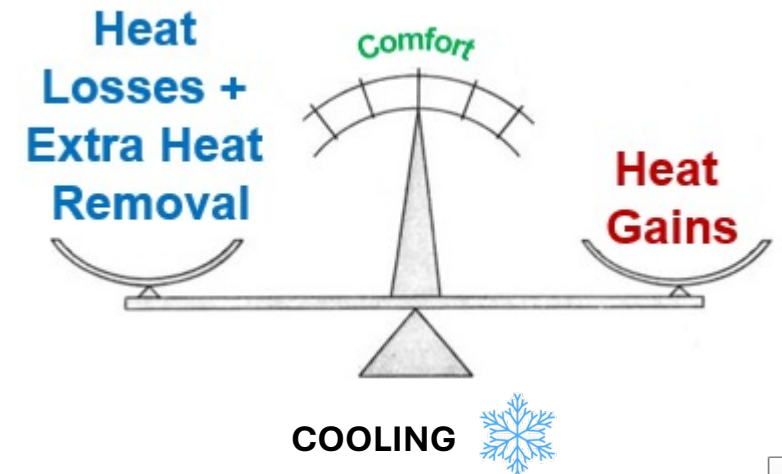
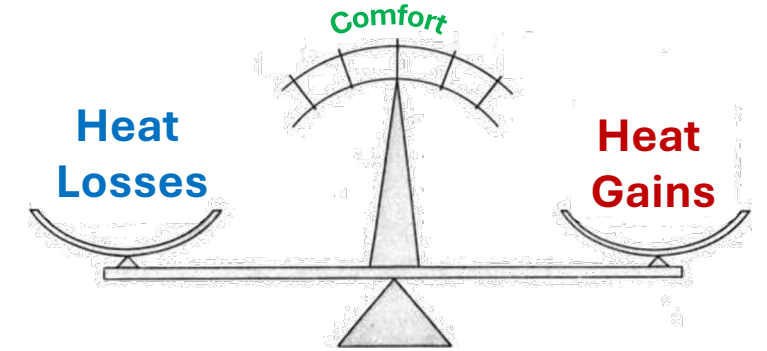
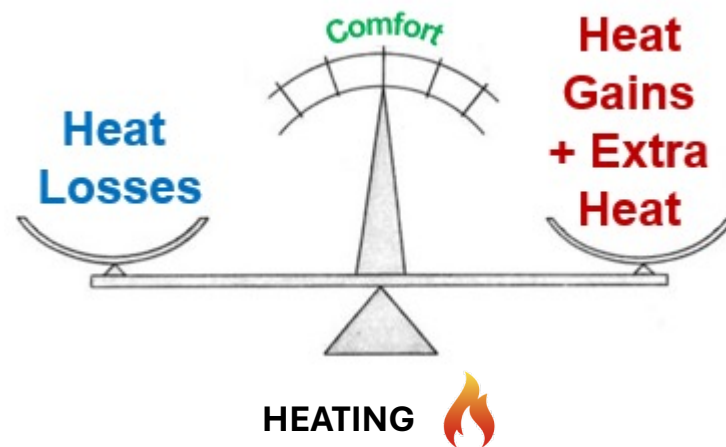
Energy demand in buildings

- **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

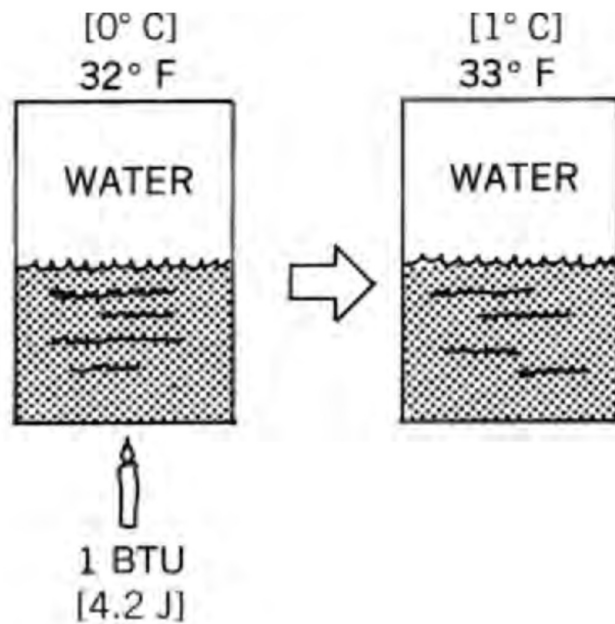
- A **comfortable indoor temperature** is *maintained* by *balanced* **heat losses** and **heat gains**
- **Heating** or **cooling** is needed when *they are imbalanced* and **extra** heat addition or removal is **necessary**



Types of heat

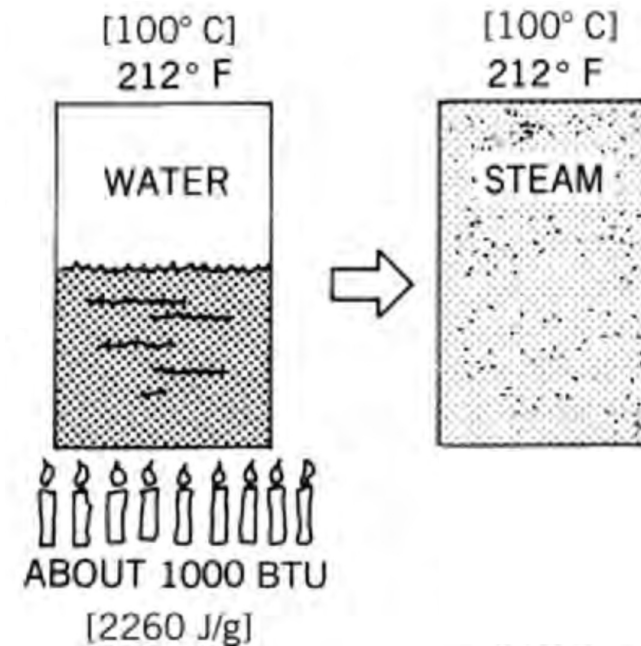
Sensible heat

Random motion of molecules—can be measured by a thermometer



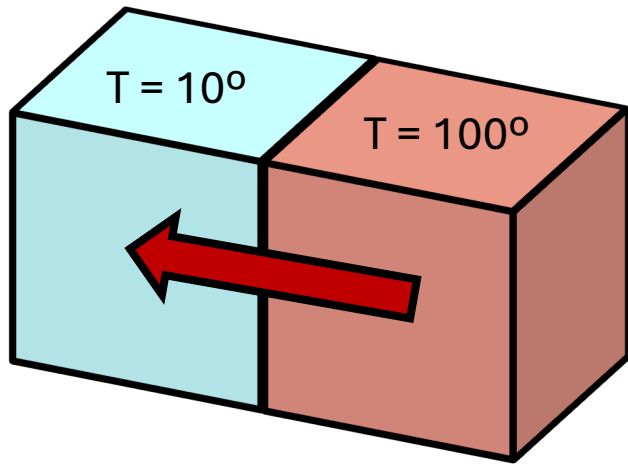
Latent heat

The change of state/phase of a material—no temperature change

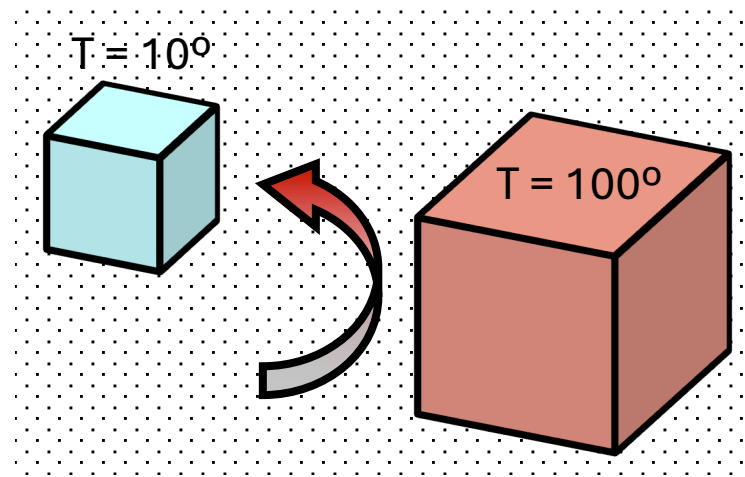


Heat transfer

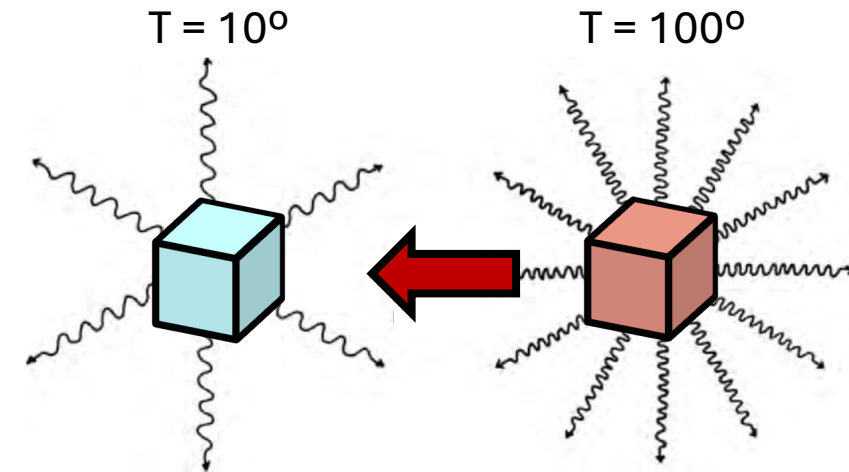
Three types of heat flow:



Conduction
(two surfaces in contact)



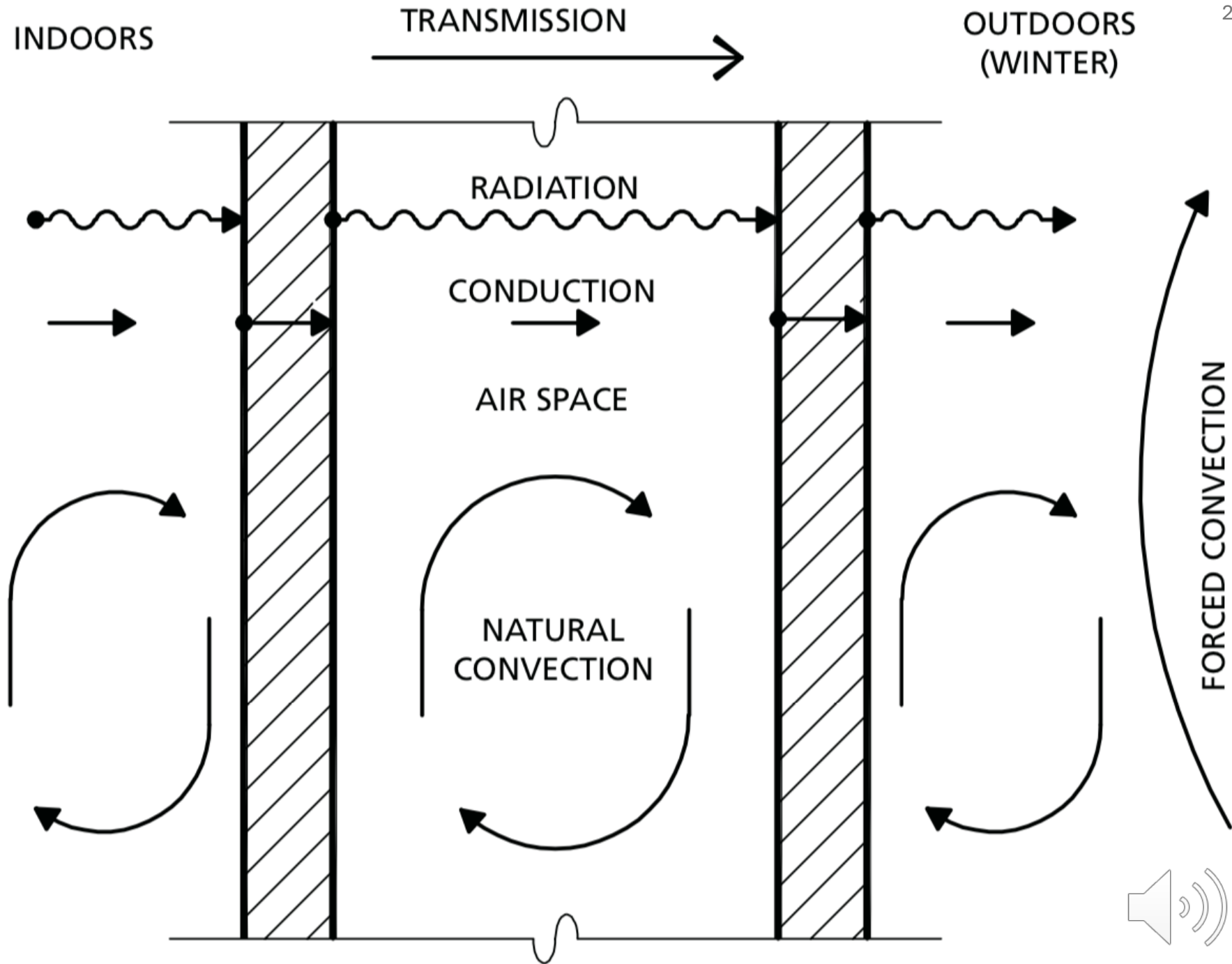
Convection
(heat moved through a fluid)



Radiation
(hotter masses radiate more)

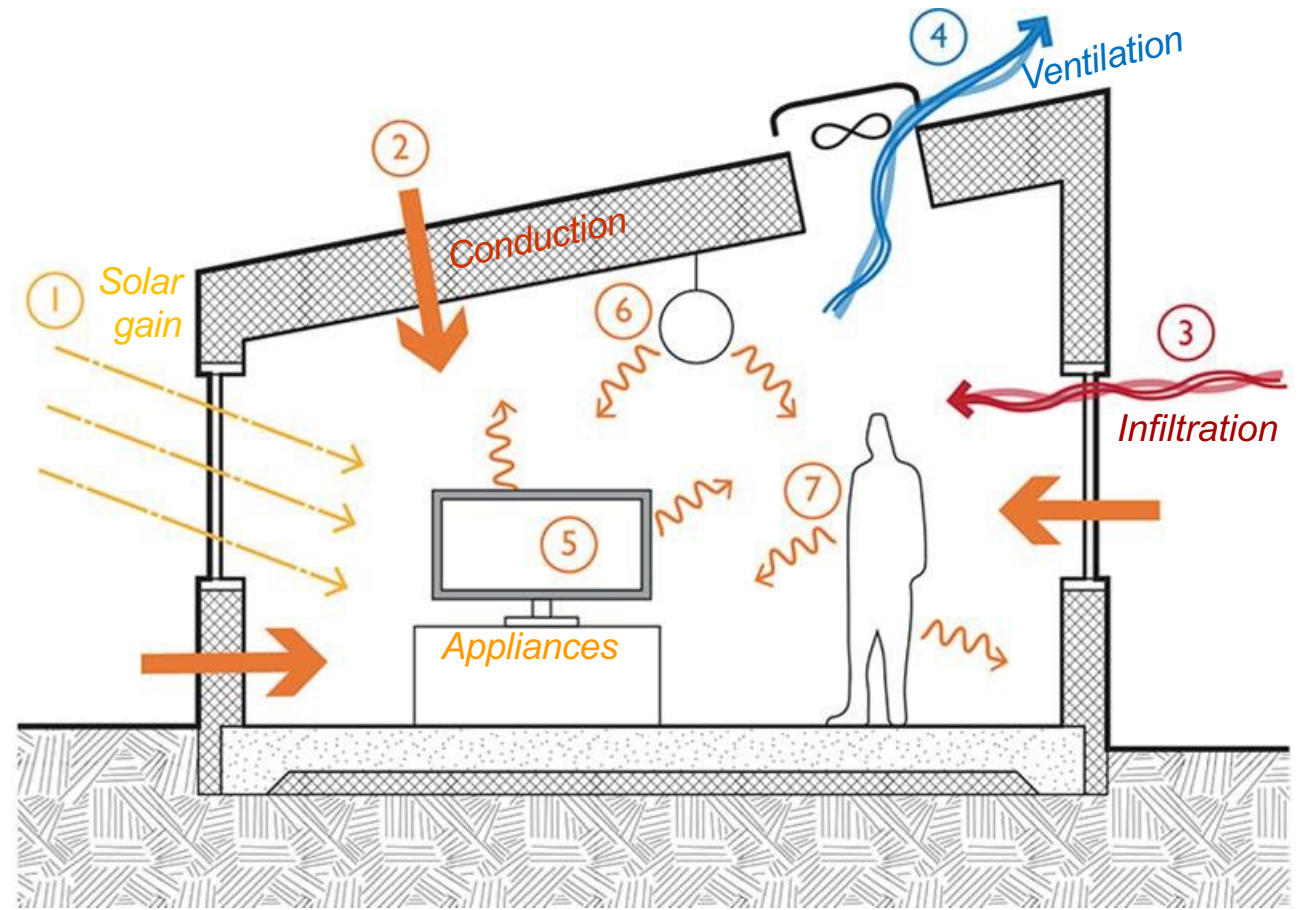


Building heat flows



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

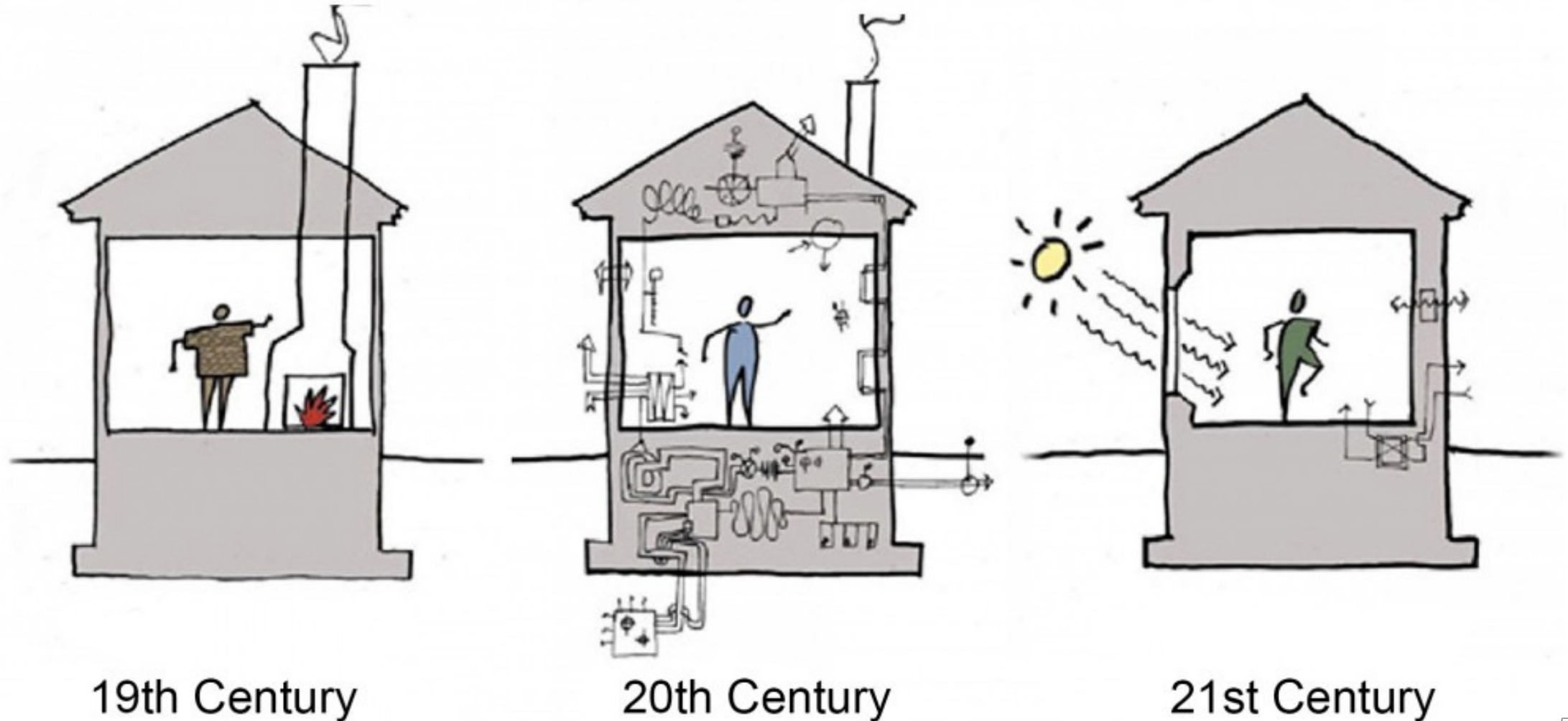
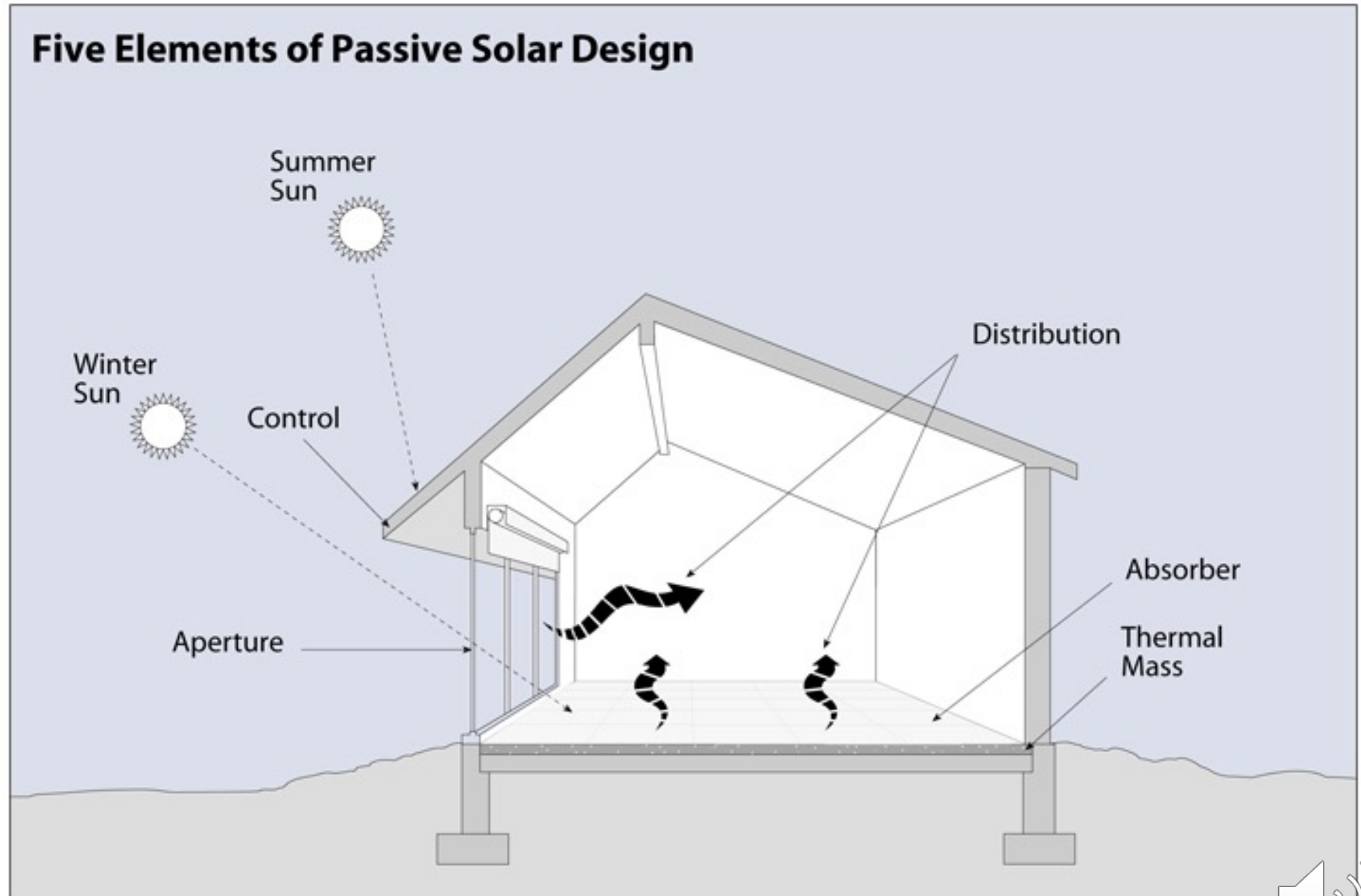


Image source: Albert, Righter and Tittmann Architects

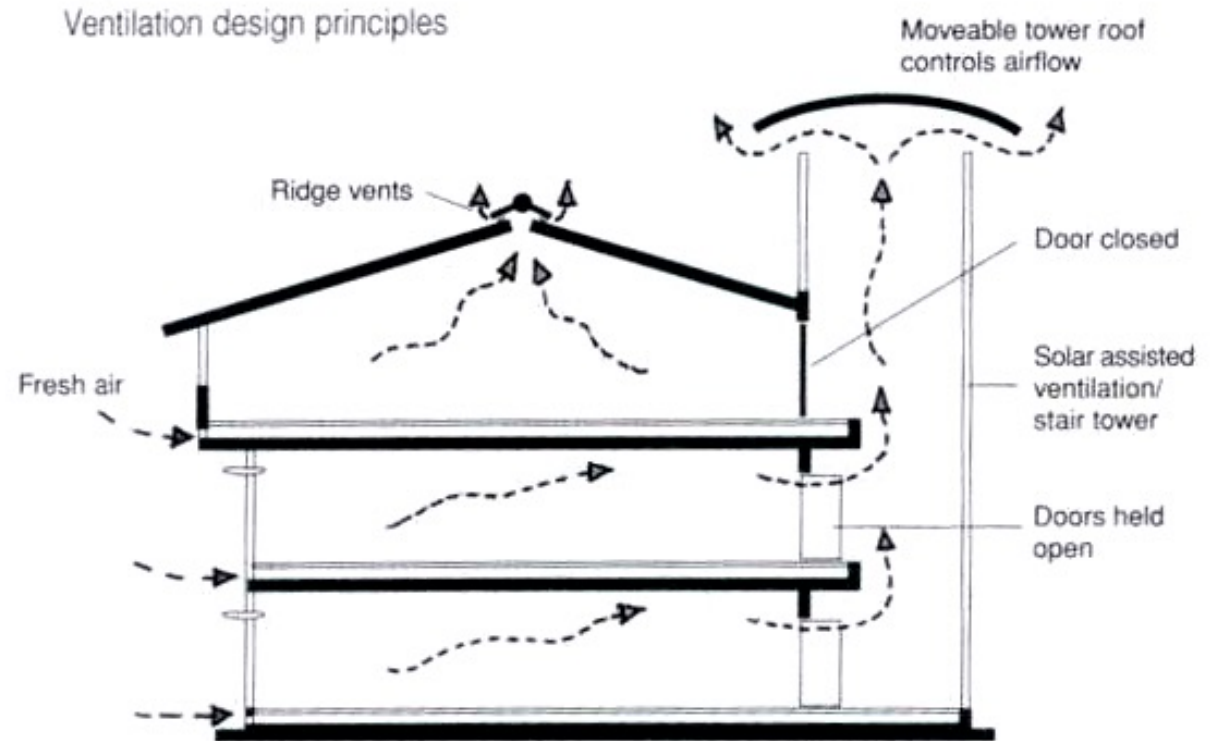


Passive heating systems



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



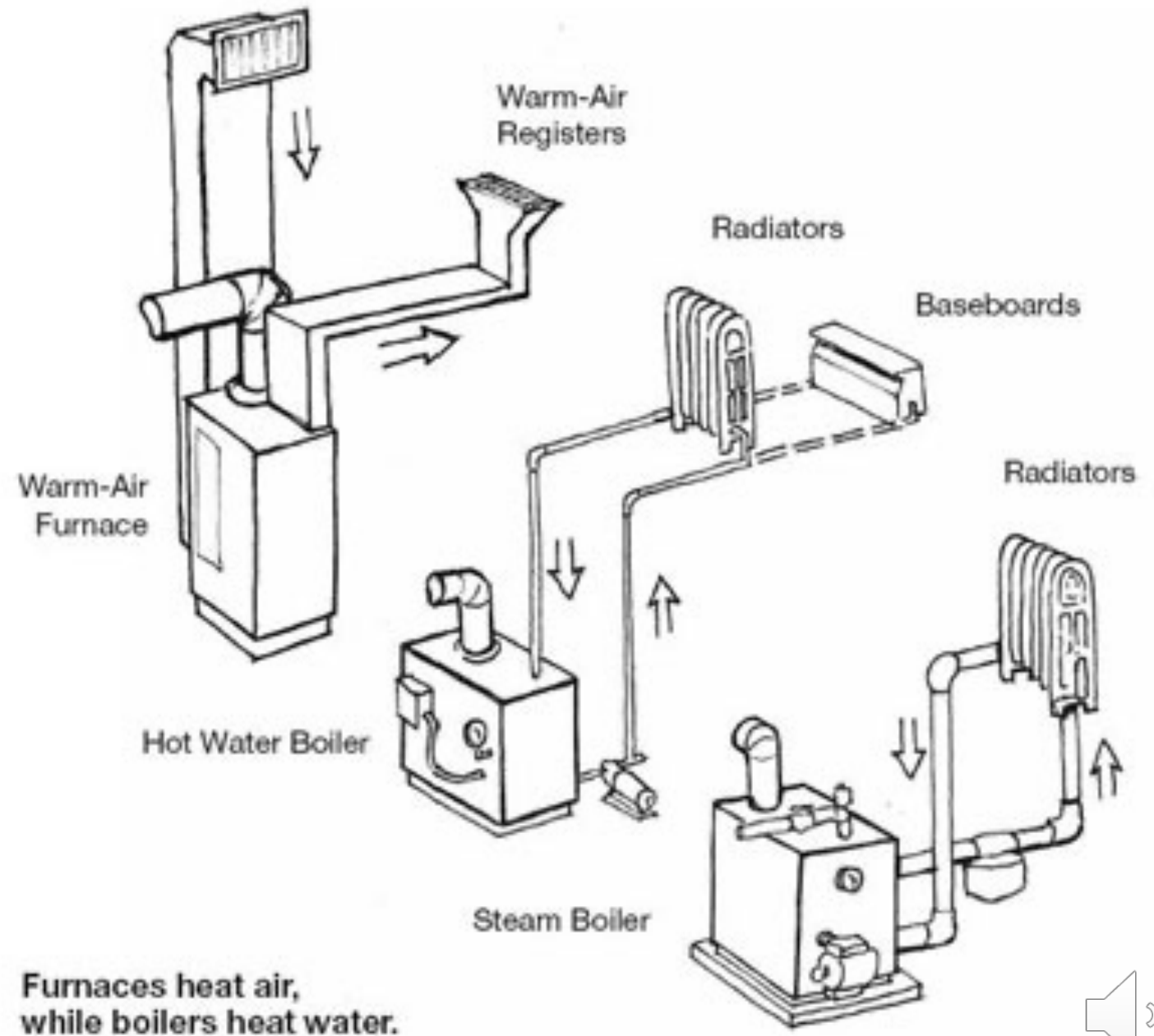
Passive cooling: evaporative cooling

- 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 heating systems

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



Efficiency: AFUE

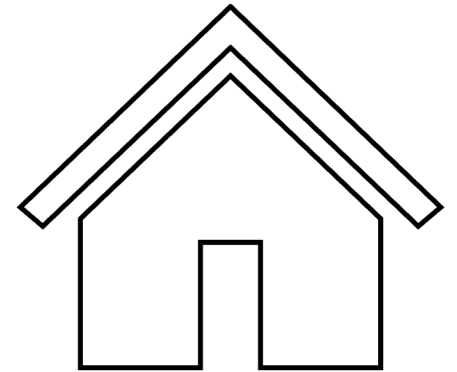
- Efficiency: the ratio of **useful work obtained** in a process to the **total energy expended**
- What is the maximum efficiency for a system that creates heat?
 - In buildings, heat can be created from chemical energy (e.g., oil) or electrical energy
- What type of heat is involved in furnaces and boilers?



What are the ways we can add heat to a building?

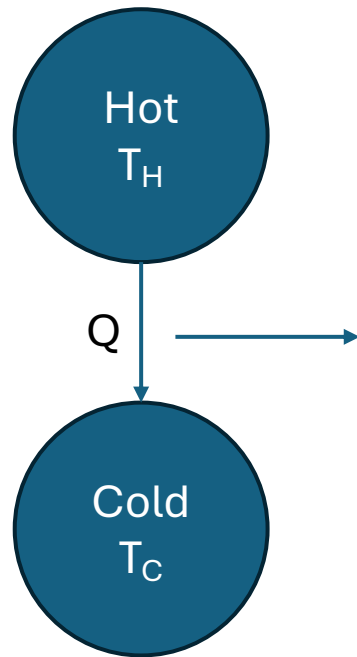
- With furnaces, heat is created (transformed from chemical or electric energy)
- Is it possible to move heat from the outside?
- In a heat engine, heat flow is used to create mechanical work (power)
 - Example: Internal combustion engine
- In a heat pump, mechanical work is used to move heat against its natural flow
- These machines use sensible heat (temperature differences), latent heat, and pressure differences
 - Ideal gas law: $PV=nRT$

Outside Temperature
-10°C / 263 K

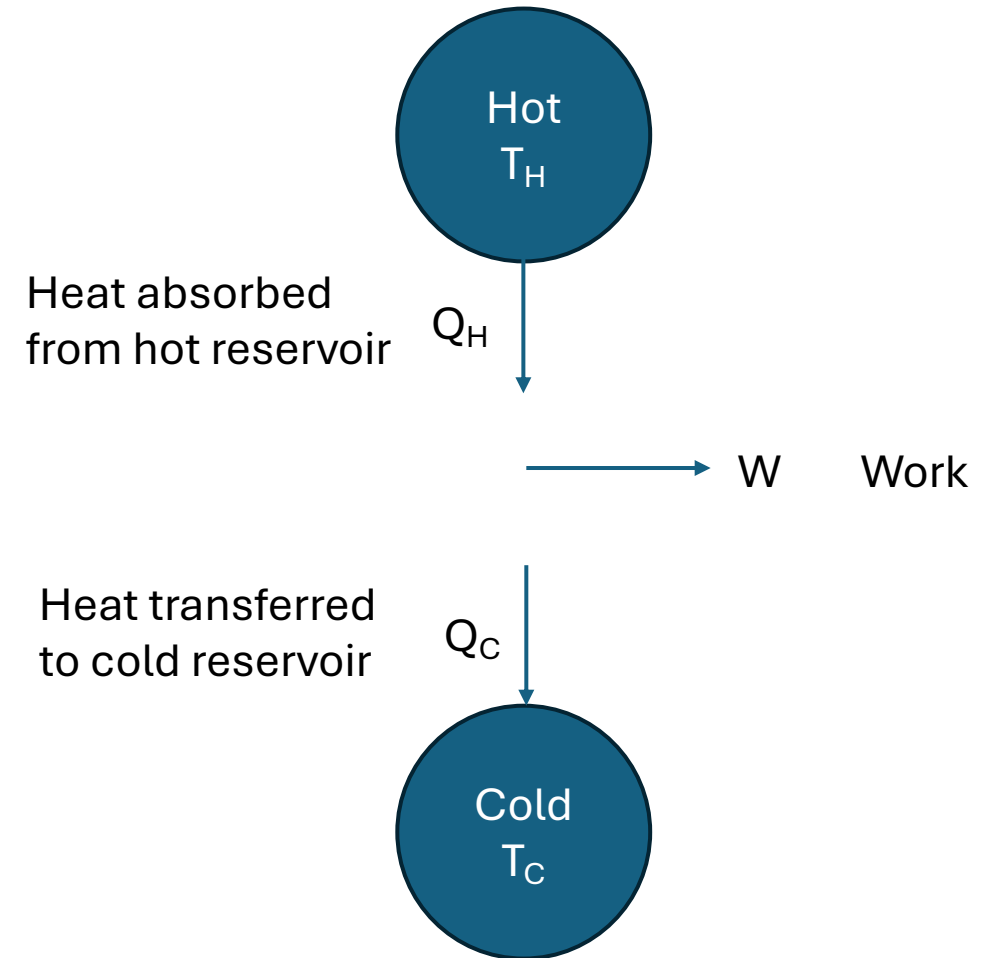


Inside Temperature
20°C / 293 K





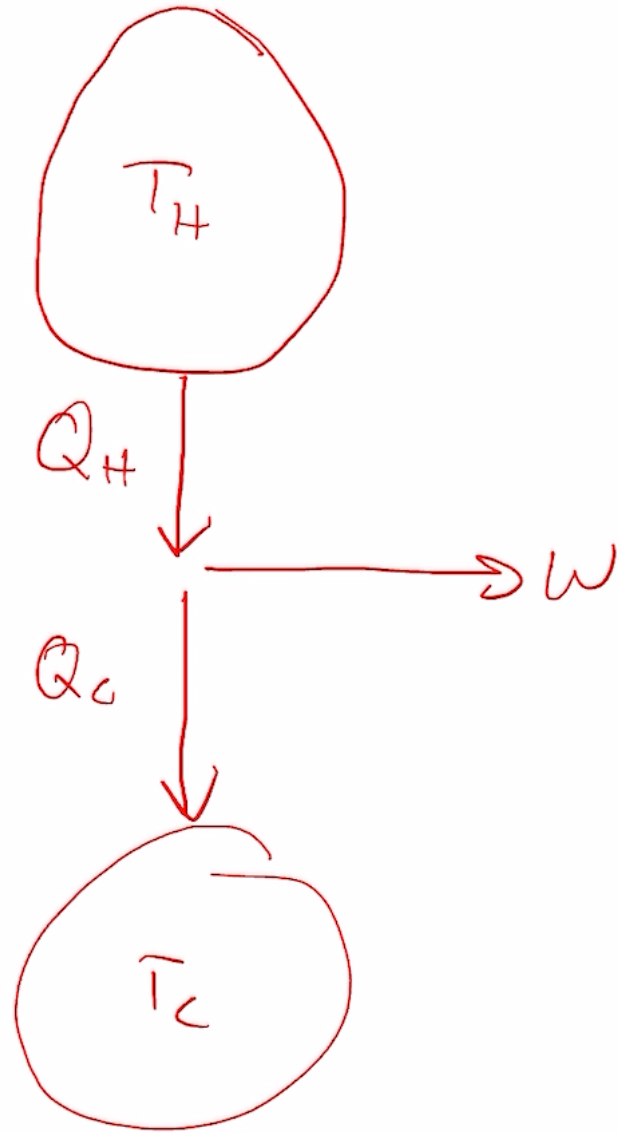
Some of this heat flow could be converted into mechanical work



First law of thermodynamics: Conservation of Energy $\rightarrow W = Q_h - Q_c$



$$W = Q_H - Q_C$$



If reversible
↳ max efficiency

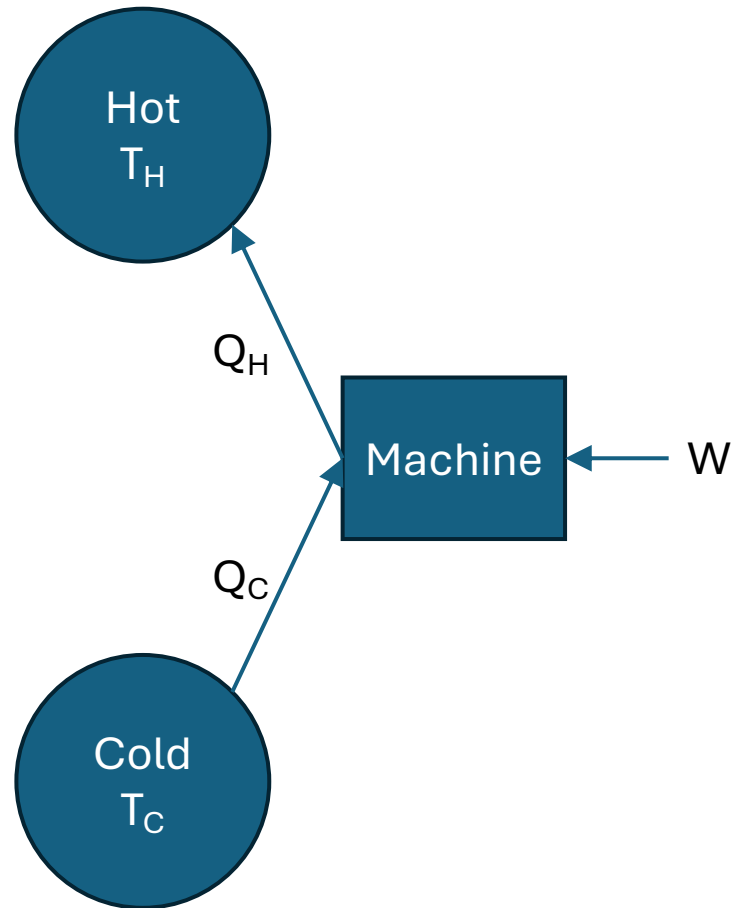
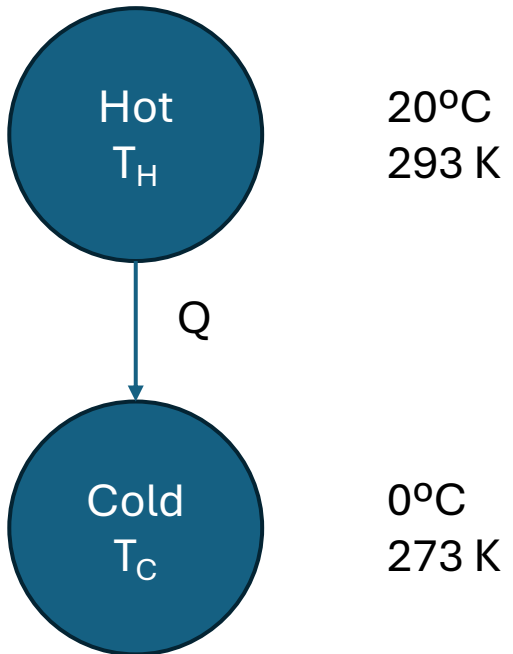
$$\left. \begin{aligned} \frac{Q_H}{T_H} - \frac{Q_C}{T_C} &= 0 \\ \frac{Q_H}{T_H} &= \frac{Q_C}{T_C} \end{aligned} \right\} \text{no entropy increase}$$

$$W = Q_H - Q_C$$

$$= Q_H - \frac{Q_H}{T_H} T_C$$

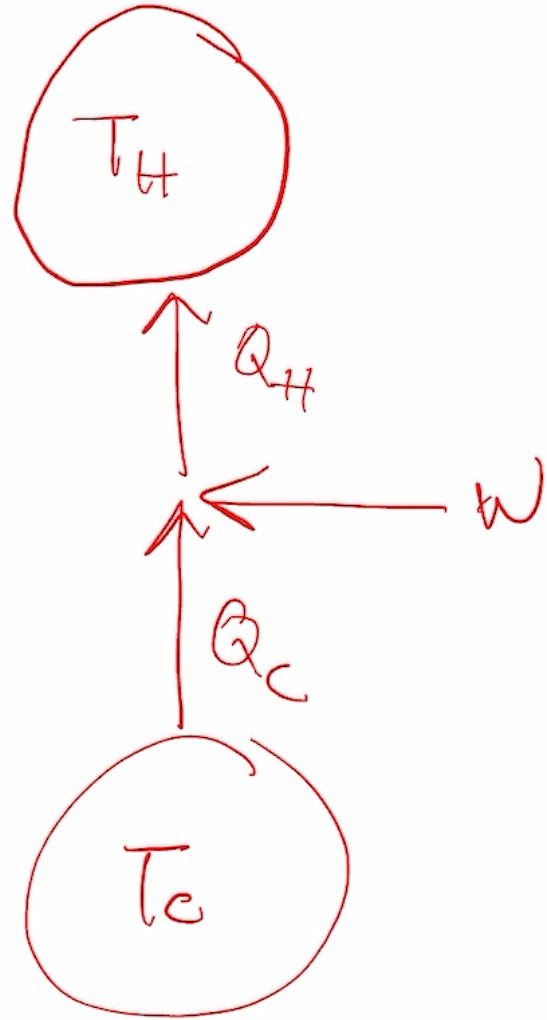
$$= Q_H \left(1 - \frac{T_C}{T_H} \right)$$

efficiency $\left(\frac{W}{Q_H} \right) = 1 - \frac{T_C}{T_H} = \frac{T_H - T_C}{T_H}$



One of the best ways we know how to apply work to fluids is by applying changes in pressure





$$W = Q_H - Q_C$$

$$\frac{Q_H}{T_H} = \frac{Q_C}{T_C}$$

$$\text{COP} = \frac{Q_H}{W}$$

$$W = Q_H - \frac{Q_H}{T_H} T_C$$

$$= Q_H \left(1 - \frac{T_C}{T_H} \right)$$

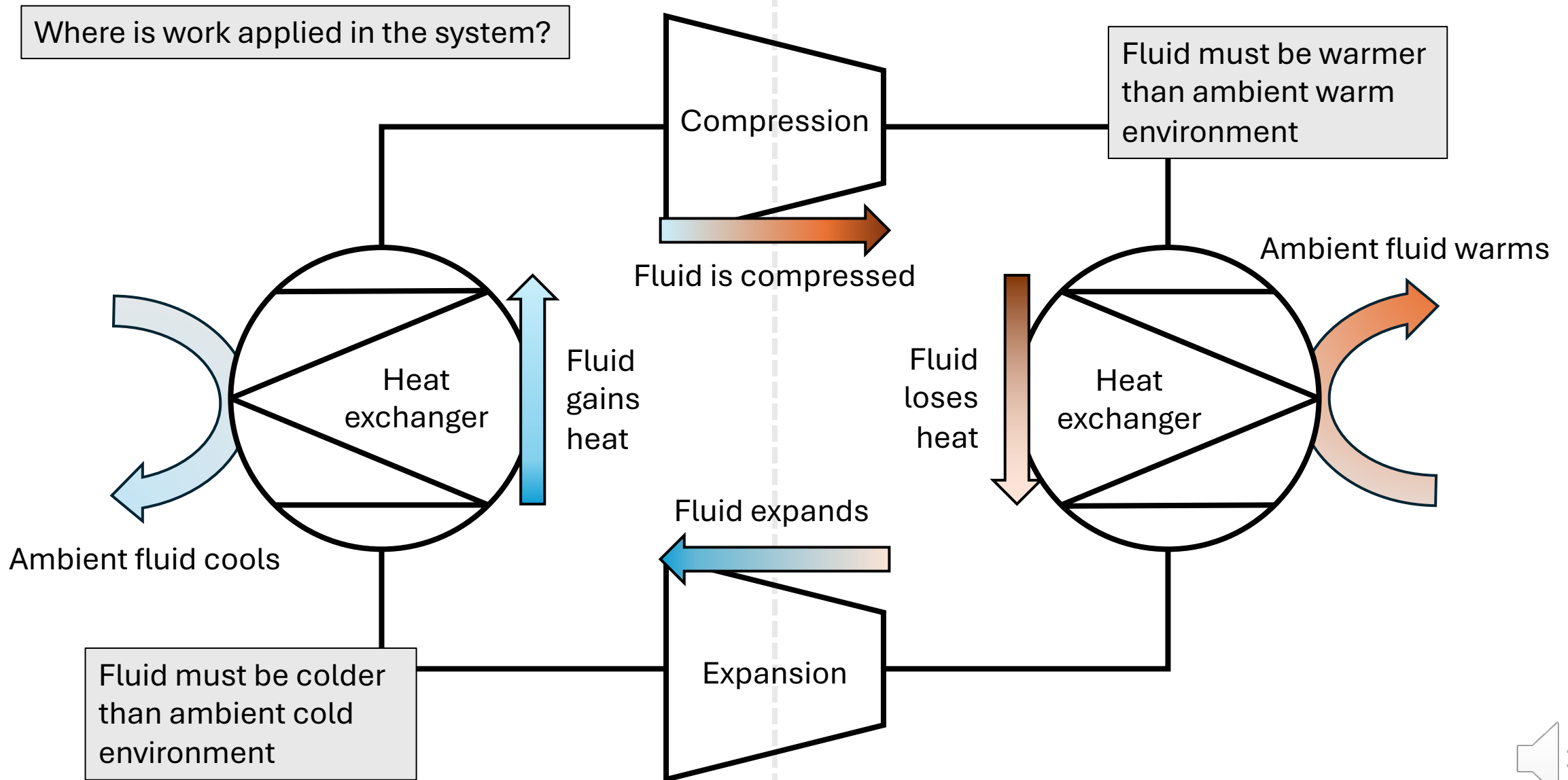
$$= \frac{Q_H}{W} \left(1 - \frac{T_C}{T_H} \right)$$

$$\frac{Q_H}{W} = \frac{1}{1 - \frac{T_C}{T_H}}$$

$$= \frac{1}{\frac{T_H - T_C}{T_H}}$$

$$\text{COP} = \frac{T_H}{T_H - T_C}$$

Ambient cold environment (T_c) \xrightarrow{Q} Ambient warm environment (T_H)

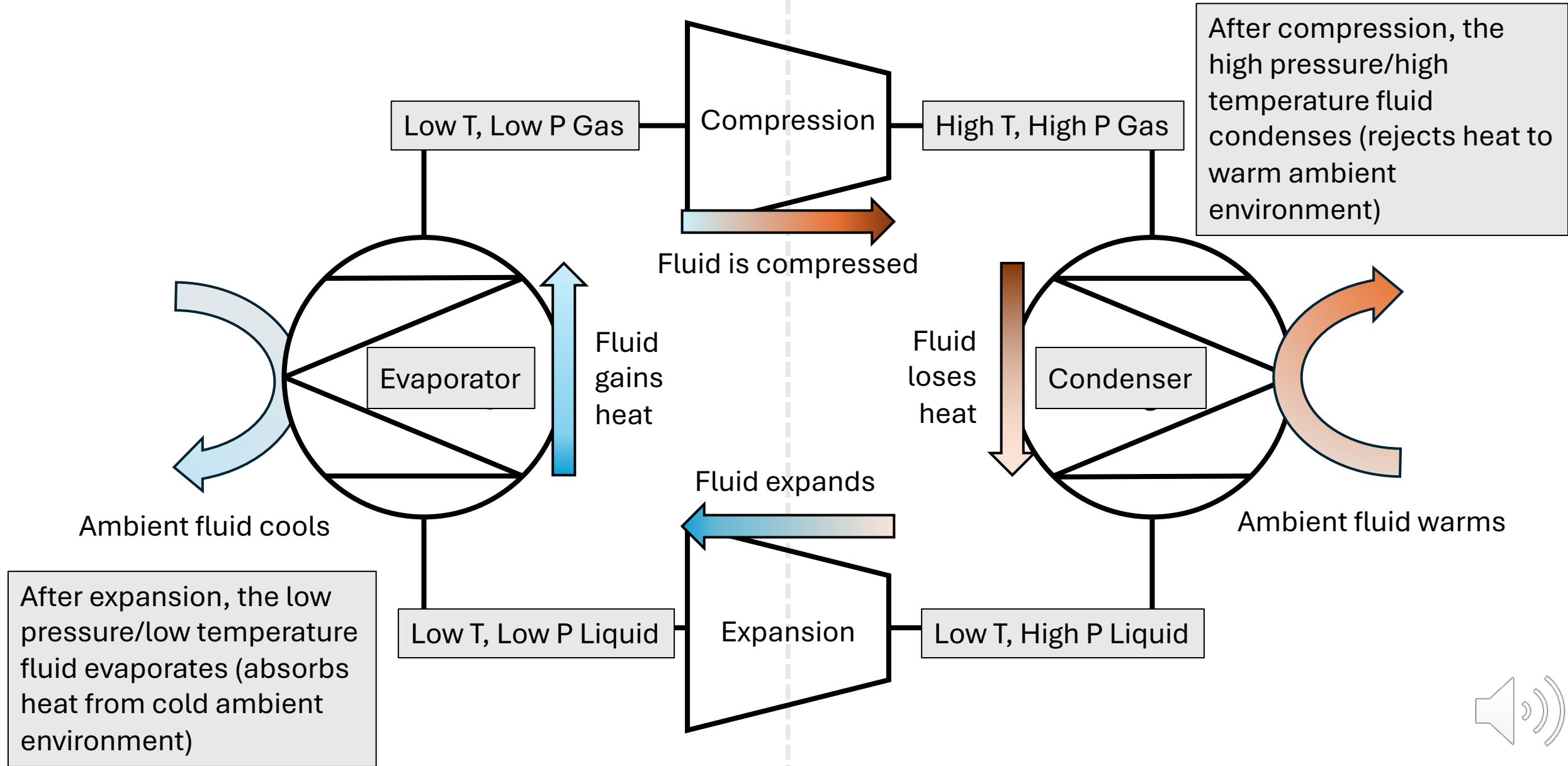


Ambient cold environment (T_c)

Ambient warm environment (T_H)

The vapor-compression cycle

To maximize the heat exchange, we can take advantage of latent heat properties



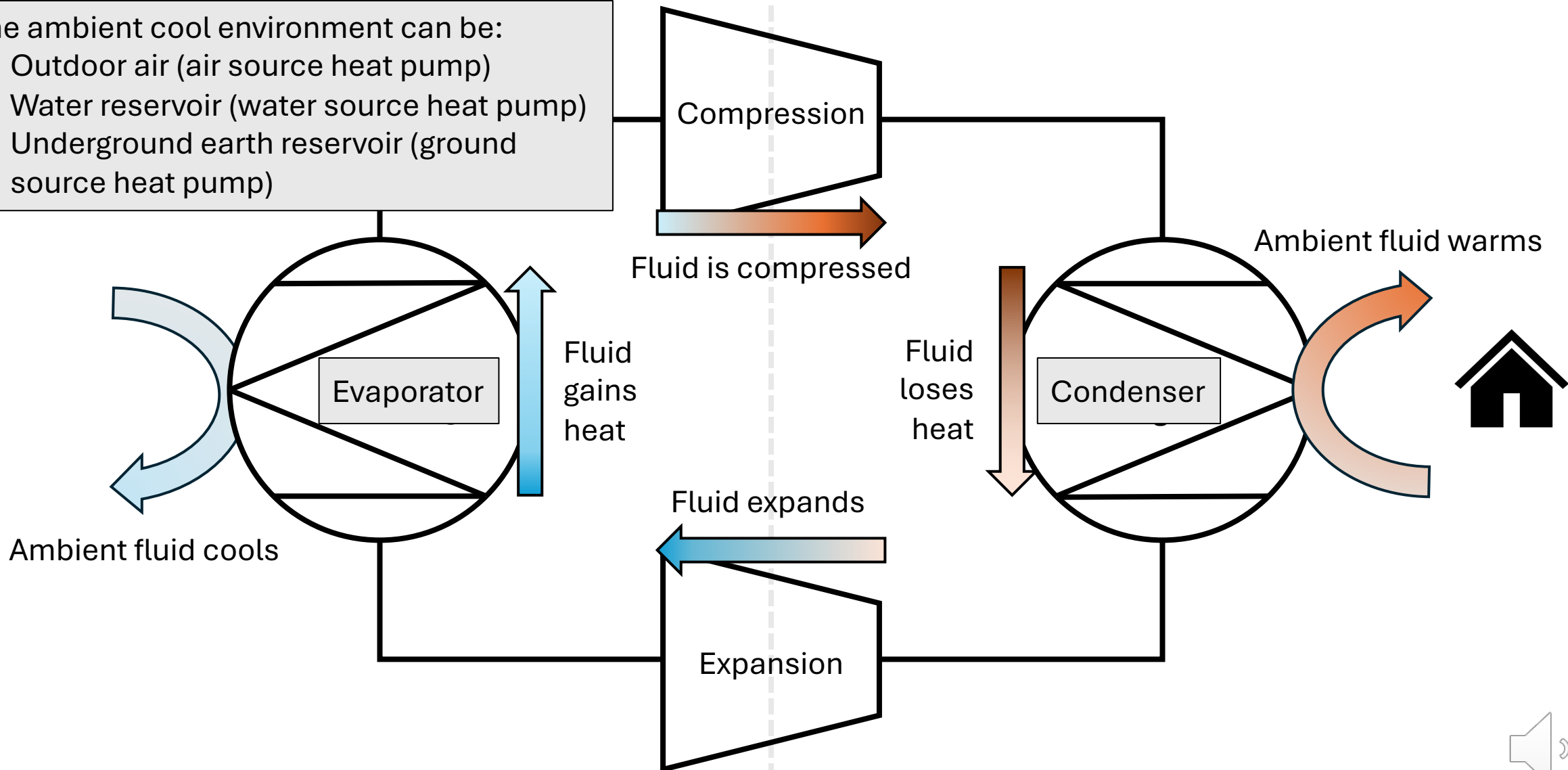
Ambient cold environment (T_c)

Ambient warm environment (T_H)

The vapor-compression cycle

The ambient cool environment can be:

- Outdoor air (air source heat pump)
- Water reservoir (water source heat pump)
- Underground earth reservoir (ground source heat pump)



How to measure performance?

- General coefficient of performance (COP) equation:

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

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

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



Question: what is the theoretical maximum efficiency of a heat pump?

- Less than 100%
- 100%
- Greater than 100%

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



Heat pump exercise

- If the indoor temperature is 20°C and the outdoor temperature is -10°C, what is the maximum COP of this heat pump?

$$\text{COP} = \frac{T_H}{T_H - T_C} = \frac{293 \text{ K}}{30 \text{ K}} = 9.7\bar{6}$$

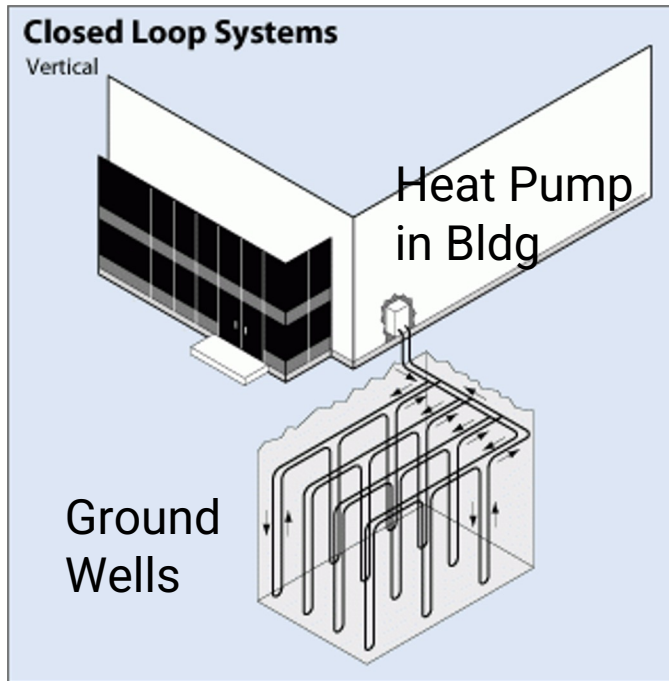
- If we install a heat pump with a COP of 3, and it is consuming 200W, how much heat is it adding to the indoor environment?

$$\text{COP} = \frac{Q_H}{W}$$
$$3 = \frac{Q_H}{200 \text{ W}} \rightarrow Q_H = 600 \text{ W}$$

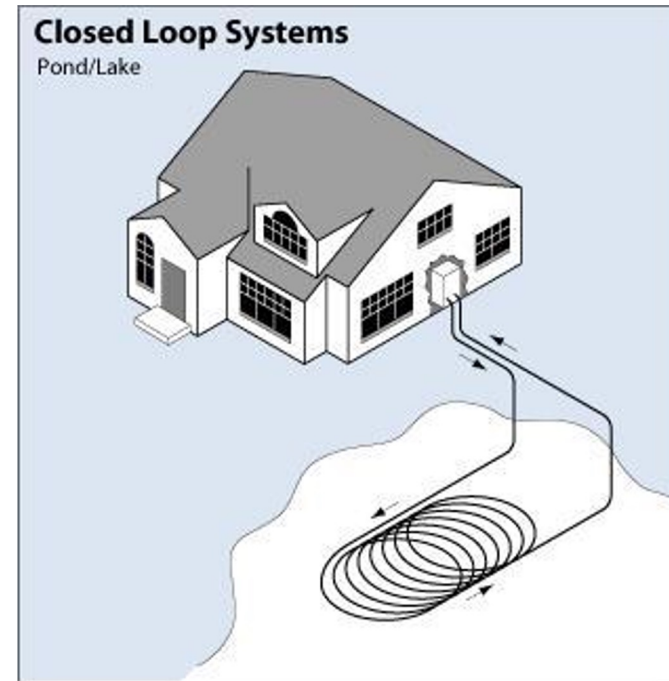
Air source heat pump



Water and ground source heat pump



Ground used as heat source/sink



Pond/lake used as heat source/sink

EPFL uses a heat pump system for heating and cooling, with Lac Lemman as the heat source/sink

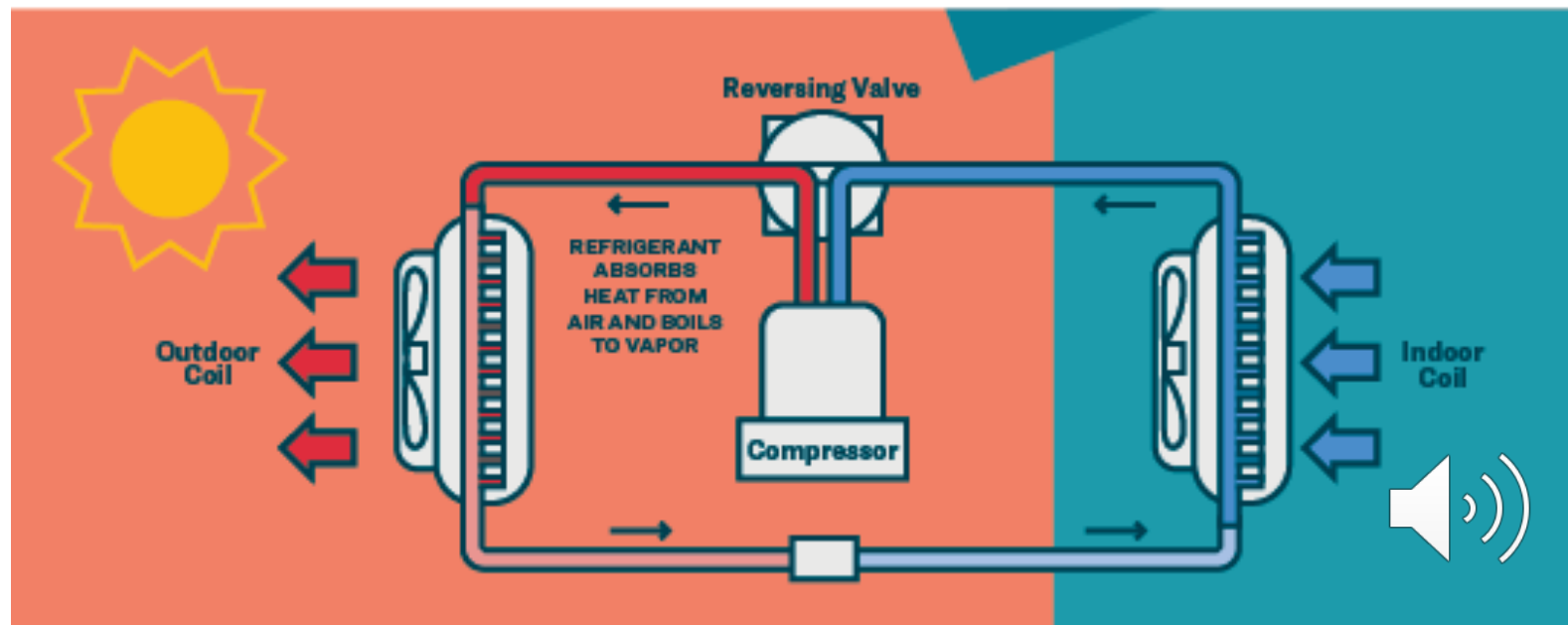
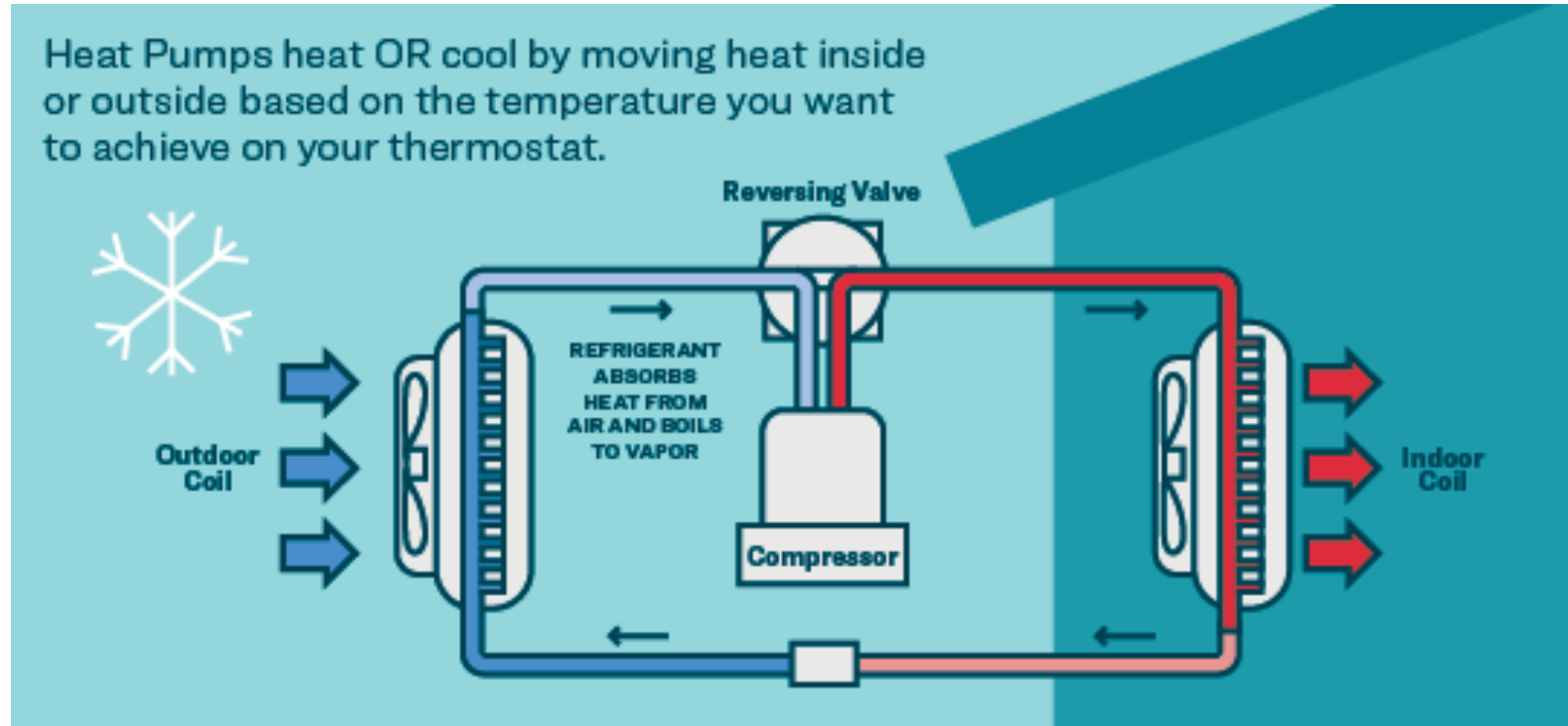
Source: U.S. Department of Energy



Active cooling systems

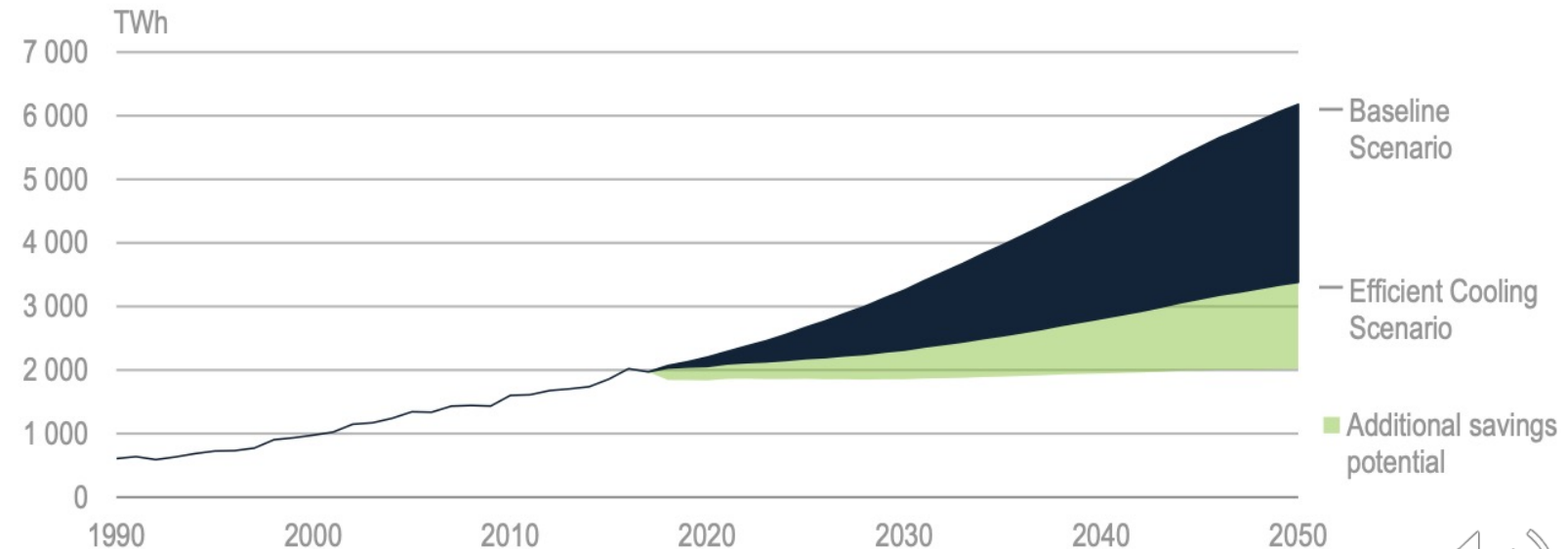
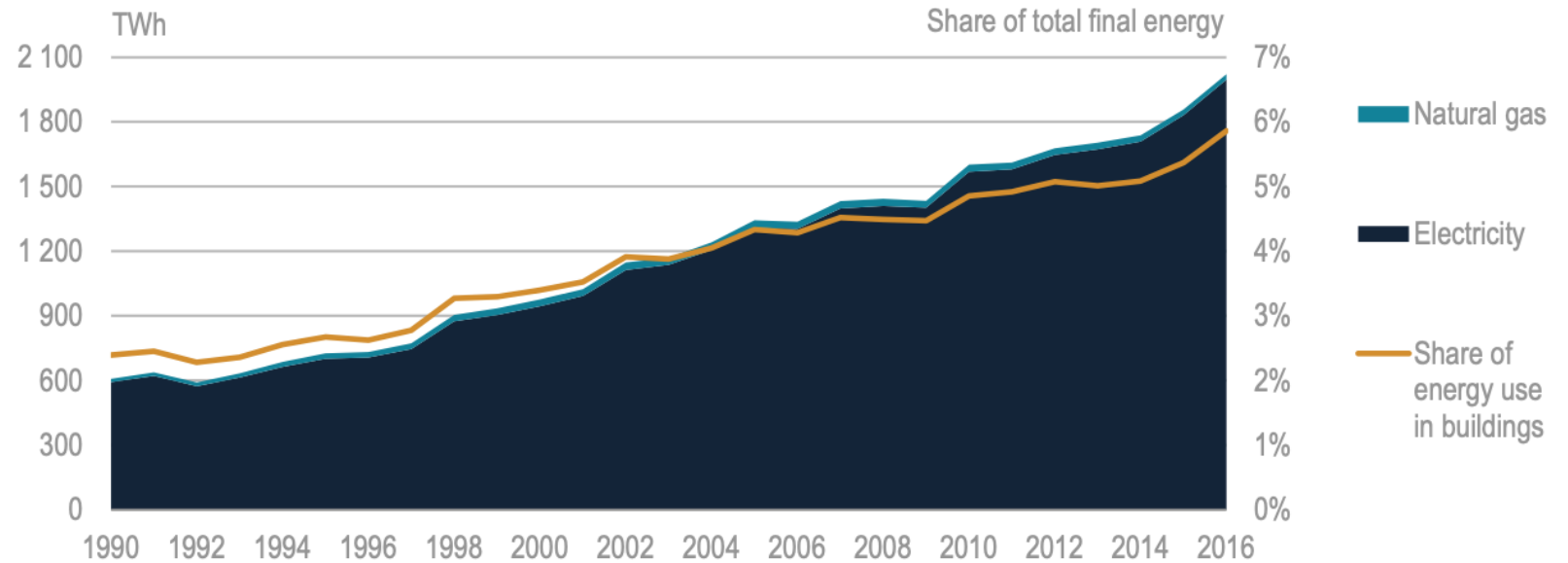
- Heat pumps can cool as well
 - You just reverse the system
- Air conditioners operate in the same way

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



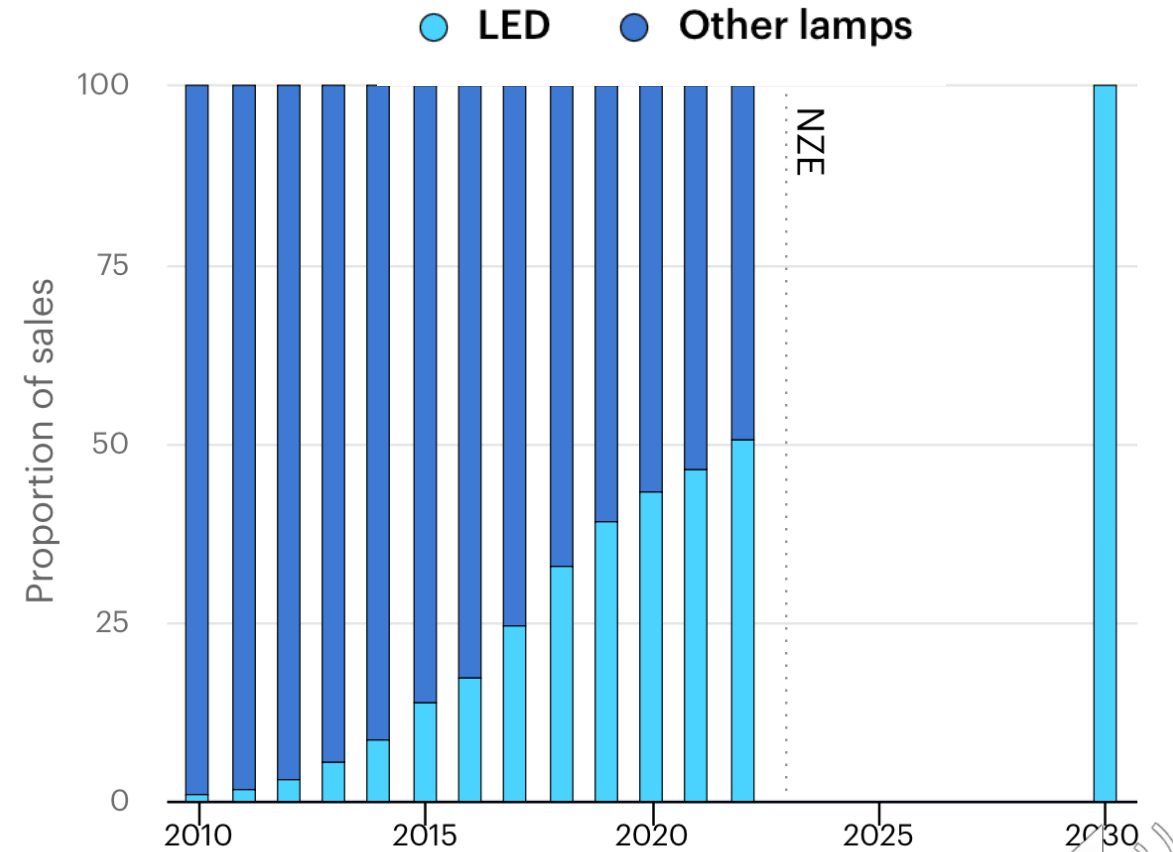
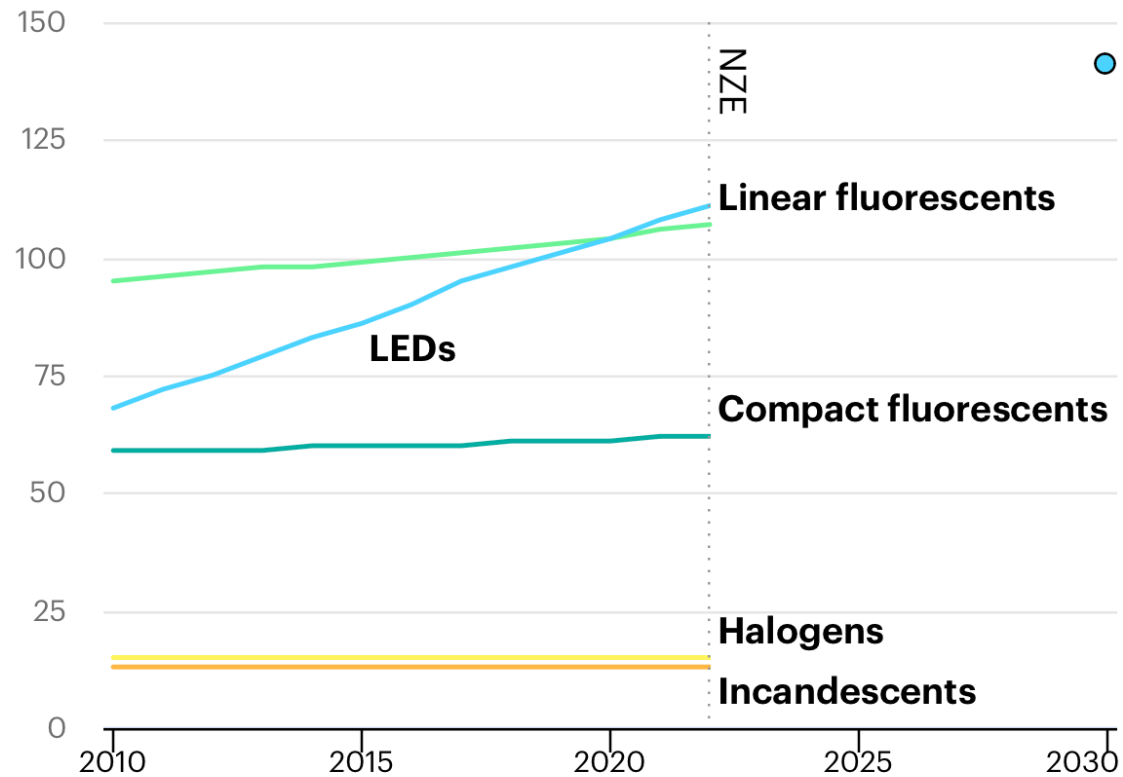
The past and future of cooling

- 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



Supplying the other energy demands in buildings: lighting

lumens/watt



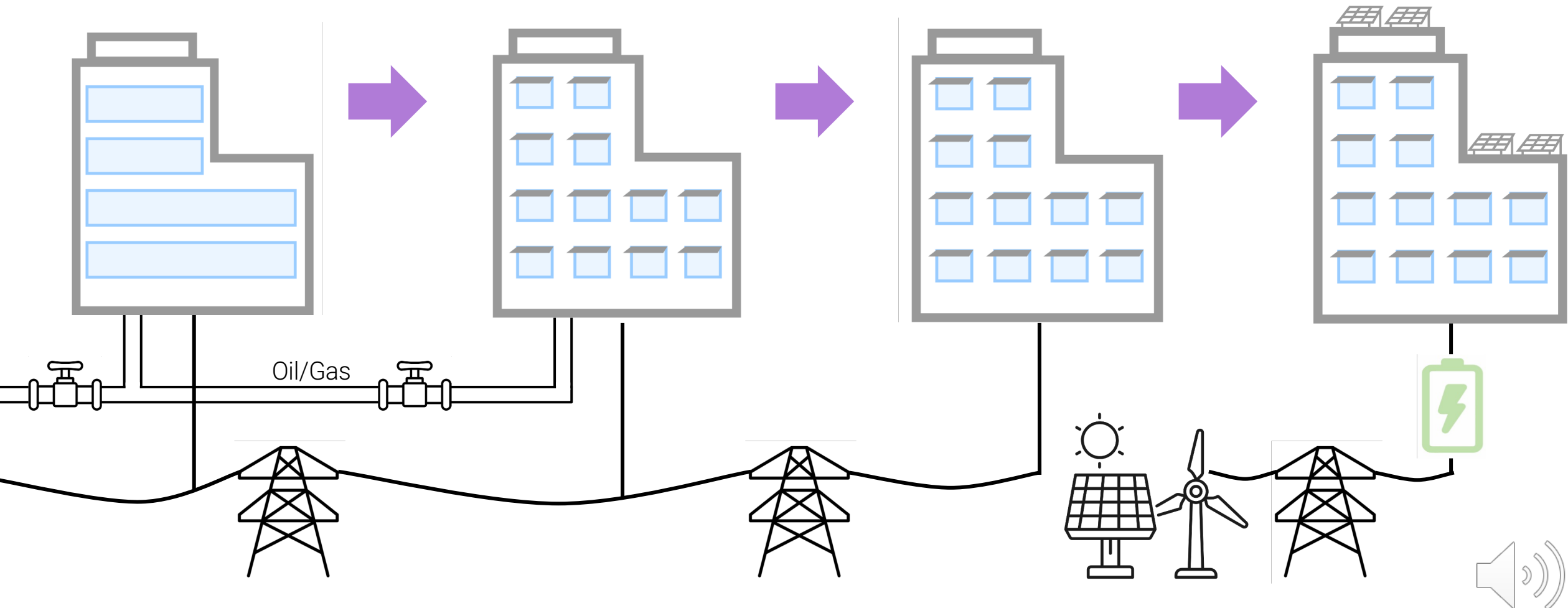
Design Path to Operational Decarbonization

Typical Building

Energy Efficiency

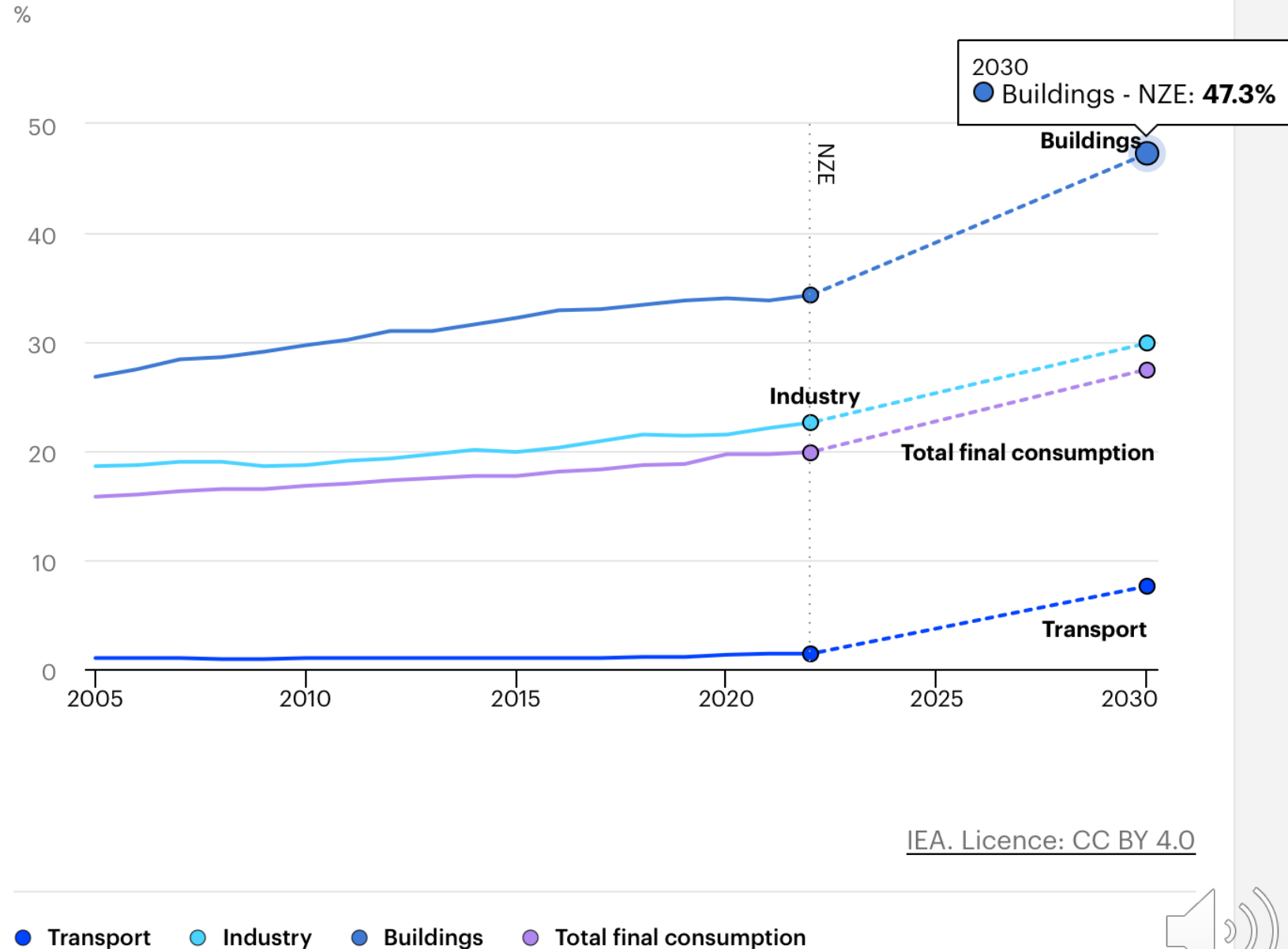
Electrification

Renewable Energy



Electrification

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



The primary ways we use energy in buildings

- Heating
 - Furnaces
 - Boilers
 - Electric resistance
 - Heat pumps
- Cooling
 - Air conditioners (heat pumps)
- Ventilation (replacing indoor air for air quality)
- Lighting
- Appliances

Heating reduction strategies:

- Avoid heat loss (better design/materials)
- Use the sun
- Use more efficient systems

Cooling reduction strategies:

- Avoid heat gain (better design/materials)
- Use natural ventilation or evaporative cooling
- Use more efficient systems



Case study: American Institute of Architects HQ



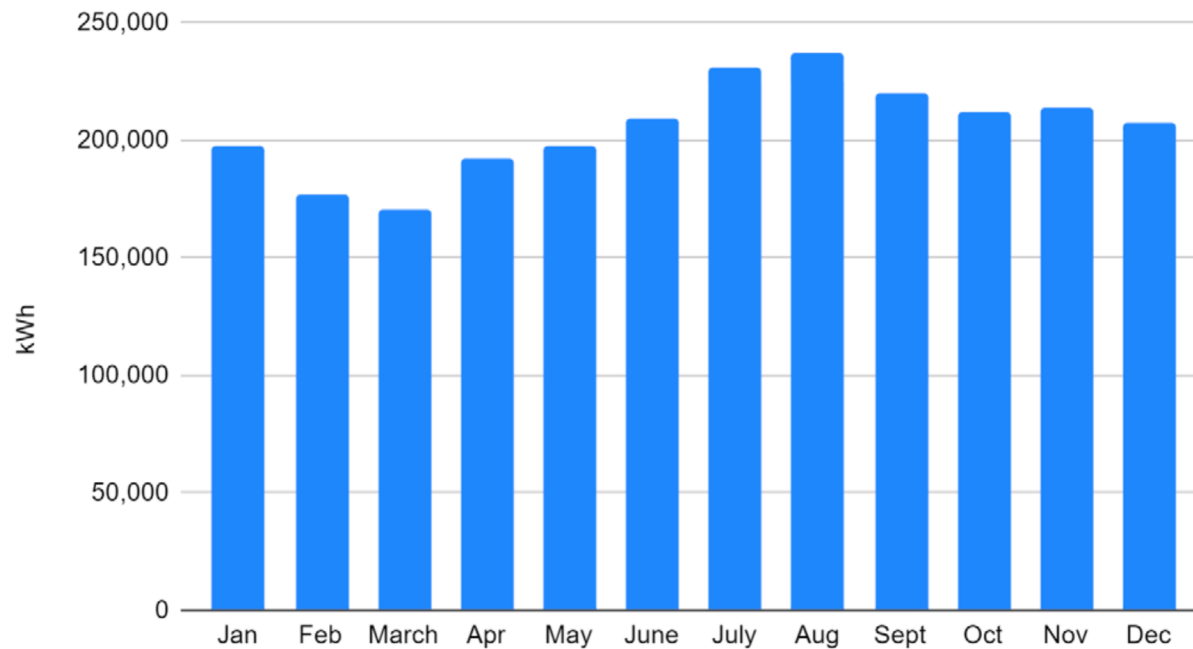
Case study: American Institute of Architects HQ

- 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

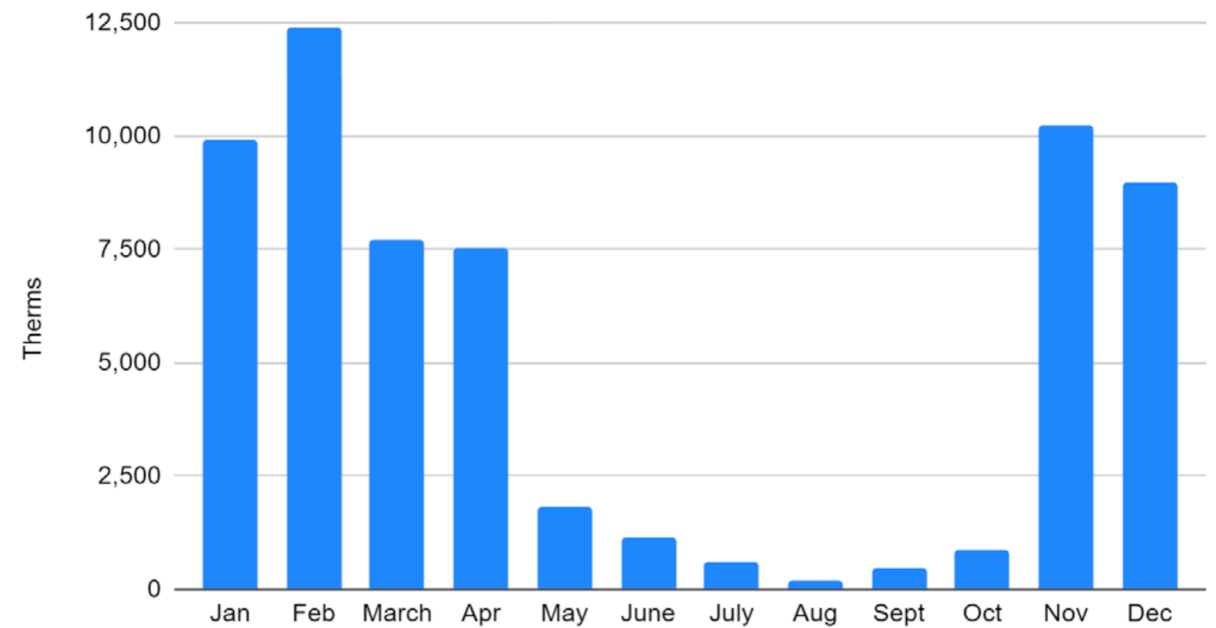


Case study: American Institute of Architects HQ

Electricity Consumption 2019

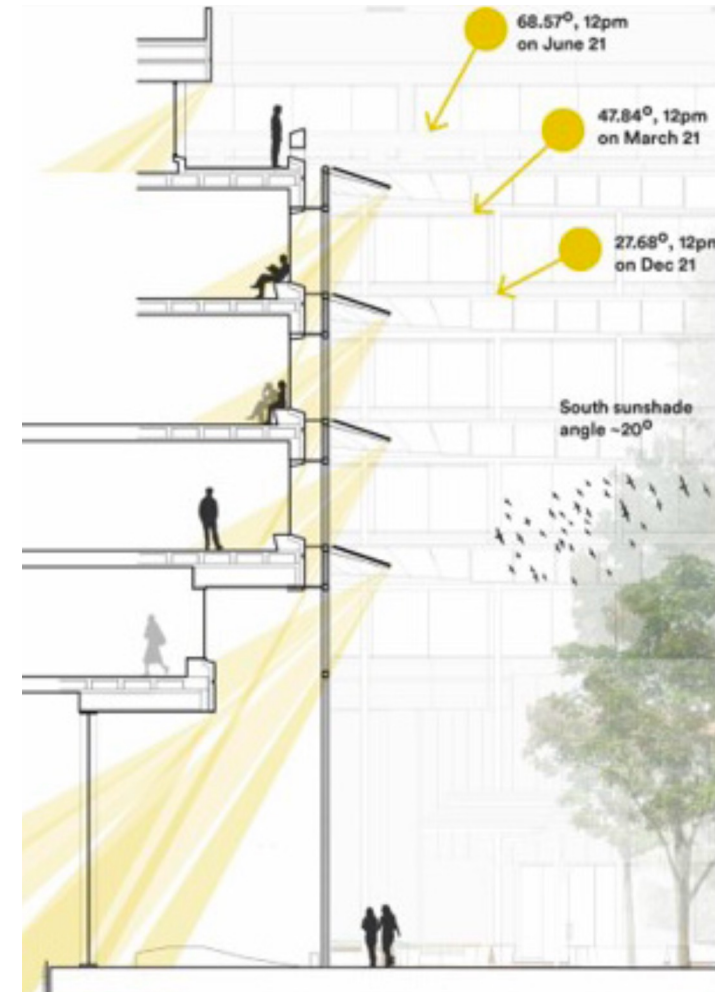


Gas Consumption 2019



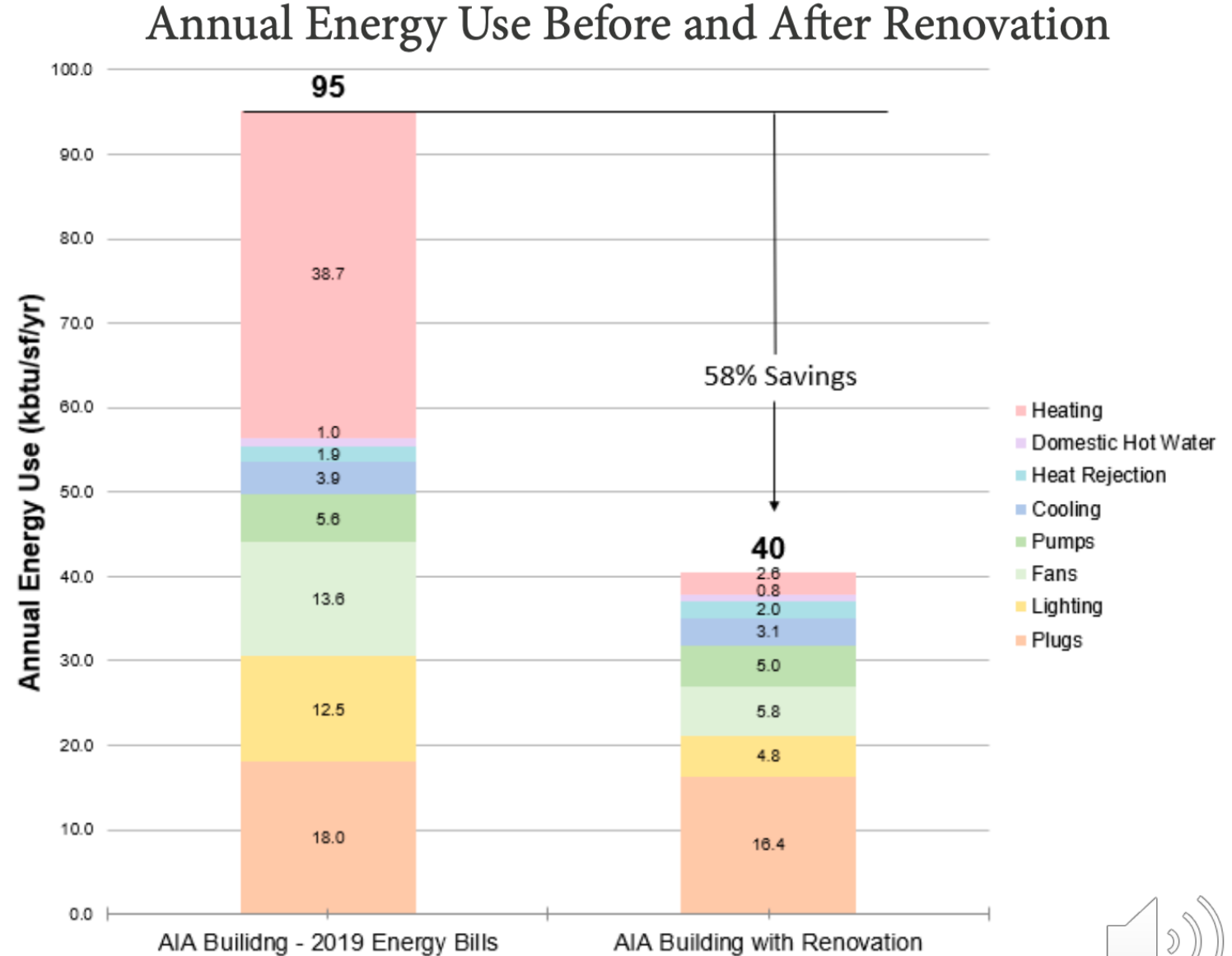
Case study: American Institute of Architects HQ

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



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



Elimination of Annual Operational GHG Emission

