Developing Sustainable Urban Infrastructure

From research to practice

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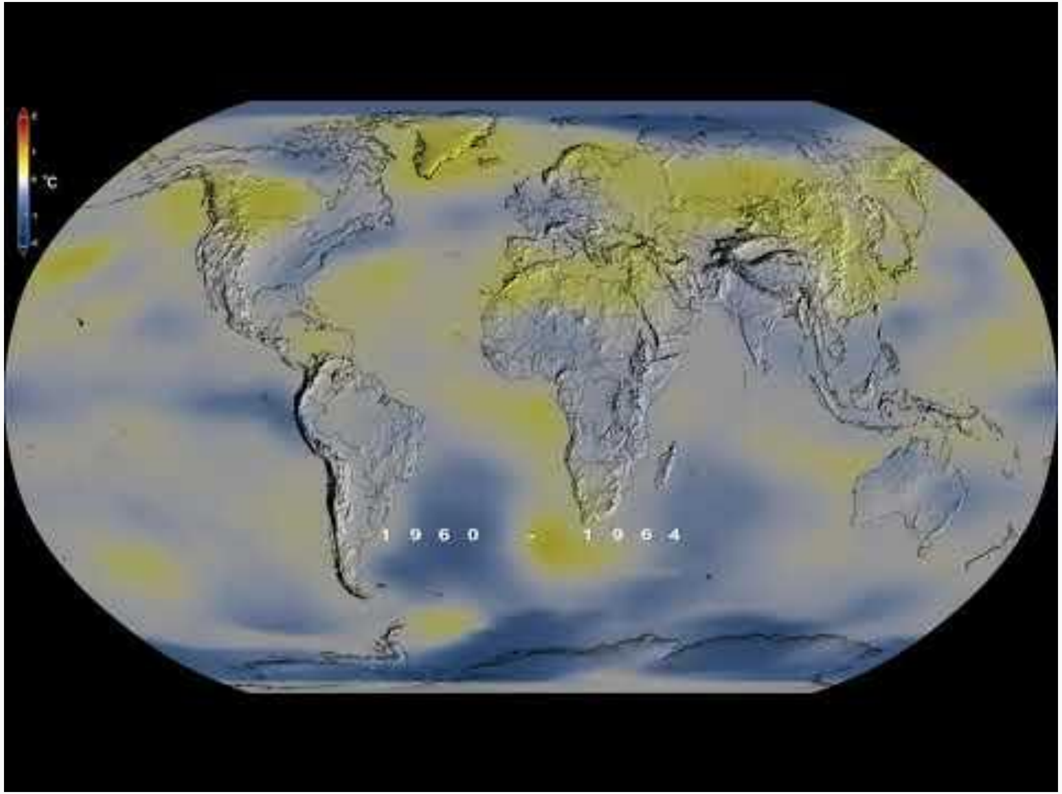
UNIVERSITY OF ALBERTA
FUTURE ENERGY SYSTEMS

Long-term warming trend

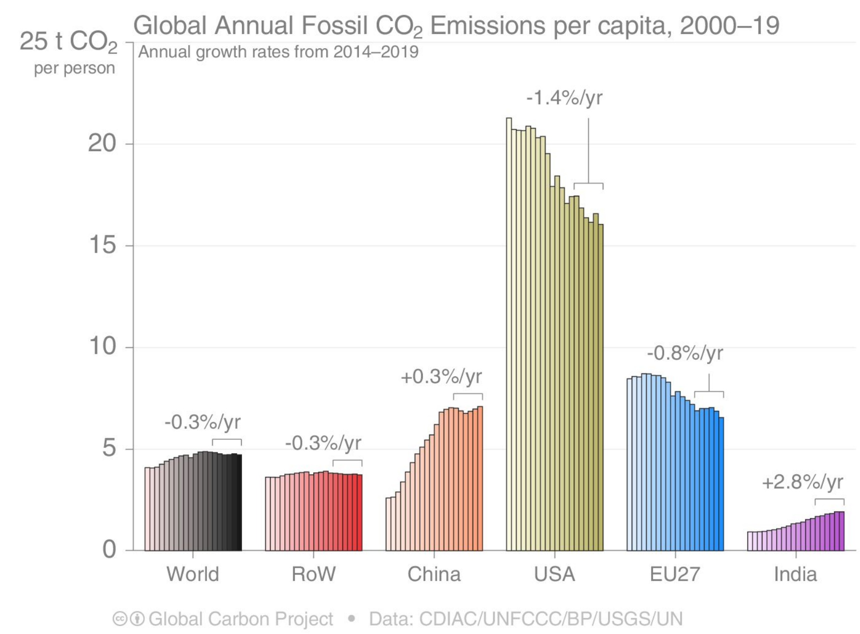


Earth’s global average surface temperature in 2020 tied with 2016 as the warmest year on record

It was 1.02℃ warmer than the baseline (1951–1980 mean)

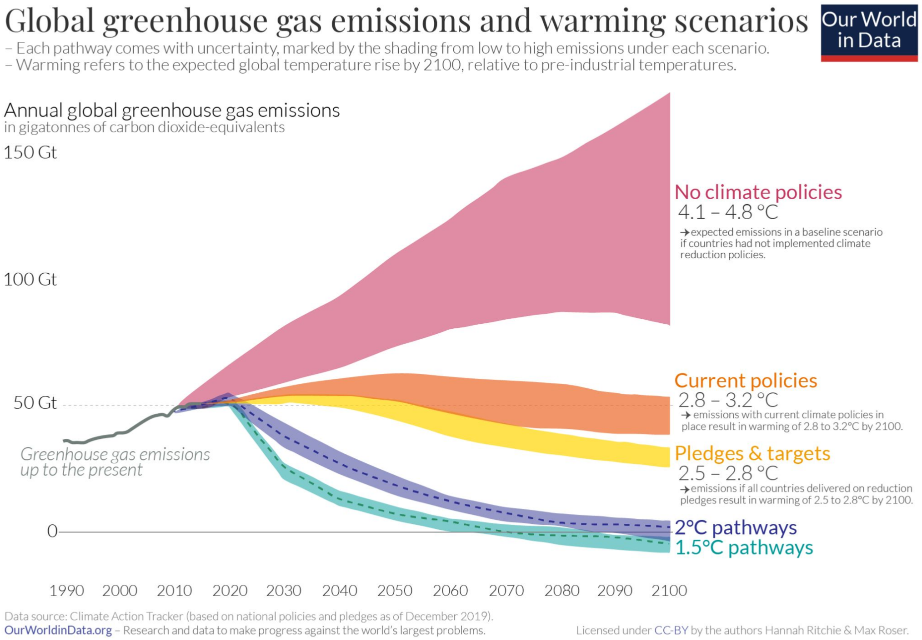
Source: NASA Climate Change, YouTube Channel

Efforts to combat climate change


Global Annual Fossil CO_2 Emissions per capita, 2000–19

Annual growth rates from 2014–2019

Global Carbon Project • Data: CDIAC/UNFCCC/BP/USGS/UN


Global greenhouse gas emissions and warming scenarios

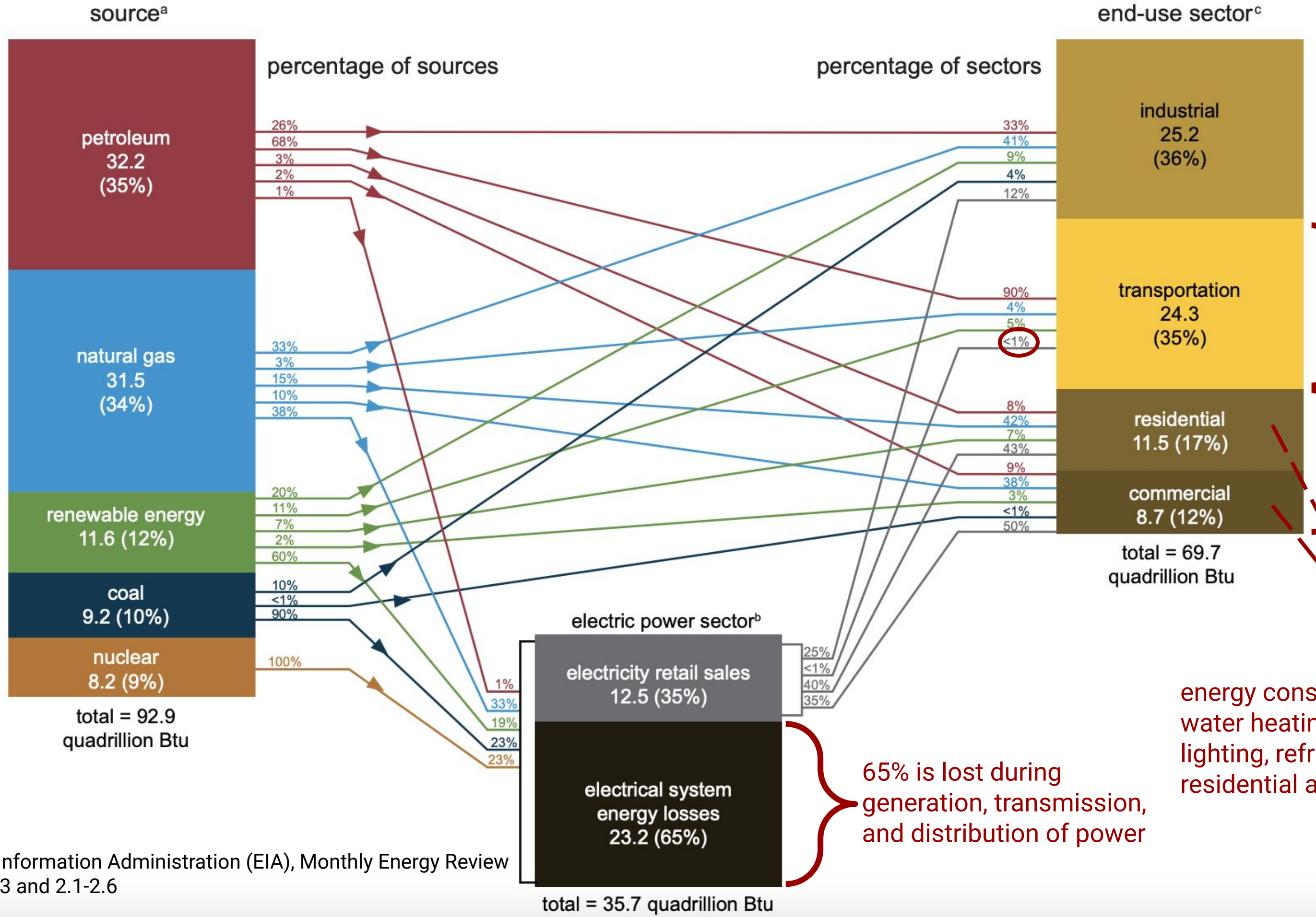
– Each pathway comes with uncertainty, marked by the shading from low to high emissions under each scenario.
– Warming refers to the expected global temperature rise by 2100, relative to pre-industrial temperatures.

Data source: Climate Action Tracker (based on national policies and pledges as of December 2019).
OurWorldinData.org – Research and data to make progress against the world's largest problems.

Paris accord: keep the rise in global average temperature to well below 2°C compared to pre-industrial levels by the end of the century

U.S. energy consumption by source and sector, 2020

quadrillion British thermal units (Btu)



99% comes from primary sources

75% of electricity consumption

energy consumed for space heating, water heating, air conditioning, lighting, refrigeration and cooking in residential and commercial buildings

65% is lost during generation, transmission, and distribution of power

Sources: U.S. Energy Information Administration (EIA), Monthly Energy Review (April 2021), Tables 1.3 and 2.1-2.6

How to increase efficiency?

- Renewable integration and resource management (supply side)
  - Firming renewable power
  - Managing energy storage systems
- Reduced losses in power transmission and distribution networks
  - Generating power closer to load centers
  - Storing surplus renewable generation to meet local demand during peak hours
- Increased efficiency in end use sectors (demand side)
  - Transportation electrification
  - Energy-efficient homes and buildings

rethink the design and operation of energy systems and urban infrastructure
utilize sensors, networks, analytics, and control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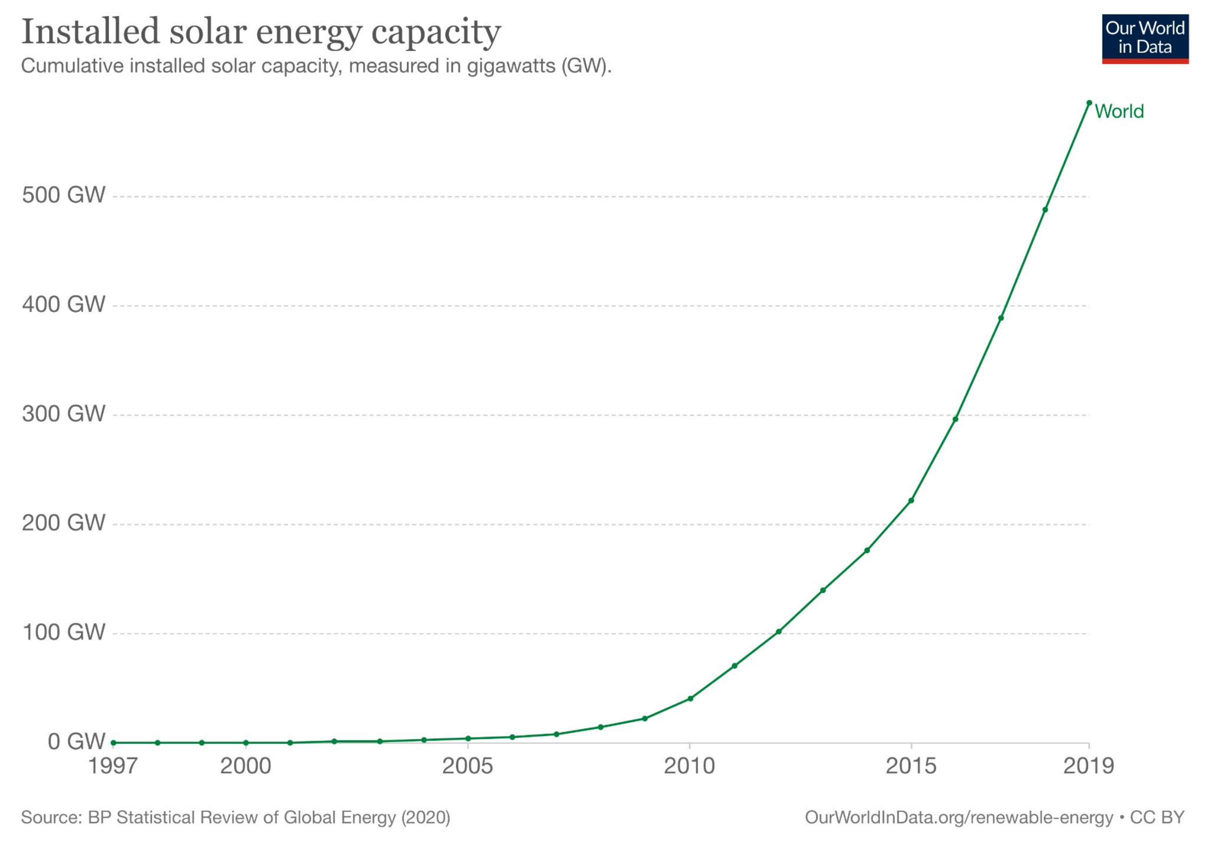
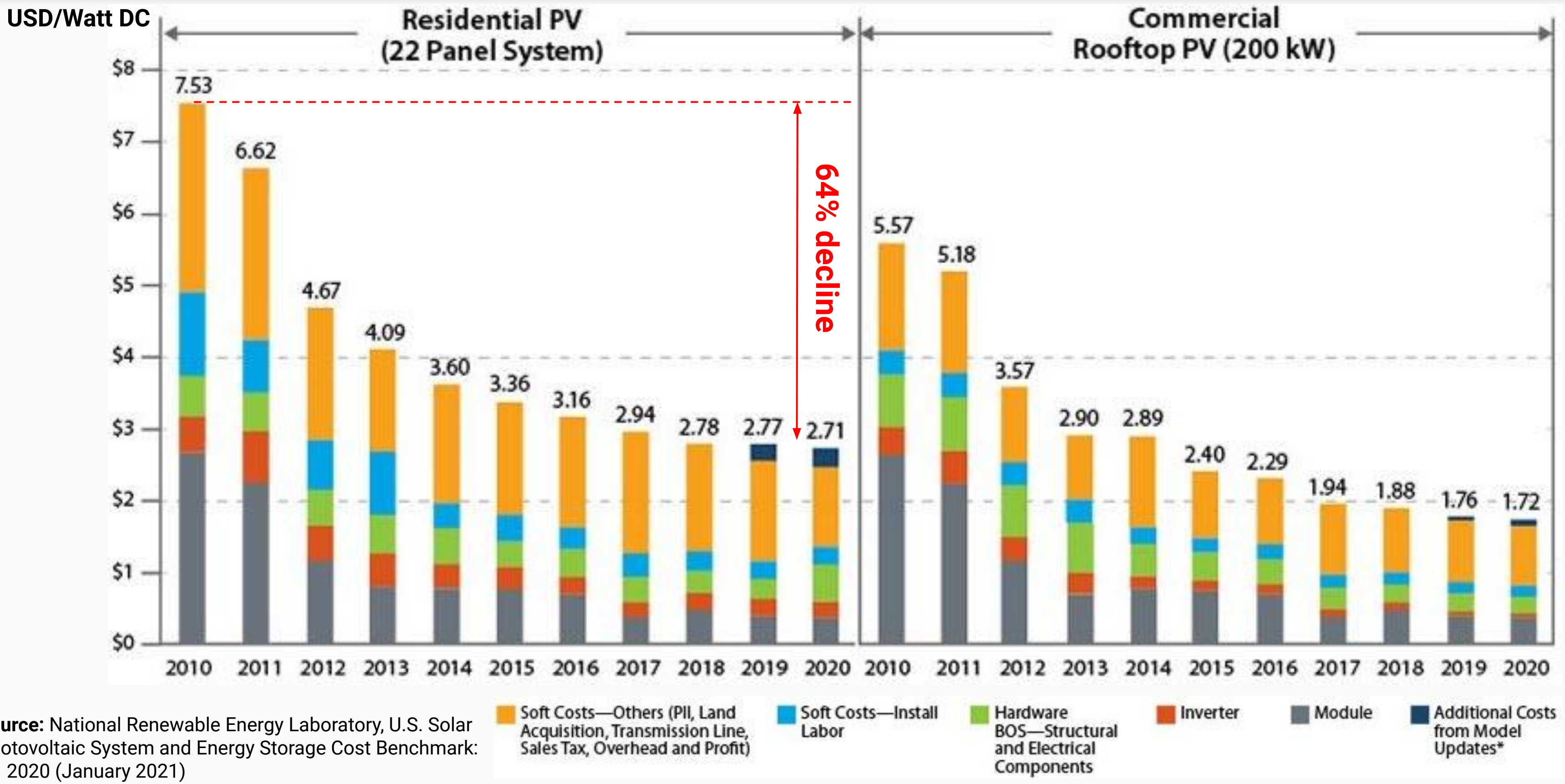
Exponential growth of solar generation capacity

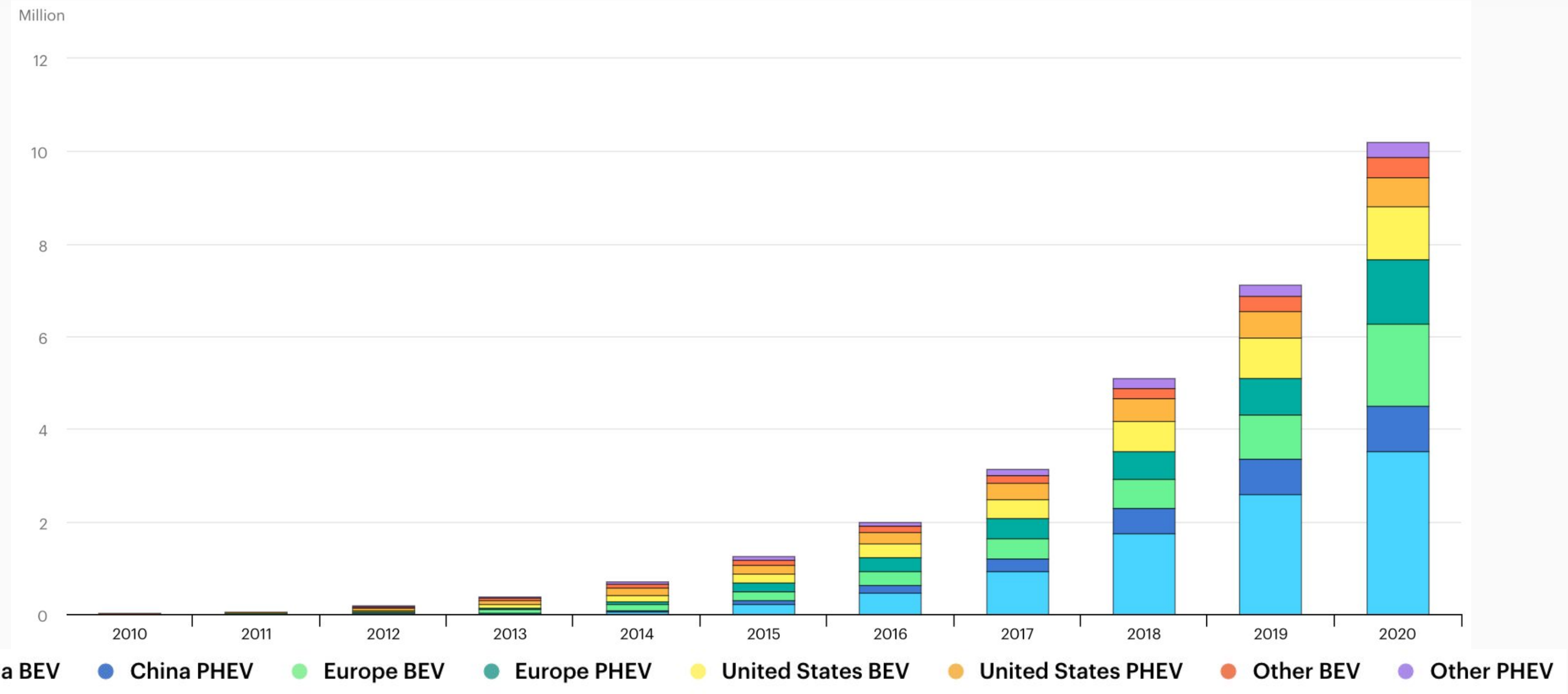


Falling costs of PV



Source: National Renewable Energy Laboratory, U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020 (January 2021)

Growing number of EVs



Source: International Energy Agency, Global electric passenger car stock 2010-2020, https://www.iea.org/data-and-statistics/charts/global-electric-passenger-car-stock-2010-2020

BEV: Battery Electric Vehicle
PHEV: Plug-in Hybrid Electric Vehicle

Declining costs of battery storage

- lithium-ion battery pack price has dropped by 97 percent since it was first commercially introduced in 1991
- the volume-weighted average price hit $137/kWh in 2020

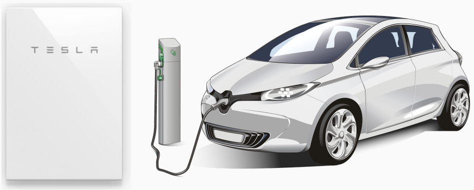


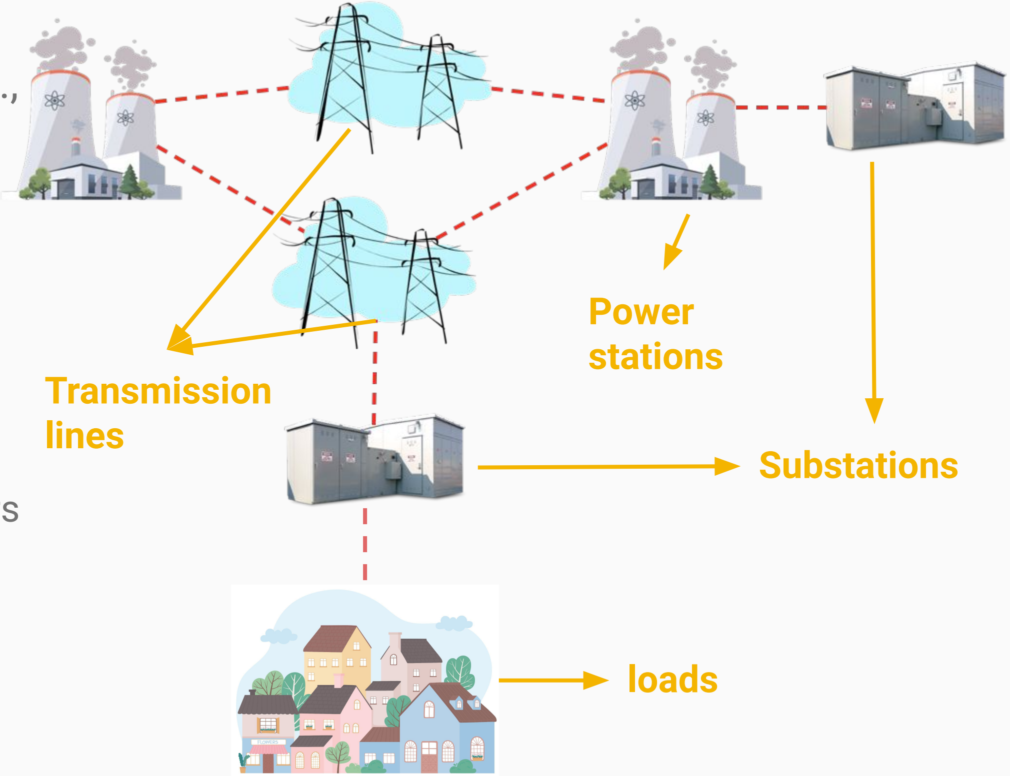
Image: Tesla Gigafactory in Shanghai

Large scale integration of renewables and energy storage is a mixed blessing!

Traditional power grid

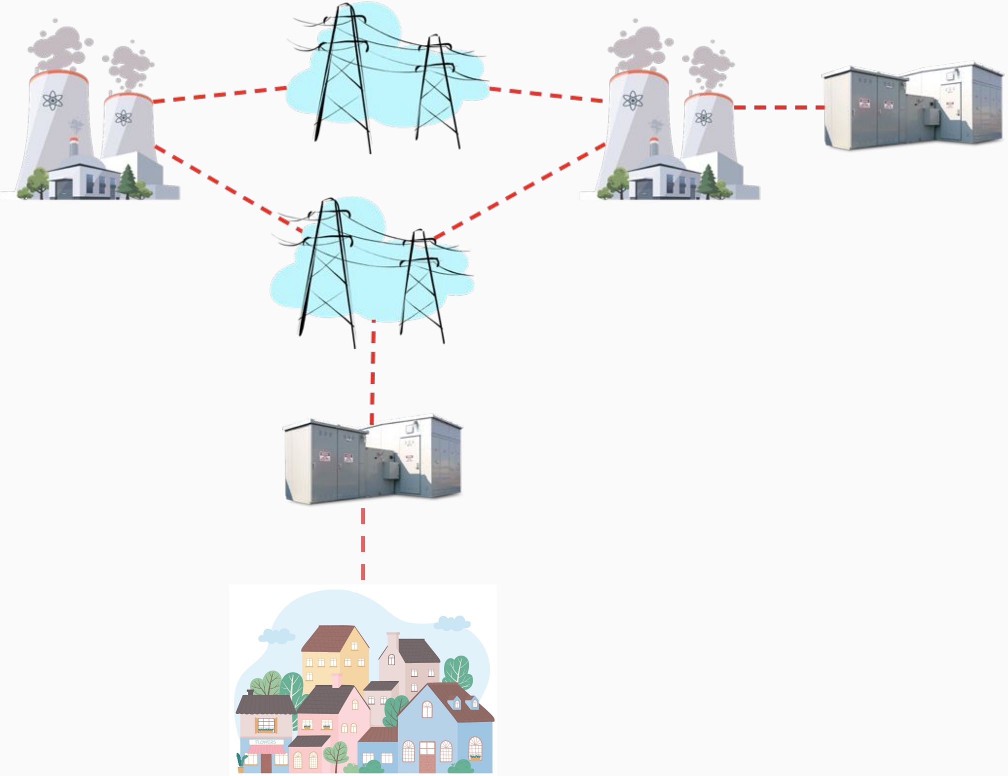
- Mostly central services and control, e.g., bulk generation scheduling, frequency control
    - continuously and precisely balance demand and supply

- Low uncertainty and variability
    - centralized and dispatchable generators
    - uncontrolled loads



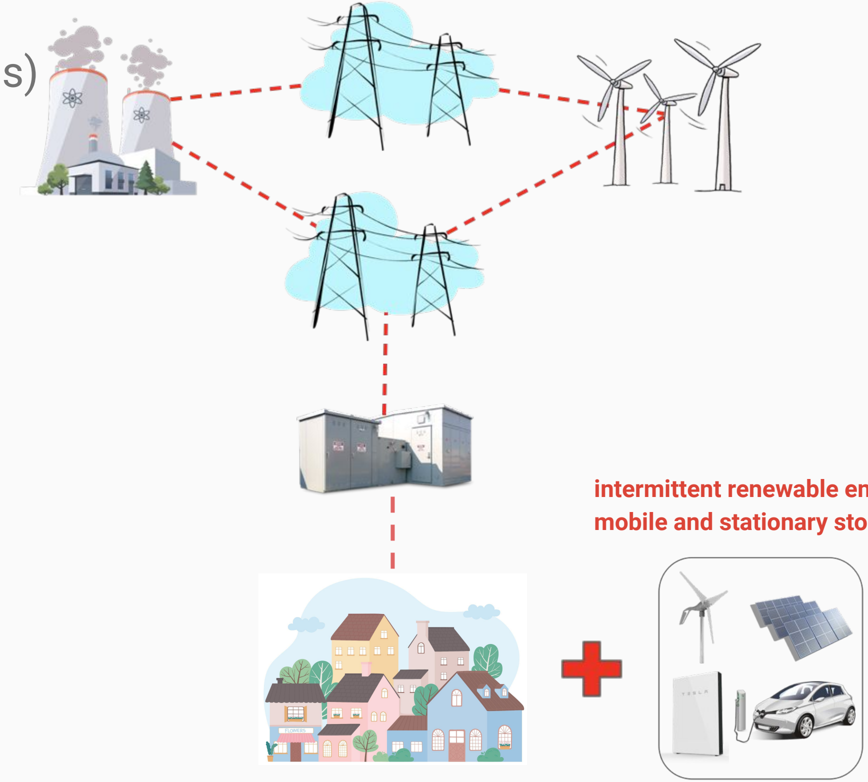
Post-war infrastructure

- Little instrumentation beyond the substation
    - outages and some faults can't be automatically detected



Modern grid

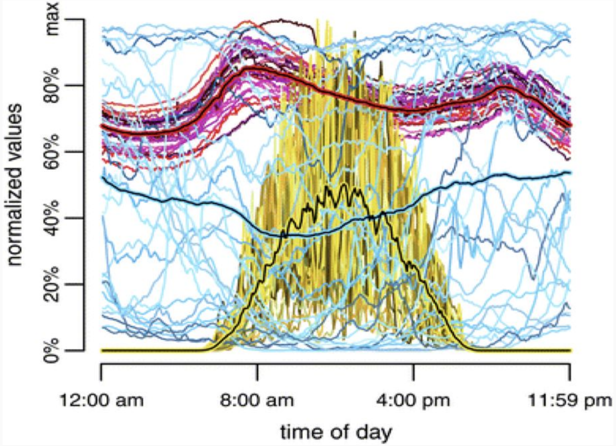
- Distributed resource clusters (microgrids)
- Decentralized services and control, e.g., voltage regulation
- Many stakeholders with competing objectives!

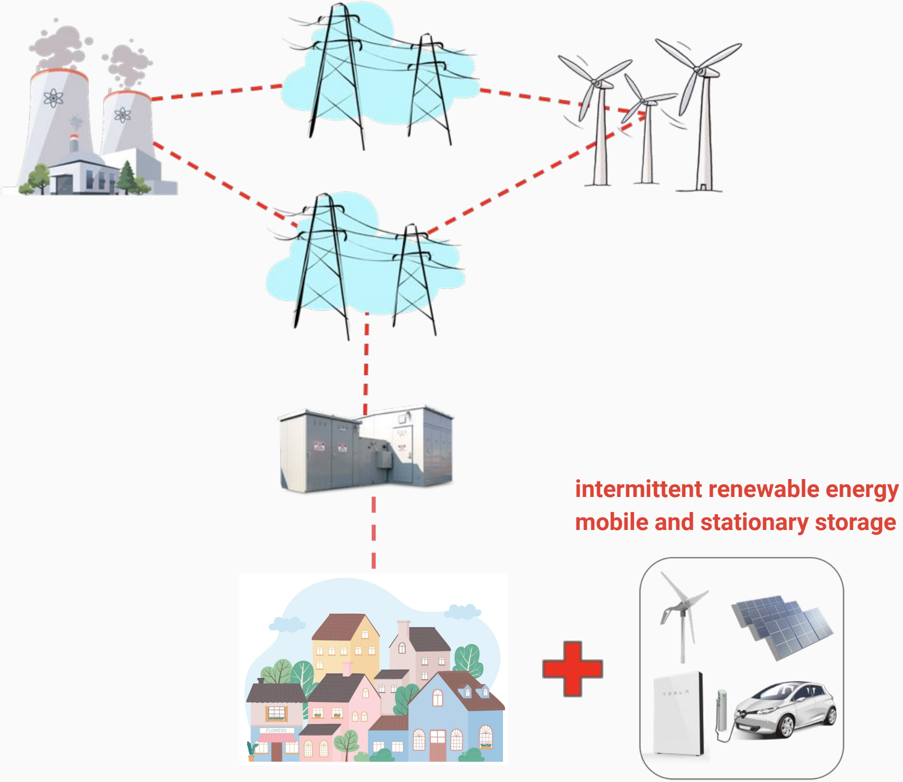


intermittent renewable energy
mobile and stationary storage

Modern grid

- High variability and uncertainty
  - intermittent renewable sources
  - mobility of electric vehicles
  - user behaviour
  - dynamic pricing



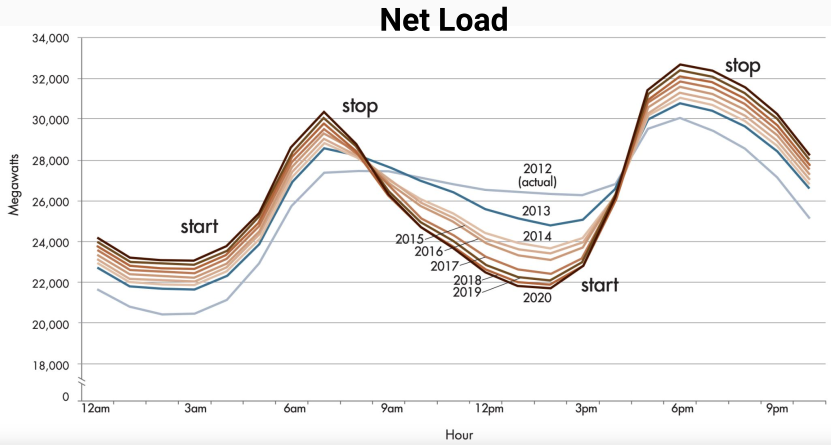


intermittent renewable energy
mobile and stationary storage

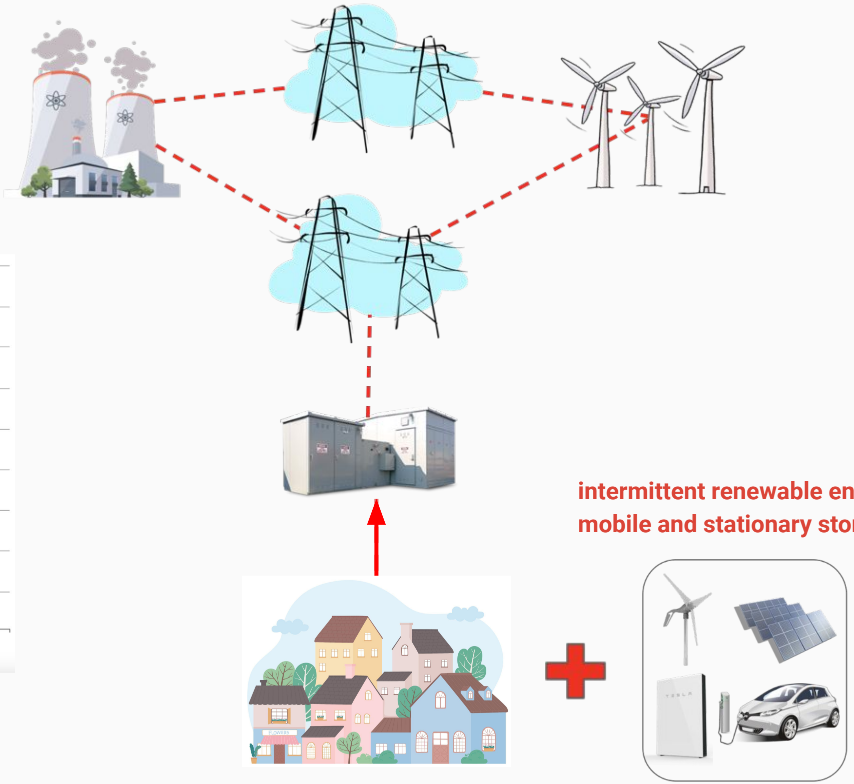
Source: C. J. Barnhart, M. Dale, A. R. Brandt, and S. M. Benson. The energetic implications of curtailing versus storing solar- and wind-generated electricity. Energy Environment Science, 6:2804 – 2810, 2013.

Modern grid

- Bidirectional power flow in distribution grids
  - over-generation of solar power



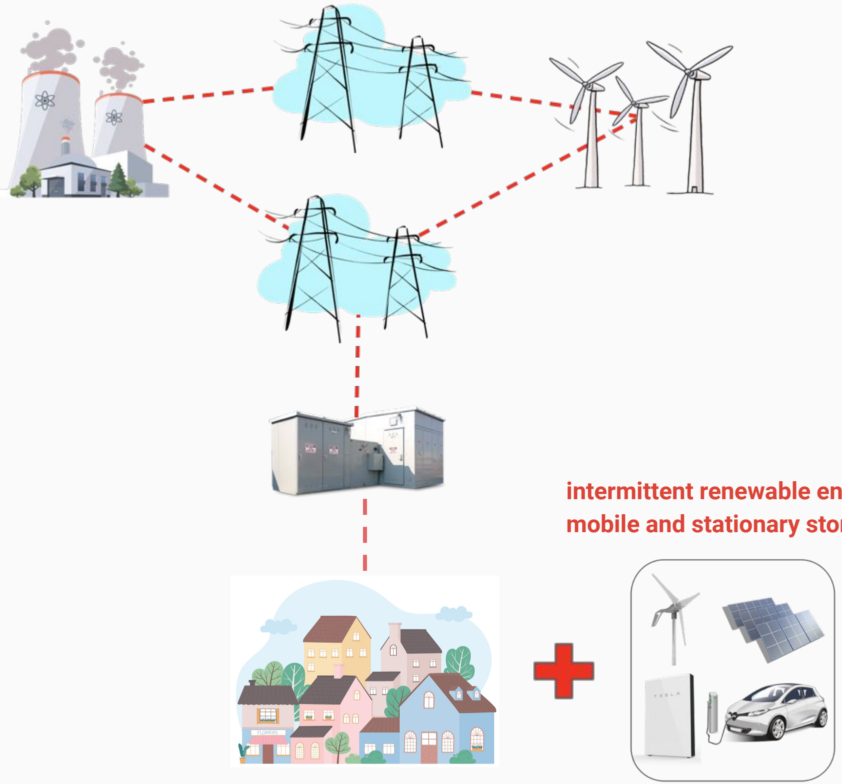
Source: California Independent Service Operator



intermittent renewable energy
mobile and stationary storage

Modern grid

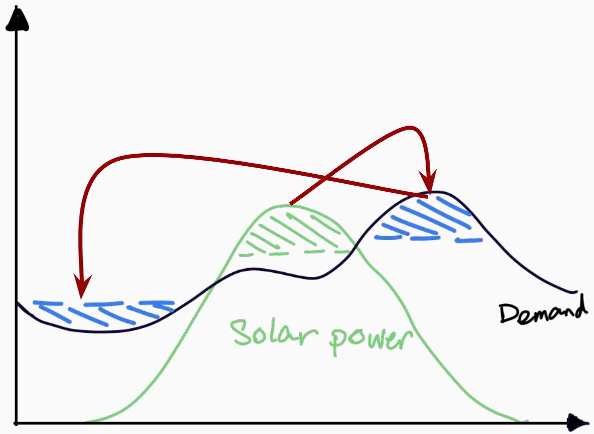
- Congestion problems
  - transformer overloading
  - voltage sags and swells

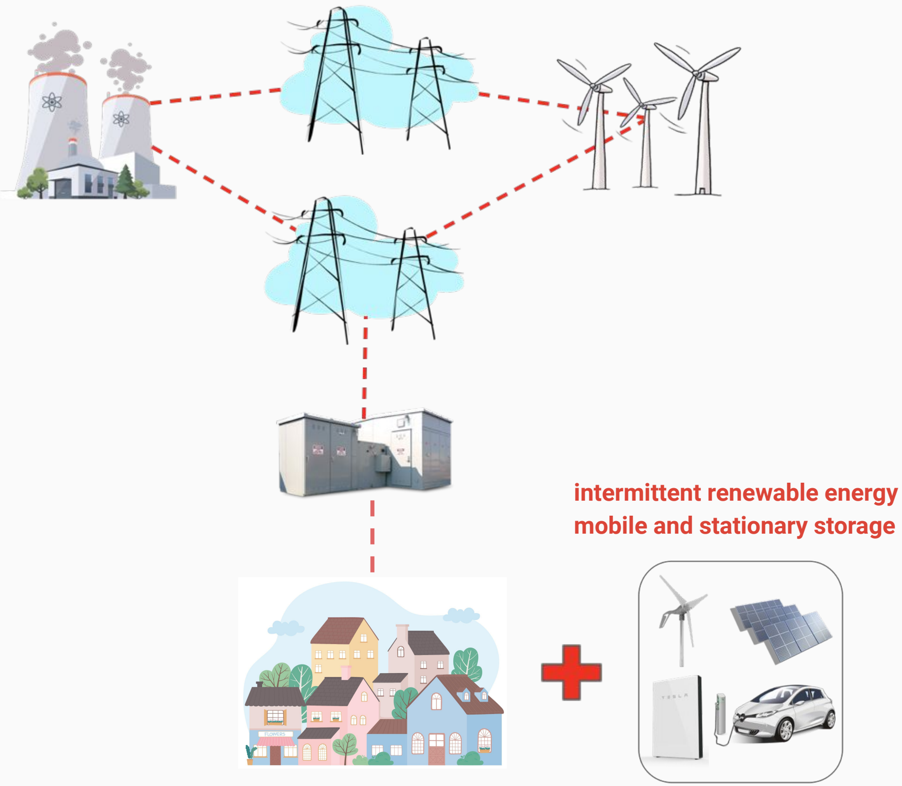


intermittent renewable energy
mobile and stationary storage

Modern grid

- More **storage** capacity (especially in the last mile)




intermittent renewable energy
mobile and stationary storage

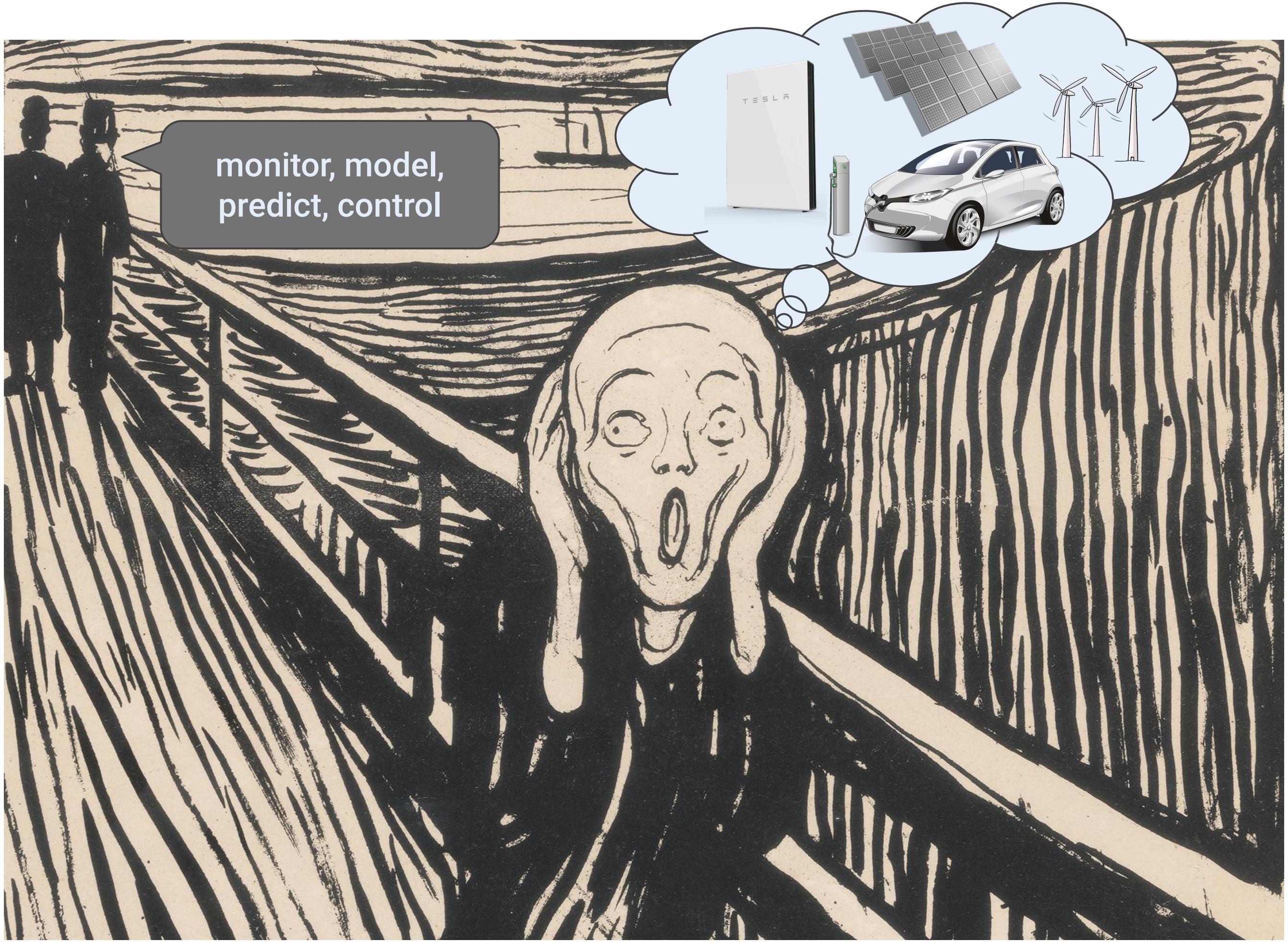

monitor, model, predict, control

Image: PSL uPMU

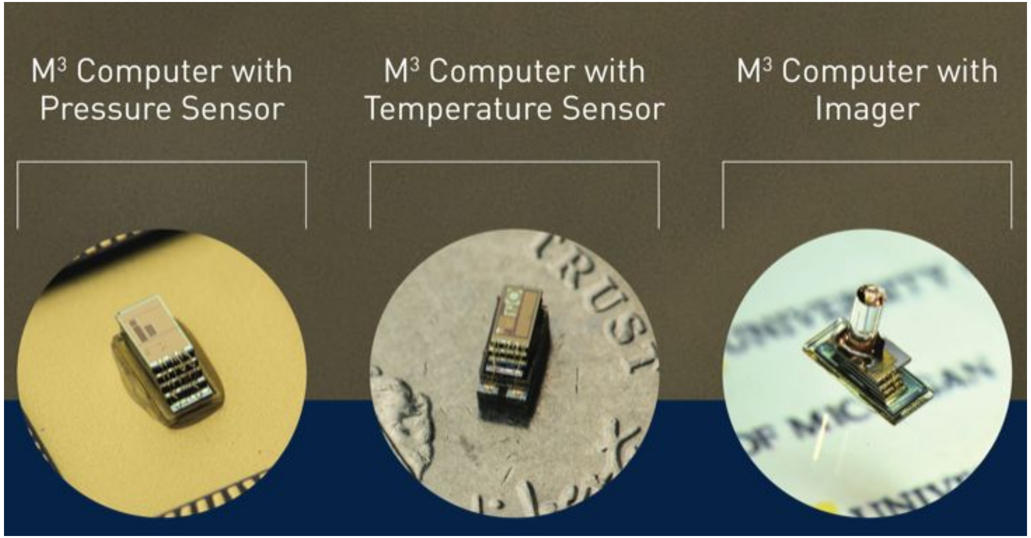


Image: Michigan Micro Mote display in Computer History Museum

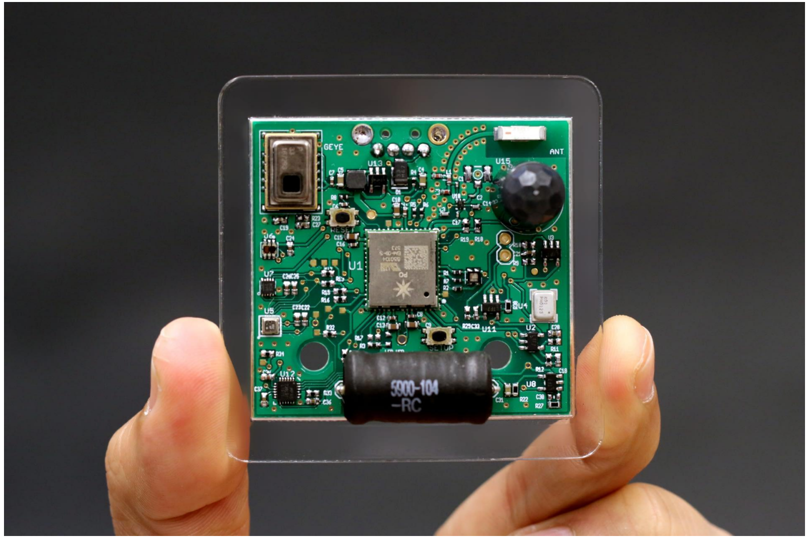
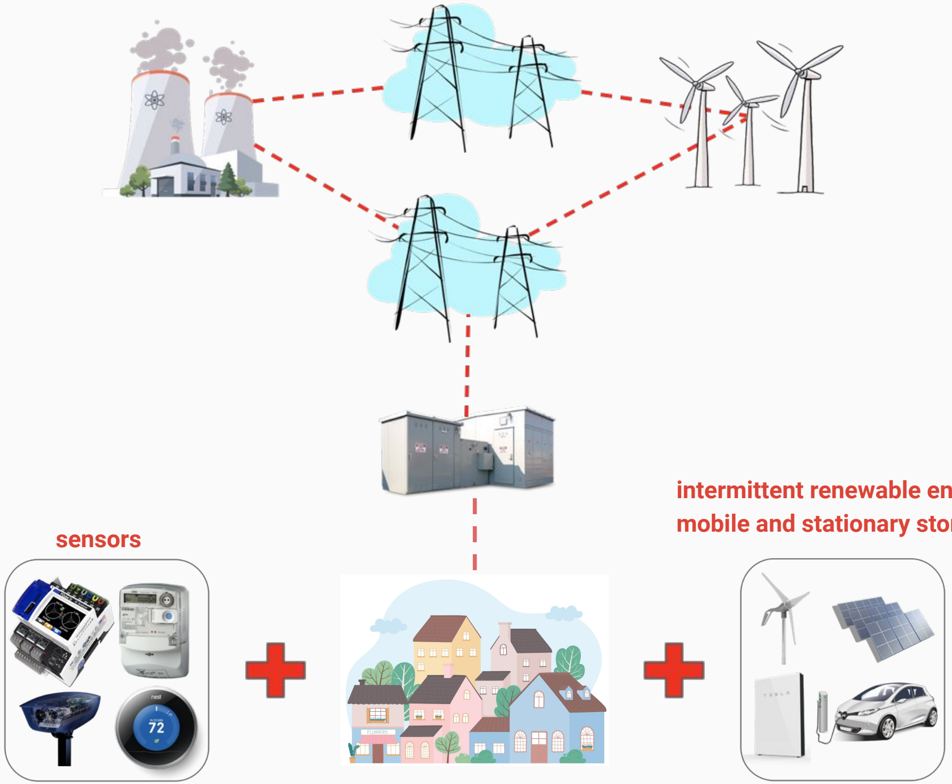


Image: Synthetic Sensors

Nimble and resilient power grid



sensors

intermittent renewable energy
mobile and stationary storage

How to improve efficiency in end use sectors?

Let’s revisit emission reduction strategies

- Renewable integration and resource management (supply side)
    - Firming renewable power
    - Managing energy storage systems
- Reduced losses in power transmission and distribution networks
    - Generating power closer to load centers
    - Storing surplus renewable generation to meet local demand
- **Increased efficiency in end use sectors** (demand side)
    - Transportation electrification
    - Smart/green/efficient homes and buildings

Transportation electrification

- where to build charging infrastructure? (design problem)
    - to address **range anxiety**
    - to be able to install enough fast chargers without causing congestion

- what charging strategy to adopt? (control problem)
    - to alleviate voltage and transformer overloading problems
    - to prolong battery lifespan
    - to meet deadlines (i.e., ensure battery is charged to the desired SoC before the next trip)
    - to treat EV owners fairly

Smart homes and buildings

- when to heat, cool, ventilate, and light building spaces? (control problem)
  - to satisfy thermal and visual comfort requirements
  - to maintain indoor air quality
  - to cut building energy use and reduce energy bills
  - to shift peak energy consumption to off-peak hours

- how to estimate building occupancy (estimation problem)
  - through multimodal sensor fusion
  - by analyzing controller response

Smart transmission and distribution networks

- how to operate energy storage systems? (control problem)
  - to firm up renewable generation
  - to relieve grid congestion
  - to address timing mismatch between solar generation and local demand
  - to reduce the electricity bill of customers

- how to identify behind-the-meter PV systems and batteries? (inference problem)
  - to proactively upgrade distribution lines and transformers
  - to implement new pricing schemes

Control of EV Charging

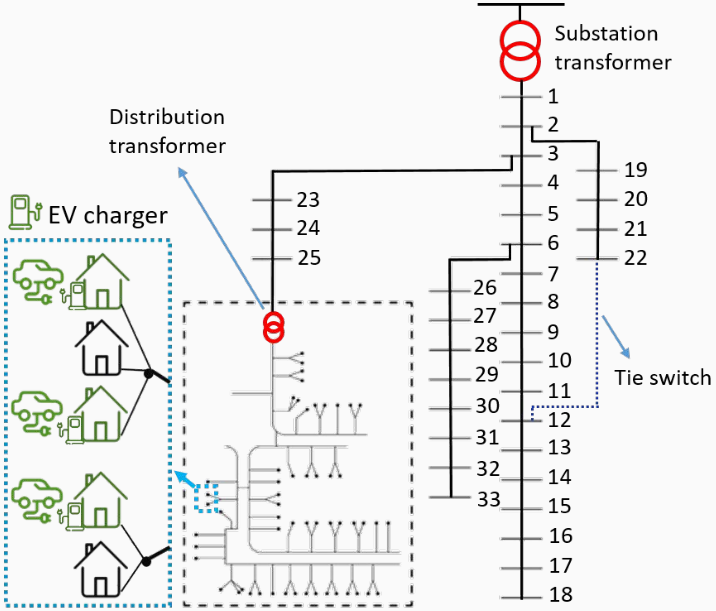
Both at home and workplace charging

EV chargers are not like home appliances

- EV chargers can consume as much power as 10 homes in North America!
  - impose a significant load on transformers
  - cause voltage drops
- It’s controlled load, i.e., the charge power can be adjusted by EVSE (charger)
  - but it’s important to charge EVs as fast as possible
- it’s hard to predict EV mobility and energy demand

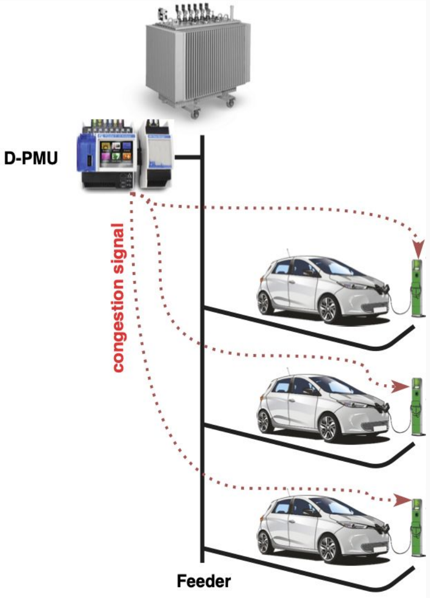
Basic idea

- control the charge power of many EVs connected at different points in the distribution grid
  - in a fair and efficient manner without causing congestion
- we can offer best-effort service as in the Internet
  - charging may not finish by the deadline if the grid is overly congested



Assumptions

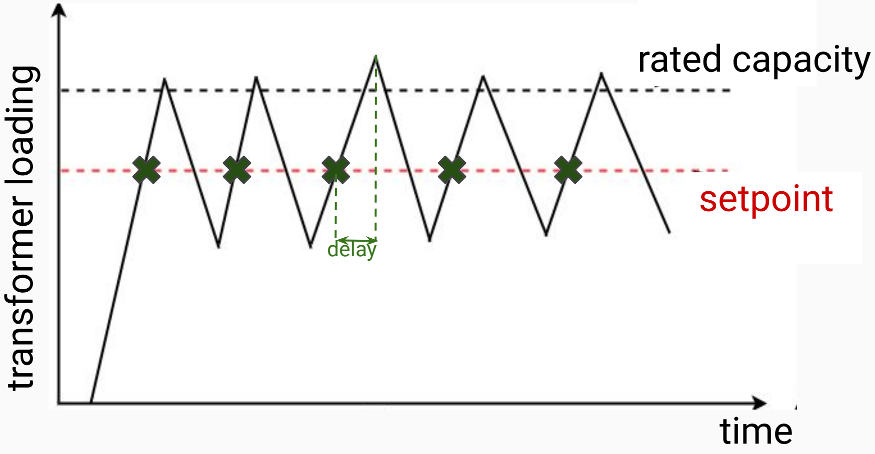
- sensors (e.g., distribution-level PMU) are installed at hotspots
  - necessary for congestion detection
- a communication network connects sensors to EV chargers
  - necessary for congestion signalling
- charging points can charge the battery at any power that does not exceed the maximum charge power



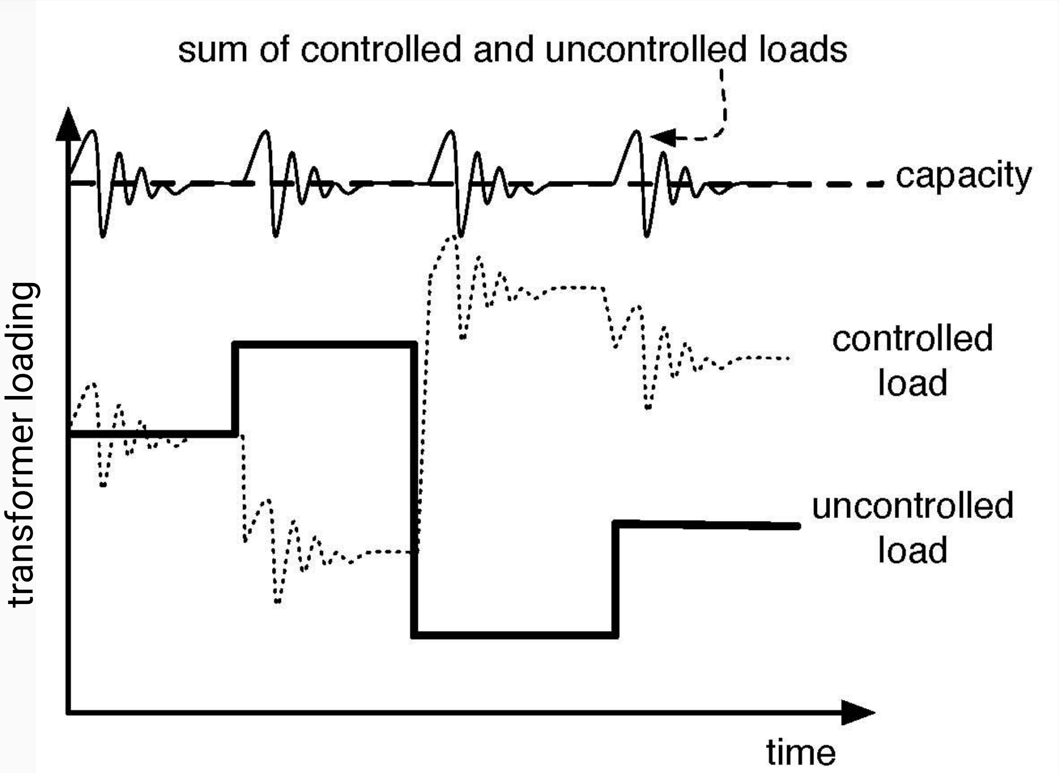
Reactive controller

- it’s a simple feedback control algorithm
    - sensors are responsible for detecting and signalling congestion
- how to set A and B?

$$x_{t+1} = \begin{cases} x_t \times B & \text{if } \textit{congested} \\ x_t + A & \text{otherwise} \end{cases}$$



Reactive controller (fair power allocation)



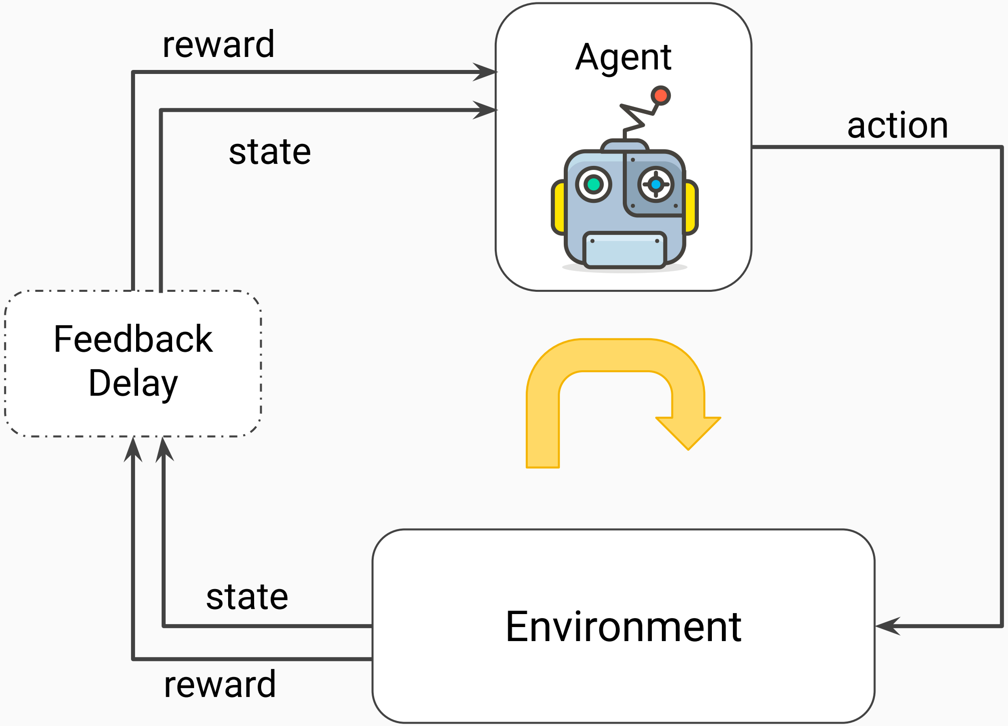
Source: Ardakanian et al., “Distributed Control of Electric Vehicle Charging”, IEEE Transactions on Smart Grid, vol.5, no.5, pp.2295-2305, 2014.

Updating rules according to network conditions

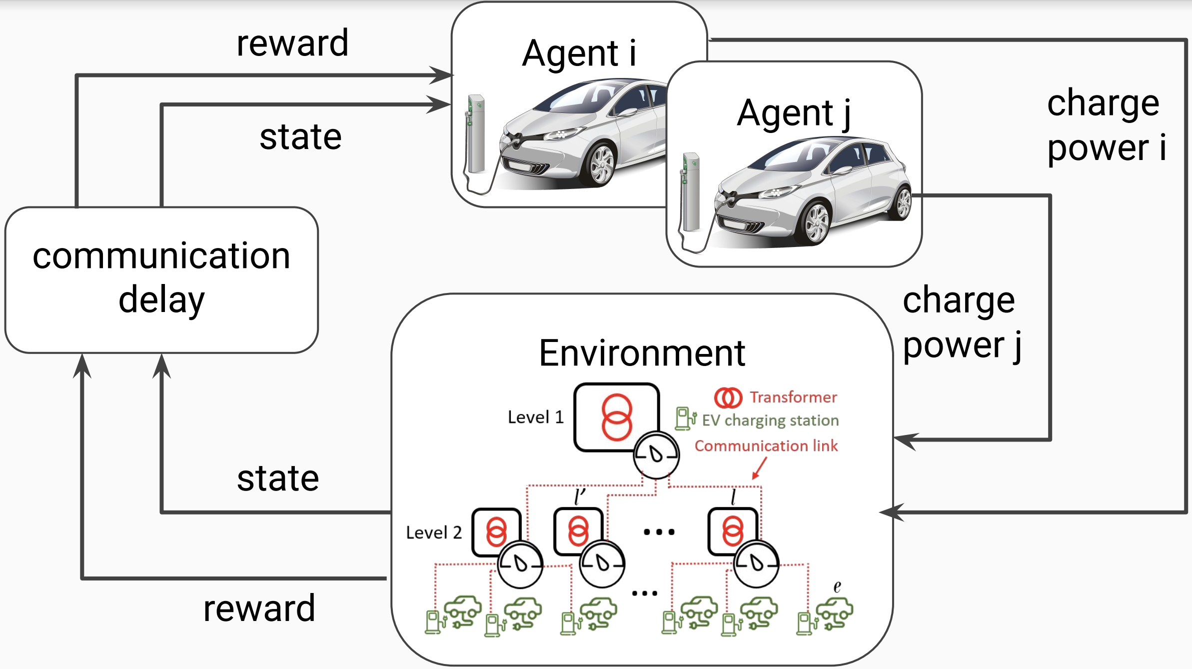
$$x_{t+1} = \begin{cases} x_t \text{ x } B^{\alpha}, & \text{if } \textit{congested} \\ x_t + A\alpha, & \text{otherwise} \end{cases}$$

- fixed rules may result in under-utilization or sustained congestion
- use fixed values for A and B, and adjust α according to the measured/estimated state of the grid
- **how?** learn a mapping from the grid state to α that maximizes the expected network utilization over time (cumulative reward)
    - using reinforcement learning

Reinforcement Learning



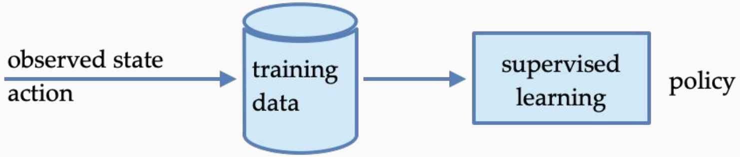
EV chargers as RL agents

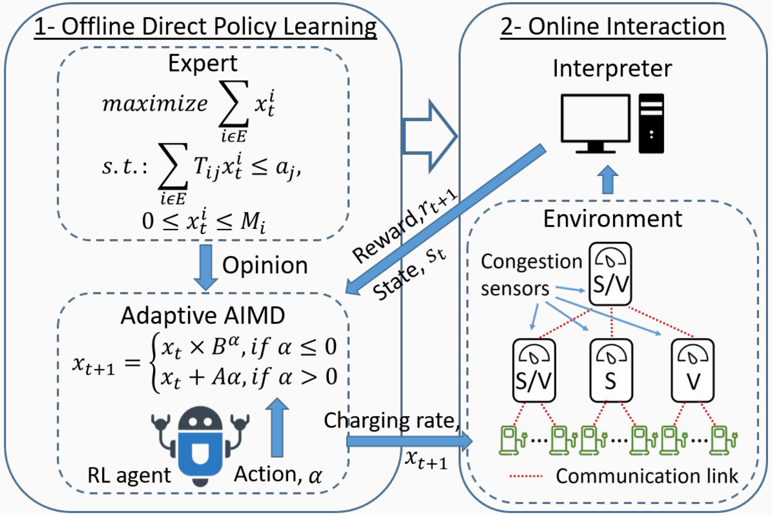


- each charging point learns to adjust α to maximize its reward
  - reward is the loading of substation transformer or negative of that if there is congestion on the path from the agent to the substation

How to reduce sample complexity of the RL algorithm?

- **imitation learning** is a supervised learning method for an RL agent to learn the policy from **expert demonstration**
    - ○ the agent learns by imitating the policy of the model-based controller





Source: Zishan et al., "Adaptive Control of Plug-in Electric Vehicle Charging with Reinforcement Learning", Proceedings of the 11th ACM International Conference on Future Energy Systems (e-Energy), pp.116-120, 2020. https://dl.acm.org/doi/10.1145/3396851.3397706

Takeaways

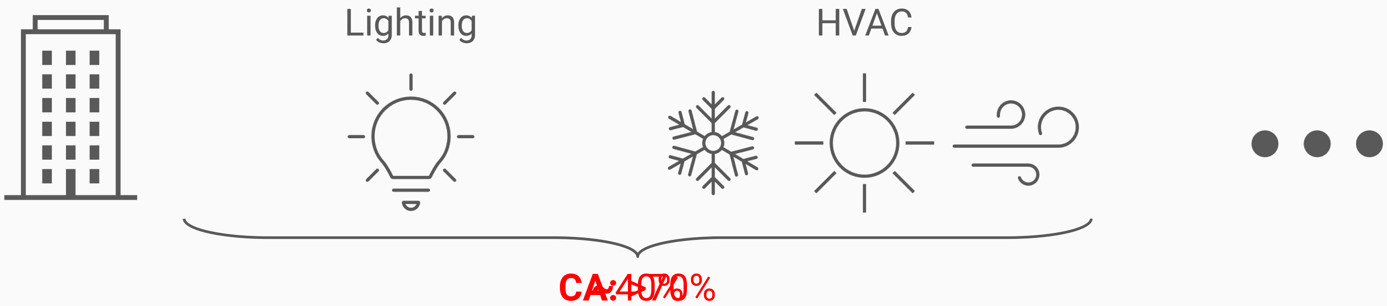
- congestion control methods originally developed for the Internet are applicable to the EV charging control problem
- optimal control strategies can be proposed for EV charging relying on sensors and communication networks

Increasing Efficiency in Smart Buildings

Through occupant-centric control of building systems

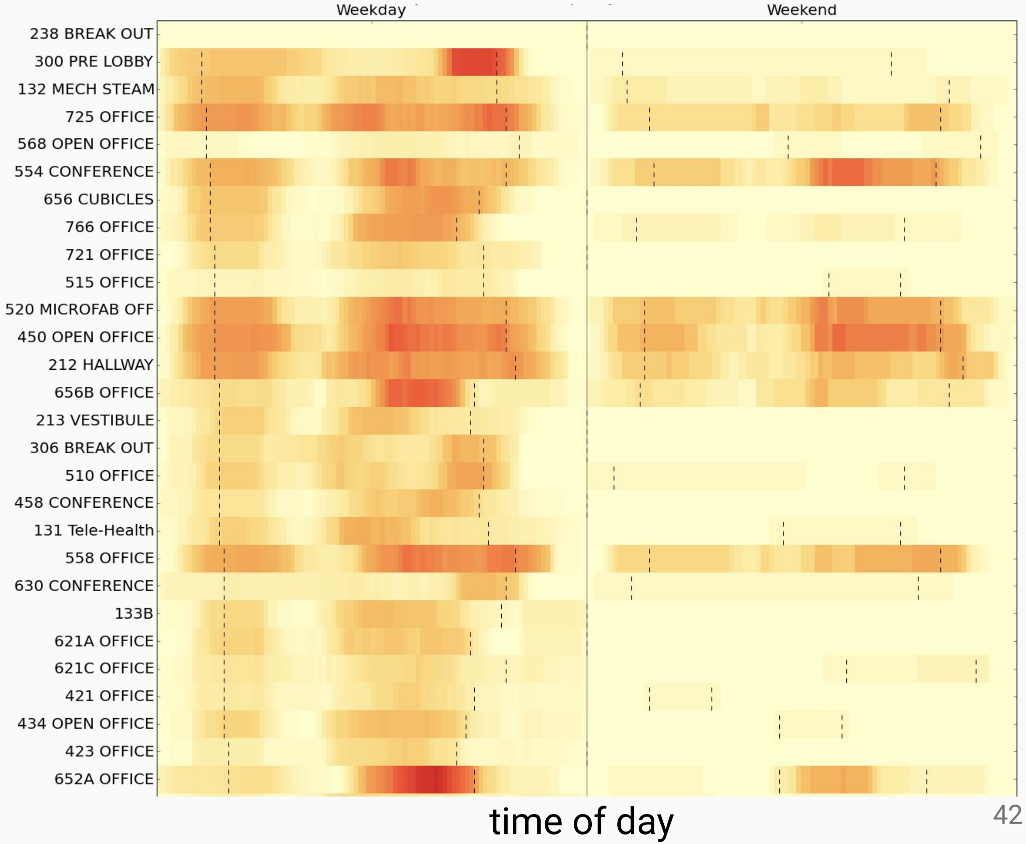
Energy consumption of building systems

- HVAC and lighting systems account for ~40% of building energy use
    - energy is consumed to satisfy thermal and visual comfort requirements
- In Canada, HVAC and lighting are typically responsible for a much larger portion of building energy use



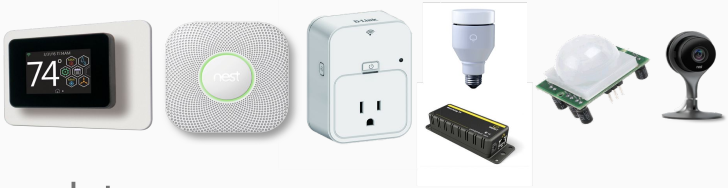
Occupancy determines building energy use

- A large amount of energy is consumed to condition and light building spaces when they are not occupied
- Occupancy cannot be directly monitored in most buildings
- Occupancy schedules change over space and time
  - existing control rules don't incorporate this information



How to save on building energy use?

Incorporate building occupancy data (measured or predicted) in control loops to achieve energy efficiency without sacrificing comfort. How?

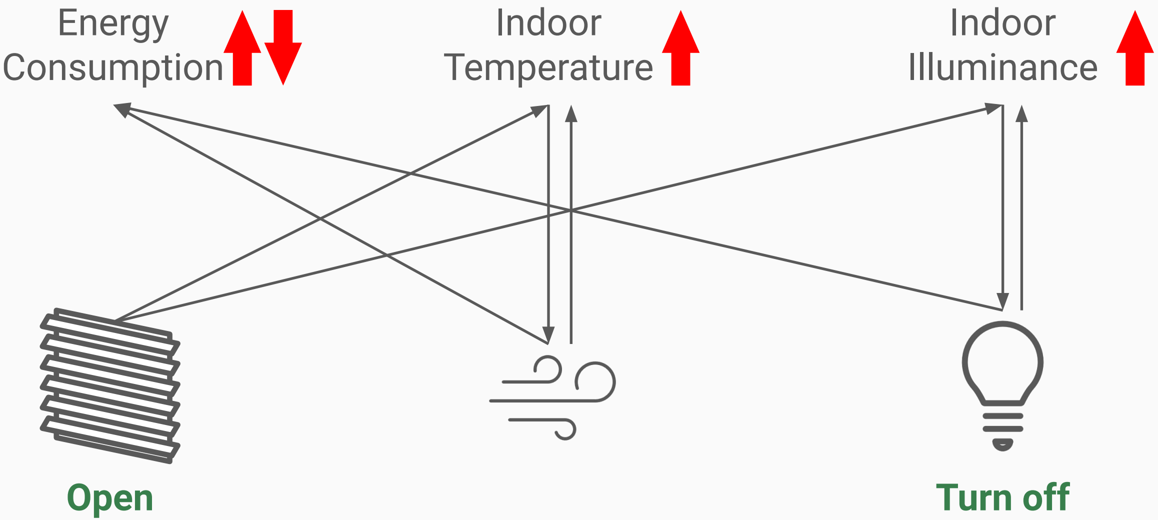


- **Approach 1:** Deploy sensors everywhere (costly)
- **Approach 2:** Estimate zone-level occupancy by fusing data collected by a smaller subset of sensors

Measure (or infer) how comfortable people are in the environment

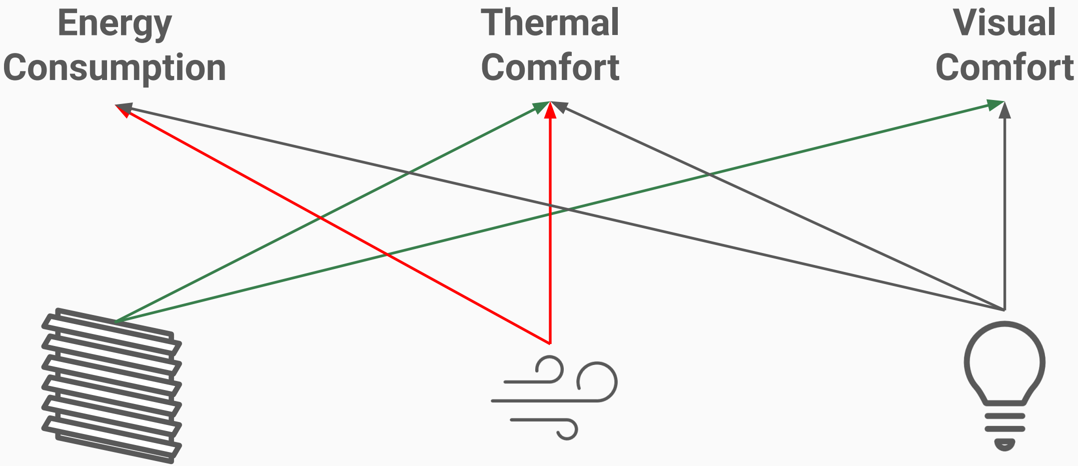
too warm
warm
neutral
cool
too cool

Saving more by controlling building systems jointly



But it is difficult to model these interactions

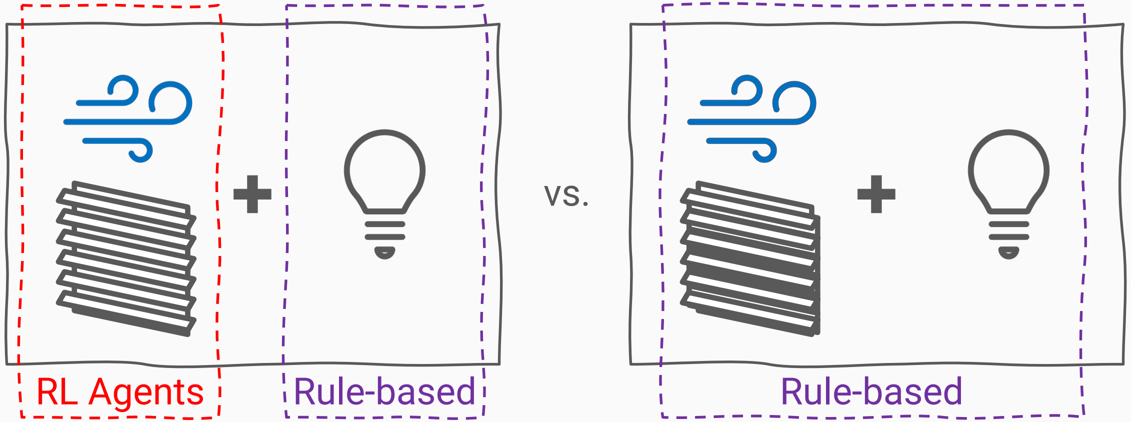
Motivation for joint control of building systems



it is difficult to understand the impact of an action on control objectives

Proposed solution

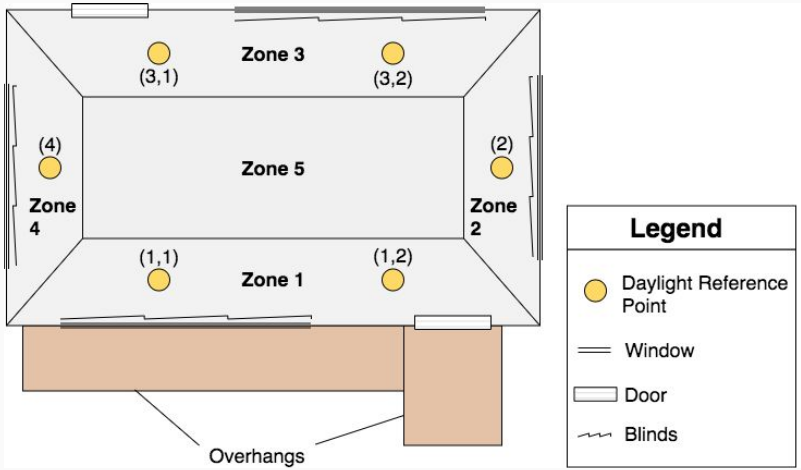
- Jointly control the HVAC system supply air temperature and blind angle setpoints using model-free RL algorithms with and without auto dimming of lights
- Our results show that we can save 11% more energy in winter and 31.8% more energy in summer over existing rule-based control strategies that rely on zone-level occupancy information



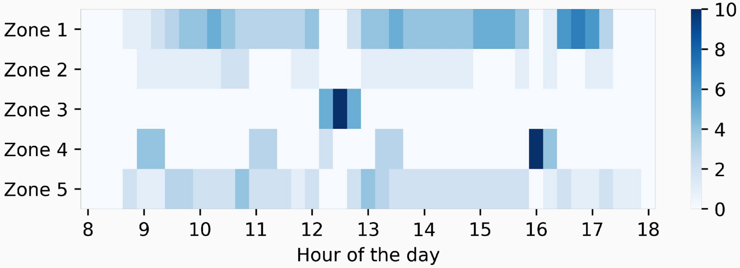
☀ 31.8% saving

❄ 11.0% saving

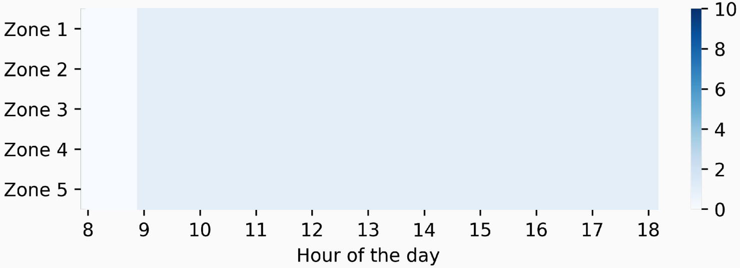
Evaluation in test building



5-zone building



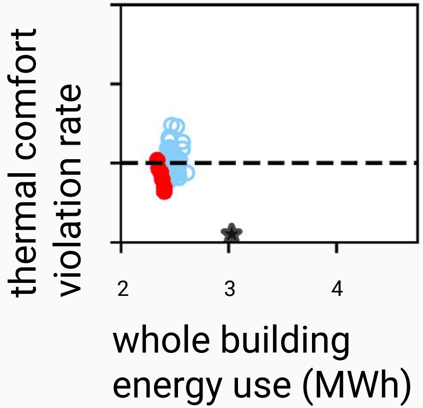
Zone-level occupancy



Building-level occupancy

Summary of results

- Joint control of building systems could provide a better trade-off compared to when they are controlled separately
- Incorporating high resolution occupancy data would greatly benefit the control agents
- The facilities manager can navigate the three-way trade-off between energy use, thermal comfort, and visual comfort by tweaking reward parameters



Red dots are Pareto optimal points

Highest acceptable comfort violation rate

Concluding remarks

- We need to do more than just increasing the share of renewables in the supply mix to combat climate change
- Leveraging pervasive sensing, broadband communication, and advanced control we can improve efficiency in urban infrastructure and energy systems
- Several ideas can be borrowed from the design of the Internet and computer systems

SCRG

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