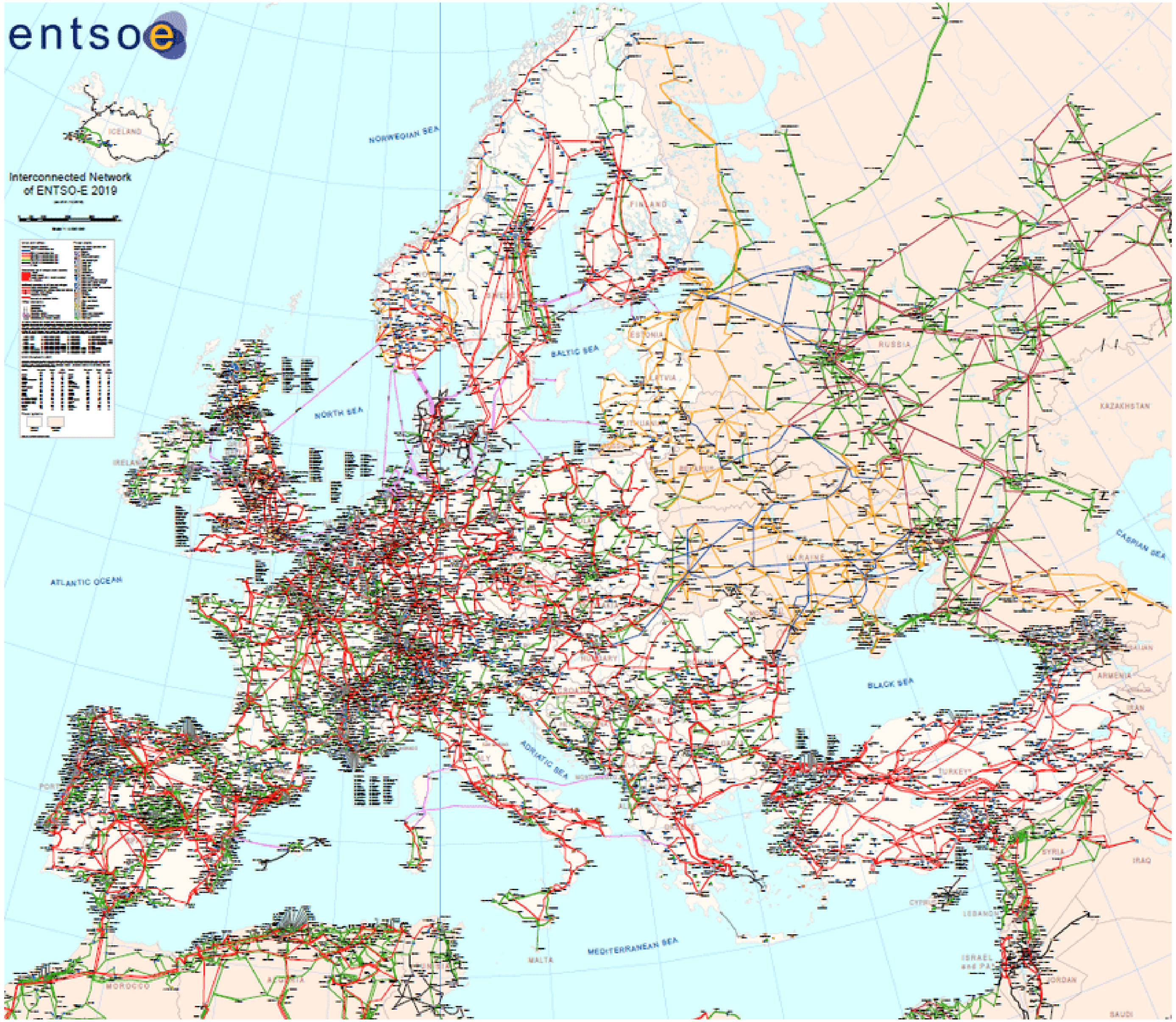
46770 Integrated Energy Grids

Aleksander Grochowicz

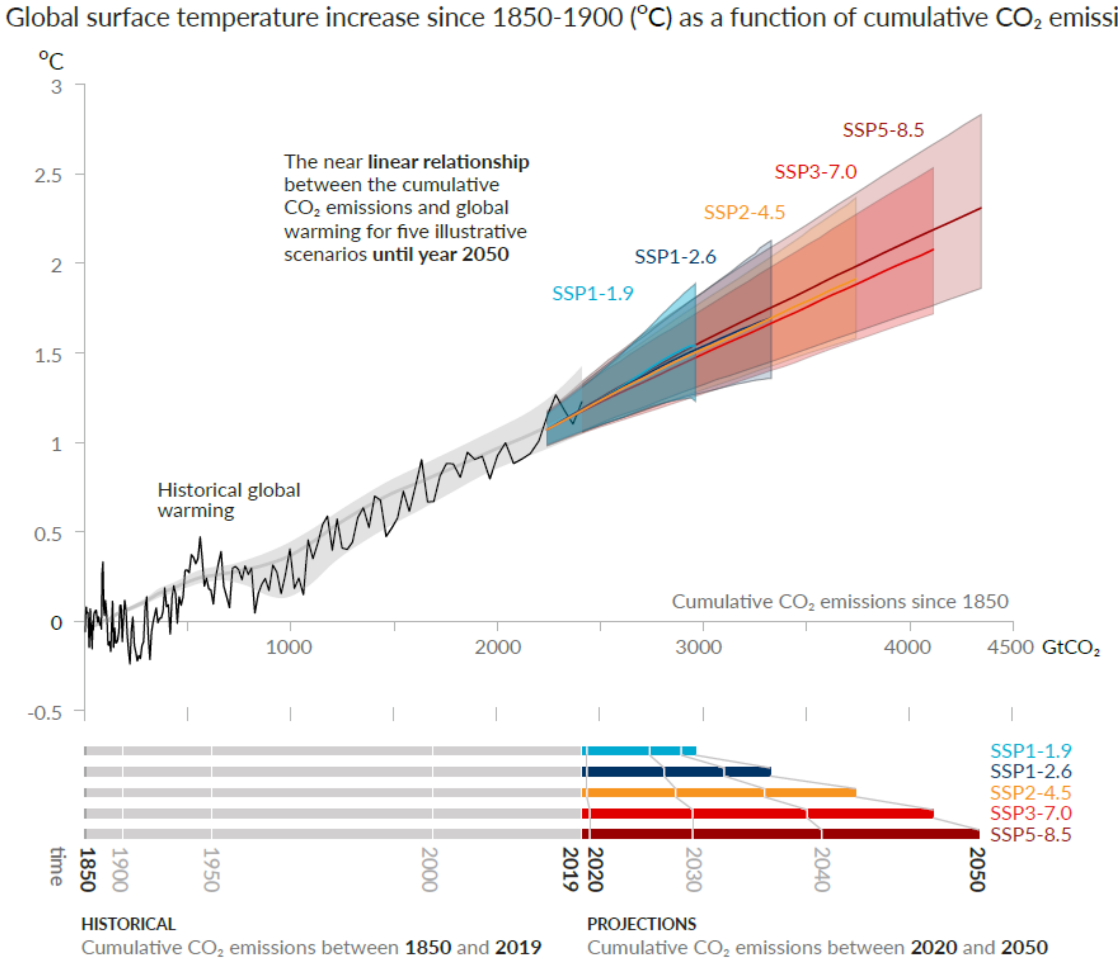
Lecture 1 – Balancing renewable generation

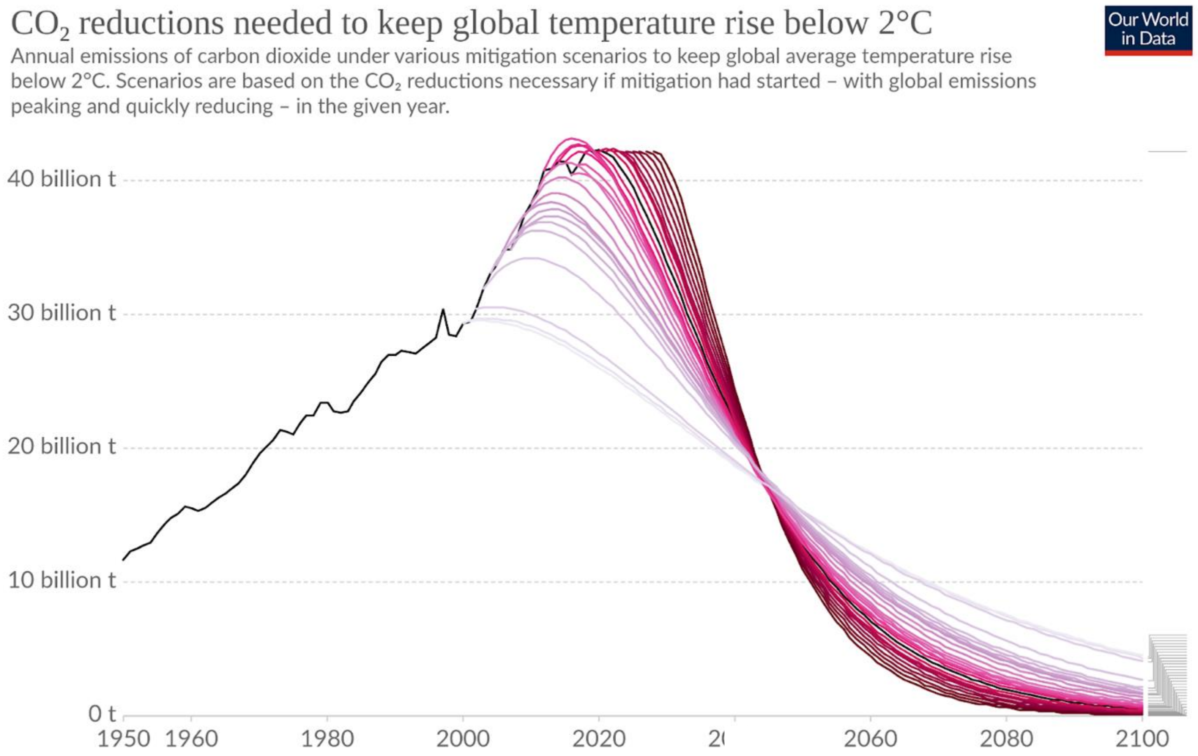
Introduction



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

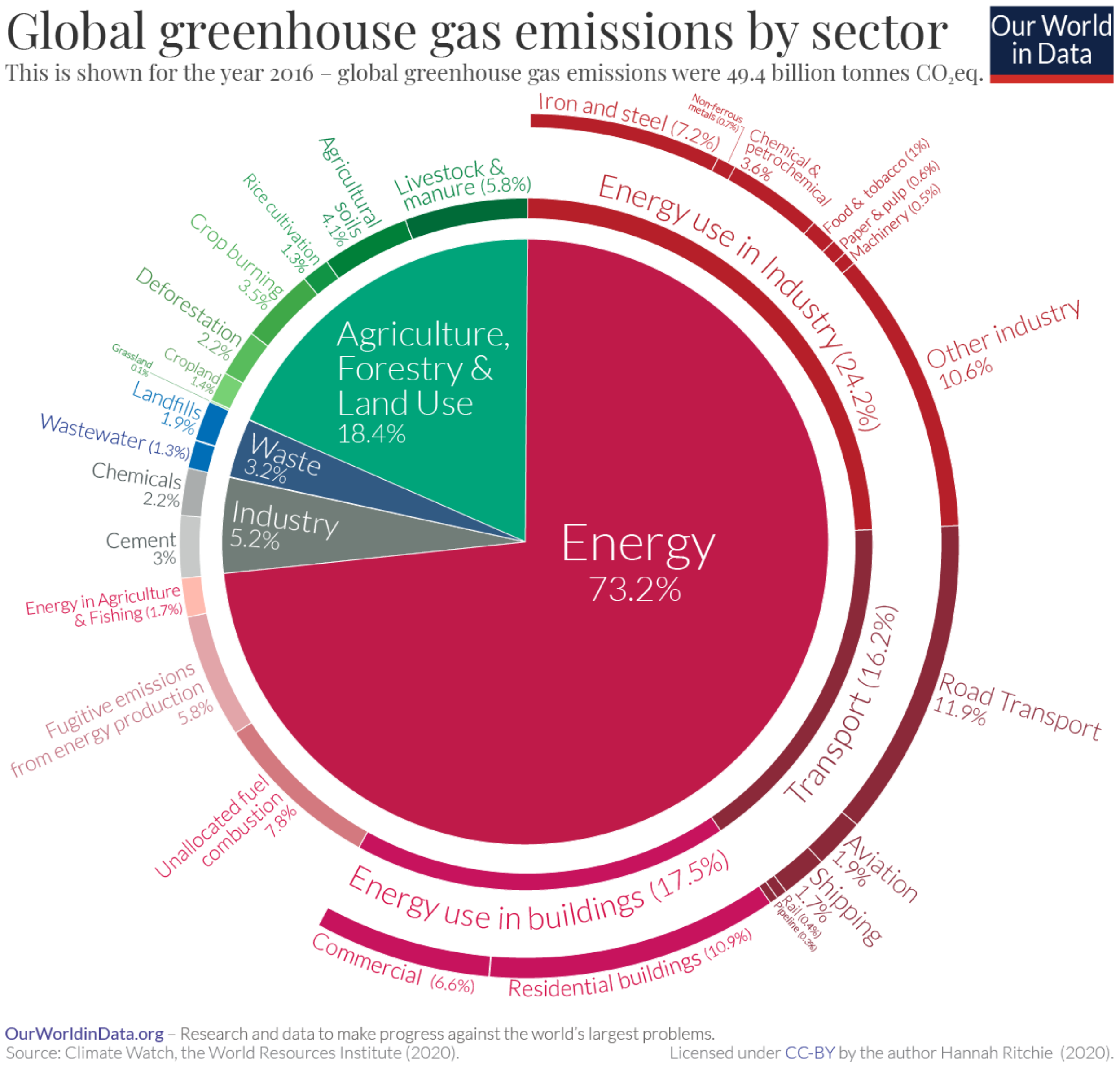
Climate change and the challenge ahead



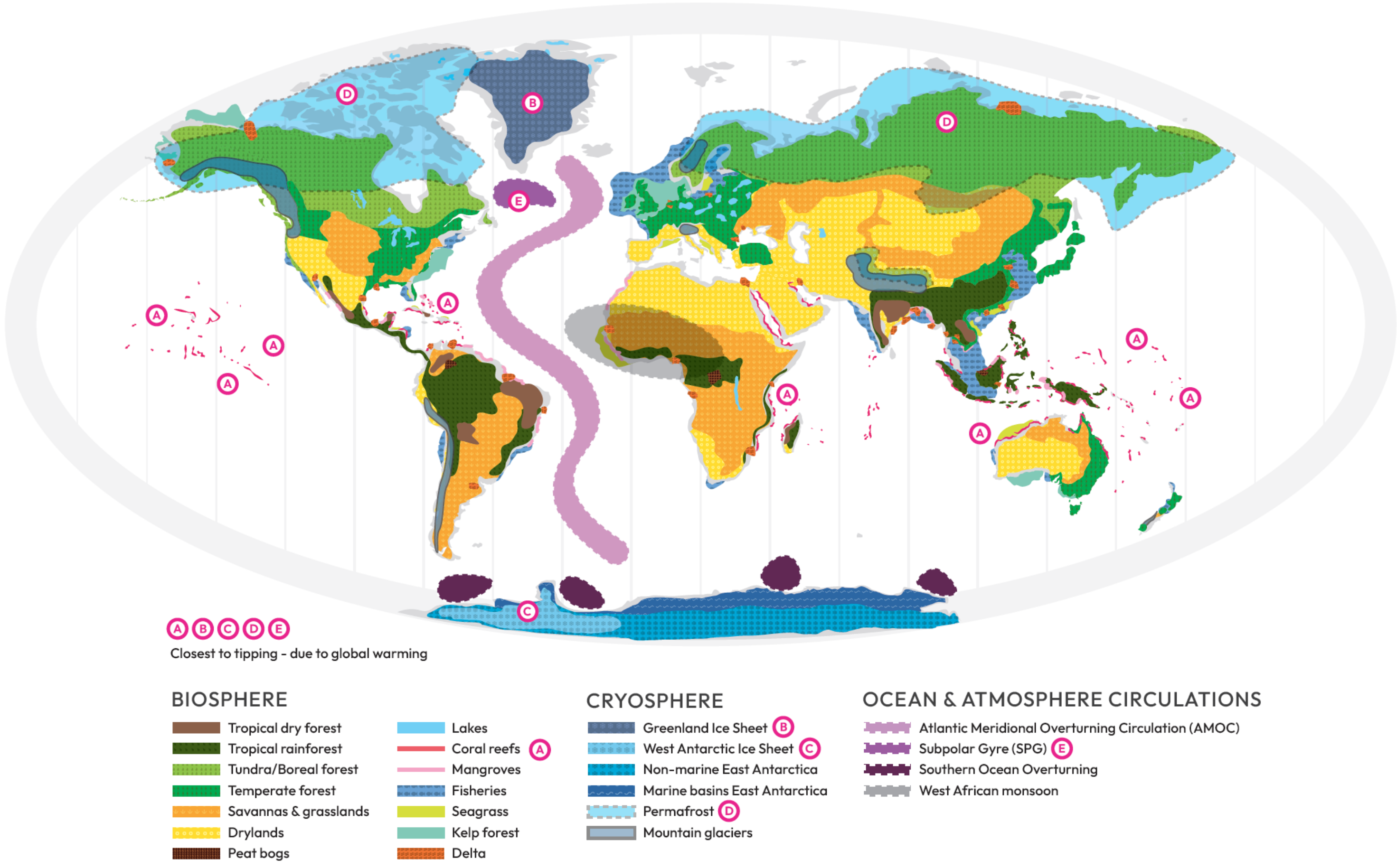


Ref: IPCC 6th Assessment Report (2021)

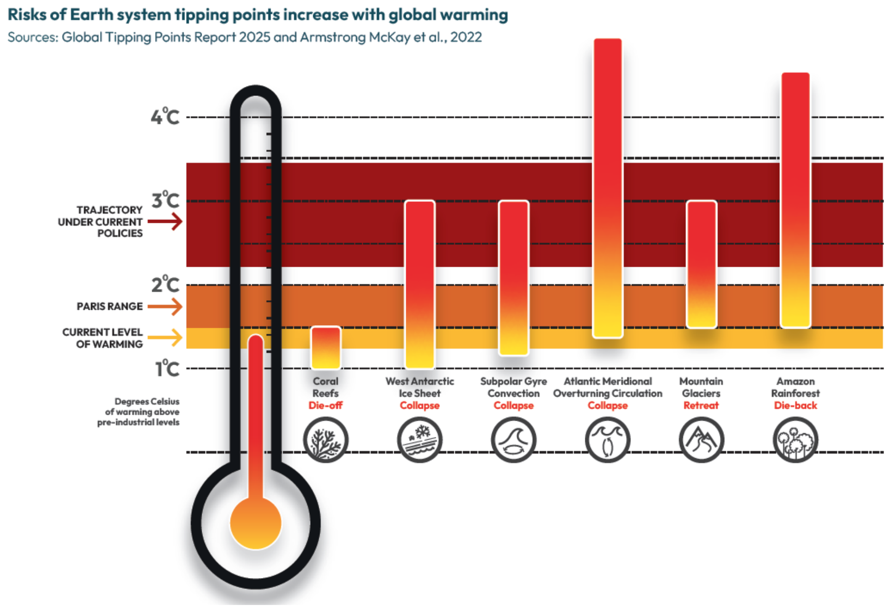
Mitigating climate change requires transforming the energy sector



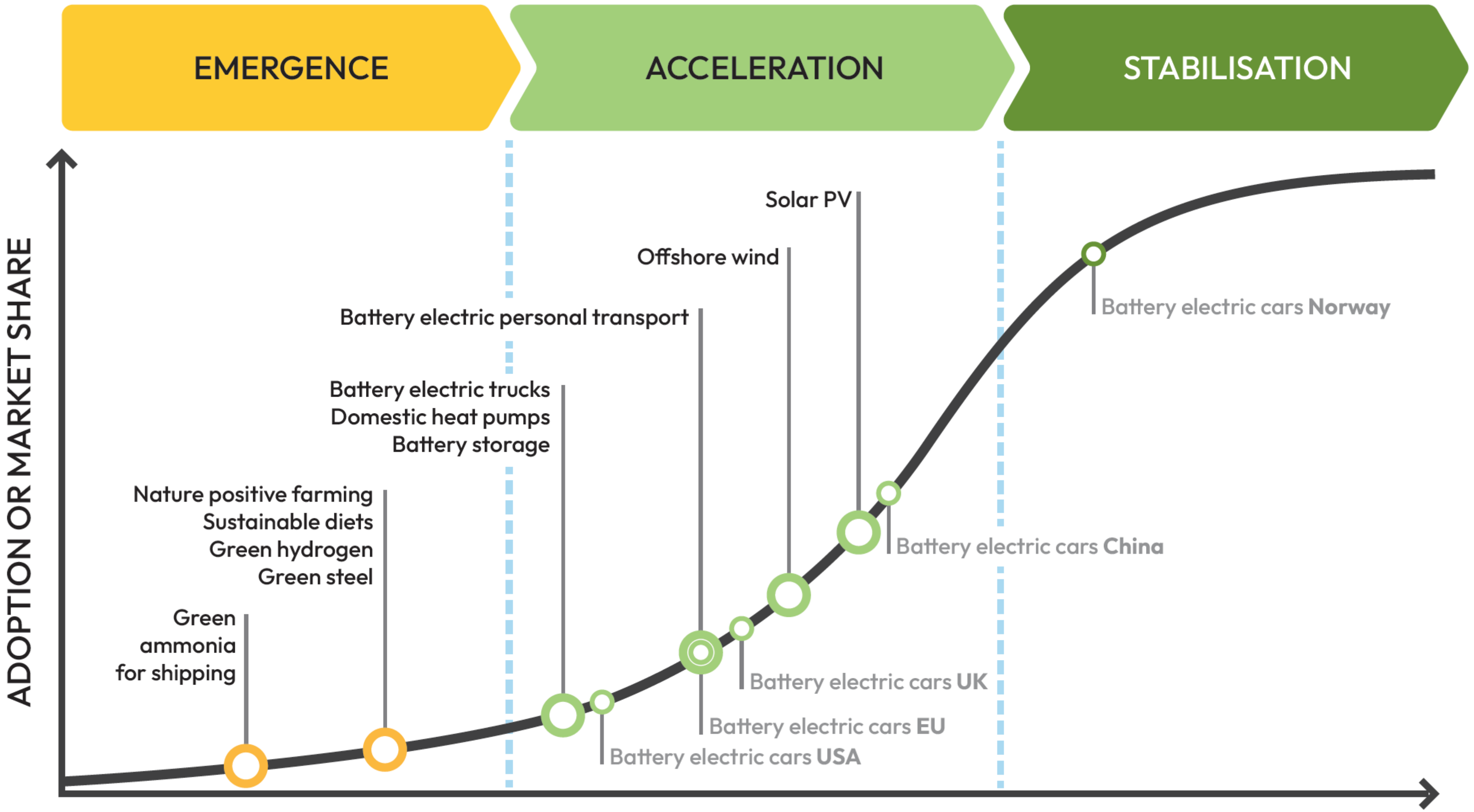
It's not just about temperatures, but also biodiversity,…



Source: Global Tipping Points Report 2025

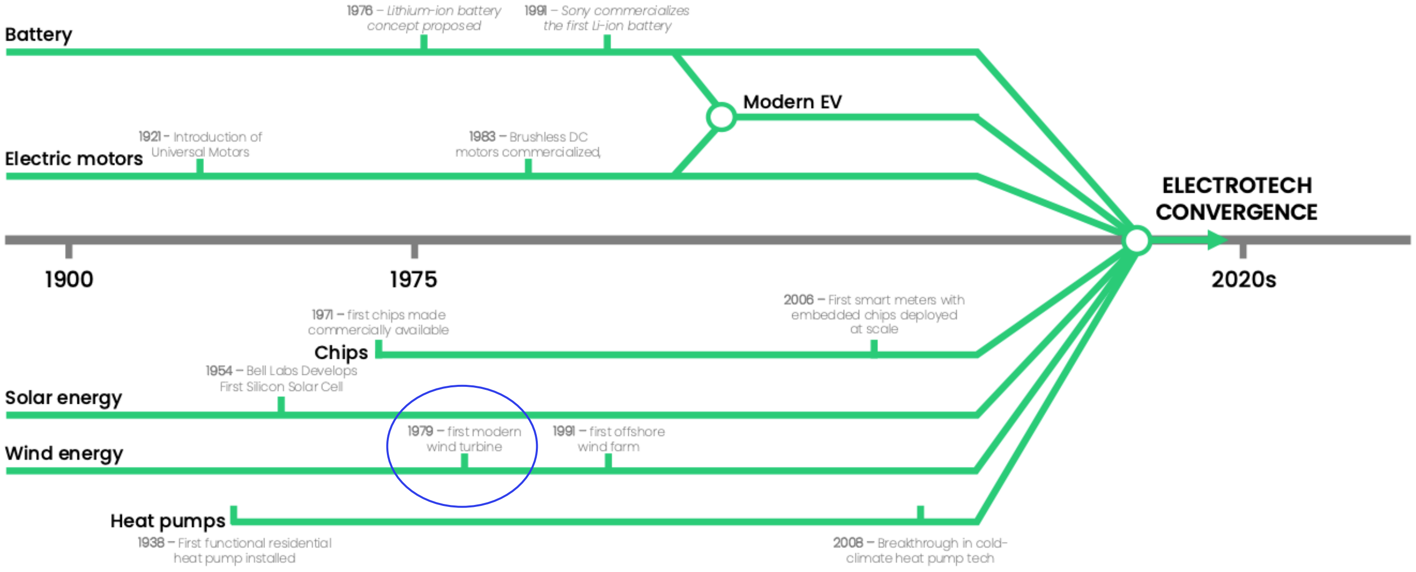


Not all tipping points are doomsday scenarios

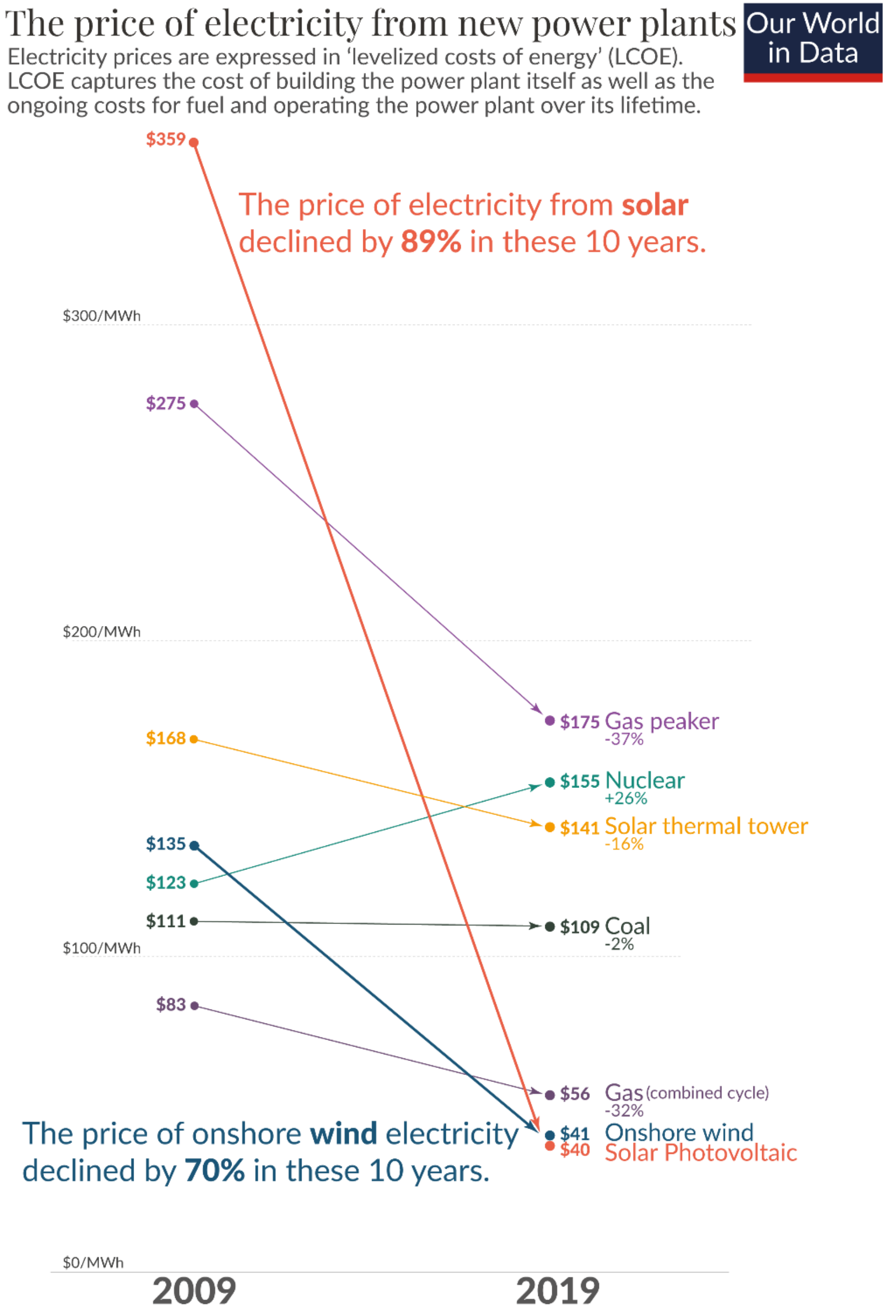


Source: Global Tipping Points Report 2025

Wind and solar have dramatically reduced their cost



Source: Ember

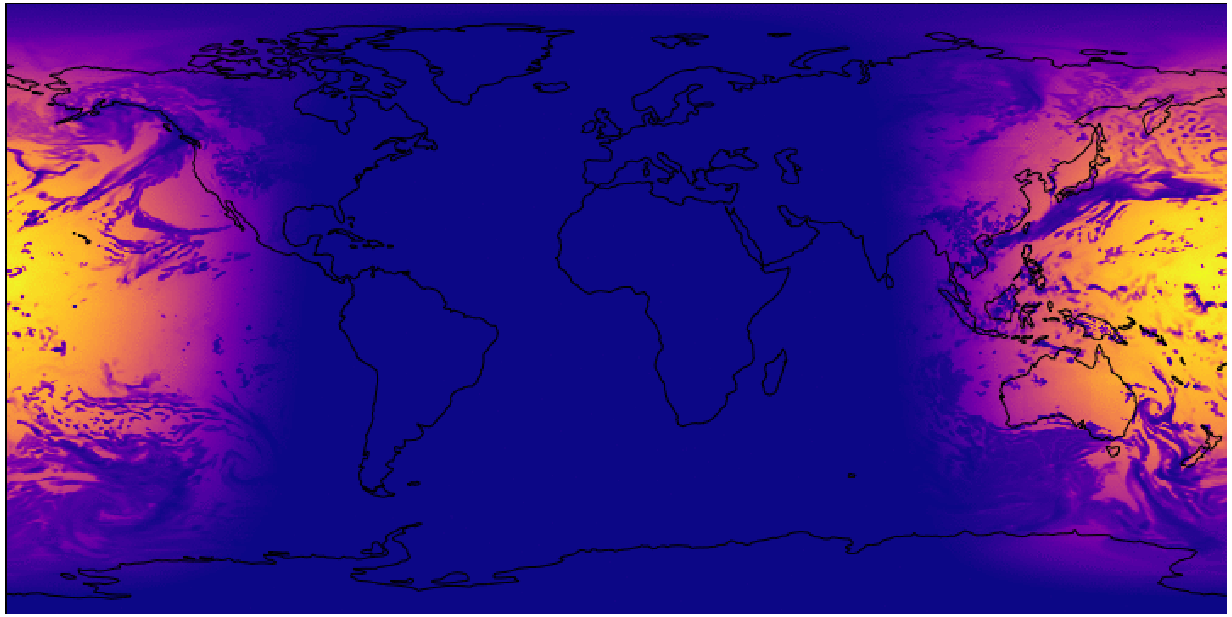


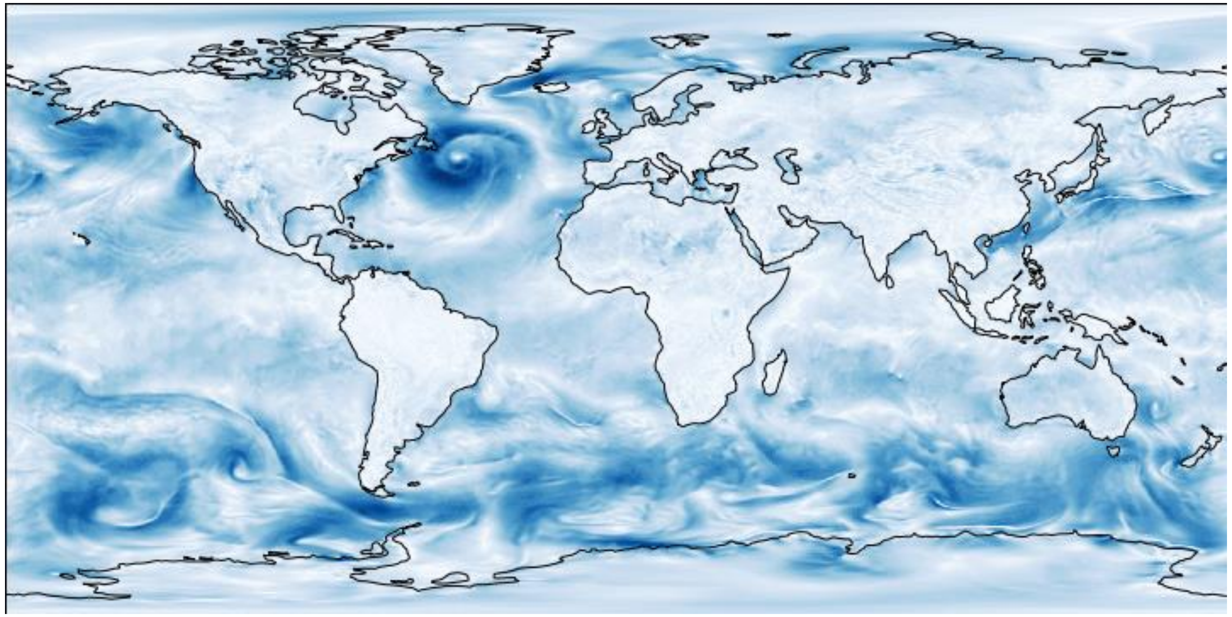
https://www.danmarkpaafilm.dk/film/nibe-vindmoellerne

https://www.tvindkraft.dk/how-it-began-the-history-of-wind-power/

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

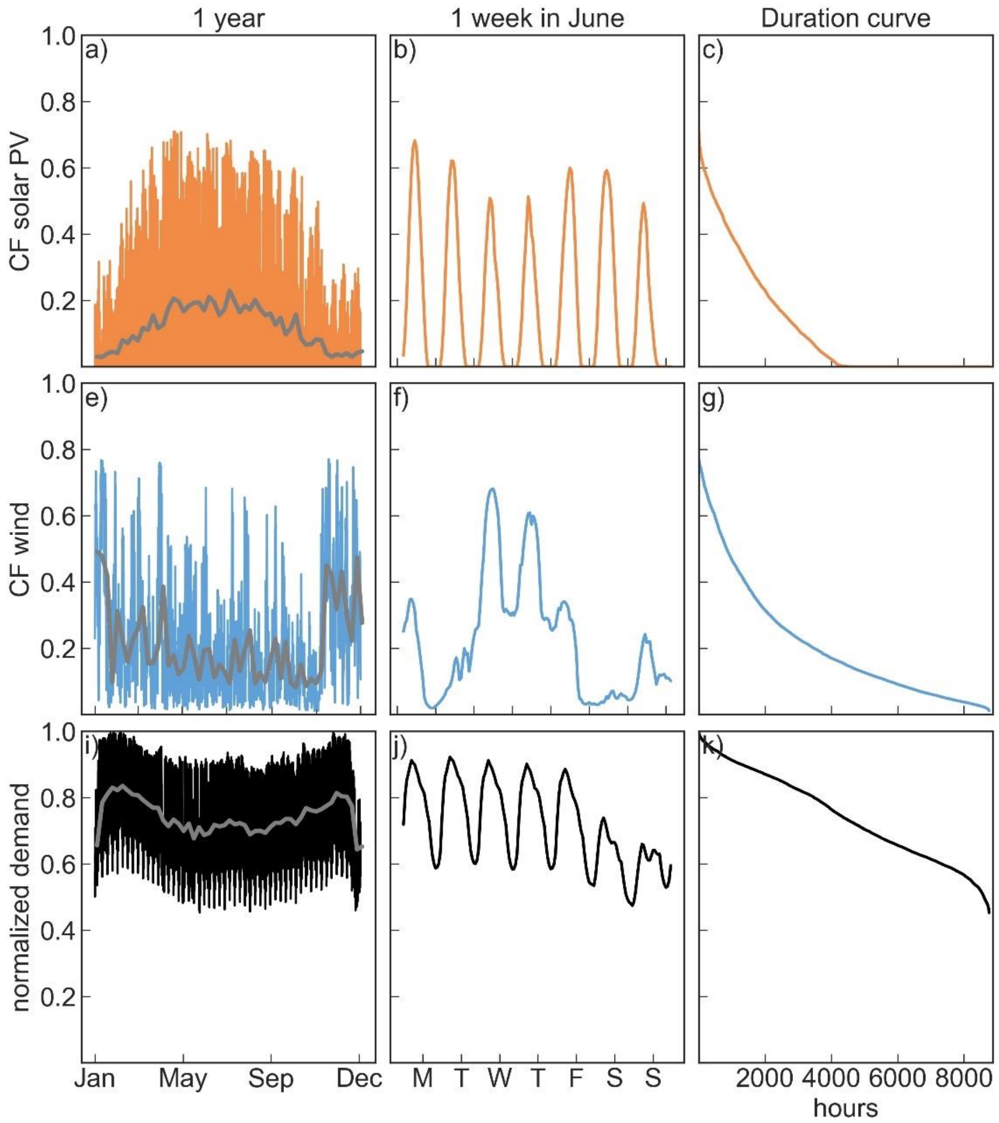


Fig: Solar, wind and electricity demand in Germany [Victoria, 2024]

Solar PV and wind energy cause 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.

$$CF_t = \frac{\text{actual electrical energy output}}{\text{installed capacity} \cdot 1 \text{ hour}} \qquad \overline{CF_t} = \frac{\text{annual electrical energy output}}{\text{installed capacity} \cdot 8760 \text{ hours}}$$

- 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

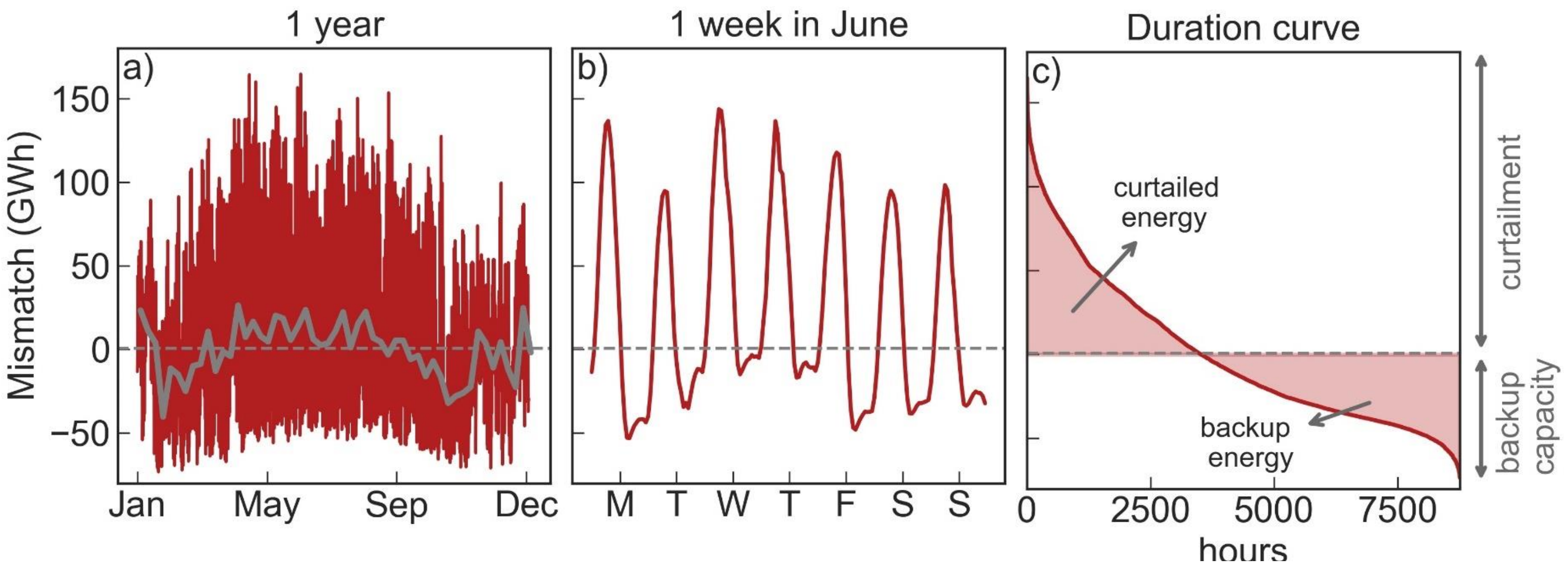
Mismatch between renewable generation and demand

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

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

Assuming: $\sum_t g_t^W + \sum_t g_t^S = \sum_t d_t$

$$\sum_t g_t^W = \sum_t g_t^S$$



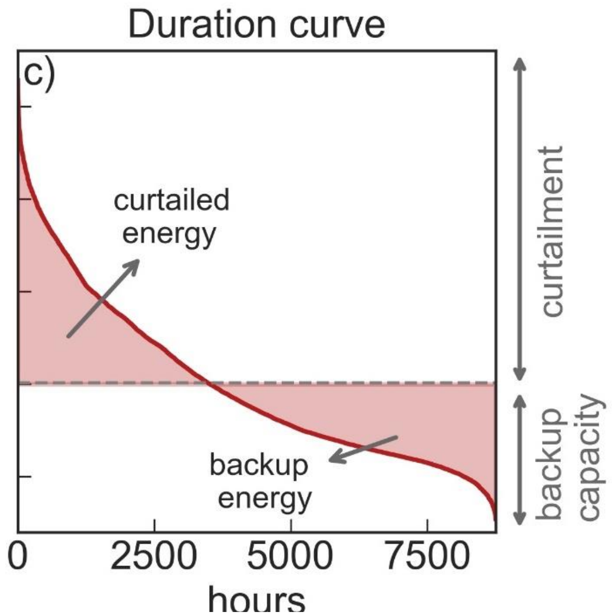
renewable energy is wasted

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

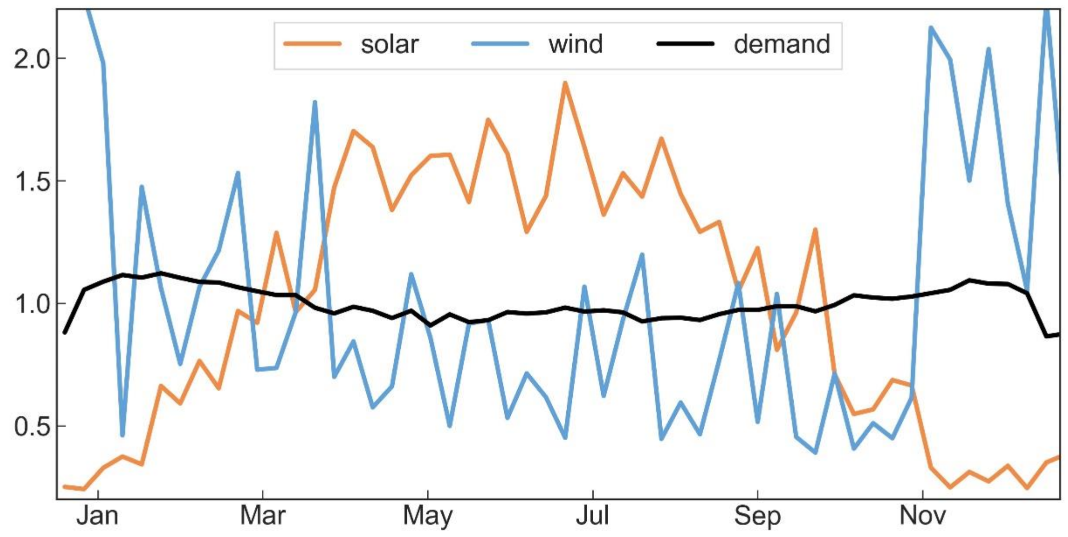
Cf. Problem 1.1

Mismatch between renewable generation and demand

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



Solar and wind show opposite seasonal variation (in most regions)



backup energy $E_B = \sum_{t=0}^{8759} \Delta_t^-$

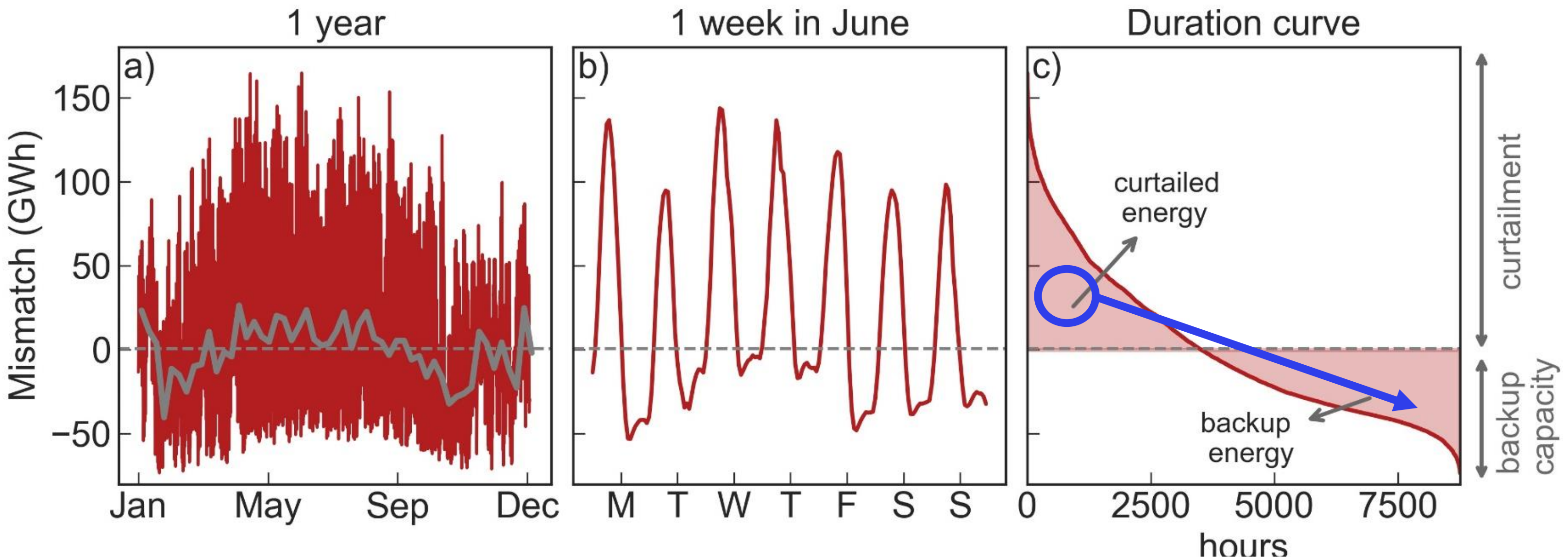
backup capacity $C_B = \max |\Delta_t^-|$

curtailed energy $E_C = \sum_{t=0}^{8759} \Delta_t^+$

See Problem 1.3

Mismatch between renewable generation and demand

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



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.

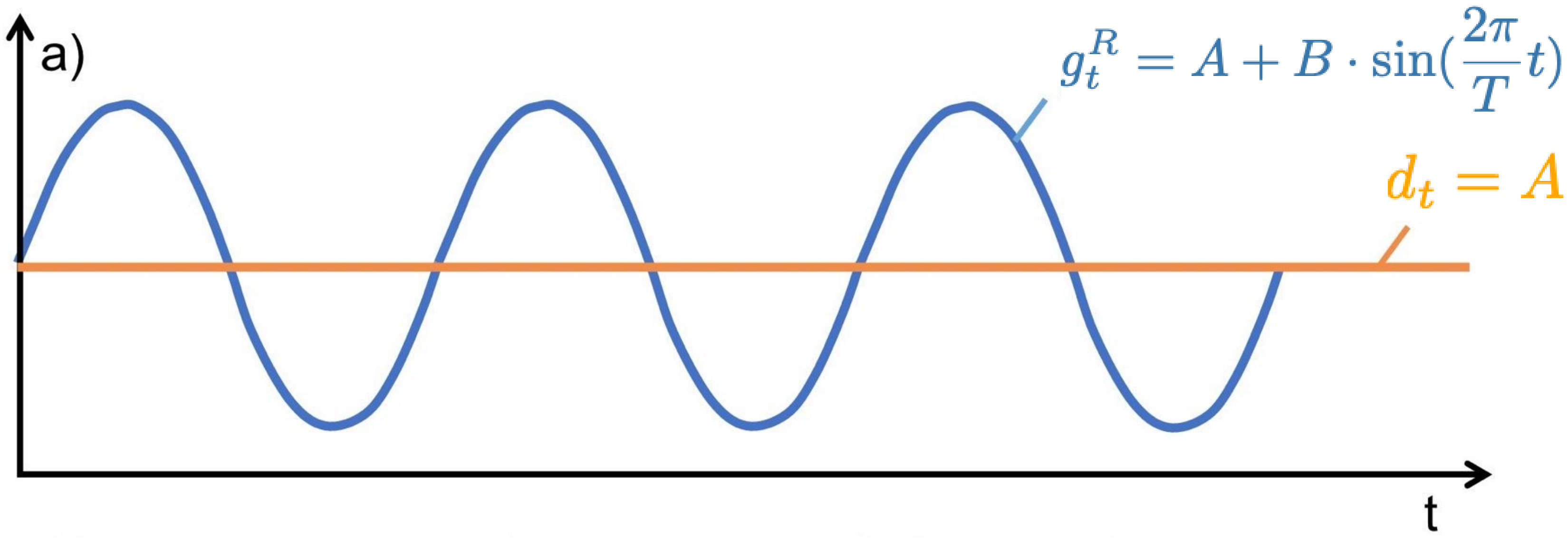
Balancing using storage

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)

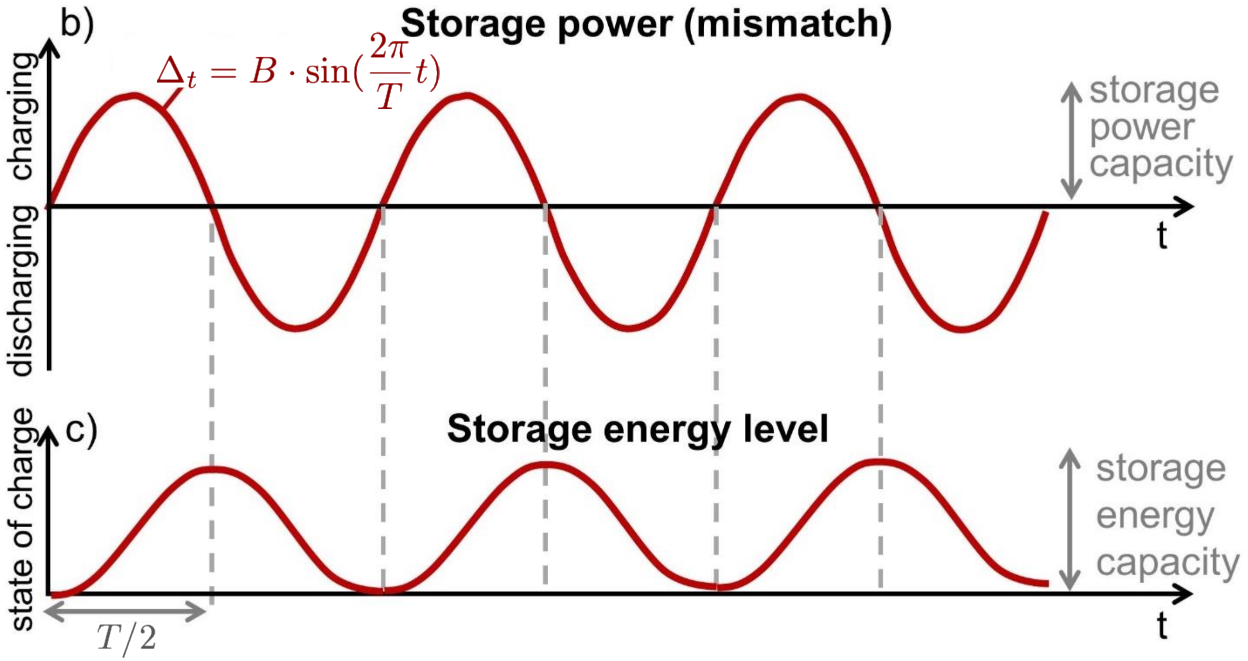
Let's assume a constant electricity demand *D* = *A* and a variable renewable generator that oscillates with period T.



Balancing using storage

We can plot the mismatch as the difference between renewable generation and demand.

$$\Delta_t = g_t^R - d_t = A + B \cdot \sin(\frac{2\pi}{T}t) - A$$



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

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

$$\Delta_t = B \cdot \sin(\frac{2\pi}{T}t)$$

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:

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

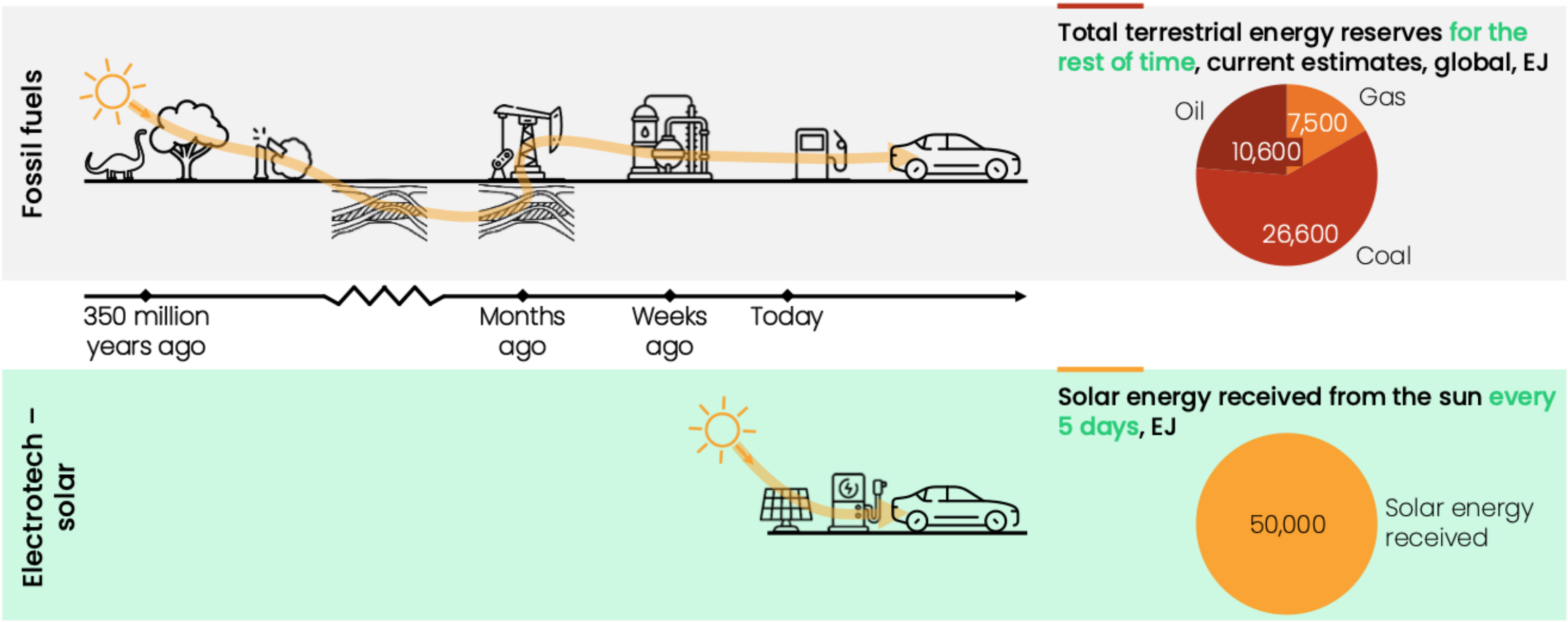
The dominant frequencies for wind and solar determine the storage necessary to balance them:

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)



Source: Ember

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 regional integration

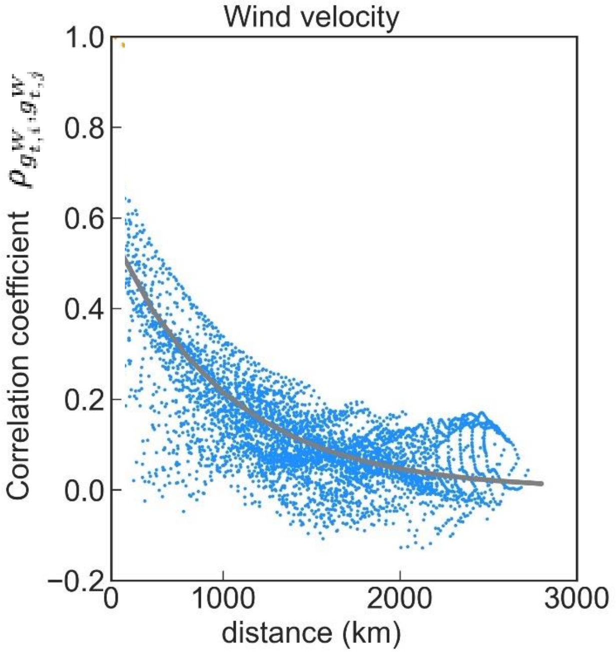
Transmission moves energy from regions with a generation excess to those with a deficit.

The correlation coefficient for wind velocity

$$\rho_{g^W_{t,i}, g^W_{t,j}} = \frac{cov(g^W_{t,i}, g^W_{t,j})}{\sigma_{g^W_{t,i}} \cdot \sigma_{g^W_{t,j}}}$$

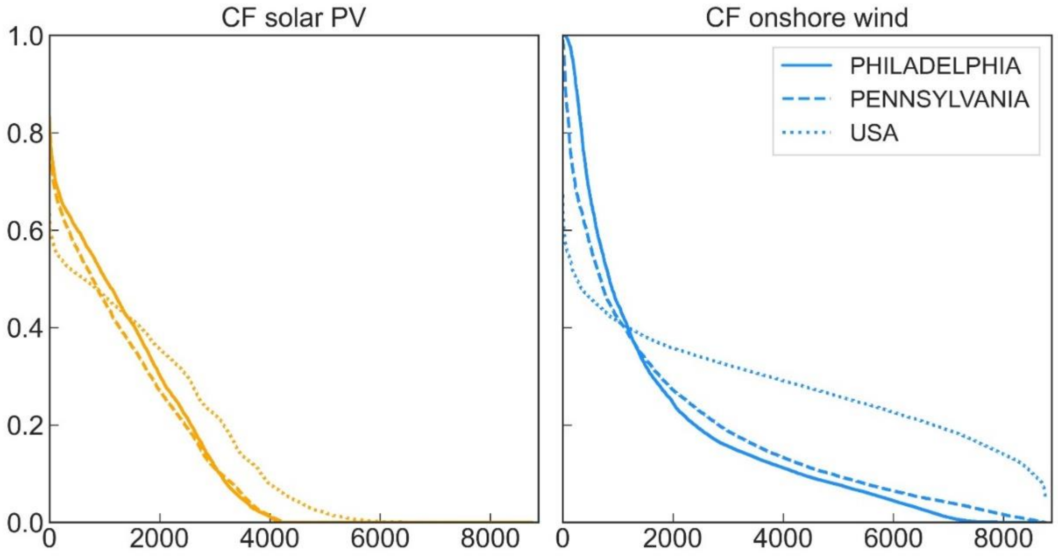
follows an exponential decay with distance

$$\rho_{g^W_{t,i}, g^W_{t,j}} = \exp(-\frac{1}{\xi_c} d_{i,j})$$



Victoria, 2024

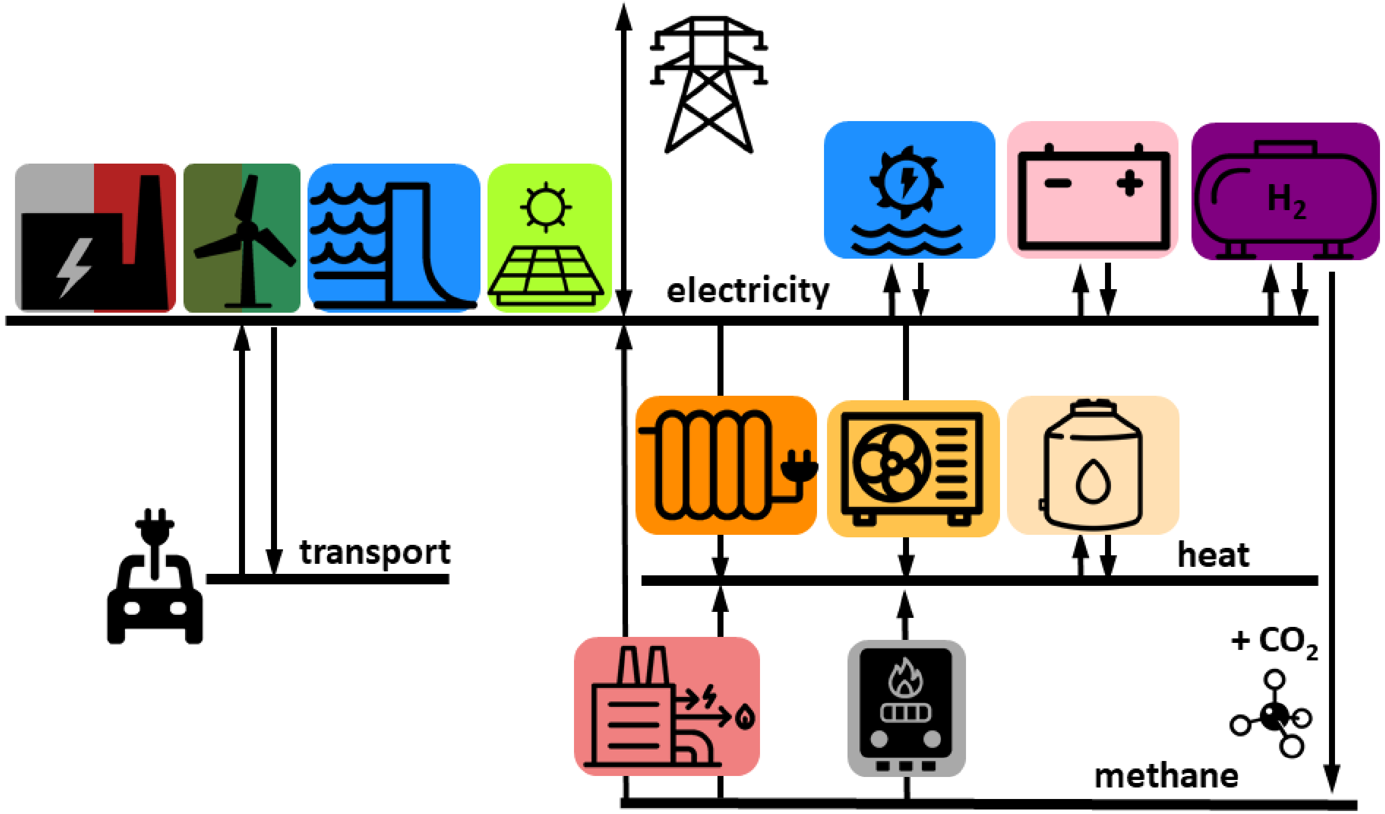
283 miles (485 km)



See Problem 1.4

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 / other carriers

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

Further readings and additional resources

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

Recommended watching:

The Tipping Points of Climate Change – and Where We Stand

https://www.youtube.com/watch?v=Vl6VhCAeEfQ

How cheap renewable energy is finally flattening emissions

https://www.youtube.com/watch?v=Z8JFCJP70rg

Welcome to the Era of Energy Disruption

https://www.youtube.com/watch?v=VXwGvLj4rak

How electricity gets to you

https://www.youtube.com/watch?v=xhxo2oXRiio

Problems for this lecture

Install python, gurobi, and course environment

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

Review tutorials on python, numpy, pandas and matplotlib

https://aleks-g.github.io/integrated-energy-grids/intro-python.html (et al)

Complete Multiple-choice test in Lecture 1 in DTU Learn

To be presented next lecture:

Problems 1.1 (**Group 1**)
Problems 1.2, 1.3 (**Group 2**)
Problems 1.4 and –optional- Problem 1.5 (**Group 3**)