


Energy Systems, Summer Semester 2026

Lecture 1: Organisation & Introduction

Prof. Tom Brown, Philipp Glaum

[Department of Digital Transformation in Energy Systems](#), Institute of Energy Technology, TU Berlin

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1. Administration
2. Course Structure
3. What is Energy System Modelling?
4. The Greenhouse Gas Challenge & The Energy System
5. Invitation: Balancing Variable Renewable Energy in Europe

Administration

Prof. Dr. Tom Brown

Department of 'Digital Transformation in Energy Systems', Institute of Energy Technology

I specialise in the modelling of energy systems to meet strict greenhouse gas emission targets. I work at the intersection of engineering, economics, informatics, mathematics & meteorology.

Philipp Glaum is a research assistant in our group and will lead the tutorials; he can also answer any organisational questions (p.glaum@tu-berlin.de). Please do not email me.

Group website: <https://www.tu.berlin/ensys>

Personal website: <https://nworbmot.org/>

You can find links to lecture notes, exercise sheets and all other information on ISIS:

<https://isis.tu-berlin.de/course/view.php?id=47916>

Course abbreviation: [SoSe 2026] Energy Systems

Announcements will also be made there, and you can ask questions in the discussion forum.

All lecture slides will be available there as PDFs shortly before each lecture.

MTS: Energy Systems (6 LP)

Registration:

- via MTS (up to one week before the exam)
- Erasmus: try via MTS, if that fails, register via ISIS (exam registration)

- Written exam in presence
- 90-minute exam
- Dates: 04.08.2026 1030-1200, 24.09.2026 1330-1500
- Sample exams in last weeks of lectures
- Content: as in lecture and tutorials
- Voluntary group project (six unsupervised study periods in June) can boost grade by 5 points
- No programming is needed in the exam (students only need to know programming for the group project)

3 ECTS seminar together with Prof. Gunnar Luderer's group at PIK (Potsdam Institut für Klimafolgenforschung)

- Students analyse a recent research paper on energy system modelling looking at transformation of energy system over next decades
- Students prepare a 20-minute presentation and present it for discussion
- Presentations as a block at the end of the lecture-free period
- Students work on topic with a supervisor during semester (2-3 meetings)
- Topics will be presented during a lecture in May 2026, presentations in September 2026
- Example topics: integration of renewable energy, hydrogen trade, storage modelling, endogenous learning, role of carbon capture

[Seminar ISIS page](#)

6 ECTS course led by Dr. Fabian Neumann

- Students get hands-on experience modelling and analysing future energy systems
- All coursework in programming language Python plus associated libraries
- Focus on renewable energy resources, storage and network infrastructures
- Working with real data on weather, land use, power plants, grids and demand
- Learn about the challenges and solutions for a successful transition towards climate-neutral energy systems across the globe

[Course ISIS page](#)

First lecture: Tue 14th April 2026 1415 in BIB 014.

3 ECTS excursion on Friday 3rd July 2026 to Verbio Biogas Plant near Schwedt (2 hours by bus).

The biogas plant uses exclusively straw as a feedstock, making it a pioneer in sustainable biomass.

Students have to give a 7-minute presentation and write up a report afterwards.

Day	Time	Location	Event
Tuesday	1000-1200	H 0111	Lecture
Wednesday	1000-1200	HFT-TA 101	Tutorial
Thursday	1600-1800	HFT-TA 131	Lecture

First lecture: Tuesday 14th April 2026, last lecture: Thursday 16th July 2026

First tutorial: Wednesday 22nd April 2026

Some of the exercises will require you to program in **Python**, so please do an online tutorial in Python if you don't know it. We will help you to install Python and the requisite libraries.

Mathematics requirements: linear algebra, Fourier analysis, basic calculus, basic statistics.

There is no book which covers all aspects of this course. In particular there is no good source for the combination of data analysis, complex network theory, optimisation and energy systems. But there are lots of online lecture notes. The world of renewables also changes fast...

The following are concise:

- Joshua Adam Taylor, “Convex Optimization of Power Systems”, Cambridge University Press, 2018
- Volker Quashning, “Regenerative Energiesysteme”, Carl Hanser Verlag München, 2015
- Leon Freris, David Infield, “Renewable Energy in Power Systems”, Wiley, 2006
- Göran Andersson Skript, “Elektrische Energiesysteme: Vorlesungsteil Energieübertragung,” online
- D.R. Biggar, M.R. Hesamzadeh, “The Economics of Electricity Markets,” Wiley, 2014

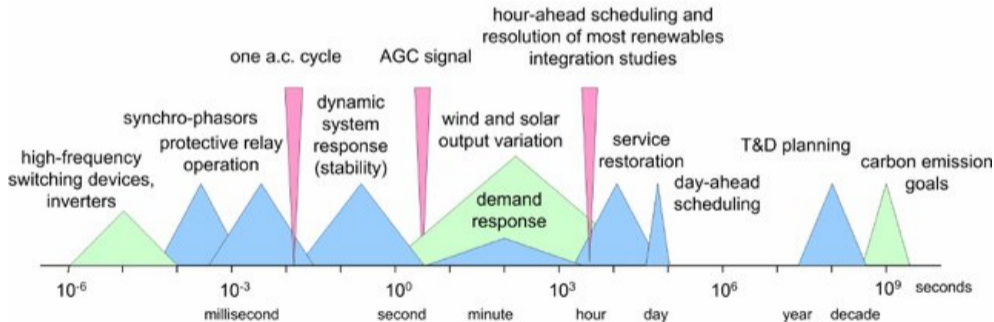
Course Structure

Energy System Modelling requires methods and skills from several disciplines:

- **Engineering:** Technical description of energy system components and interactions
- **Economics:** Efficient allocation of resources and infrastructure to meet consumer preferences
- **Informatics:** Large datasets, complex interactions
- **Meteorology:** Influence of weather and climate on demand and variable renewables
- **Geology:** Underground storage, geothermal power
- **Biology:** Biomass-Food-Water nexus
- **Sociology:** Impacts of consumer behaviour and preferences on energy system
- **Politics:** What policies are feasible and can be enabled in time

- Measuring energy
- Time series analysis for demand and renewables
- Backup generation, curtailment
- Network modelling in power systems
- Storage modelling
- Optimization theory
- Energy system economics
- Learning curves and long-term dynamics
- Reducing emissions in transport, heat and industry
- Current research topics

We will focus on the righthand side (hours to decades):



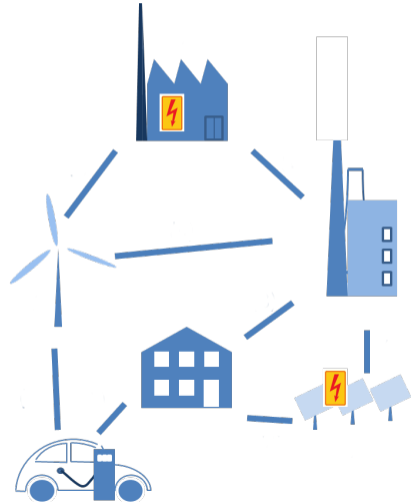
What is Energy System Modelling?

Energy System Modelling is about the overall **design** and **operation** of the energy system.

- What are our **energy needs**?
- What **infrastructure** do they require?
- **Where** should it go?
- How much will it **cost**?

The answers to these questions affect **hundreds of billions** of euros of spending per year in Europe.

Researchers deal with these questions by **building computer models** of the energy system and then, for example, **optimizing** its design and operation.



Broadly speaking, we model energy systems to help **society** make decisions. Examples:

Government agencies commission studies to look at possible future scenarios:

But also companies and non-governmental organisations:



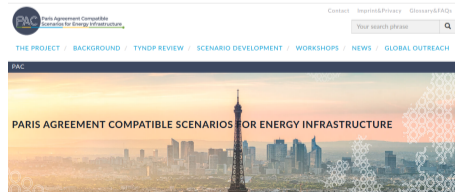
MENÜ

Suchbegriff eingeben

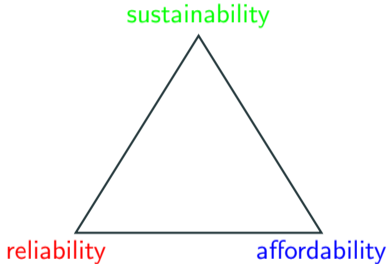


ARTIKEL [Energiedaten und -szenarien](#)

Langfrist- und Klimaszenarien



Optimization - but with respect to what? We design with respect to three goals:

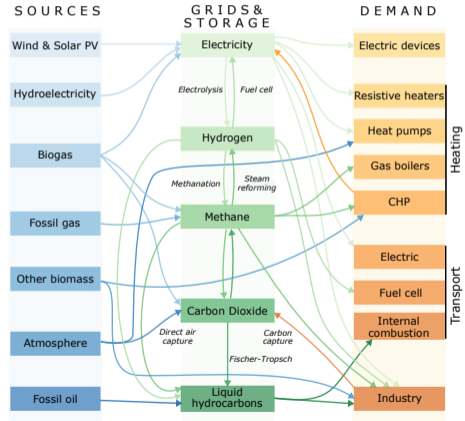
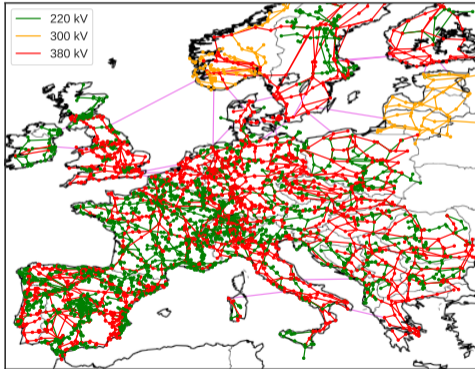


- **Sustainability:** Respect environmental constraints (greenhouse gases, air quality, preservation of wildlife), social and political constraints (geopolitics, public acceptance of transmission lines, onshore wind, nuclear power)
- **Reliability:** Ensure energy services are delivered whenever needed, even when the wind isn't blowing and the sun isn't shining, and even when components fail
- **Affordability:** Deliver energy at a reasonable cost

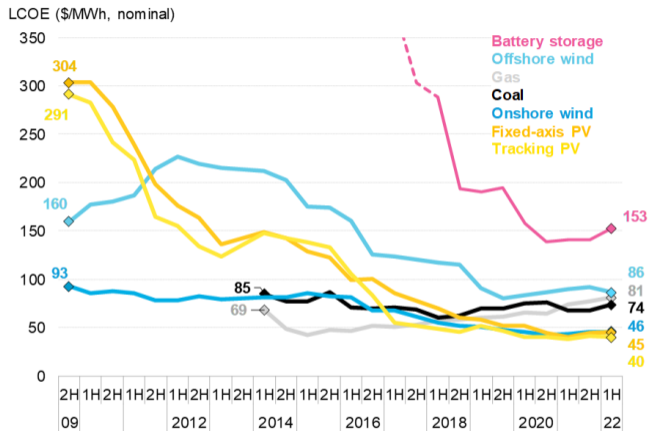
Some of these policy targets can come into **conflict** - an **energy trilemma**.

Why it's hard: many components and interactions

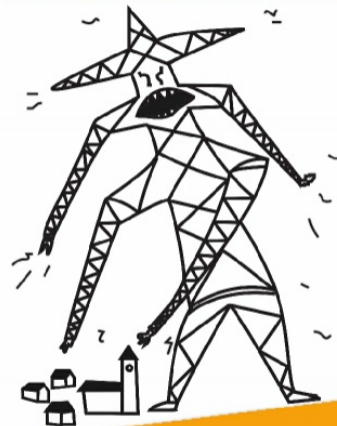
Need to model: (at least) all of Europe for market integration; enough spatial and temporal detail to capture all important effects; all interactions between energy sectors; correct physics.



Why it's hard: non-linearities and social effects



www.berngau-gegen-monstertrasse.de

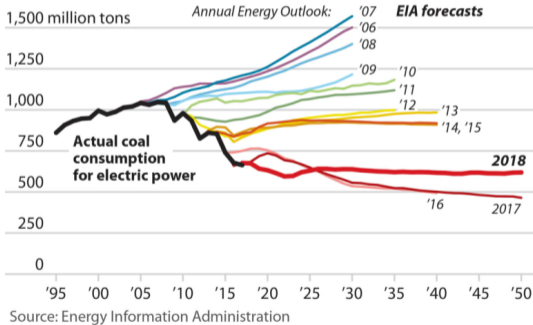


Nein! ZUR MONSTERTRASSE!

Not everyone gets it right...

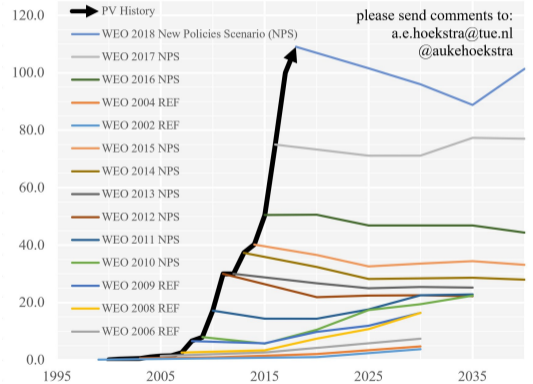
EIA Coal Consumption Forecasts, 2006-2018

Each year, the Energy Information Administration releases its Annual Energy Outlook, which includes a long-term forecast for U.S. coal consumption for electric power generation. However, the forecasts have been wildly inaccurate, even in the near term.



Annual PV additions: historic data vs IEA WEO predictions

In GW of added capacity per year - source International Energy Agency - World Energy Outlook



05.02.2014

Ifo-Chef Sinn zur Energiewende

"Die einzige Hoffnung der Menschheit war die Atomkraft"

Von Nils-Viktor Sorge

Teilen: [f](#) [K](#) [t](#) [+](#) [in](#) [t](#) [p](#)



Wirtschaftsforscher Sinn: "Ruinen einer völlig verzerrten und ideologischen Energiepolitik"

Sinn's study was [debunked](#) using an open model (he exaggerated storage requirements by 'up to **two orders of magnitude**')

HOME » WIRTSCHAFT » E-AUTO: HANS-WERNER SINN RÄUMT MIT WEIT VERBREITETEM MYTHOS AUF

„Großer Schwindel“: Hans-Werner Sinn räumt mit Mythos über E-Autos auf

BI Business Insider Deutschland
26 Dec 2019

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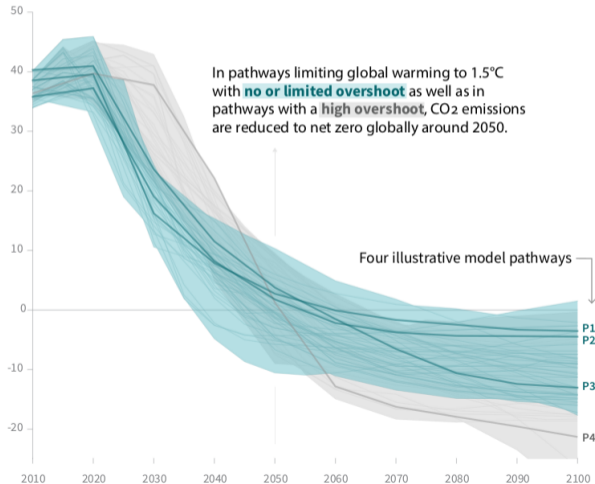


Sinn's study was [debunked](#), shown to use cherry-picked assumptions

The Greenhouse Gas Challenge & The Energy System

Global total net CO₂ emissions

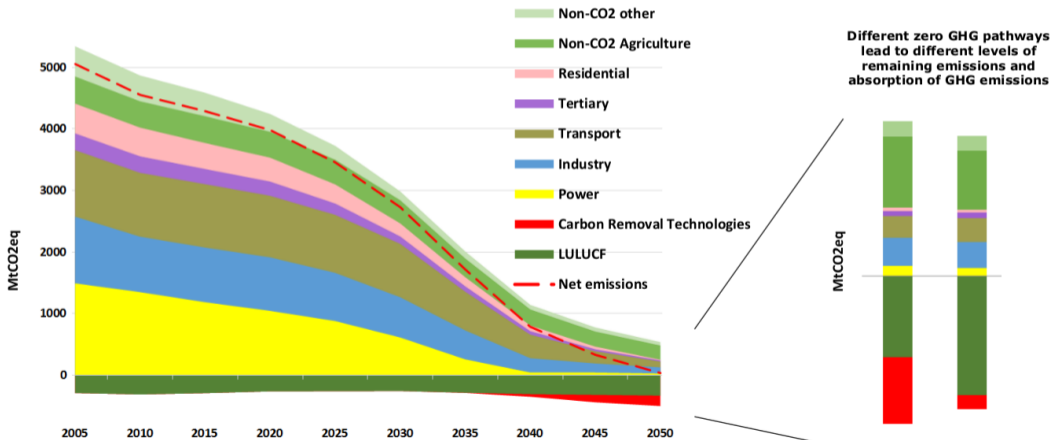
Billion tonnes of CO₂/yr



- Scenarios for global CO₂ emissions that limit warming to 1.5°C about industrial levels (**Paris agreement**)
- Today emissions **still rising**
- Level of use of negative emission technologies (NET) depends on rate of progress
- 2°C target without NET also needs rapid fall by 2050
- Common theme: **net-zero by 2050**

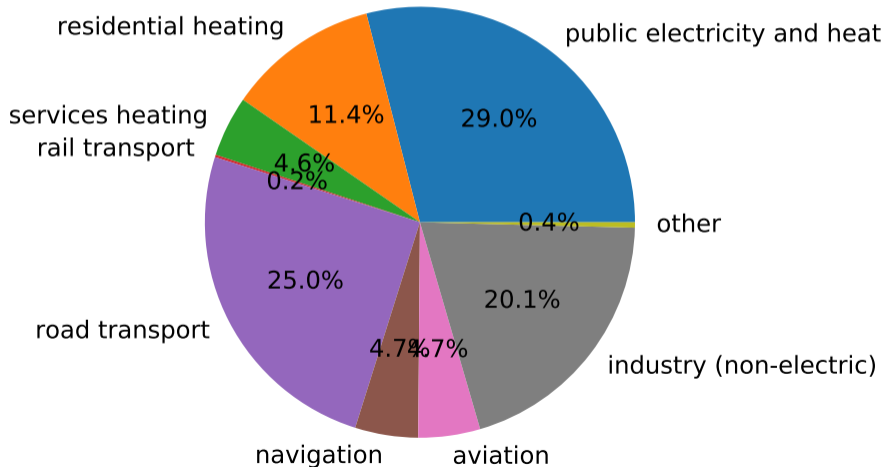
The Greenhouse Gas Challenge: Net-Zero Emissions by 2050

Paris-compliant 1.5° C scenarios from European Commission for **net-zero GHG in EU by 2050**. This target has been adopted by the EU and enshrined in the **European Green Deal**.



It's not just about electricity demand...

EU28 CO₂ emissions in 2016 (total 3.5 Gt CO₂, 9.7% of global):



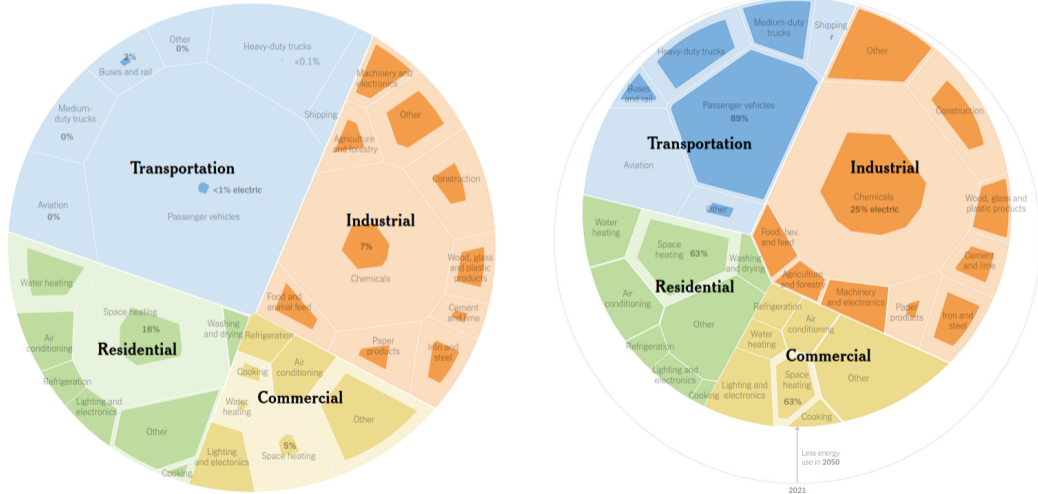
Electrification is essential to decarbonise sectors such as transport, heating and industry, since we can use low-emission electricity from e.g. wind and solar to displace fossil-fuelled transport with electric vehicles, and fossil-fuelled heating with electric heat pumps.

Some scenarios show a **doubling or more of electricity demand**.

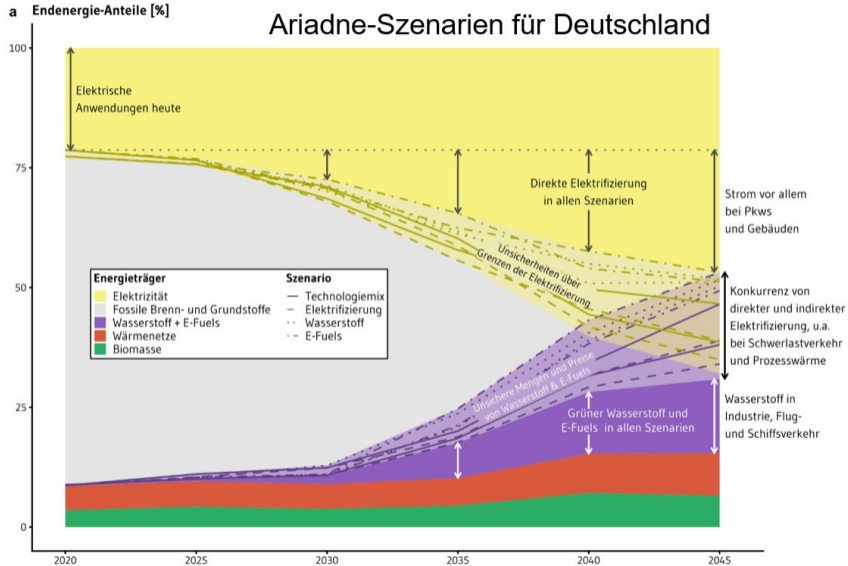


Many scenarios show an increase in electrification

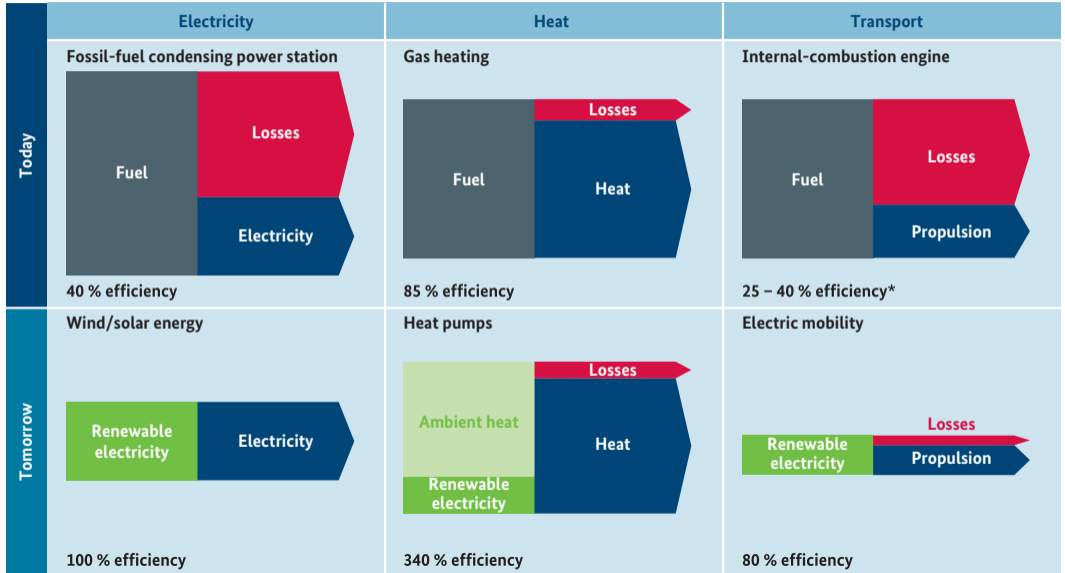
Electricity as a fraction of final energy demand in 2019 versus 2050 in United States.



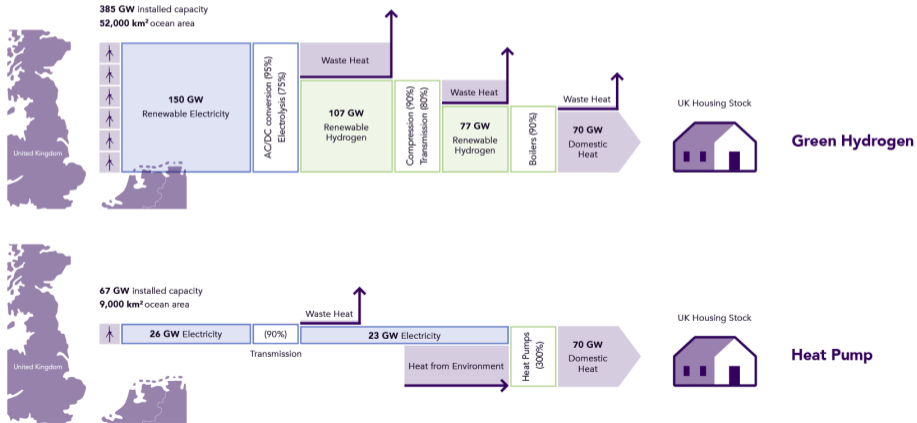
Many scenarios show increase in electrification



Efficiency of renewables and electrification

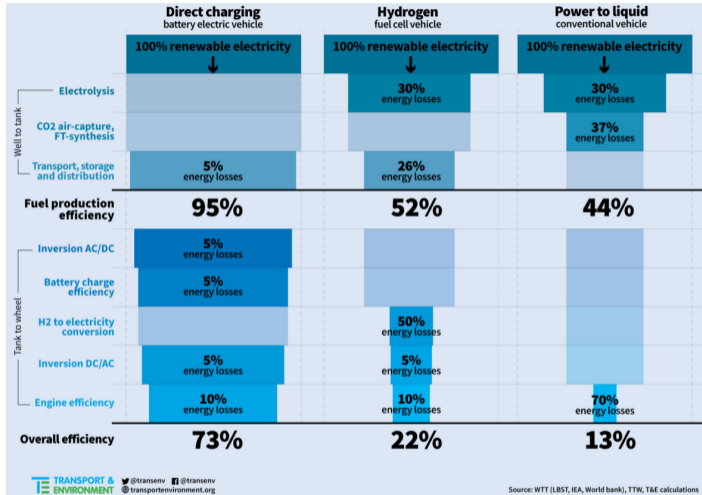


Heating the UK with Heat Pumps or Green Hydrogen



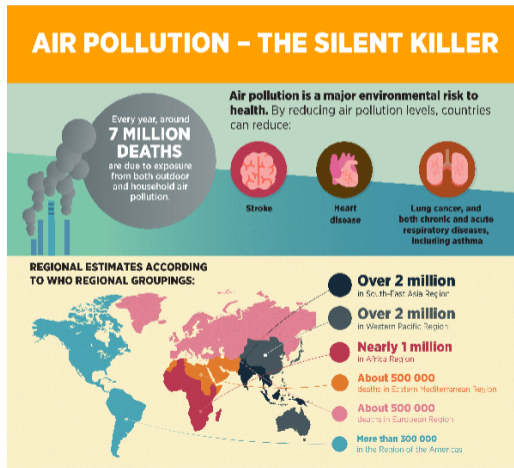
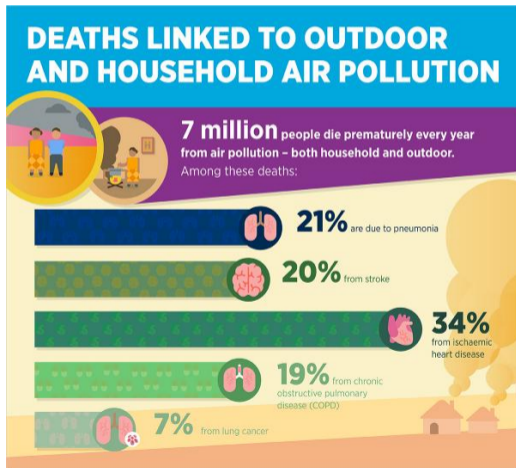
h₂

Electric vehicles versus efuels



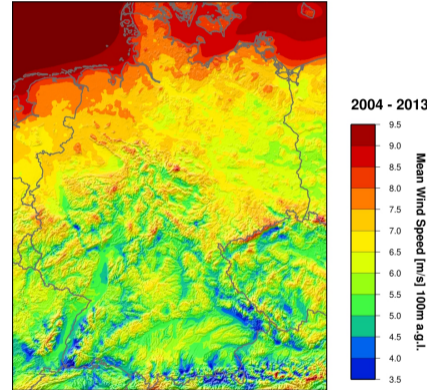
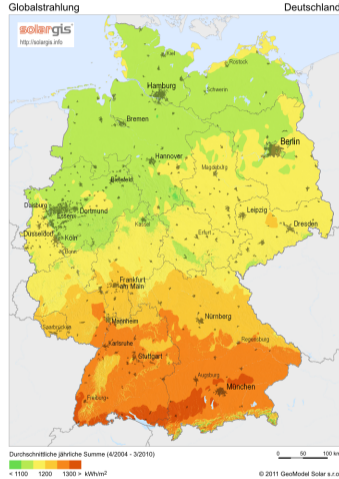
Important caveat: efficiency is not cost. There are regions in the world (e.g. Patagonia) with very inexpensive wind and solar resources for efuels, where low cost could outweigh losses.

Air pollution from fossil fuel burning is linked to higher mortality (deaths) and morbidity (diseases, e.g. aggravation of asthma).

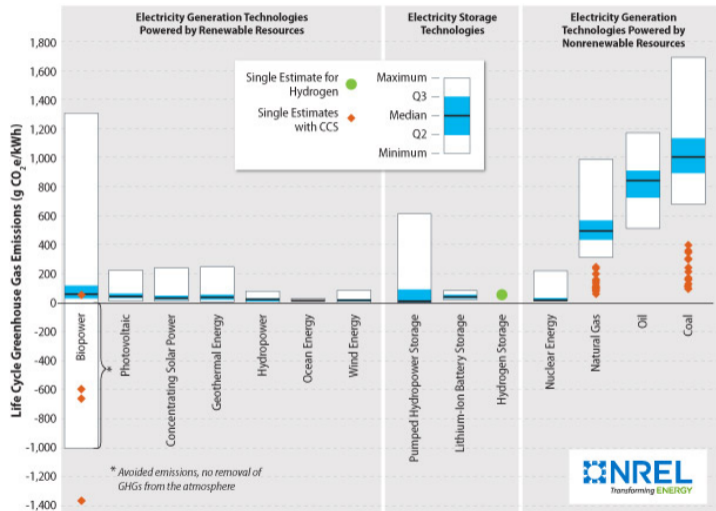


Why focus on wind and solar for electricity generation?

- construction and operation have low greenhouse gas emissions
- good wind and sun are available in many parts of the world
- worldwide potential that exceeds demand by many factors
- rapidly falling costs

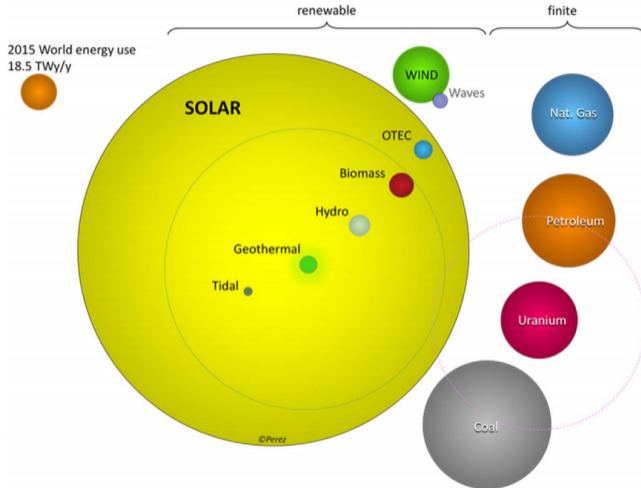


Life Cycle Analysis (LCA) of generation technologies



Estimates	276 (+4)	46	36	35	149	10	186	16	29	1	99	80 (+13)	24	164 (+11)
References	57 (+2)	17	10	15	22	5	69	4	3	1	27	47 (+11)	10	53 (+9)

- **Life Cycle Analysis (LCA)** includes emissions and other impacts from construction, lifetime and end-of-life of generation assets (excluding land use here)
- Includes e.g. emissions from producing materials for generators (e.g. silicon for PV panels, concrete and steel for wind)
- PV, wind, geothermal and nuclear score well



RENEWABLE

Solar	23,000 TWy/y	Biomass	2-6 TWy/y
Wind	75-130 TWy/y	Hydro	3-4 TWy/y
Waves	0.2-2 TWy/y	Geotrm	0.2-3++ TWy/y
OTEC	3-11 TWy/y	Tidal	0.3 TWy/y

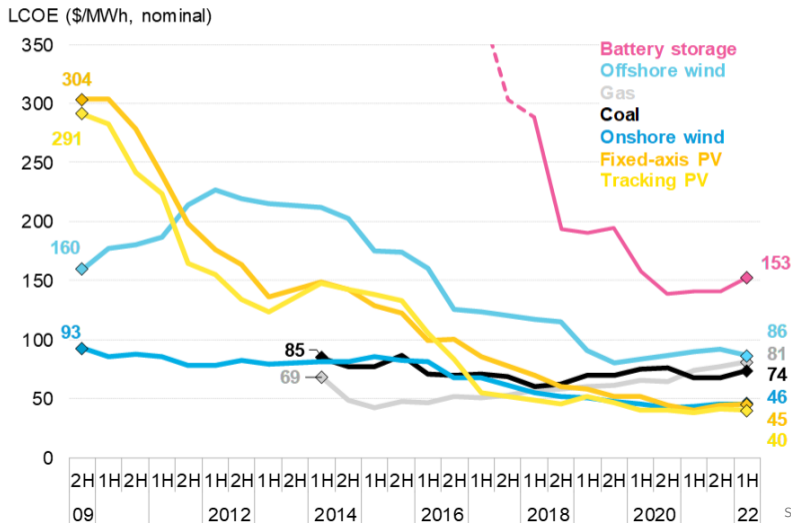
FINITE

Nat. Gas	220 TWy
Petroleum	335 TWy
Uranium	185++ TWy
Coal	830 TWy

- Potentials for wind and solar exceed current demand by many factors (ignoring variability)
- Other renewable sources include wave, tidal, geothermal, biomass and hydroelectricity
- Uranium depends on the reactor: conventional thermal reactors can extract 50-70 times less than fast breeders

Low cost of wind & solar per MWh (NB: ignores variability)

LCOE = **Levelised Cost of Energy** = Total Costs / Energy Output

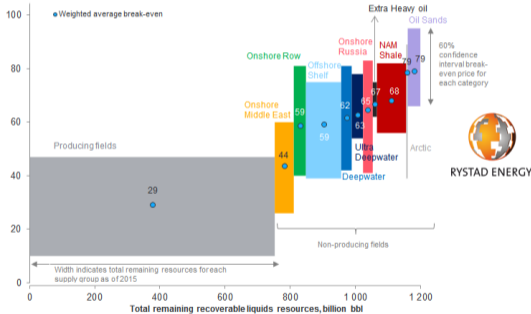


Fundamental shift from scarce exhaustible to renewable energy

Fossil fuel costs rise with exploitation (can also drop with innovation)

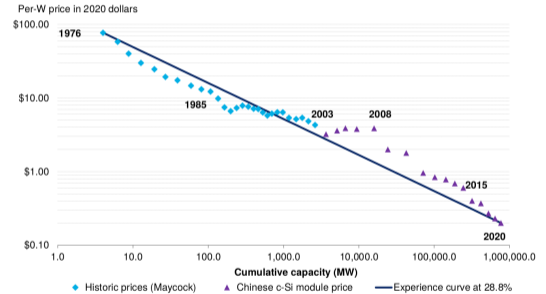
Solar and wind costs drop with innovation (can rise locally where land is scarce)

GLOBAL LIQUIDS COST CURVE*
Real Brent USD/bbl



*The break-even price is the Brent oil price at which NPV equals zero using a real discount rate of 7.5%. Resources are split into two life cycle categories: producing and non-producing (under development and discoveries). The latter is further split into several supply segment groups. The curve is made up of more than 20,000 unique assets based on each asset's break-even price and remaining liquids resources in 2015. Source: Rystad Energy UCube September 2015

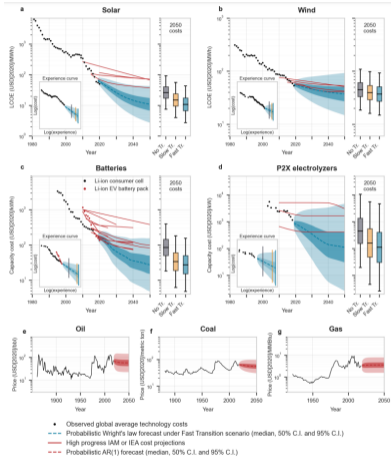
PV module experience curve (2020\$/W, MW)



(1 TW of solar generates ~1200 TWh/a compared to global electricity demand of ~24,000 TWh/a)

(2019 consumption was ~37 billion barrels)

4 critical technologies: wind, solar, batteries, electrolyzers



All the critical technologies for the energy transition share a small unit size, enabling fast production and installation, economies of scale in manufacturing and learning-by-doing.

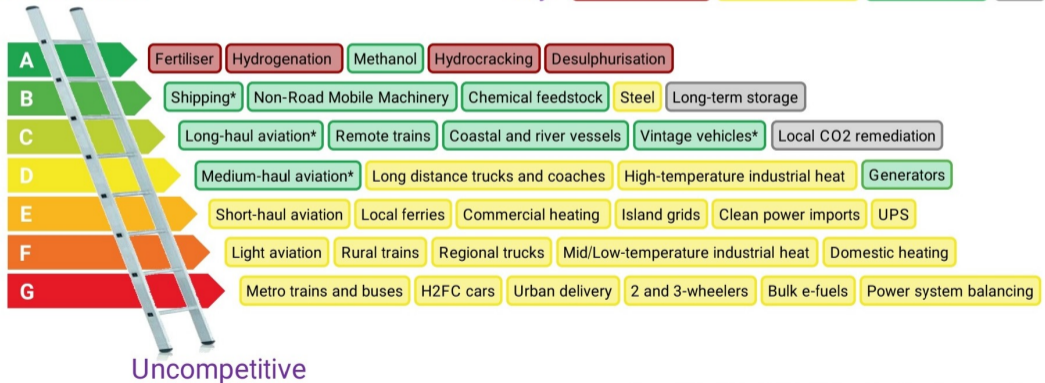
- **Low-cost electricity** from wind and solar.
- **Batteries** for mobility and balancing applications.
- **Electrolytic hydrogen** (splitting water) for everything else: long-duration storage, aviation, shipping, industry.
- **Heat pumps** (missing from graphic) for building comfort and some low-temperature industry applications.

Hydrogen: the backstop of the energy transition

Clean hydrogen can do almost everything, but competes with direct electrification. Some say **champagne of energy transition**; could also say **backstop** for what efficiency and electrification don't reach.

Unavoidable

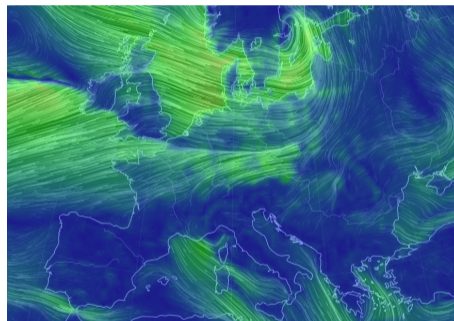
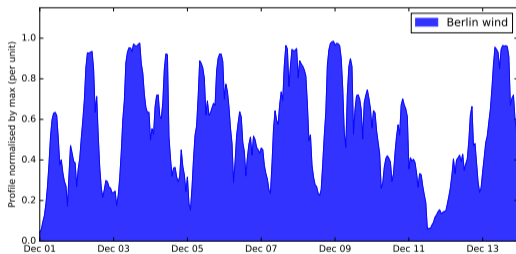
Key: No real alternative Electricity/batteries Biomass/biogas Other



* Most likely via ammonia or e-fuel rather than H2 gas or liquid

Source: Michael Liebreich/Liebreich Associates, *Clean Hydrogen Ladder, Version 4.1, 2021*. Concept credit: Adrian Hiel, Energy Cities. [CC-BY 3.0](#)

But must take account of variability...



WWW.BERNGAU-GEGEN-MONSTERTRASSE.DE



Sustainability doesn't just mean taking account of environmental constraints.

There are also **social and political constraints**, particularly for transmission grid and onshore wind development.



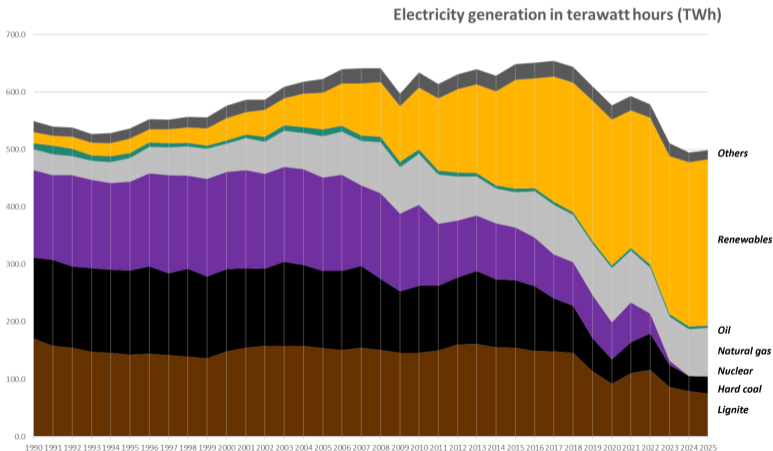
Energiewende: The Energy Transition, consists of several parts:

- Transition to an energy system with low greenhouse gas emissions
- Renewables replace fossil-fuelled generation (and nuclear in some countries)
- Increasing integration of international electricity markets
- Better integration of transmission constraints in electricity markets
- Sector coupling: heating, transport and industry electrify
- More decentralised location and ownership in the power sector

Renewables reached 56% of gross electricity in Germany in 2025

Gross electricity production in Germany 1990 - 2025, by source.

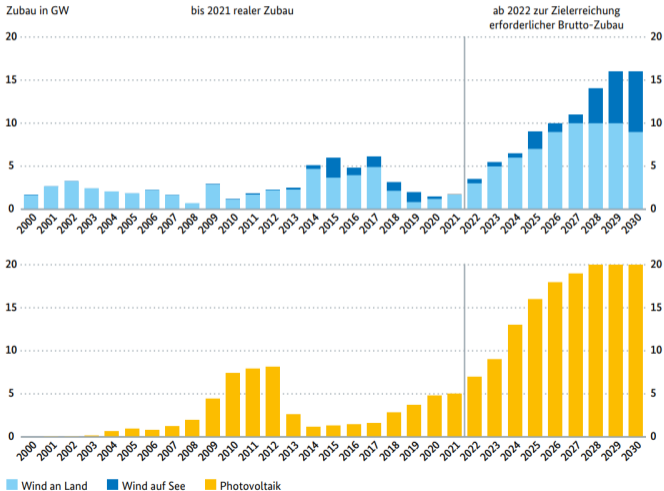
Data: AGEB 2025.



Build-out rates for wind and solar need to increase rapidly

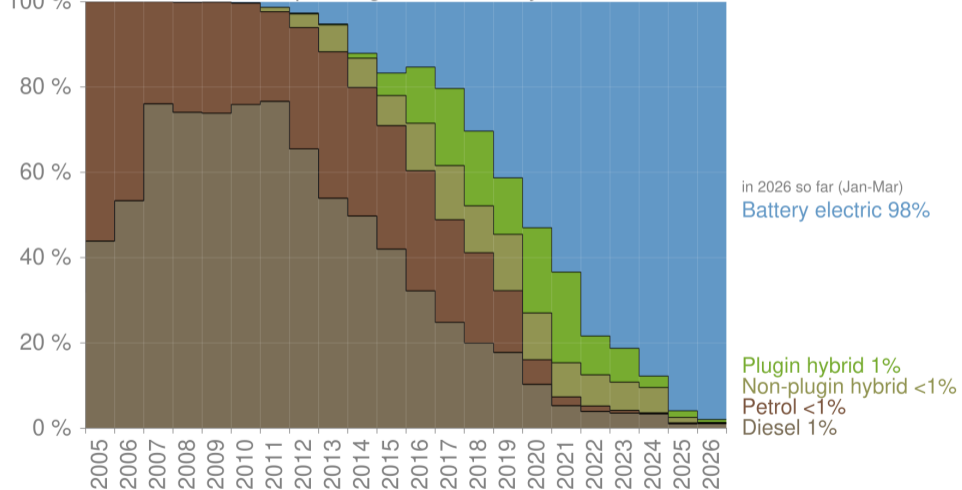
Germany has target of 80% renewable electricity by 2030, 100% by 2035.

Ausbau Wind und Photovoltaik



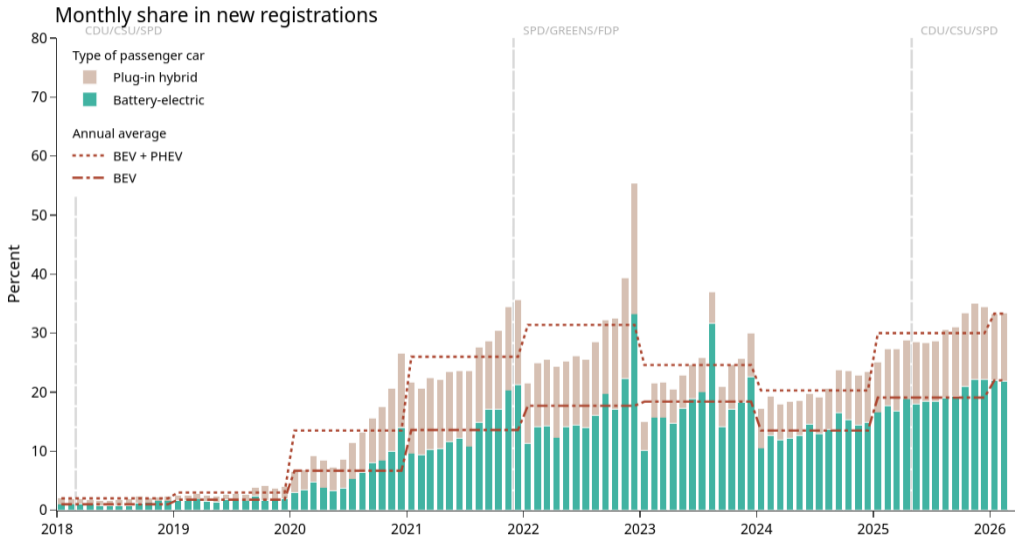
Electric vehicles take off, first in Norway

Annual sales of new passenger cars: Norway



©@robbieandrew.bsky.social ● Data: SVV/OFV

Electric vehicles: Germany catching up?



Last Update: 16.03.2026

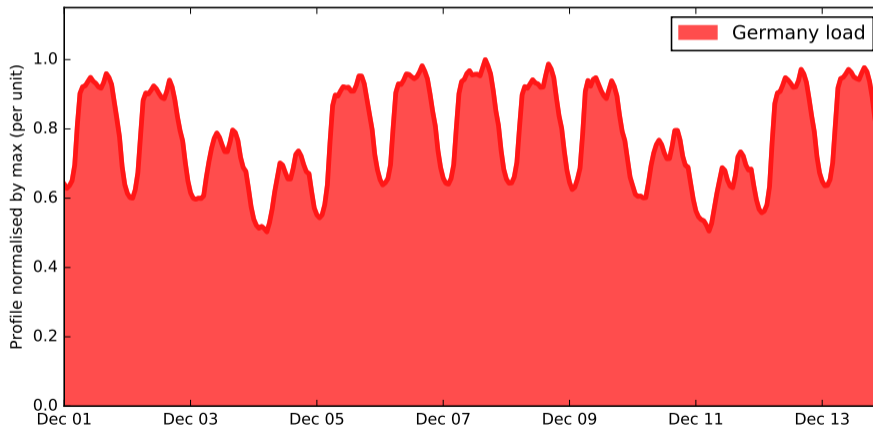
Source: [Open Energy Tracker, 2026](#)

Invitation: Balancing Variable Renewable Energy in Europe

1. What **infrastructure** (wind, solar, hydro generators, heating/cooling units, storage and networks) does a highly renewable energy system require and **where** should it go?
2. Given a desired CO₂ emissions reduction (e.g. 95% compared to 1990), what is the **cost-optimal** combination of infrastructure?
3. How do we deal with the **variability** of wind and solar: balancing in space with networks or in time with storage?

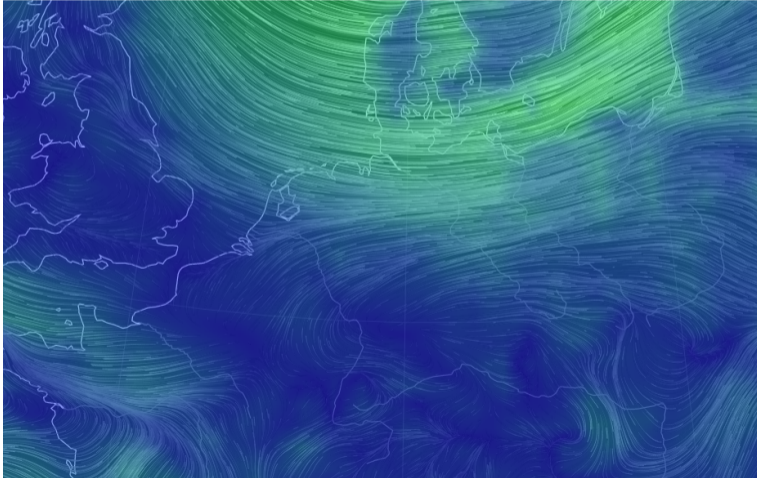
Electricity consumption is much more regular

Electrical demand is much more regular over time - dealing with the **mismatch** between locally-produced wind and the demand would require a lot of storage...

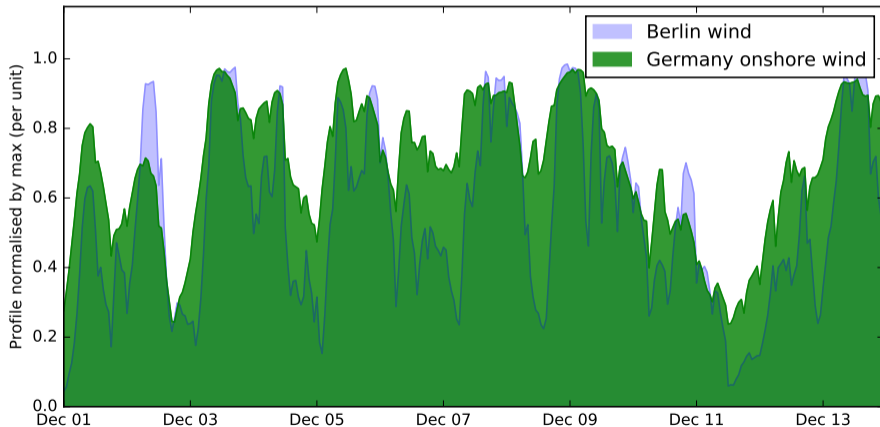


Variability: Different wind conditions over Germany

The wind does not blow the same at every site at every time: at a given time there are a variety of wind conditions across Germany. These differences **balance out over time and space**.

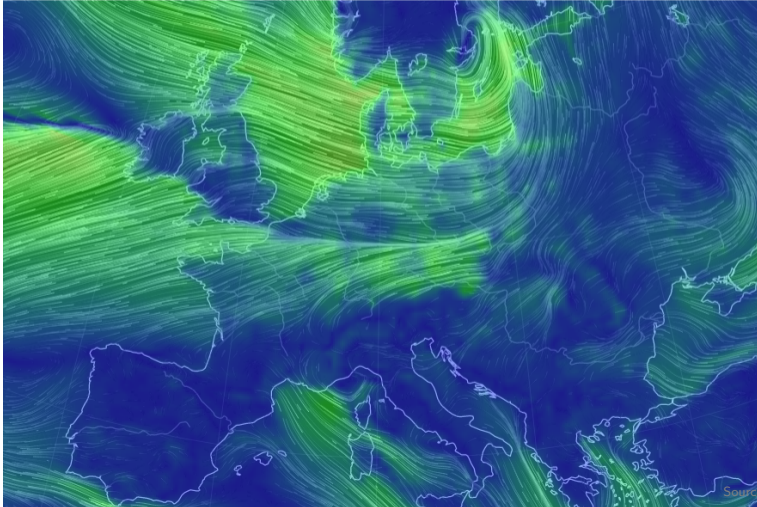


For a whole country like Germany this results in valleys and peaks that are somewhat smoother, but the profile still frequently drops close to zero.

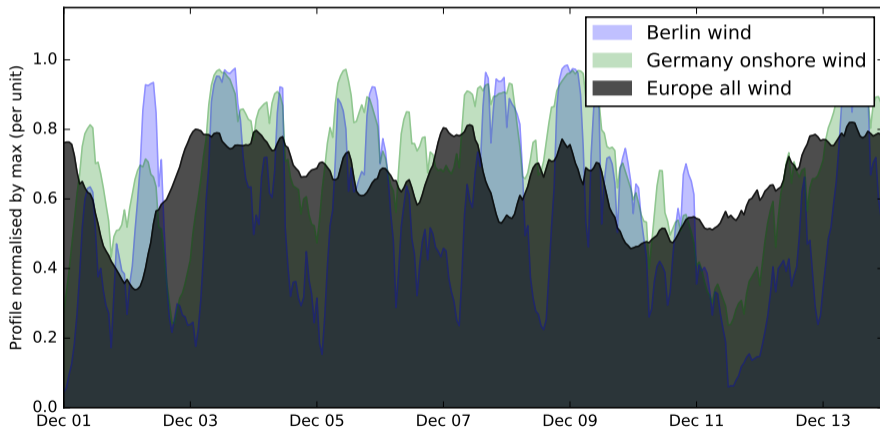


Variability: Different wind conditions over Europe

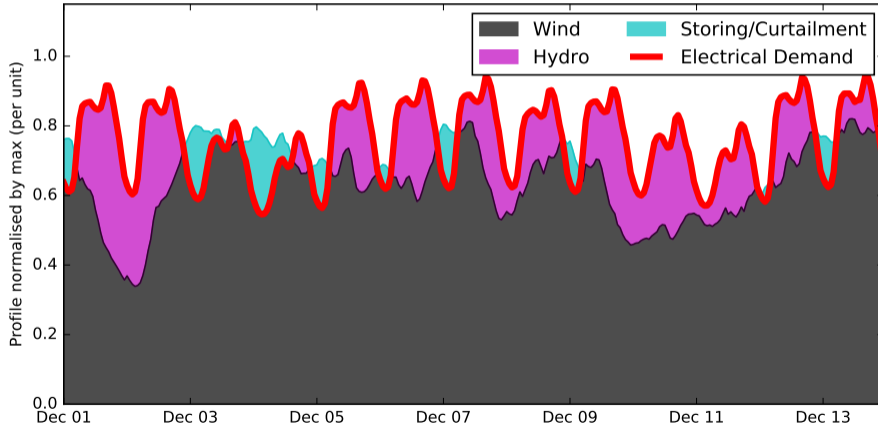
The scale of the weather systems are bigger than countries, so to leverage the full smoothing effects, you need to integrate wind at the **continental scale**.

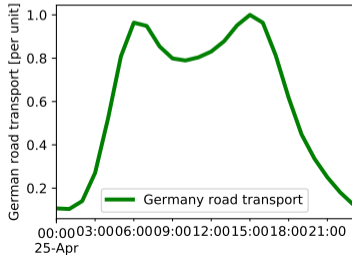
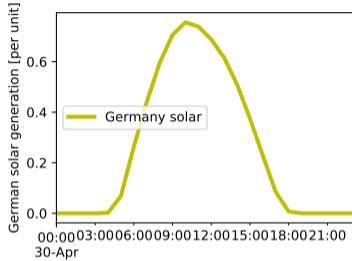


If we can integrate the feed-in of wind turbines across the European continent, the feed-in is considerably smoother: we've eliminated most valleys and peaks.



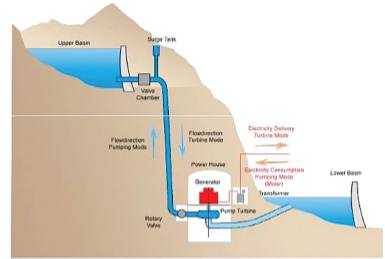
Flexible, renewable hydroelectricity from storage dams in Scandinavia and the Alps can fill many of the valleys; excess energy can either be curtailed (spilled) or stored.

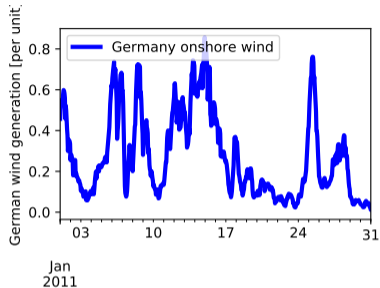




Daily variations in supply and demand can be balanced by

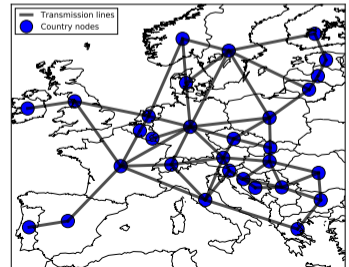
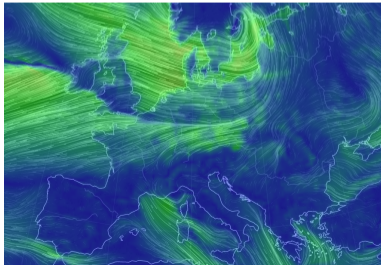
- **short-term storage** (e.g. batteries, pumped-hydro, small thermal storage)
- **demand-side management** (e.g. battery electric vehicles, industry)
- **east-west grids over multiple time zones**

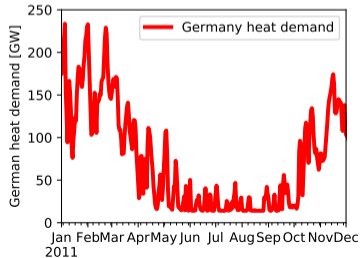
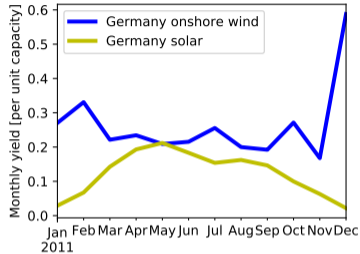




Weekly variations in supply and demand can be balanced by

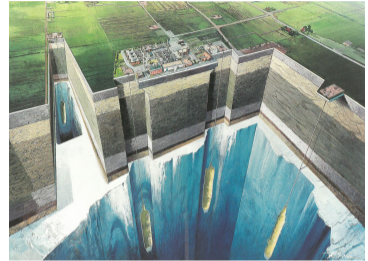
- **medium-term storage** (e.g. chemically with hydrogen or methane storage, thermal energy storage, hydro reservoirs)
- **continent-wide grids**



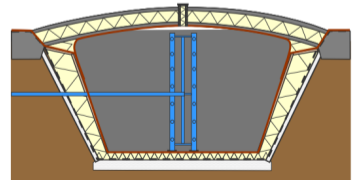


Seasonal variations in supply and demand can be balanced by

- **long-term storage** (e.g. underground hydrogen or methane storage, long-term thermal energy storage, hydro reservoirs)
- **north-south grids over multiple latitudes**



Pit thermal energy storage (PTES)
(60 to 80 kWh/m³)



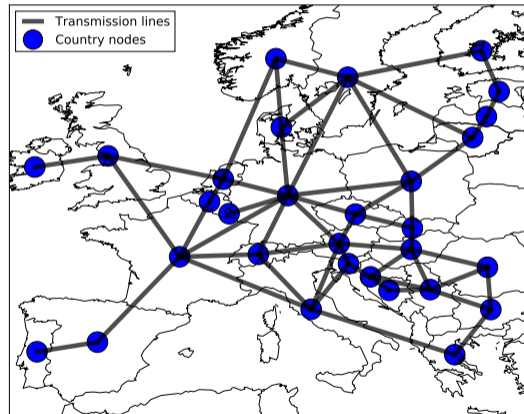
Avoid too many assumptions. Fix the **boundary conditions**:

- Meet demand for energy services
- Reduce CO₂ emissions
- Conservative predictions for cost developments
- No/minimal/optimal grid expansion

Then **let the math decide the rest**, i.e. choose the number of wind turbines / solar panels / storage units / transmission lines to minimise total costs (investment **and** operation).

Generation, storage and transmission optimised **jointly** because they are **strongly interacting**.

- Meet all electricity demand.
- Reduce CO₂ by 95% compared to 1990.
- **Generation** (where potentials allow): onshore and offshore wind, solar, hydroelectricity, backup from natural gas.
- **Storage**: batteries for short term, electrolyse hydrogen gas for long term.
- **Grid expansion**: simulate everything from no grid expansion (like a **decentralised solution**) to optimal grid expansion (with significant **cross-border trade**).



Find the long-term cost-optimal energy system, including investments and short-term costs:

$$\text{Minimise } \left(\begin{array}{c} \text{Yearly} \\ \text{system costs} \end{array} \right) = \sum_i \left(\begin{array}{c} \text{Annualised} \\ \text{capital costs} \end{array} \right) + \sum_{i,t} \left(\begin{array}{c} \text{Marginal} \\ \text{costs} \end{array} \right)$$

subject to

- meeting **energy demand** at each node i (e.g. region) and time t (e.g. hour of year)
- wind, solar, hydro (variable renewables) **availability time series** $\forall i, t$
- **transmission constraints** between nodes, **linearised power flow**
- (installed capacity) \leq (**geographical potentials** for renewables)
- **CO₂ constraint** (e.g. 95% reduction compared to 1990)

In short: mostly-greenfield investment optimisation, multi-period with linear power flow.

Optimise transmission, generation and storage **jointly**, since they're strongly interacting.

Inputs	Description
$d_{i,t}$	Demand (completely inelastic)
$G_{i,s,t}$	Per unit availability for wind and solar
$\hat{G}_{i,s}$	Generator installable potentials
various	Existing hydro data
various	Grid topology
η_*	Storage efficiencies
$C_{i,s}$	Generator capital costs
$O_{i,s,t}$	Generator marginal costs
c_ℓ	Line costs

→

Outputs	Description
$G_{i,s}$	Generator capacities
$g_{i,s,t}$	Generator dispatch
F_ℓ	Line capacities
$f_{\ell,t}$	Line flows
λ_*, μ_*	Lagrange/KKT multipliers of all constraints
f	Total system costs

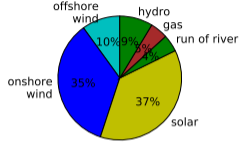
Quantity	Overnight Cost [€]	Unit	FOM [%/a]	Lifetime [a]
Wind onshore	1182	kW _{el}	3	20
Wind offshore	2506	kW _{el}	3	20
Solar PV	600	kW _{el}	4	20
Gas	400	kW _{el}	4	30
Battery storage	1275	kW _{el}	3	20
Hydrogen storage	2070	kW _{el}	1.7	20
Transmission line	400	MWkm	2	40

Interest rate of 7%, storage efficiency losses, only gas has CO₂ emissions, gas marginal costs.

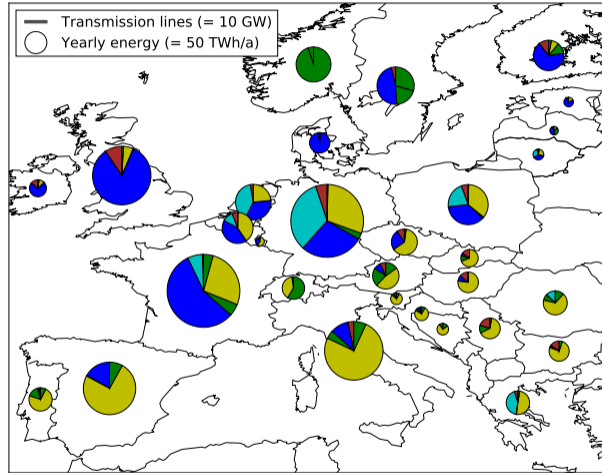
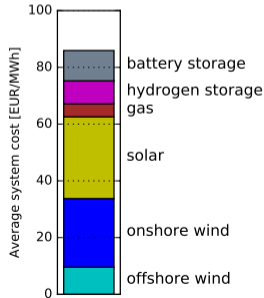
Batteries can store for 6 hours at maximal rating (efficiency 0.9×0.9), hydrogen storage for 168 hours (efficiency 0.75×0.58).

Costs: No interconnecting transmission allowed

Technology by energy:



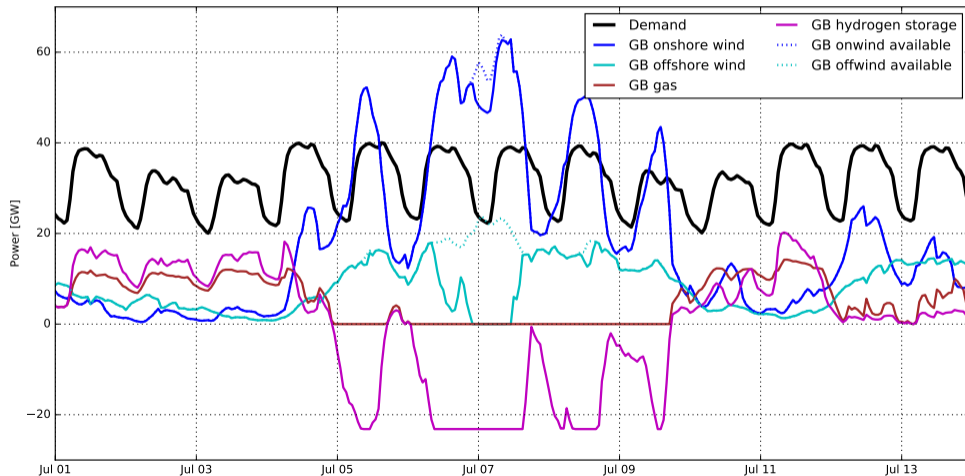
Average cost €86/MWh:



Countries must be self-sufficient at all times; lots of storage and some gas to deal with fluctuations of wind and solar.

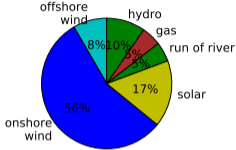
Dispatch with no interconnecting transmission

For Great Britain with no interconnecting transmission, excess wind is either stored as hydrogen or curtailed:

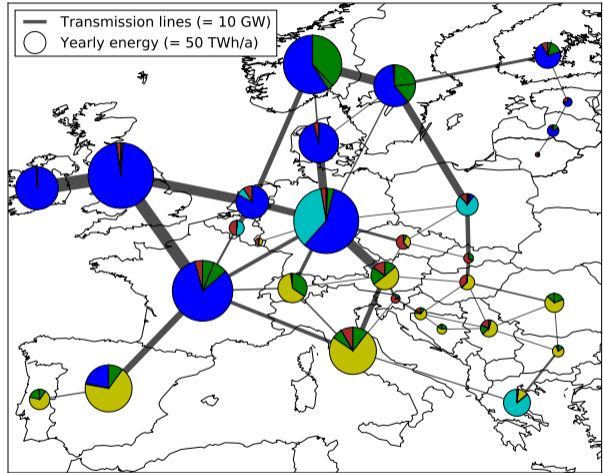
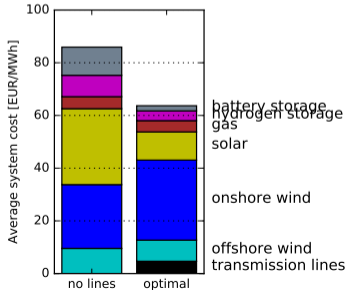


Costs: Cost-optimal expansion of interconnecting transmission

Technology by energy:



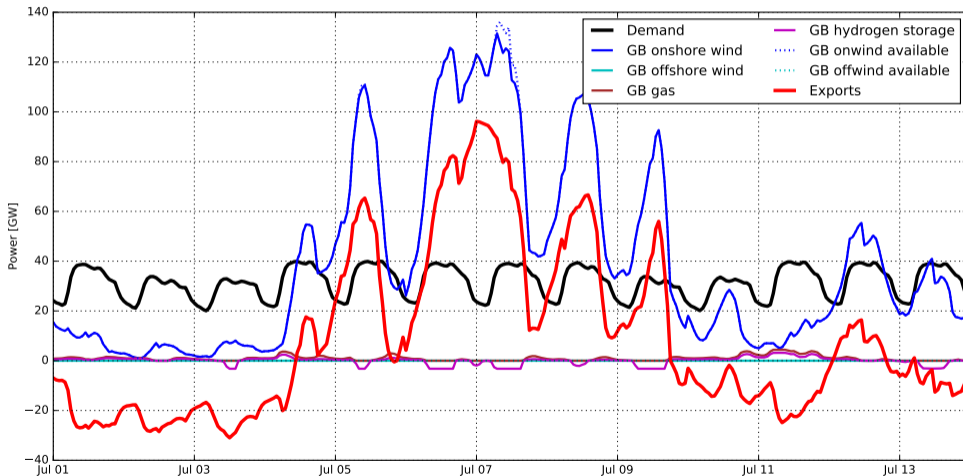
Average cost €64/MWh:



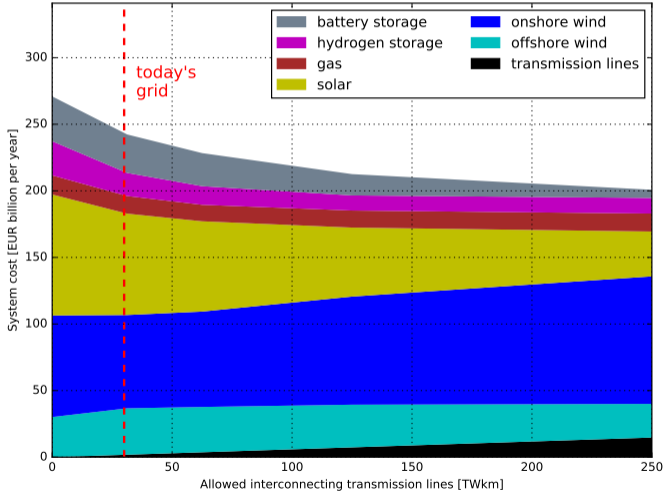
Large transmission expansion; onshore wind dominates. This optimal solution may run into public acceptance problems.

Dispatch with cost-optimal interconnecting transmission

Almost all excess wind can now be exported:

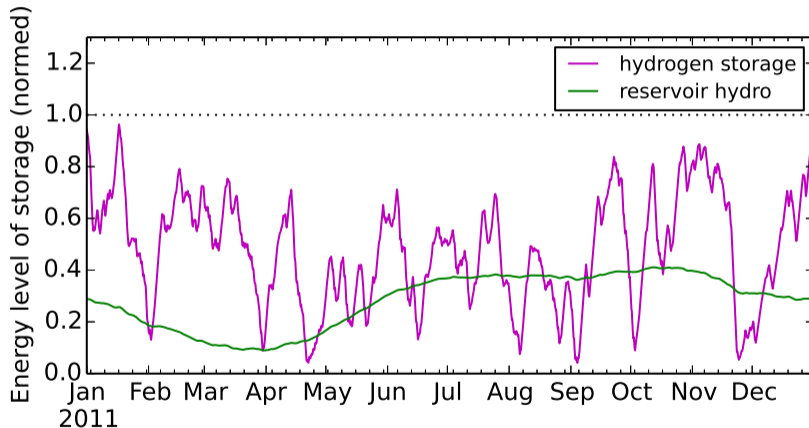


Electricity Only Costs Comparison



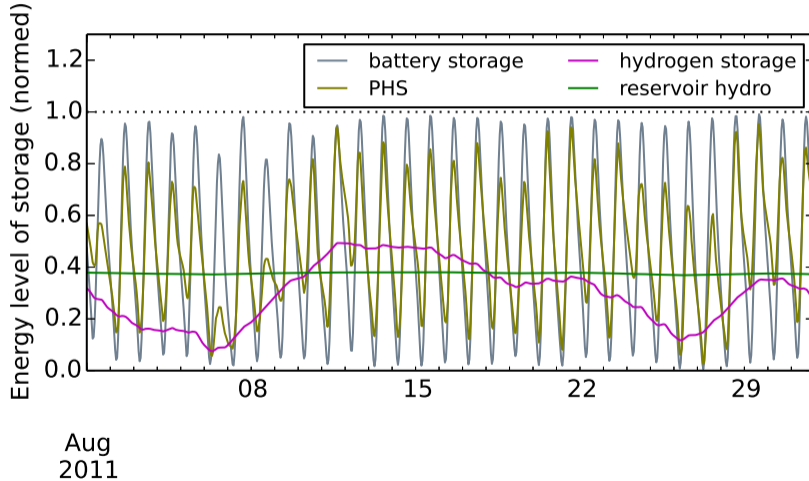
- Average total system costs can be as low as € 64/MWh
- Energy is dominated by wind (64% for the cost-optimal system), followed by hydro (15%) and solar (17%)
- Restricting transmission results in more storage to deal with variability, driving up the costs by up to 34%
- Many benefits already locked in at a few multiples of today's grid

Different flexibility options have difference temporal scales



- Hydro reservoirs are **seasonal**
- Hydrogen storage is **multi-weekly**

Different flexibility options have difference temporal scales



- Pumped hydro and battery storage are **daily**

This example has several features which will accompany us through the lecture course:

1. We have to account for the variations of wind and solar in **time** and **space**.
2. These variations take place at **different scales** (daily, multi-week, seasonal).
3. We often have a choice between balancing in **time** (with storage) or in **space** (with networks).
4. Optimisation is important to increase cost-effectiveness, but we should also look at **near-optimal** solutions.

Full paper reference: D. Schlachtberger, T. Brown, S. Schramm, M. Greiner, “The Benefits of Cooperation in a Highly Renewable European Electricity Network”, Energy, 134, 469-481, 2017, [arXiv:1704.05492](https://arxiv.org/abs/1704.05492).