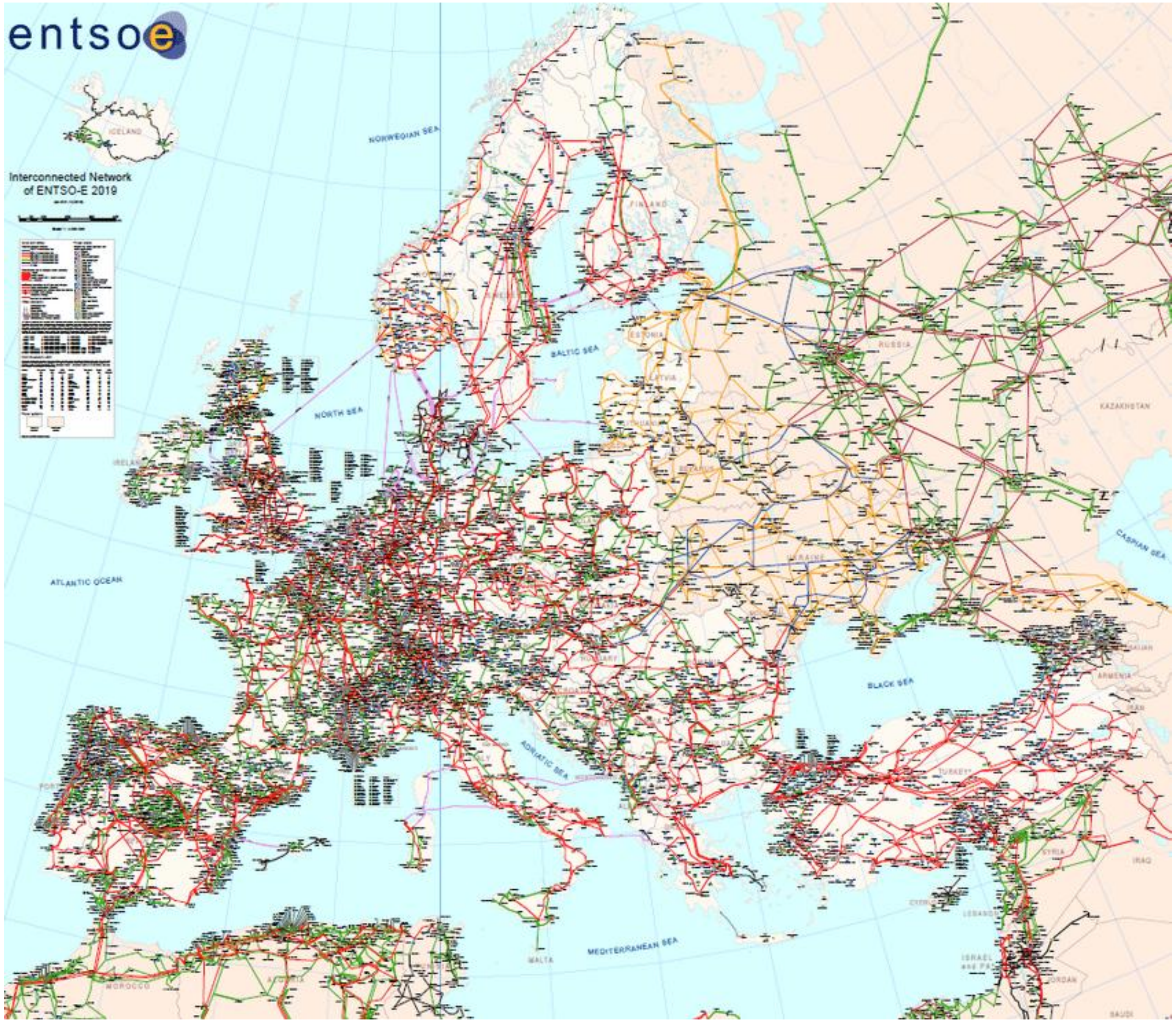
46770 Integrated energy grids

Marta Victoria

Lecture 1 – Balancing renewable generation

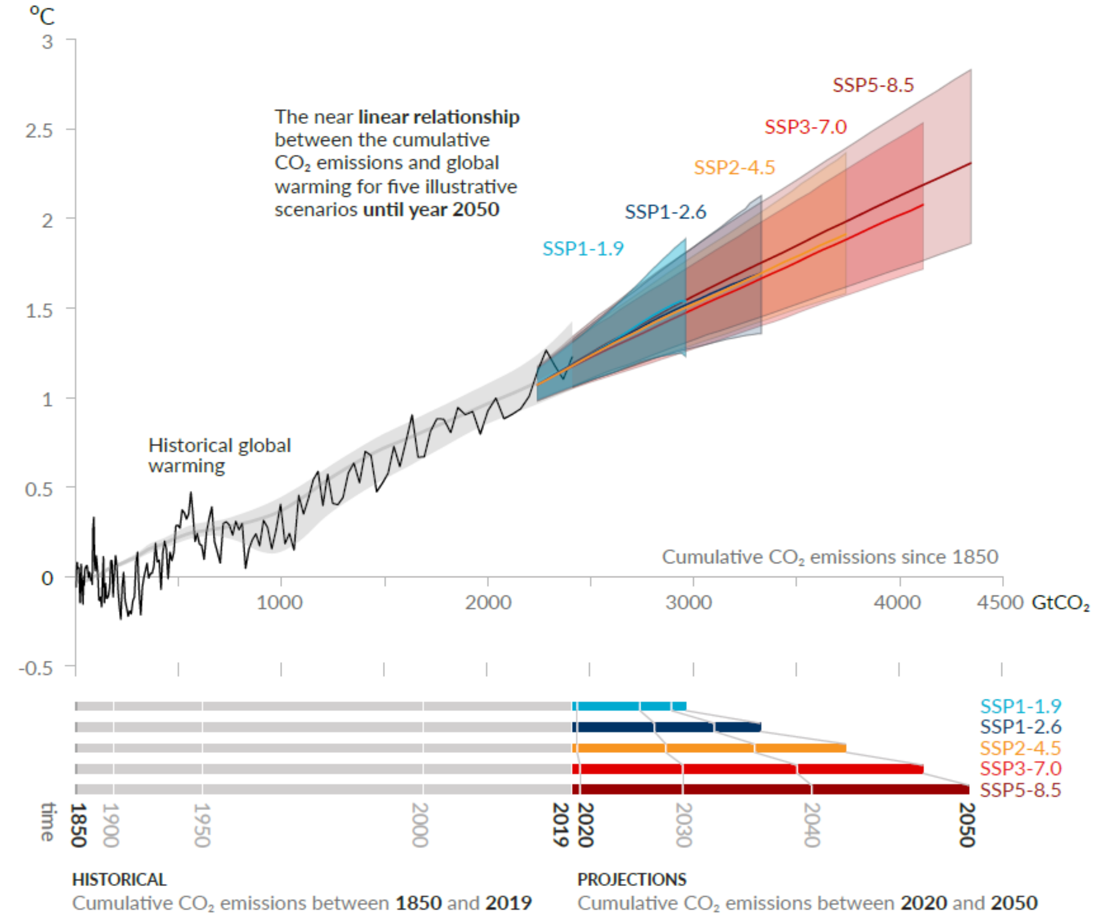
Introduction



The power grid is the largest machine we have ever built, but climate change mitigation demands its profound and rapid transformation.

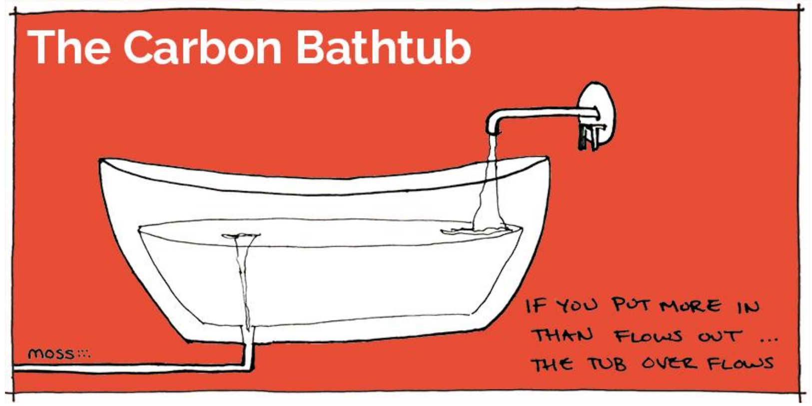
Climate change

Global surface temperature increase since 1850-1900 (°C) as a function of cumulative CO_2 emissions ($GtCO_2$)

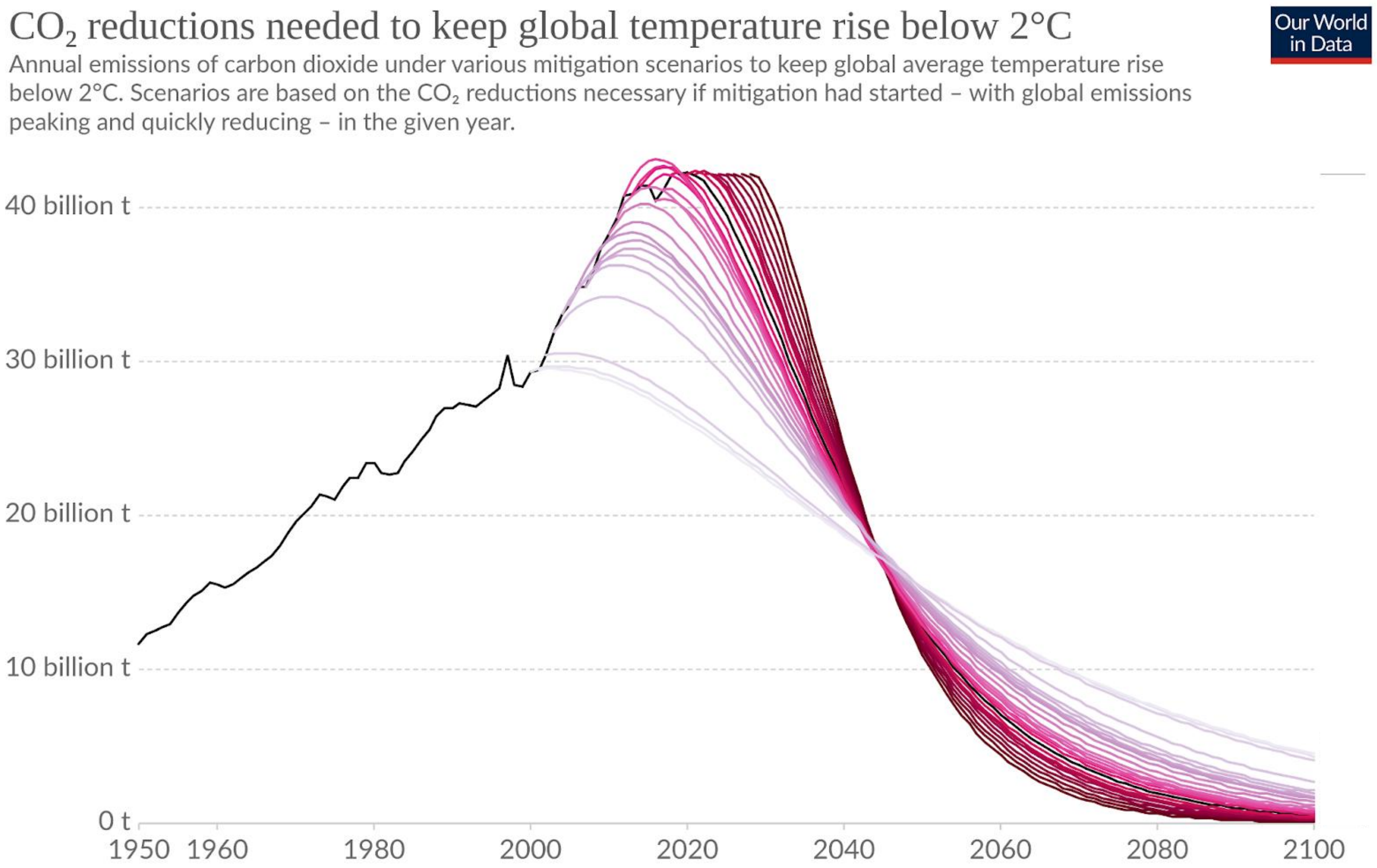


Ref: IPCC 6th Assessment Report (2021)

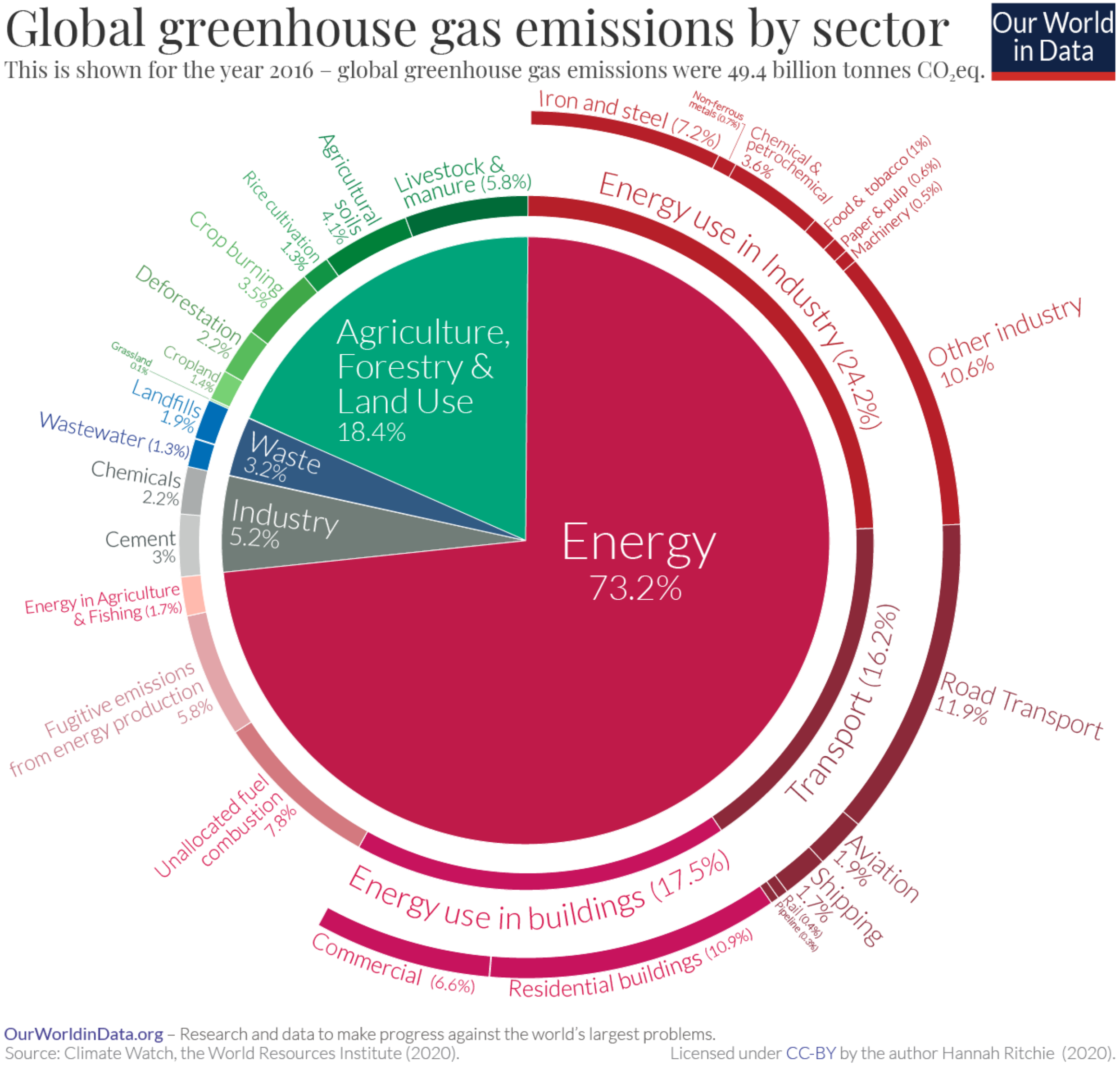
It is a cumulative problem



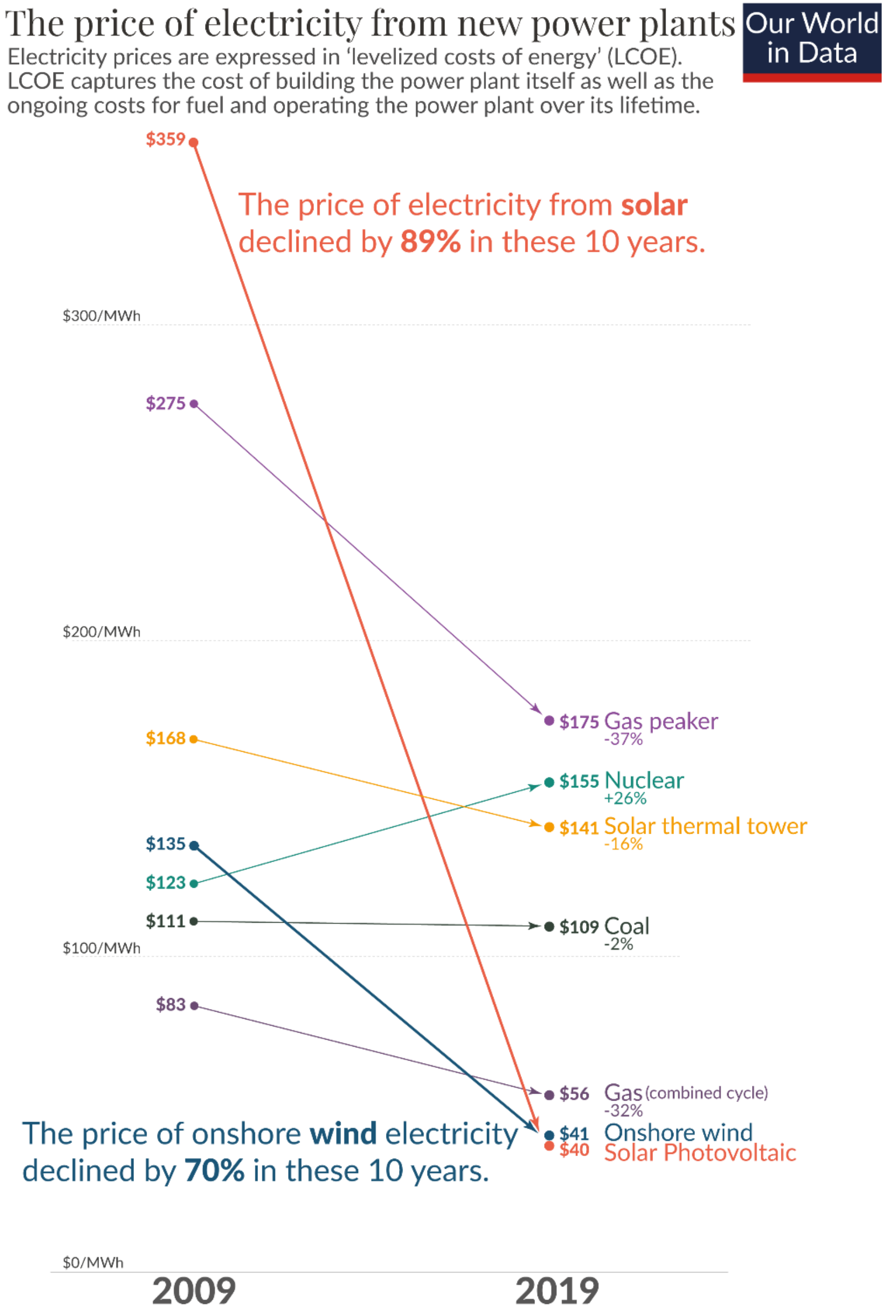
The challenge ahead



Mitigating climate change requires transforming the energy sector

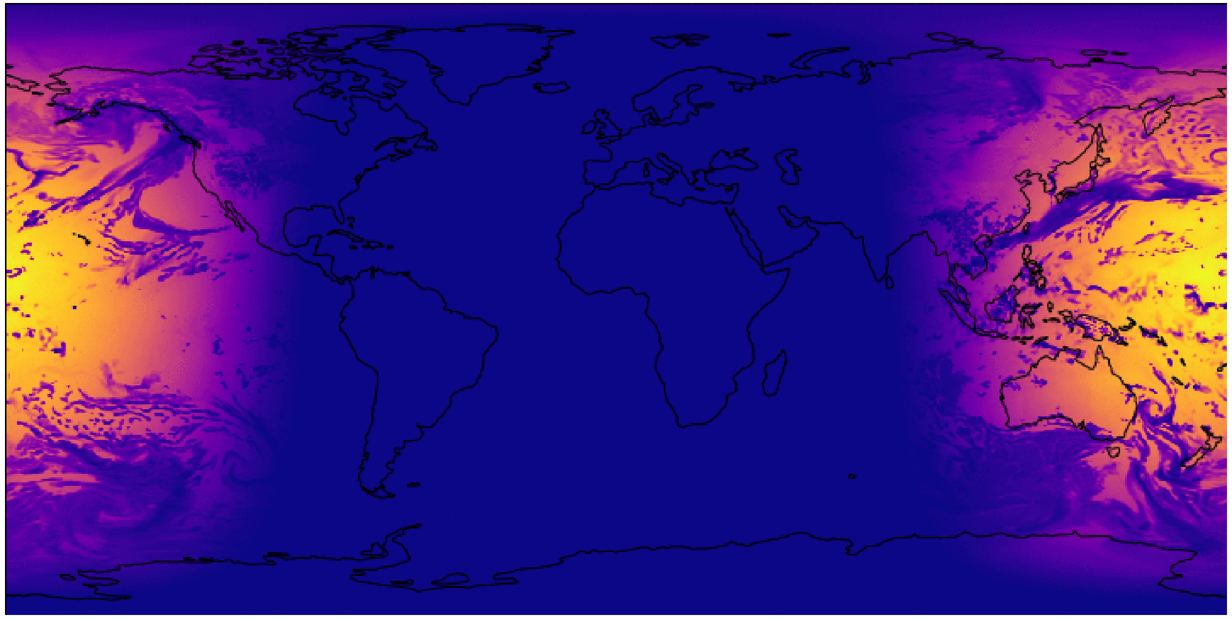


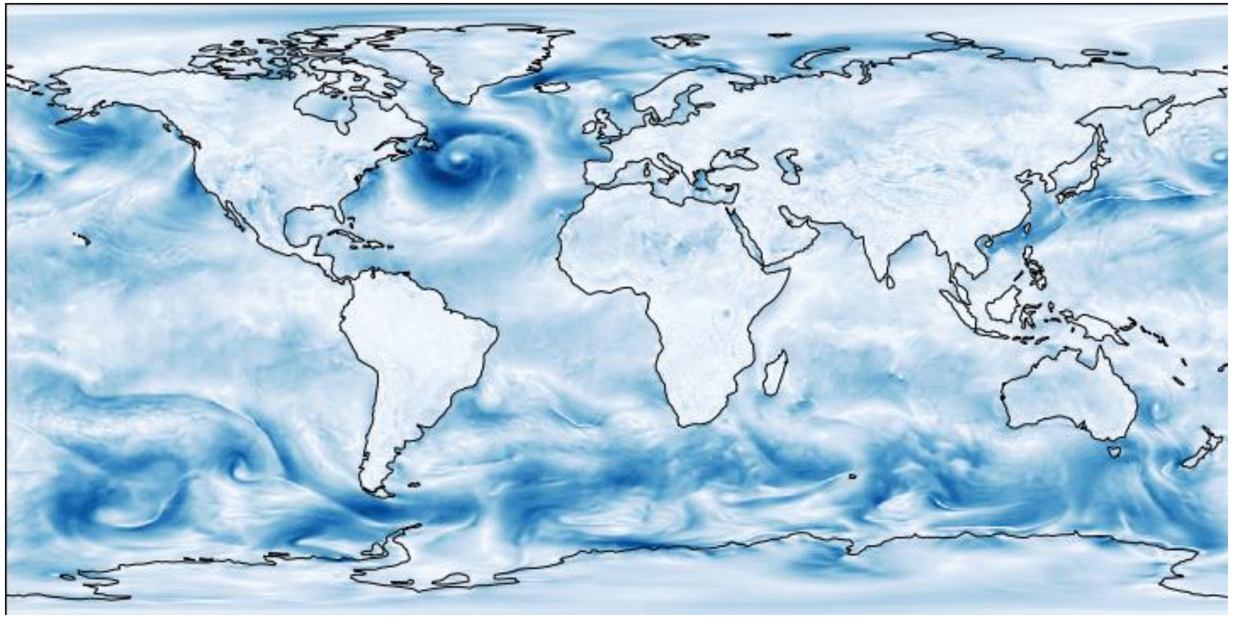
Wind and solar have dramatically reduced their cost



Balancing solar and wind generation

Systems with high solar and wind penetration requires balancing fluctuations at different time scales.





Learning goals for this lecture

- Describe different strategies for balancing fluctuations in renewable energy generation.
- Describe the role that energy grids can play in balancing renewable energy generation.
- Calculate the main properties of the ideal storage to balance a certain fluctuating time series.
- Calculate the local correlation length for solar irradiation and wind velocity.
- Apply time series analysis to evaluate the main fluctuations in solar PV, wind generation, and demand time series.

Balancing solar and wind

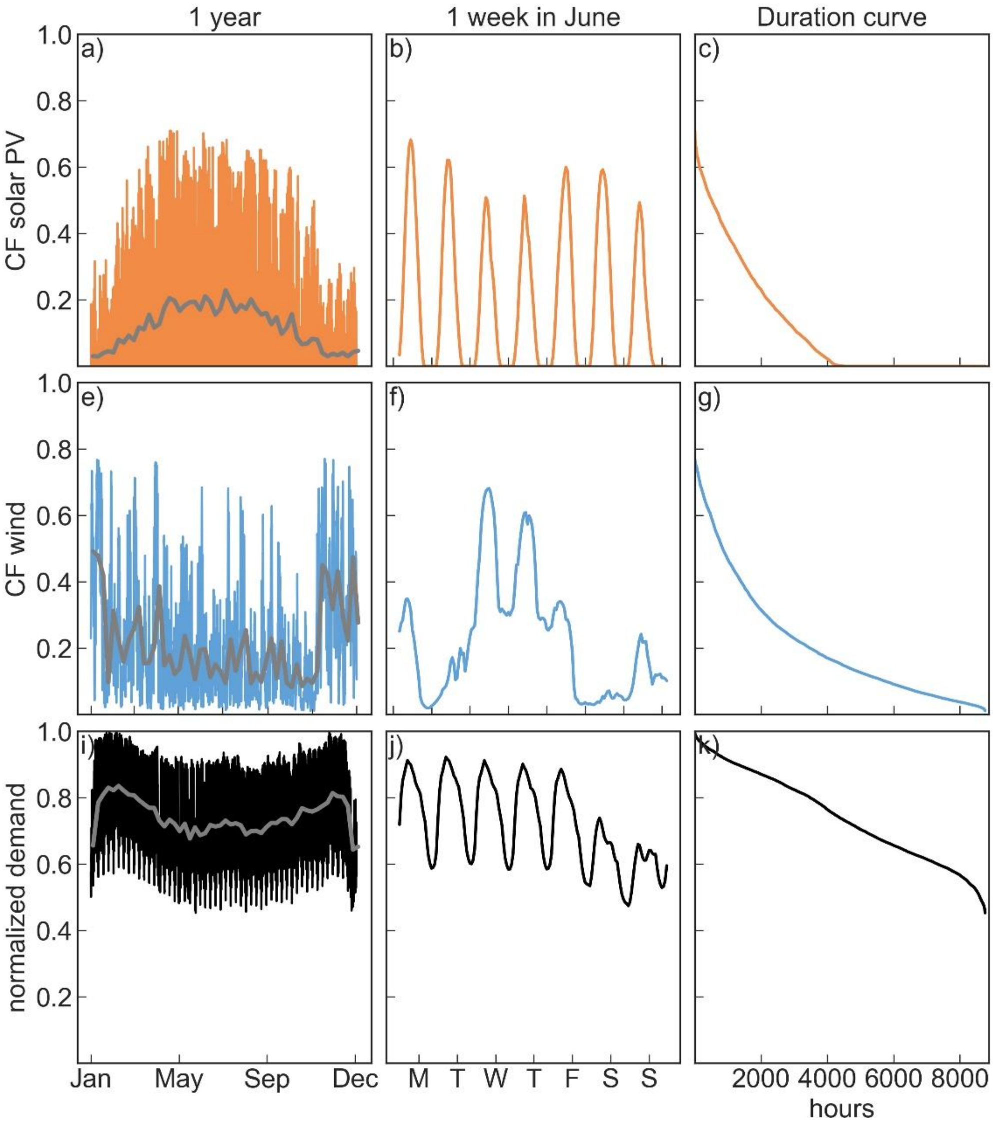


Fig: Solar, wind and electricity demand in Germany
Victoria, 2024

Solar PV and wind energy show negligible CO_2 emissions and are cost-competitive.

Can we rebuild our energy systems using solar and wind?

Hydropower is renewable and dispatchable, but its potential expansion is limited in many regions.

Other technologies (nuclear, biomass…) might contribute, but we focus on understanding the challenges associated with large penetration of solar and wind.

$$CF_t = \frac{\text{actual electrical energy output}}{\text{installed capacity} \cdot 1 \text{ hour}} \qquad \langle CF \rangle = \frac{\text{actual electrical energy output (in one year)}}{\text{installed capacity} \cdot 8760 \text{ hour}}$$

- Electricity demand, solar and wind energy fluctuations show different frequencies!
- Solar PV and wind show opposite seasonal variation (in most regions)
- Capacity factors (CF) for wind and solar <1 due to regional integration

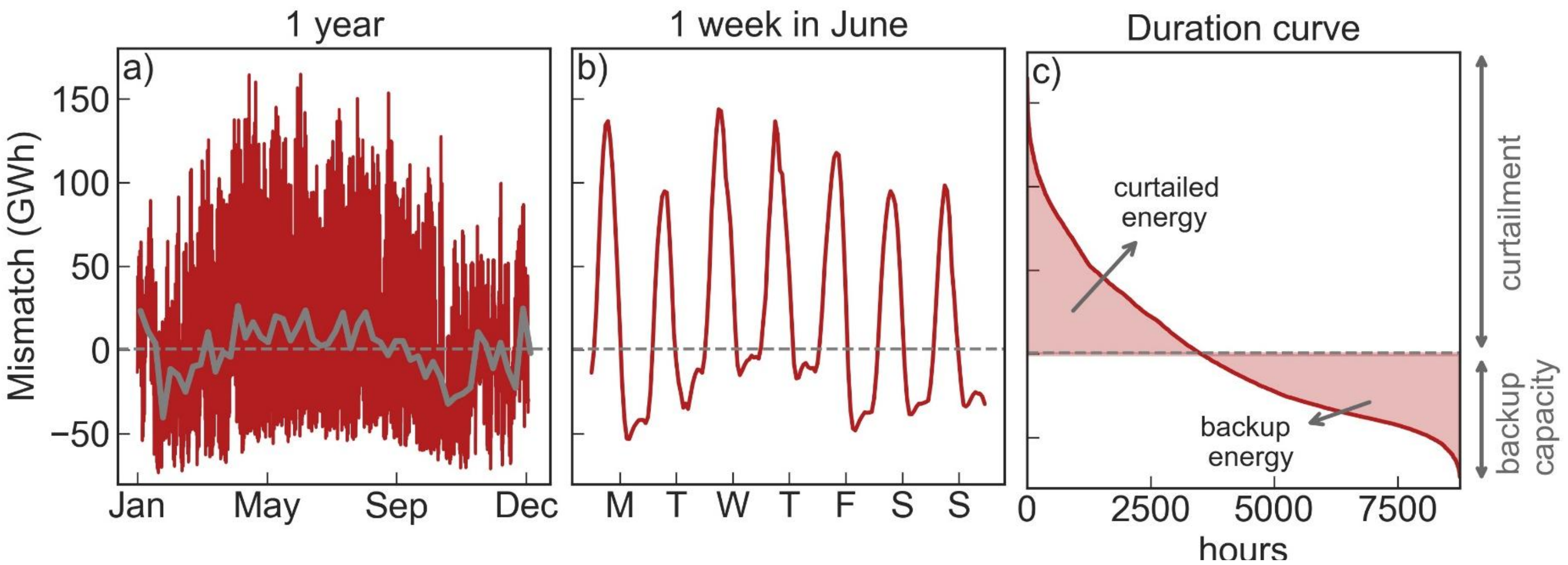
Mismatch between renewable generation and demand

We define mismatch as the difference between renewable generation and demand.

$$\boxed{\Delta_t = g_t^W + g_t^S - d_t}$$

Assuming: $\langle g_t^W \rangle + \langle g_t^S \rangle = \langle d_t \rangle$

$\langle g_t^W \rangle = \langle g_t^S \rangle$



renewable energy is wasted

It needs to be produced by a dispatchable technology: hydro, gas, coal, nuclear …

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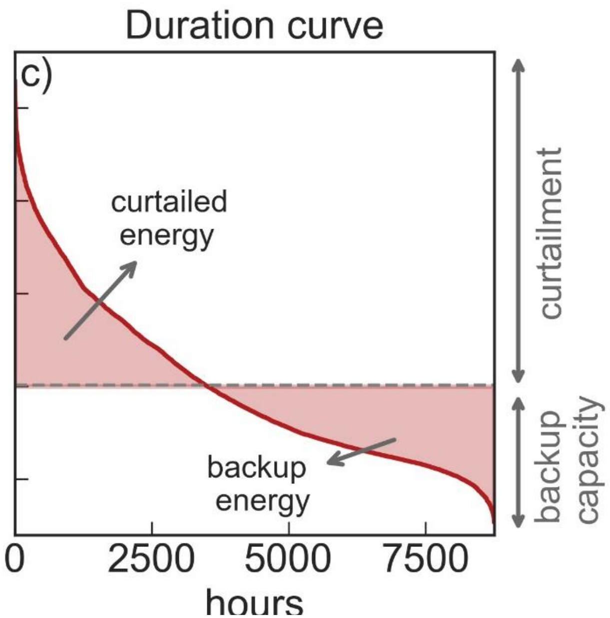
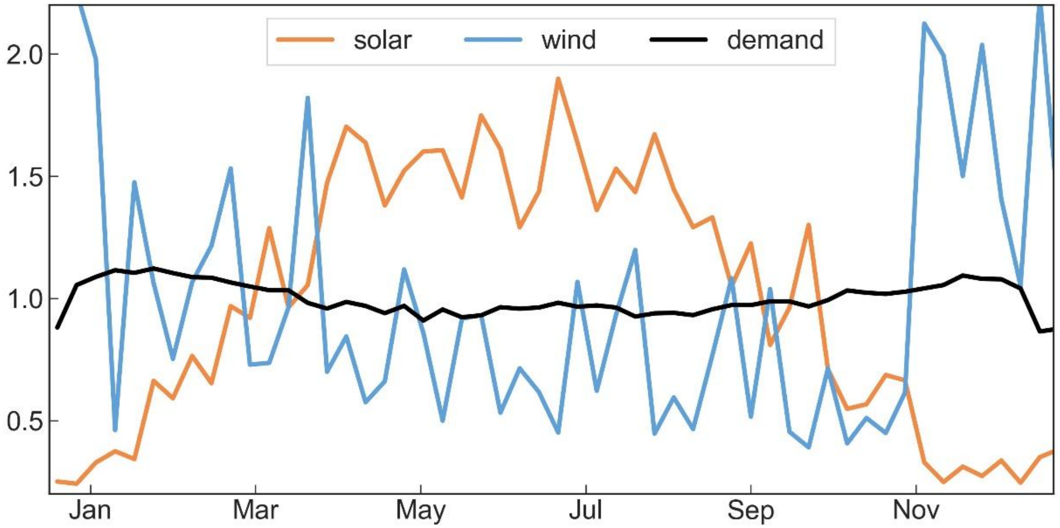
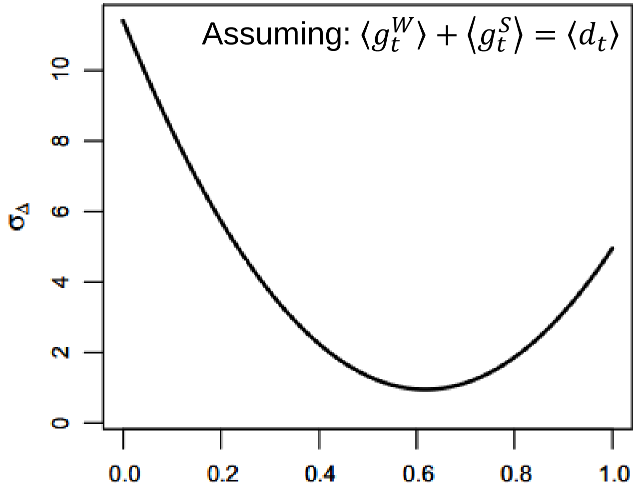




The standard deviation of mismatch indicates the need for balancing.

There is a certain combination of wind and solar that minimizes that need



$$\alpha = \frac{< g_t^W >}{< g_t^S > + < g_t^W >}$$

backup energy $E_B = \sum_0^{8759} \Delta_-$

backup capacity $C_B = \max(|\Delta_-|)$

curtailed energy $E_C = \sum_0^{8759} \Delta_+$

See Problem 1.3 proposed in this lecture

Heide et al., *Seasonal optimal mix of wind and solar power in a future, highly renewable Europe*, Renewable Energy 35 (2010)

Mismatch between renewable generation and demand

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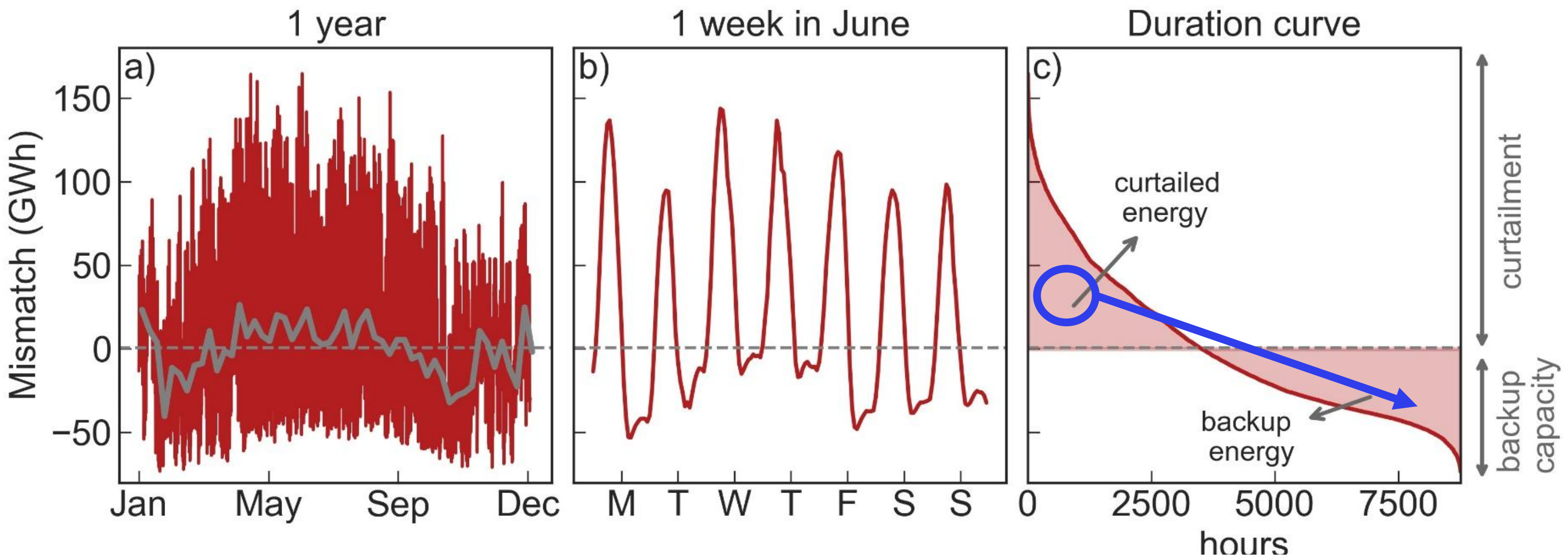


renewable energy is wasted

It needs to be produced by a dispatchable technology: hydro, gas, coal, nuclear …

Two main strategies to balance mismatch:

- Storage moves energy from time steps in which there is an excess of generation to time steps in which there is a deficit.
- Transmission moves energy from regions where there is an excess of generation to regions where there is a deficit.

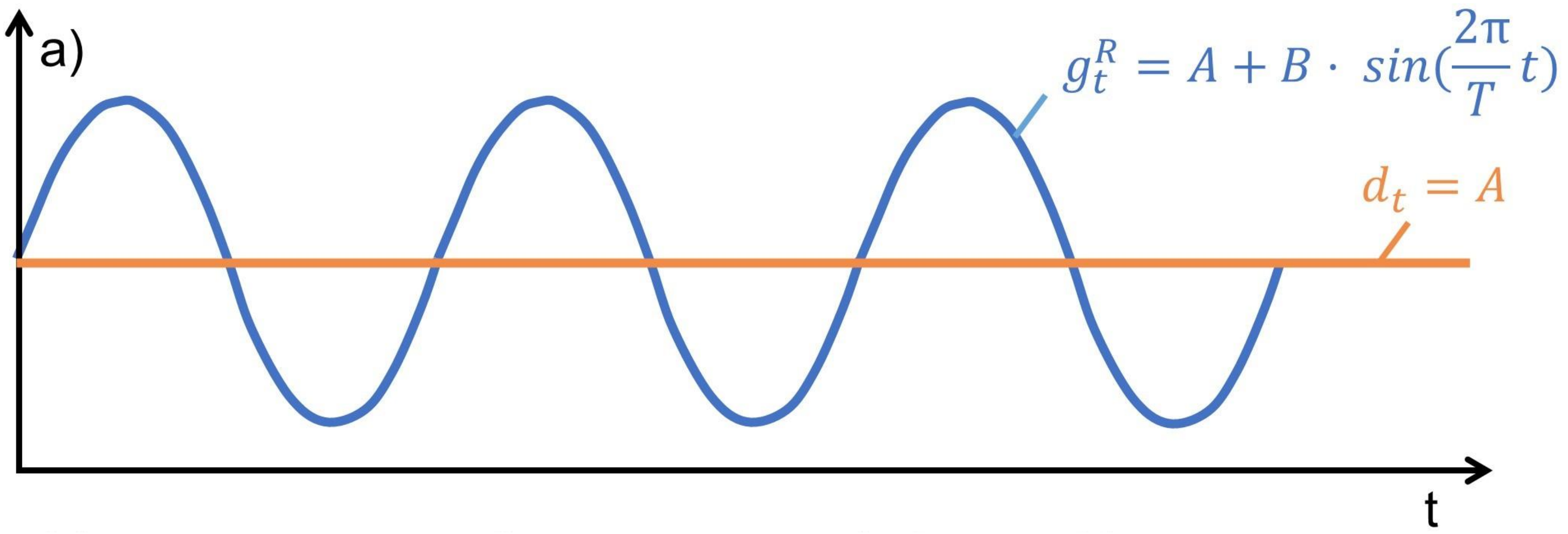
Balancing using storage

Storage moves energy from time steps in which there is an excess of generation to time steps in which there is a deficit.

The **storage energy capacity** determines how much energy can be stored while the **storage power capacity** determines how fast the storage can be charged/discharged.

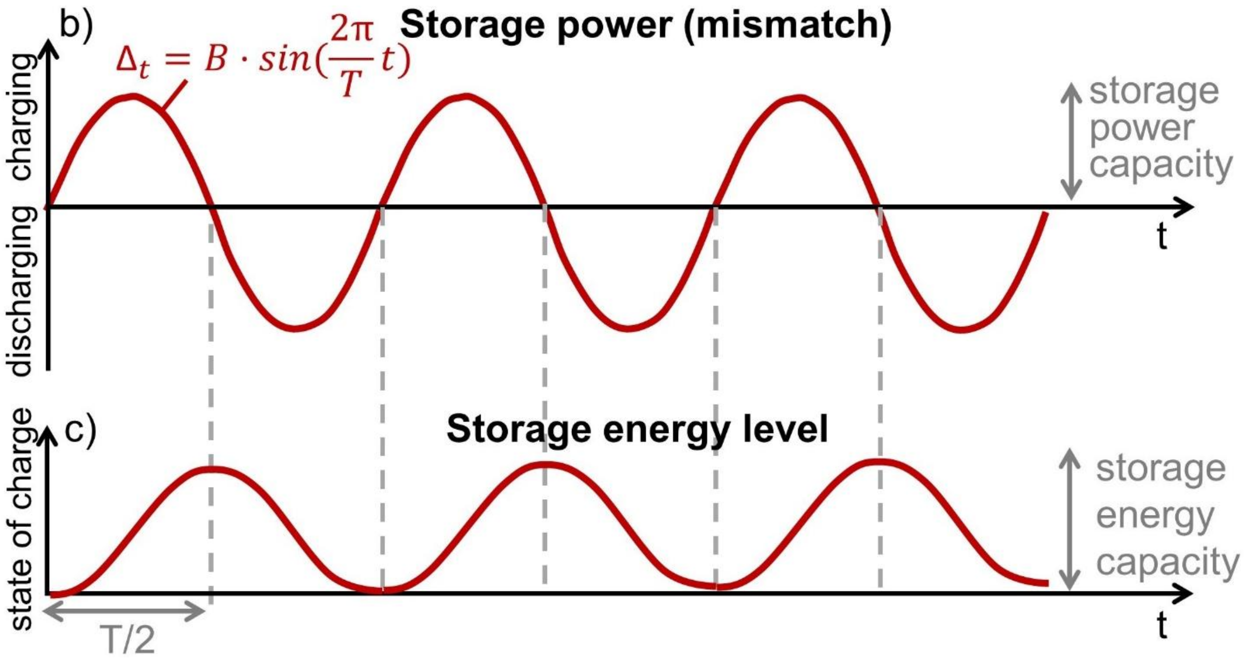
For instance, an Electric Vehicle with a battery energy capacity of 100 kWh can be charged at home with a power capacity of 11 kW (it takes 9 hours) or using a fast charger with a power capacity of 100 kW (it takes 1 hour)

Let's assume a constant electricity demand *D=A* and a variable renewable generator that oscillates with period T.



Balancing using storage

We can plot the mismatch as the difference between renewable generation and demand. $\Delta_t = g_t^R - d_t = A + B \cdot \sin\left(\frac{2\pi}{T}t\right) - A$



Power capacity is determined by the maximum value of mismatch (positive for charging power capacity and negative for discharging power capacity).

$$\text{Power capacity} = B$$

Stored energy is calculated as

$$e_t = e_{t-1} + \text{charged energy}_t - \text{discharged energy}_t$$

$$\text{Energy capacity} = \frac{BT}{\pi} \qquad \text{discharge time} = \frac{BT}{B\pi} = \frac{T}{\pi}$$

The required storage energy capacity depends on the frequency of the mismatch:

$$E_r = \int_0^{T/2} B \cdot \sin\left(\frac{2\pi}{T}t\right) dt = \frac{BT}{2\pi}\left(-\cos\left(\frac{2\pi}{T}\frac{T}{2}\right) + \cos(0)\right) = \frac{BT}{\pi}$$

The dominant frequencies for wind and solar determine the storage necessary to balance them:

Solar: T=24 hours (daily) $\text{discharge time} = \frac{T}{\pi} = \frac{24}{\pi} = 7.6 \text{ hours}$

Wind T=168 hours (weekly) $\text{discharge time} = \frac{T}{\pi} = \frac{168}{\pi} = 53 \text{ hours}$

Integrated energy grids

In the past: Networks were used to transport energy from where it is produced (large fossil-based power plants, hydropower plants, gas exporting countries …) to where it is consumed (cities and large industrial consumers)

In the future: Networks will be used to transport energy from where it is produced (locations with good renewable resources) to where it is consumed (cities and large industrial consumers)

Also, to balance renewable fluctuations by regional integration.

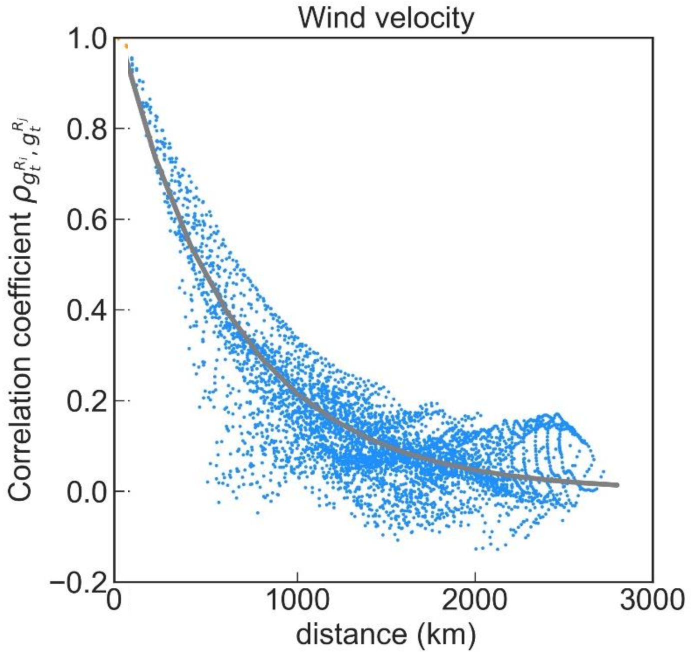
Balancing using regional integration

Transmission moves energy from regions where there is an excess of generation to regions where there is a deficit.

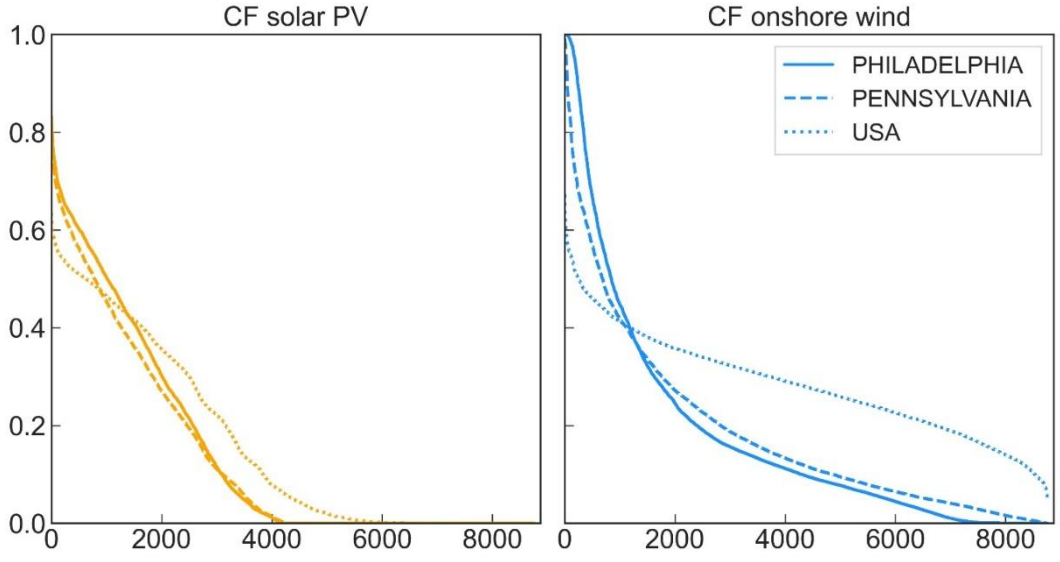
The correlation coefficient for wind velocity $\rho_{g_t^{W,i},g_t^{W,j}} = \frac{cov(g_t^{W,i},g_t^{W,j})}{\sigma_{g_t^{W,i}} \cdot \sigma_{g_t^{W,j}}}$

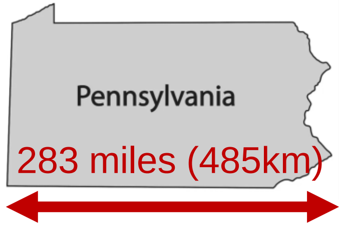
follows an exponential decay with distance $\rho_{g_t^{W,i},g_t^{W,j}} = exp(\frac{-1}{\xi_c} d_{i,j})$

Through regional integration, we can smooth the fluctuations of wind and solar generation.



Victoria, 2024

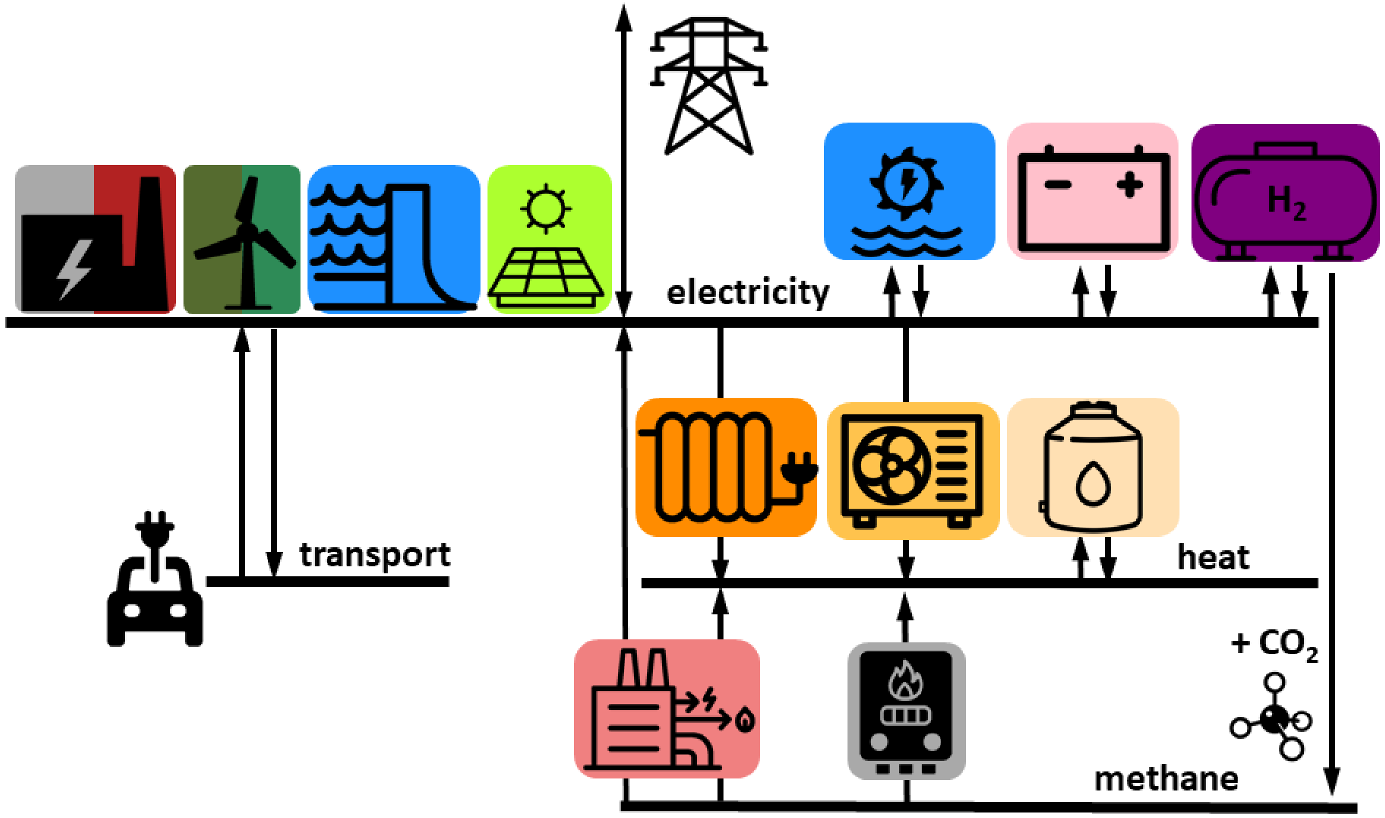




See Problems 1.4-1.5 proposed in this lecture

Sector coupling

Sector-coupling brings additional demand, but also additional flexibility



Balancing renewable generation

1. Back-up generation and curtailment

2. Storage

3. Regional integration of renewables

4. Demand-side management

5. Sector-coupling

The optimal combination of technologies depends on their cost, the local resource and the existing balancing strategies. Temporal and spatial balancing (together with demand-side management and sector-coupling) must be simultaneously considered -> **This requires optimization!**

Further readings

Chapter 14 (In particular, Section 14.1) - Large Penetration of Solar and Wind in the Energy System
https://doi.org/10.1016/B978-0-323-96105-9.00014-8

Problems for this lecture

Install python, gurobi, and course environment

https://martavp.github.io/integrated-energy-grids/intro-install.html

Review tutorials on python, numpy, pandas and matplotlib

https://martavp.github.io/integrated-energy-grids/intro-python.html

To be presented next day:

Problems 1.1 (**Group 1**)

Problems 1.2, 1.3 (**Group 2**)

Problems 1.4 and –optional- Problem 1.5 (**Group 3**)