Energy Systems, Summer Semester 2024
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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Administration

Team Details

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 scientist in the group and will lead the tutorials; he can also answer any organisational questions (**p.glaum@tu-berlin.de**).

Group website: **https://www.tu.berlin/ensys**

Personal website: **https://nworbmot.org/**

Course ISIS Website

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

https://isis.tu-berlin.de/course/view.php?id=38095

Course abbreviation: [SoSe 2024] Energy Systems

Annoucements 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.

Course Resgistration: 6 ECTS or 9 ECTS if you also attend seminar

You have two options for taking the course 'Energy Systems':

- **Energy Systems (6 LP)** Lectures + Tutorials + 90-minute Written Exam = 6 ECTS
- **Energy Systems (9 LP)** as above + Choose One of Two Seminars = 9 ECTS (Portfolioprüfung für Projekt EVT: Energiesysteme for RES/EVT MSc)

If you are in RES and switch to the new StuPO 2023 in WiSe 24/5, please choose 6 LP option.

Registration:

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

Written Exam

- Written exam in presence
- 90-minute exam in July/August/September
- 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

Seminar 1 'New Developments in Energy Markets'

Available as stand-alone (3 ECTS) or as module in Energy Systems (9 ECTS)

- Students analyse a current topic in energy markets, prepare a 20-minute presentation and present it for discussion
- Presentations as a block at the end of the lecture-free period
- Supervision and discussion led by Prof. Erdmann, Prof. Grübel and scientific employees of the department
- Students work on topic with a supervisor during semester (2-3 meetings)
- Topics will be presented during a lecture in May 2024, presentations in September 2024
- Example topics: smart meter rollout, gas crisis, market reform, EEG, European Green Deal, e-mobility, hydrogen economy, industrial decarbonisation, flexibility markets, etc.

The seminar has **its own ISIS page**.

Seminar 2 'New Research in Energy System Modelling'

Available as stand-alone (3 ECTS) or as module in Energy Systems (9 ECTS)

- Students analyse a recent research paper on energy system modelling looking at transformation of energy system 2025-2050
- Students prepare a 20-minute presentation and present it for discussion
- Presentations as a block at the end of the lecture-free period
- Supervision and discussion together with Prof. Gunnar Luderer's group at PIK (Potsdam Institute für Klimafolgenforschung)
- Students work on topic with a supervisor during semester (2-3 meetings)
- Topics will be presented during a lecture in May 2024, presentations in September 2024
- Example topics: integration of renewable energy, hydrogen trade, storage modelling, endogenous learning, role of carbon capture

The seminar will have its own ISIS page soon.

Parallel Course ‘Data Science for Energy System Modelling’

6 ECTS course starts Tuesday 16th April at 4pm, 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

Schedule for Lectures and Tutorials

Day	Time	Location	Event
Tuesday	1400-1600	C 243	Lecture
Thursday	0800-1000	H 0107	Tutorial
Thursday	1400-1600	H 1012	Lecture

First lecture: Tuesday 16th April 2024, last lecture: Thursday 18th July 2024

First tutorial: Thursday 25th April 2024

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.

Literature

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

Inter-Disciplinary Methods Required!

Energy System Modelling requires methods and skills from several disciplines:

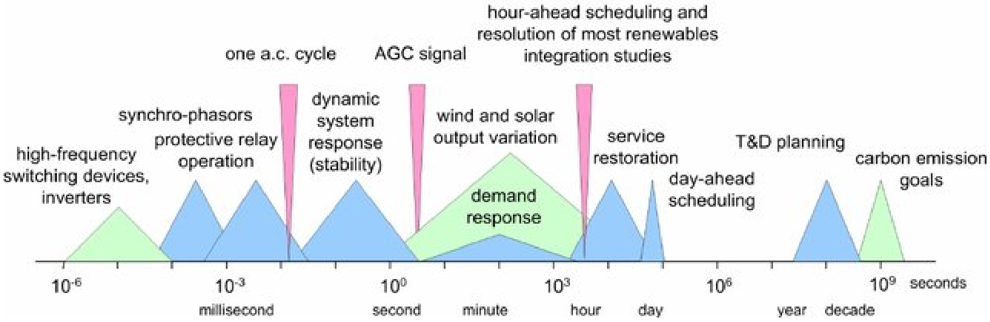
- **Engineering:** Technical description of energy system components and interactions
- **Economics:** Efficient allocation of resources and infrastructure to meet consumer preferences
- **Informatics:** Large datasets, complex interactions
- **Meteorology:** Influence of weather and climate on demand 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

Course outline

- 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

Different time scales

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



Source: doi:10.1109/EPQU.2011.6128888

What is Energy System Modelling?

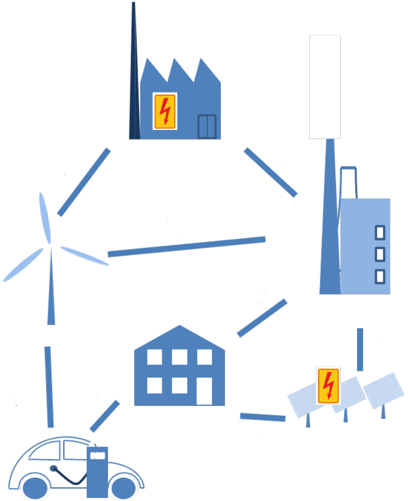
What is Energy System Modelling?

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.

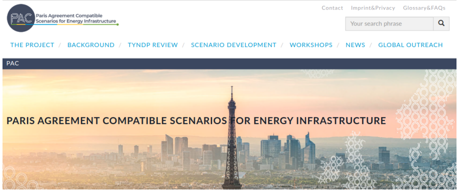


Energy System Modelling: Who is it for?

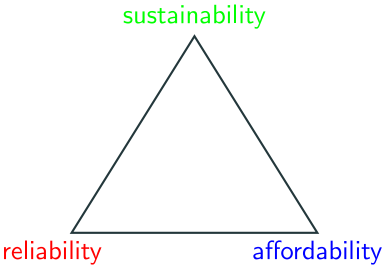
Broadly speaking, we model energy systems to help **society** make decisions. Examples:

Government agencies commission studies to look at possible future scenarios:

But also companies and non-governmental organisations:



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

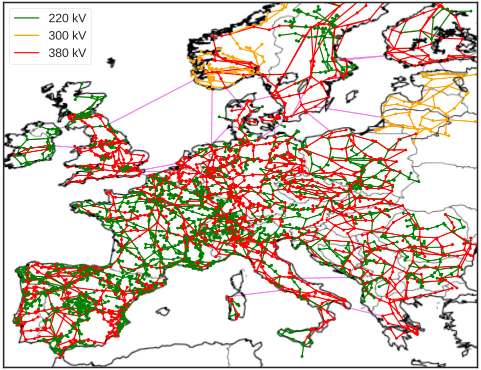


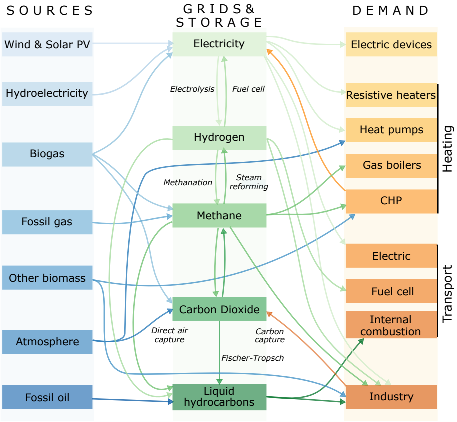
- **Sustainability**: Respect environmental constraints (greenhouse gases, air quality, preservation of wildlife), social and political constraints (geopolitics, public acceptance of transmission lines, onshore wind, nuclear power)
- **Reliability**: Ensure energy services are delivered whenever needed, 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**.

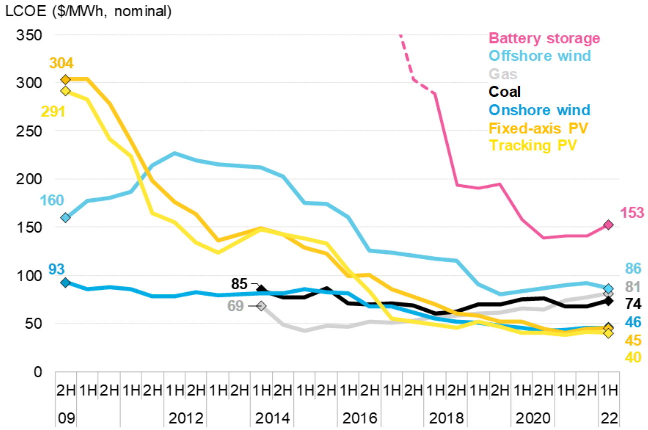
Why it's hard: many components and interactions

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.



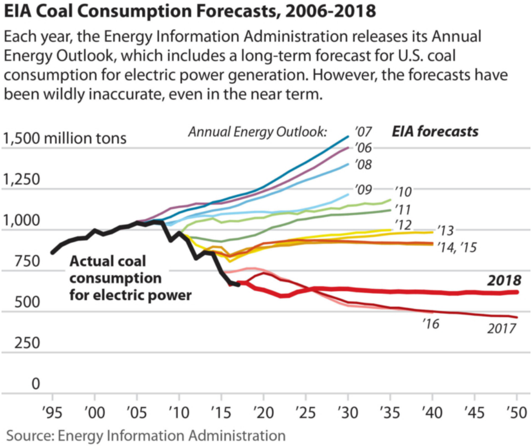


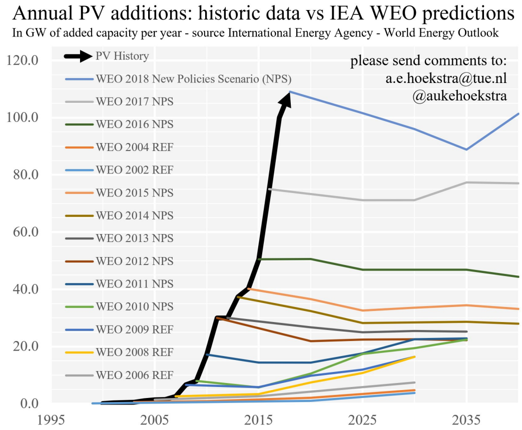
Why it's hard: non-linearities and social effects



Source: BloombergNEF, 2022

Not everyone gets it right...





…and it’s not always uncontroversial

manager magazin

Als Startseite festlegen Schlagzeilen

PREMIUM ÜBER UNS UNTERNEHMEN DIGITALES POLITIK FINANZEN JOB & KARRIERE LIFESTYLE VIDEO

Home • Politik • Energiewende • Hans-Werner Sinn vom ifo Institut über Windenergie und Energiewende

05.02.2014

ifo-Chef Sinn zur Energiewende

"Die einzige Hoffnung der Menschheit war die Atomkraft"

Von Nils-Viktor Sorge

Teilen:

DPA

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**’)

BUSINESS INSIDER CORONAVIRUS WIRTSCHAFT TECH POLITIK KARRIERE LEBEN WIS

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

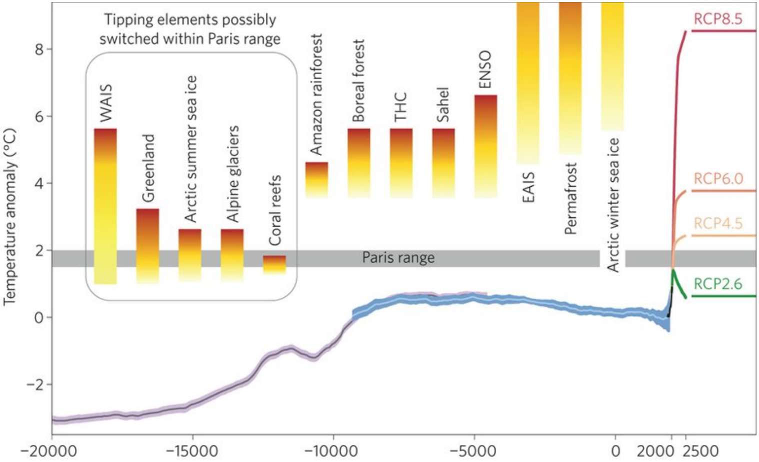
TWITTER FACEBOOK LINKEDIN WHATSAPP EMAIL PRINT

Sinn’s study was **debunked**, shown to use cherry-picked assumptions

The Greenhouse Gas Challenge & The Energy System

2015 Paris Agreement

The 2015 Paris Agreement pledged its signatories to 'pursue efforts to limit [global warming above pre-industrial levels] to **1.5°C**' and hold 'the increase...to **well below 2°C**'. These targets were chosen to avoid potentially irreversible **tipping points** in the Earth's systems.



WAIS: West Antarctic Ice Sheet ($\Rightarrow$ 5m sea level rise)

Greenland (7m)

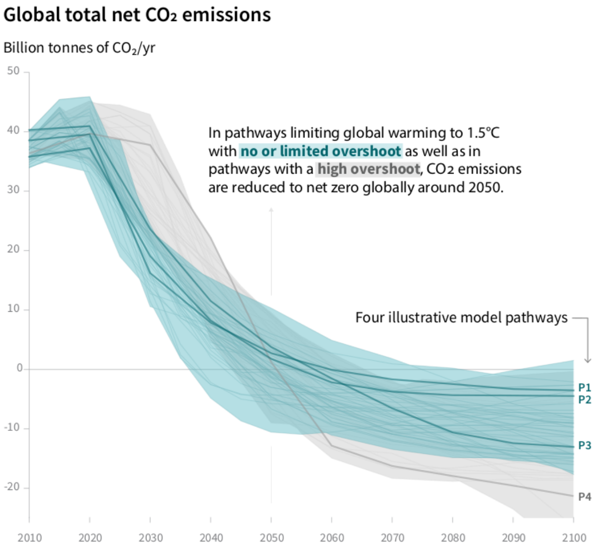
THC: thermohaline circulation (warms Europe)

ENSO: El Niño–Southern Oscillation (extreme weather)

EAIS: East Antarctic Ice Sheet ($>$ 50 m)

Source: 'Why the right climate target was agreed in Paris', Nature Climate Change, 2016

The Global Carbon Dioxide Challenge: Net-Zero Emissions by 2050



- Scenarios for global CO_2 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**

Source: IPCC SR15 on 1.5C, 2018

The Greenhouse Gas Challenge: Net-Zero Emissions by 2050

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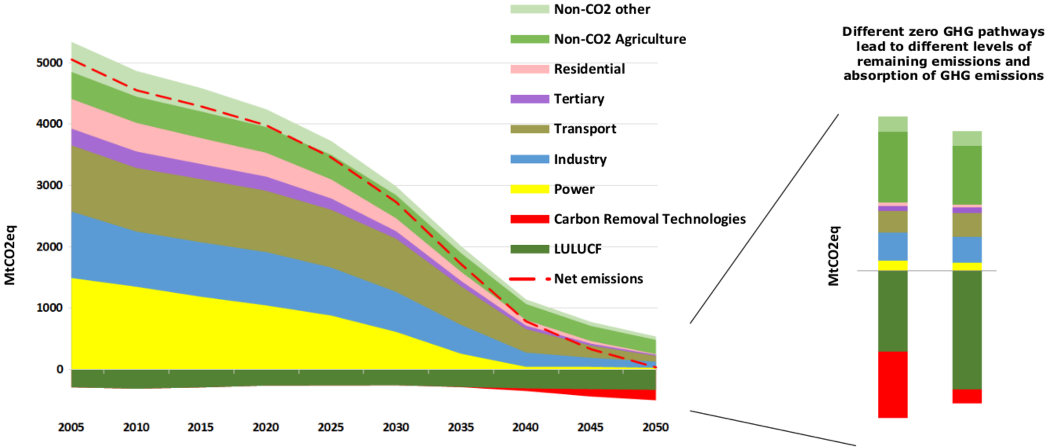
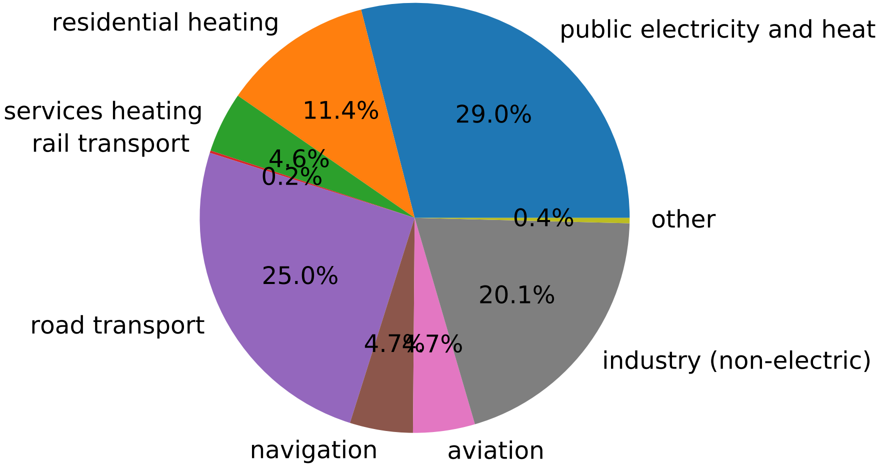
Paris-compliant 1.5° C scenarios from European Commission for **net-zero GHG in EU by 2050**. This target has been adopted by the EU and enshrined in the **European Green Deal**.



Source: European Commission 'Clean Planet for All', 2018

EU28 CO_2 emissions in 2016 (total 3.5 Gt CO_2, 9.7% of global):



Source: Brown, data from **EEA**

...but electrification of other sectors is critical for decarbonisation

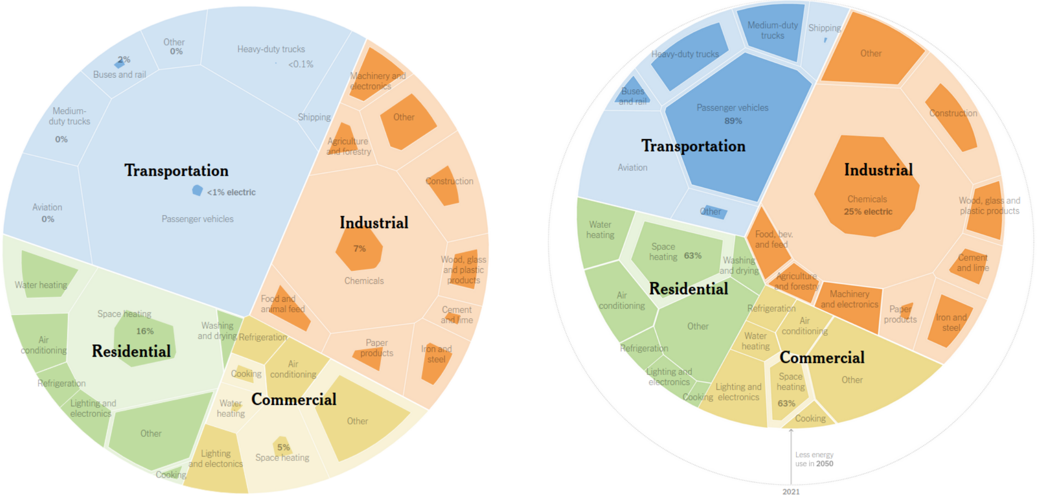
Electrification is essential to decarbonise sectors such as transport, heating and industry, since we can use low-emission electricity from e.g. wind and solar to displace fossil-fuelled transport with electric vehicles, and fossil-fuelled heating with electric heat pumps.

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

Source: Tesla; heat pump: Kristoferb at English Wikipedia

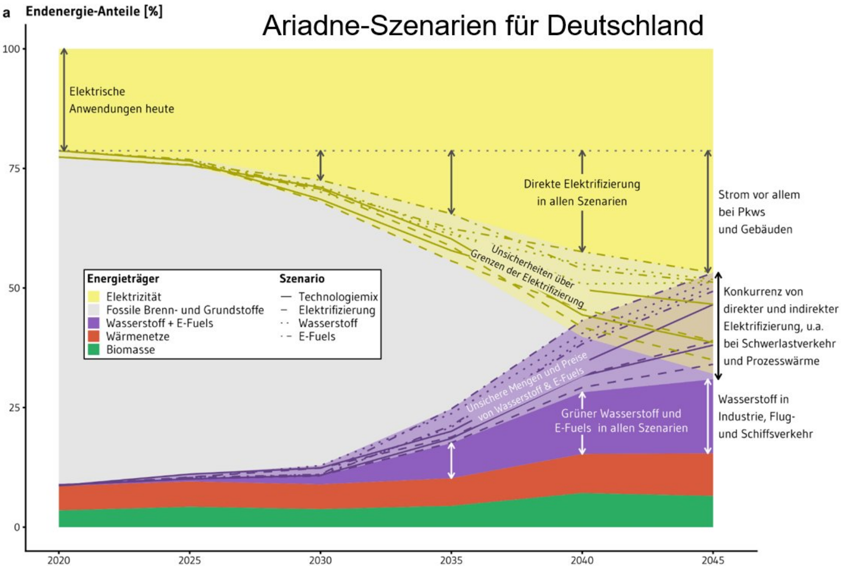
Many scenarios show an increase in electrification

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



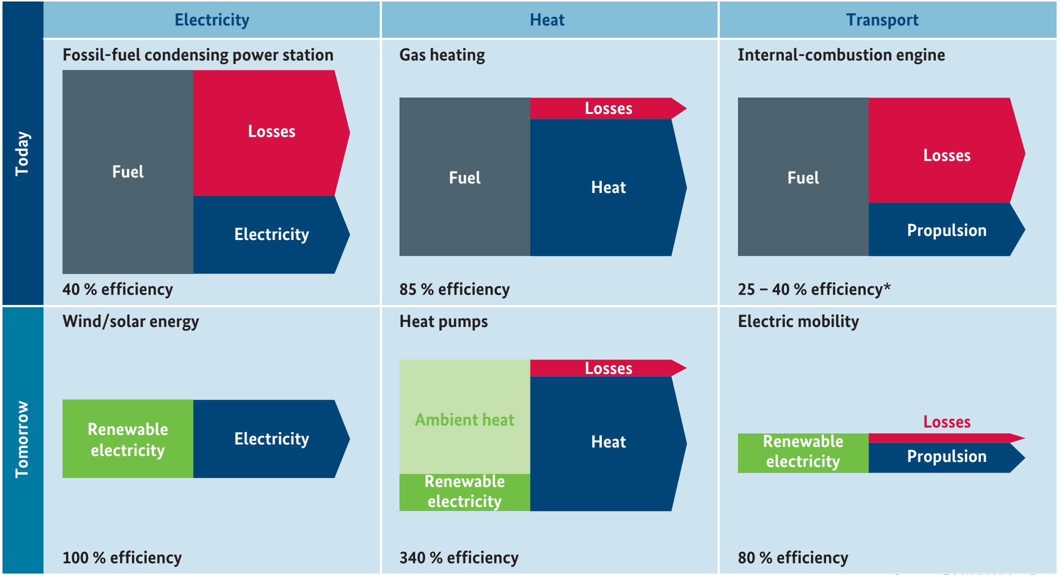
Source: New York Times, 2023

Many scenarios show increase in electrification



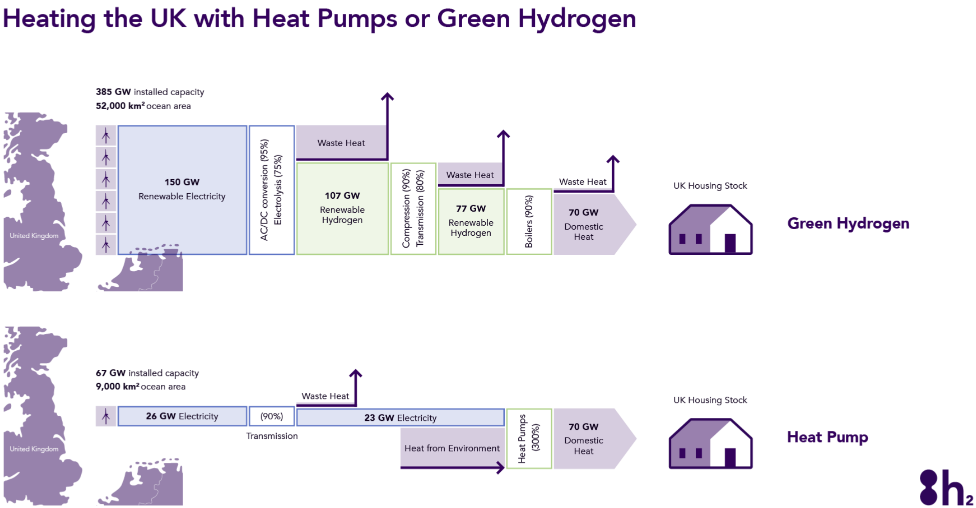
Source: ARIADNE Projekt, 2021

Efficiency of renewables and electrification



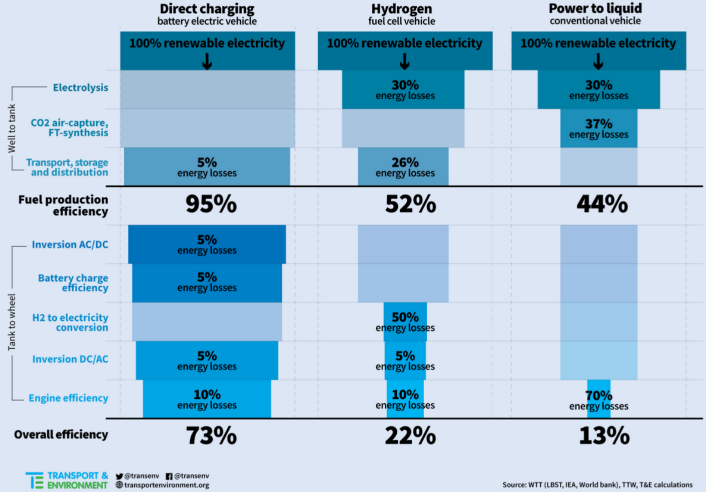
Source: BMWi White Paper 2015

Electrification via heat pumps versus hydrogen boilers



Source: Hydrogen Science Coalition

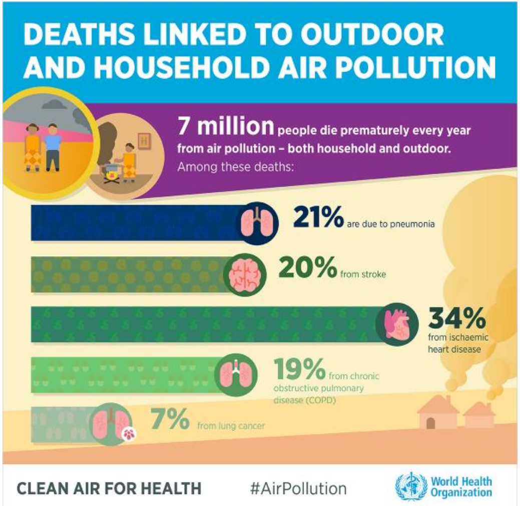
Electric vehicles versus efuels

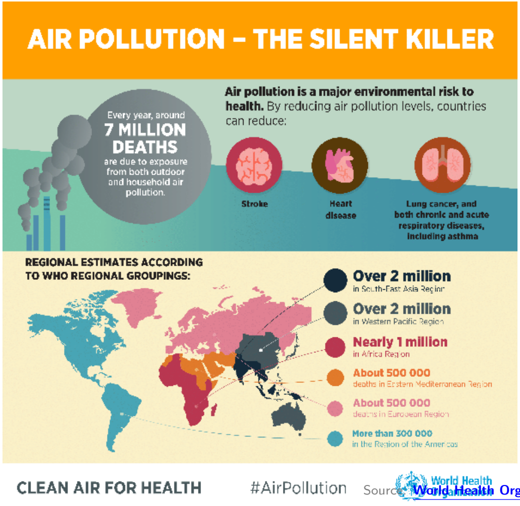


Important caveat: efficiency is not cost. There are regions in the world (e.g. Patagonia) with very inexpensive wind and solar resources for efuels, where low cost could outweigh losses.

Not just climate change: air pollution is a silent killer

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

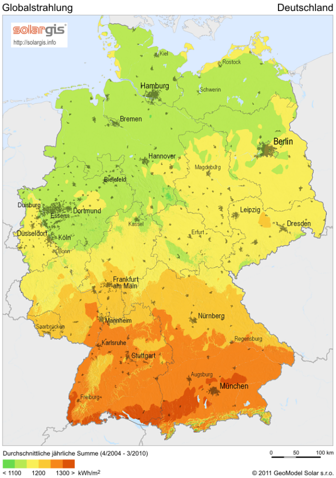


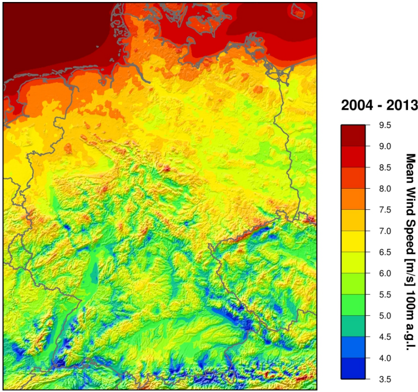


Source: World Health Organisation

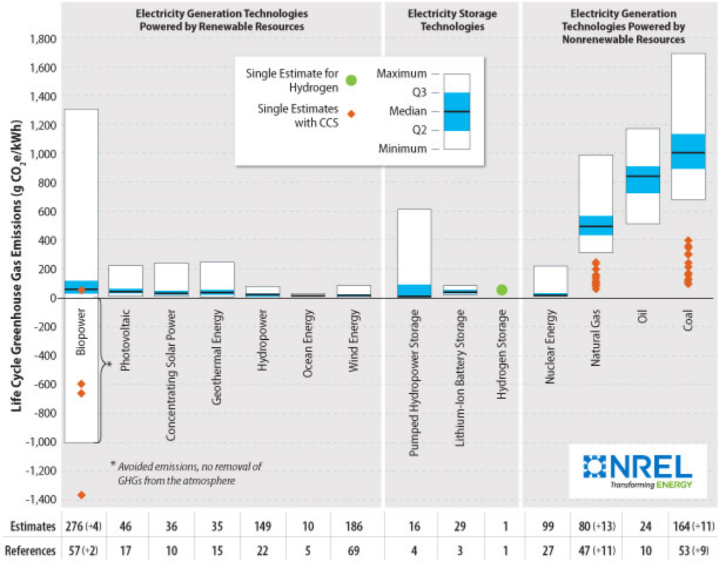
Why focus on wind and solar for electricity generation?

- 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





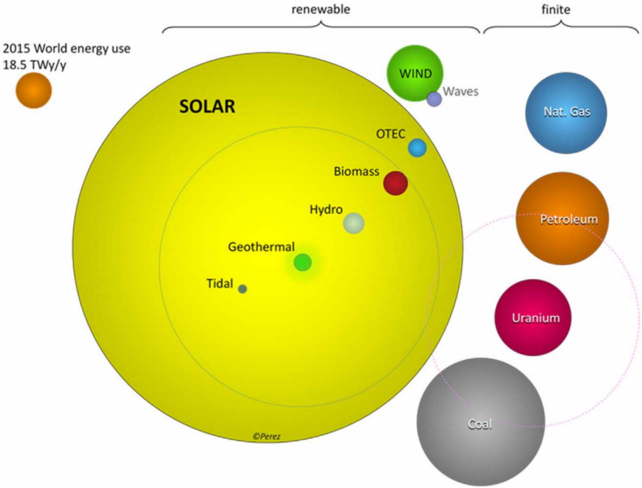
Life Cycle Analysis (LCA) of generation technologies



- **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

Source: NREL, 2021

Worldwide potentials



RENEWABLE				FINITE	
Solar	23,000 TWy/y	Biomass	2-6 TWy/y	Nat. Gas	220 TWy
Wind	75-130 TWy/y	Hydro	3-4 TWy/y	Petroleum	335 Twy
Waves	0.2-2 TWy/y	Geotrm	0.2-3++ TWy/y	Uranium	185++ TWy
OTEC	3-11 TWy/y	Tidal	0.3 TWy/y	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

Source: Perez et al, Applied Policy, 2016

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

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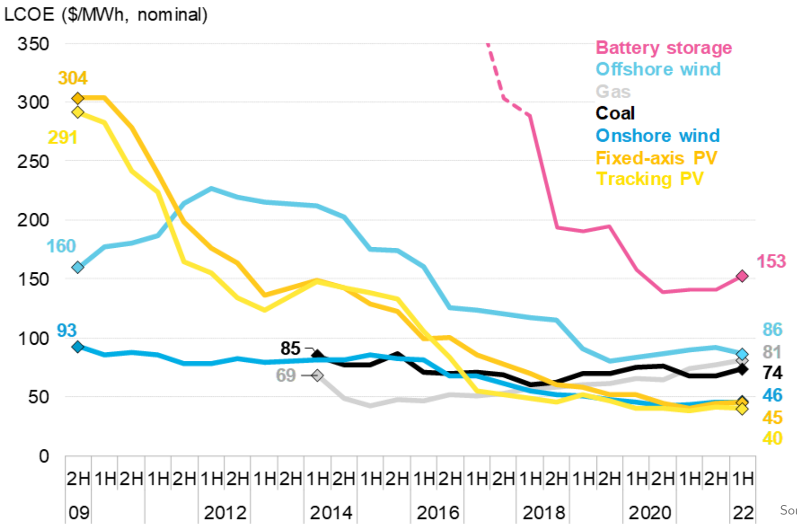
LCOE = **Levelised Cost of Energy** = Total Costs / Energy Output



Source: [BloombergNEF, 2022]

Fundamental shift from scarce exhaustible to renewable energy

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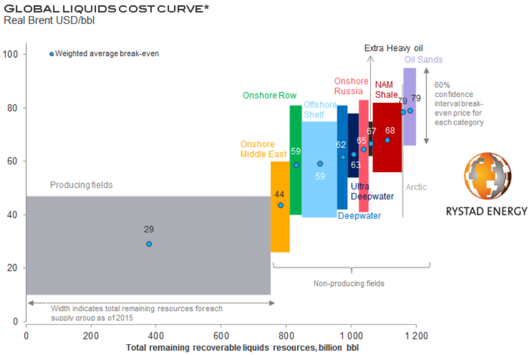
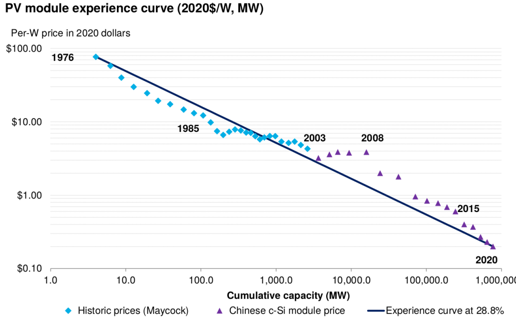
Fossil fuel costs rise with exploitation (can also drop with innovation)



*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

(2019 consumption was ∼37 billion barrels)

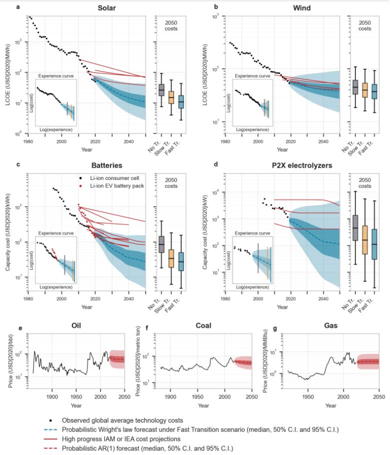
Solar and wind costs drop with innovation (can rise locally where land is scarce)



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

Source: BNEF 2021

4 critical technologies: wind, solar, batteries, electrolyzers

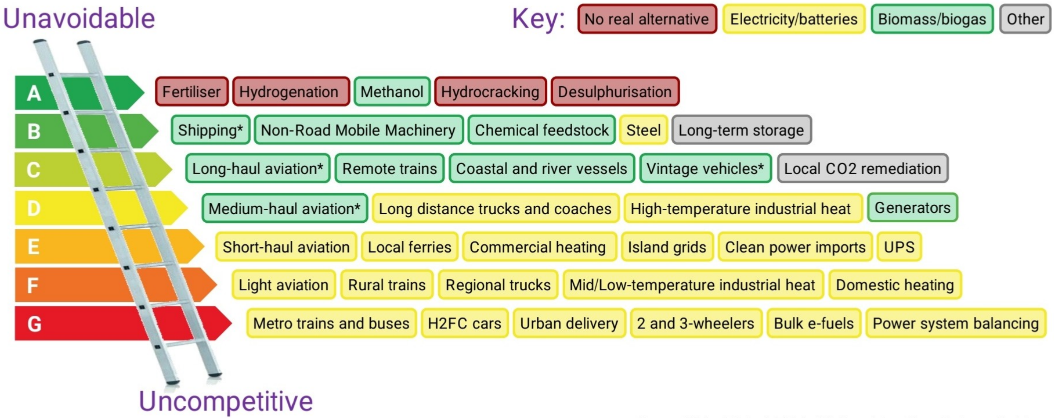


All the critical technologies for the energy transition share a small unit size, enabling fast production and installation, economies of scale in manufacturing and learning-by-doing.

- **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.

Source: Way et al, 2021

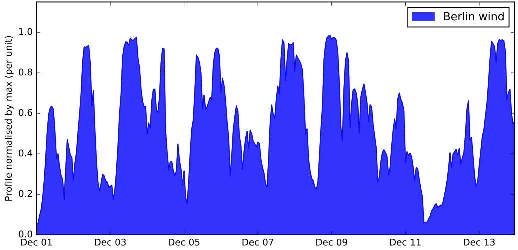
Clean hydrogen can do almost everything, but competes with direct electrification. Some say **champagne of energy transition**; could also say **backstop** for what efficiency and electrification don't reach.

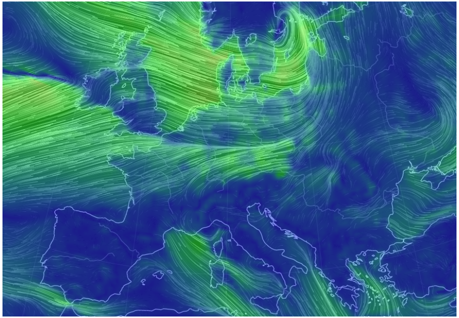


* *Most likely via ammonia or e-fuel rather than H2 gas or liquid*

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...





...and social & political constraints

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.

Energy Transition: Several changes happening simultaneously

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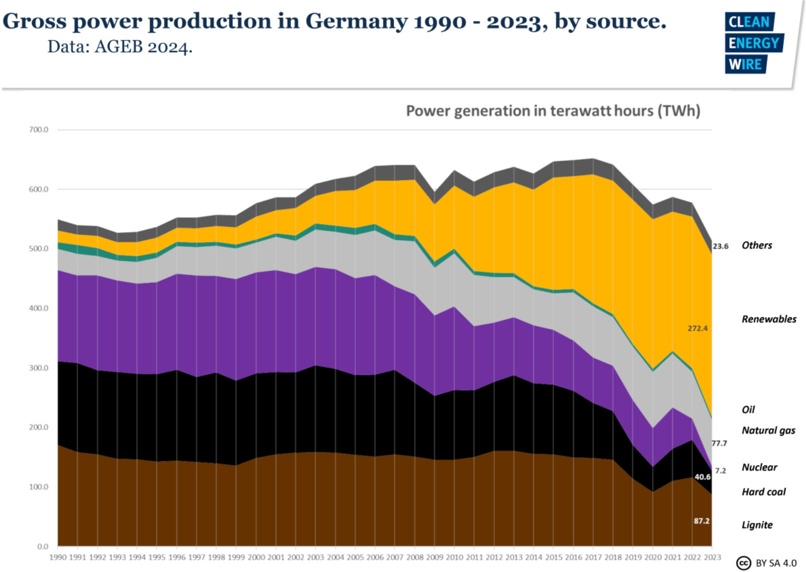
Energiewende: The Energy Transition, consists of several parts:

- 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

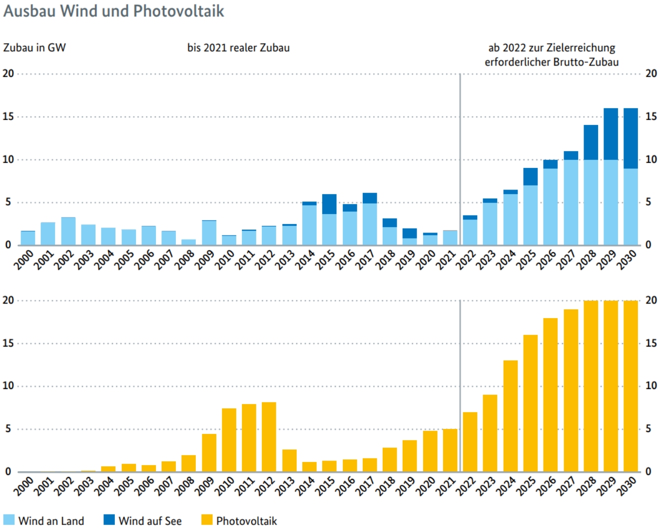
Renewables reached 52% of gross electricity in Germany in 2023



Source: Clean Energy Wire, 2024

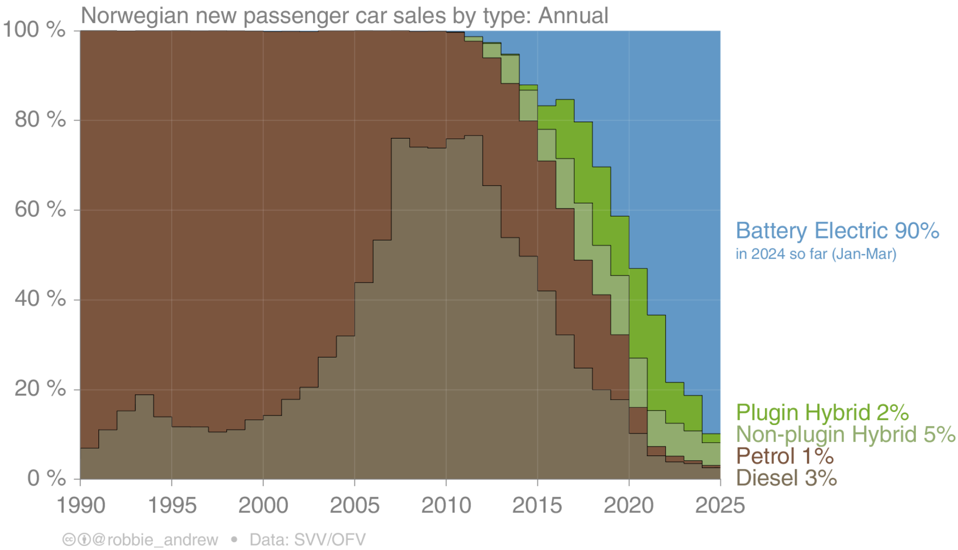
Build-out rates for wind and solar need to increase rapidly

New traffic light coalition has target of 80% renewable electricity by 2030, 100% by 2035.



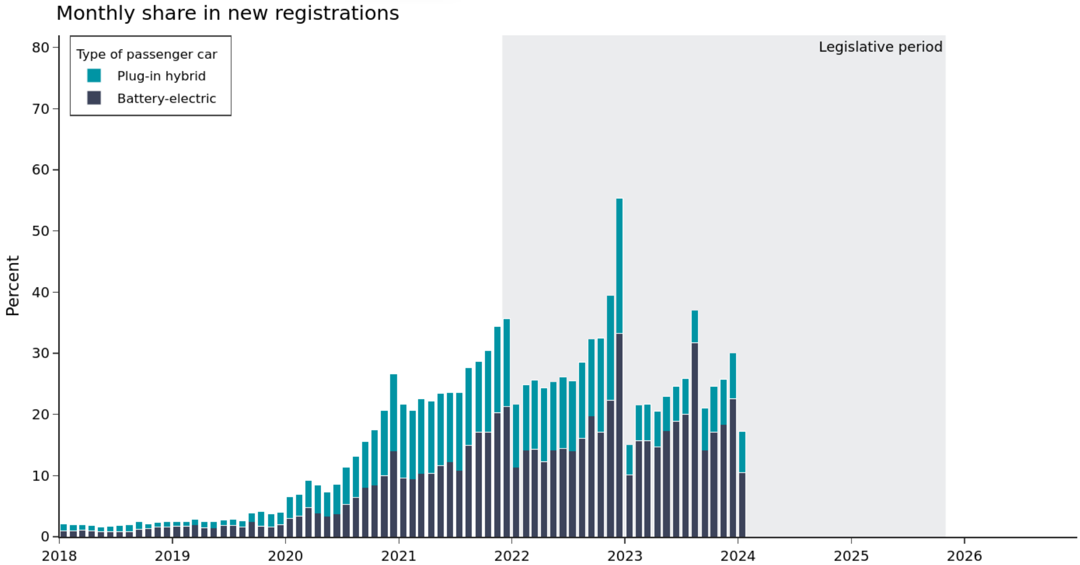
Source: BMWK, 2022

Electric vehicles take off, first in Norway



Source: **Robbie Andrew, 2024**

Electric vehicles: Germany catching up?



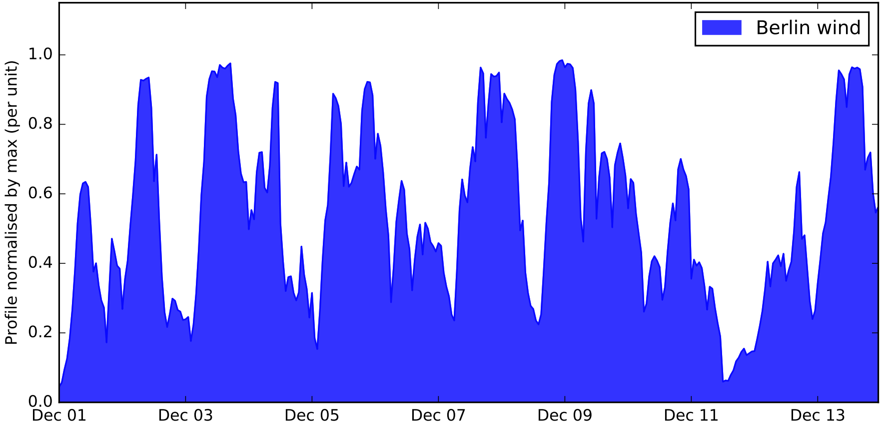
Source: Open Energy Tracker, 2024

Invitation: Balancing Variable Renewable Energy in Europe

Goals for Energy System Modelling

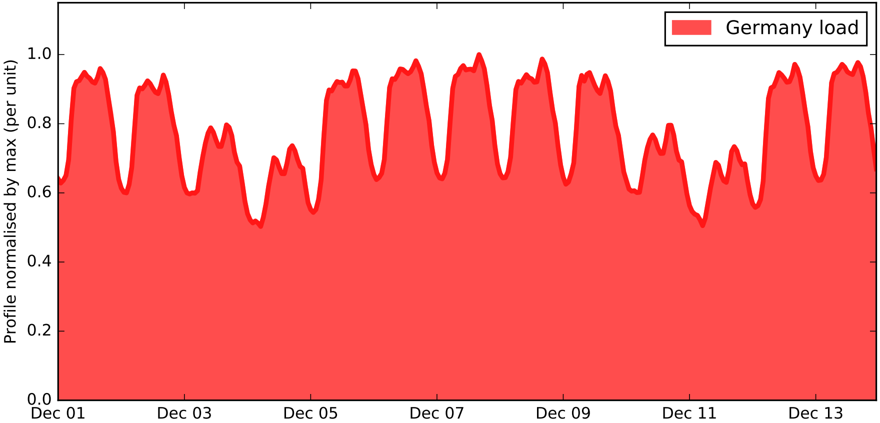
1. What **infrastructure** (wind, solar, hydro generators, heating/cooling units, storage and networks) does a highly renewable energy system require and **where** should it go?
2. Given a desired CO_2 emissions reduction (e.g. 95% compared to 1990), what is the **cost-optimal** combination of infrastructure?
3. How do we deal with the **variability** of wind and solar: balancing in space with networks or in time with storage?

Looking at the wind output of a single wind plant over two weeks, it is highly variable, frequently dropping close to zero and fluctuating strongly.

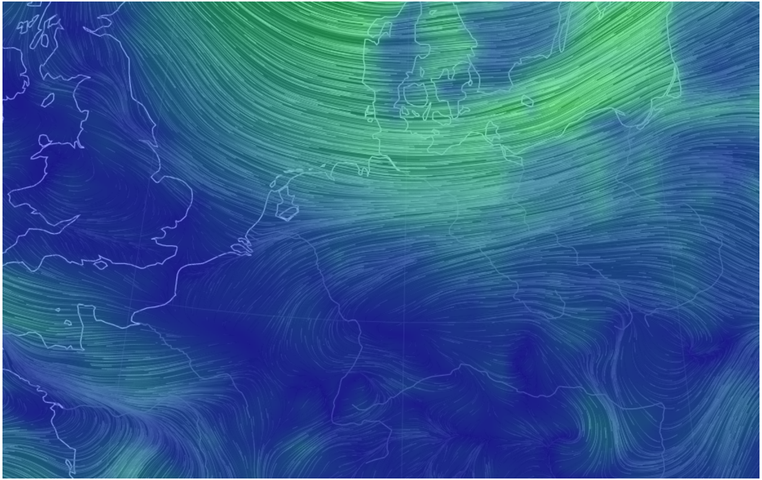


Electricity consumption is much more regular

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...

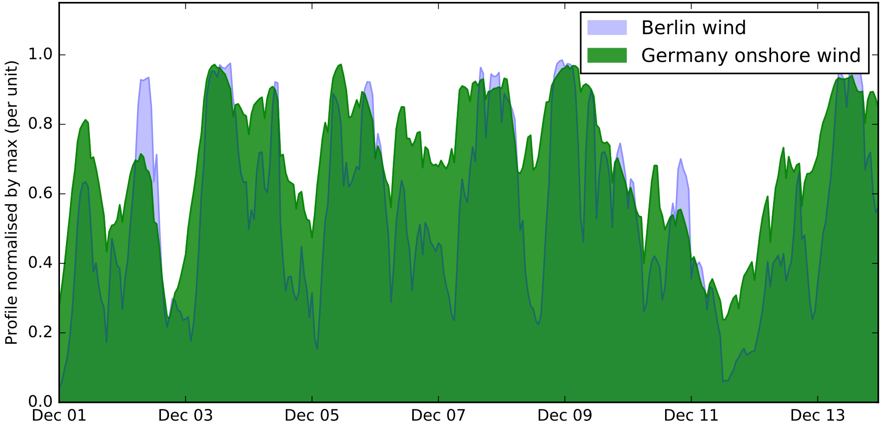


The wind does not blow the same at every site at every time: at a given time there are a variety of wind conditions across Germany. These differences **balance out over time and space**.

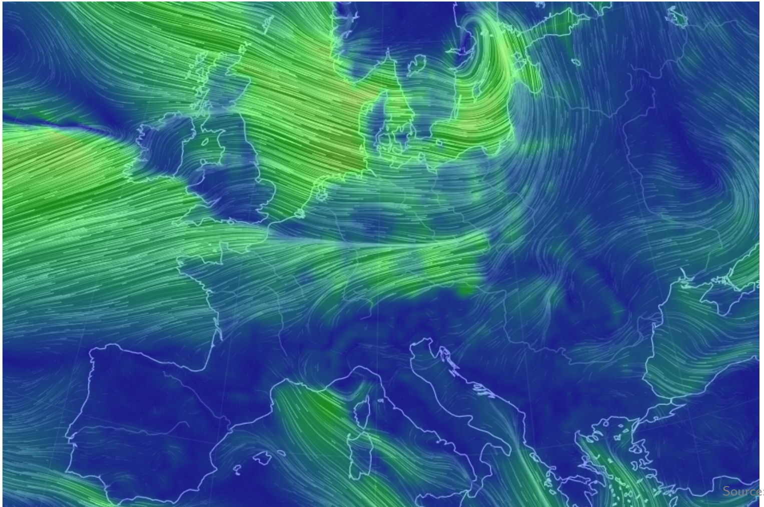


Source: https://earth.nullschool.net/

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.

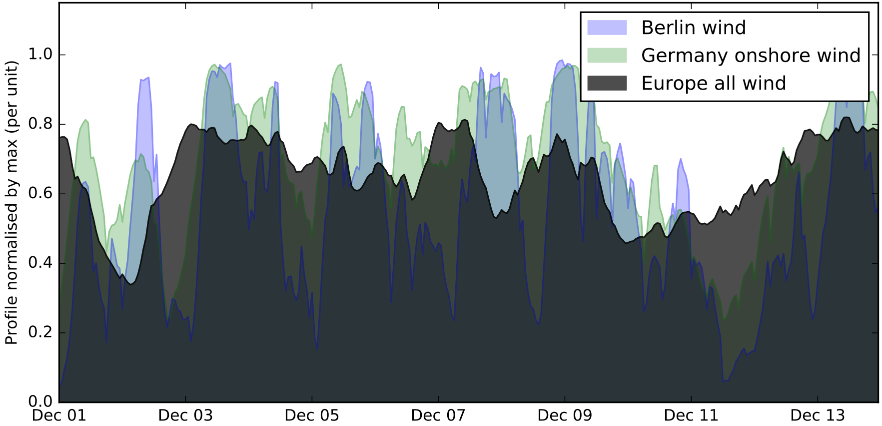


The scale of the weather systems are bigger than countries, so to leverage the full smoothing effects, you need to integrate wind at the **continental scale**.



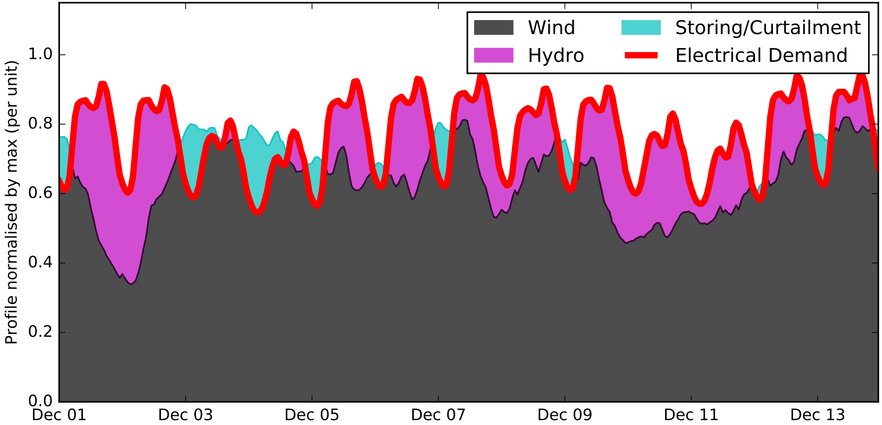
Source: https://earth.nullschool.net/

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.

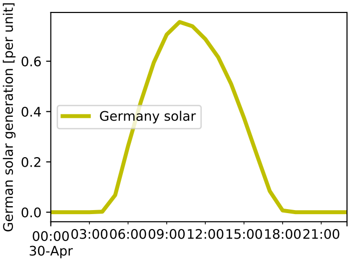


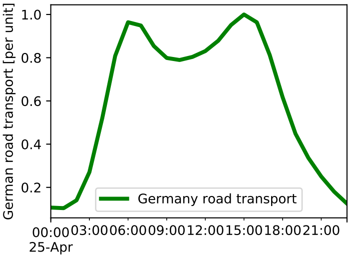
Variability: A continent: Wind plus Hydro

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.



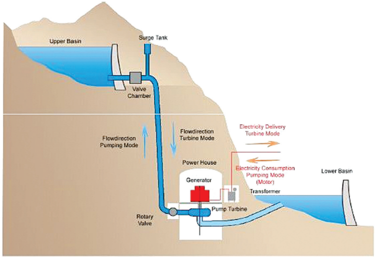
Daily variations: challenges and solutions



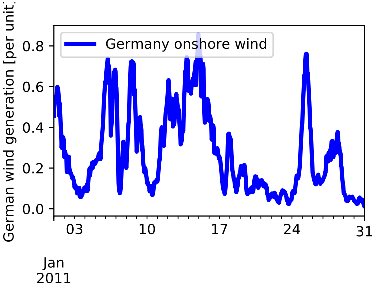


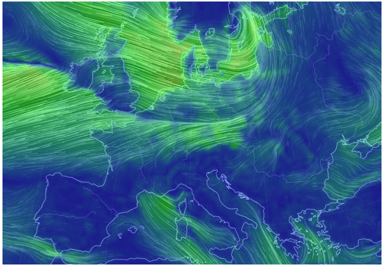
Daily variations in supply and demand can be balanced by

- **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**



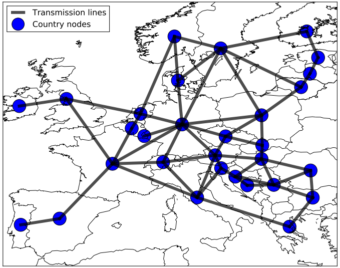
Weekly variations: challenges and solutions



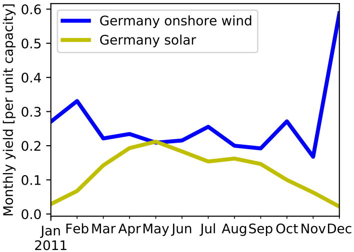


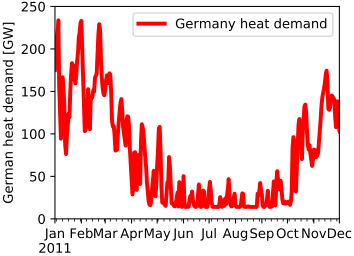
Weekly variations in supply and demand can be balanced by

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



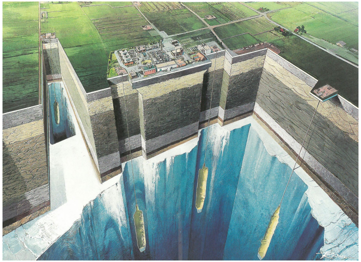
Seasonal variations: challenges and solutions



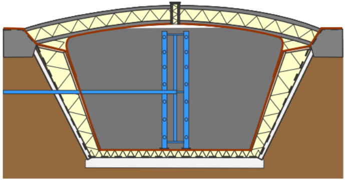


Seasonal variations in supply and demand can be balanced by

- **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)



Research approach

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

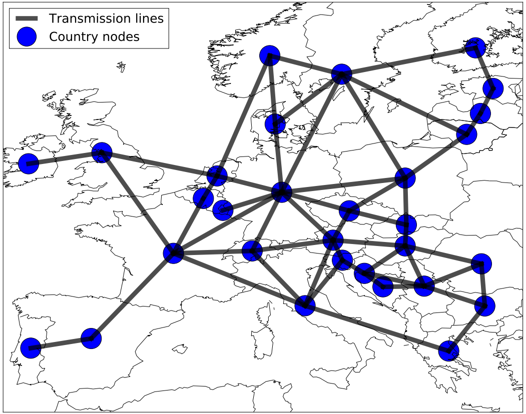
- Meet demand for energy services
- Reduce CO_2 emissions
- Conservative predictions for cost developments
- No/minimal/optimal grid expansion

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**.

Determine optimal electricity system

- Meet all electricity demand.
- Reduce CO_2 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**).



Source: PyPSA-Eur, based on ENTSO-E map

Linear optimisation of annual system costs

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

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

subject to

- meeting **energy demand** at each node n (e.g. region) and time t (e.g. hour of year)
- wind, solar, hydro (variable renewables) **availability time series** $\forall\, n, t$
- **transmission constraints** between nodes, **linearised power flow**
- (installed capacity) $\leq$ (**geographical potentials** for renewables)
- **CO_2 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.

Model Inputs and Outputs

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

$\rightarrow$

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

Costs and assumptions for the electricity sector (projections for 2030)

Technische Universität Berlin

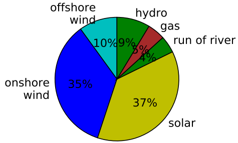
Quantity	Overnight Cost [€]	Unit	FOM [%/a]	Lifetime [a]
Wind onshore	1182	kW_{el}	3	20
Wind offshore	2506	kW_{el}	3	20
Solar PV	600	kW_{el}	4	20
Gas	400	kW_{el}	4	30
Battery storage	1275	kW_{el}	3	20
Hydrogen storage	2070	kW_{el}	1.7	20
Transmission line	400	MWkm	2	40

Interest rate of 7%, storage efficiency losses, only gas has CO_2 emissions, gas marginal costs.

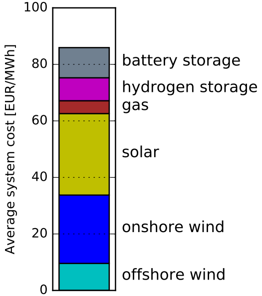
Batteries can store for 6 hours at maximal rating (efficiency 0.9×0.9), hydrogen storage for 168 hours (efficiency 0.75×0.58).

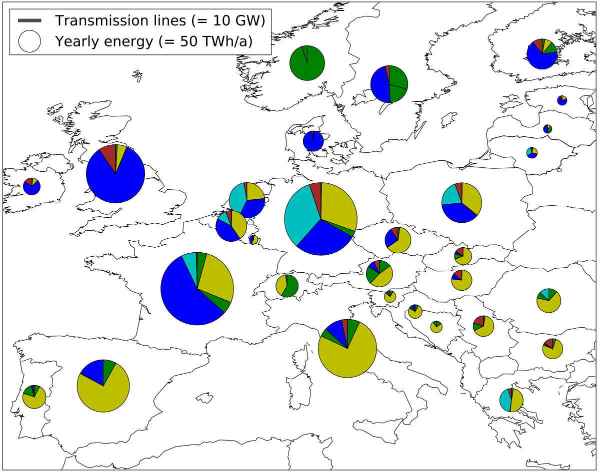
Costs: No interconnecting transmission allowed

Technology by energy:



Average cost **€86/MWh**:

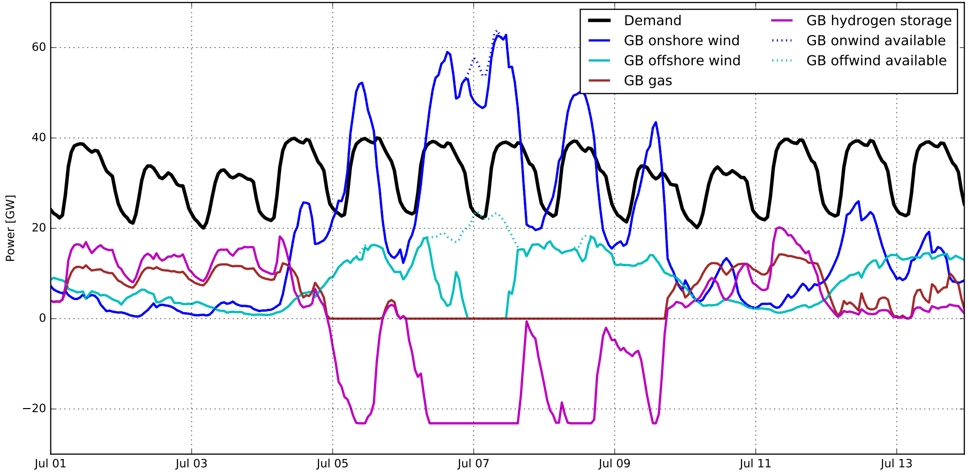




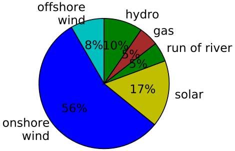
Countries must be self-sufficient at all times; lots of storage and some gas to deal with fluctuations of wind and solar.

Dispatch with no interconnecting transmission

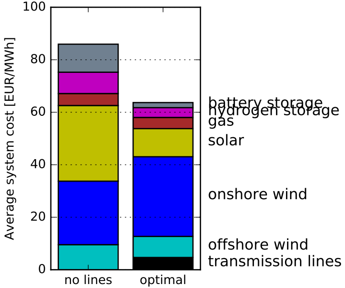
For Great Britain with no interconnecting transmission, excess wind is either stored as hydrogen or curtailed:

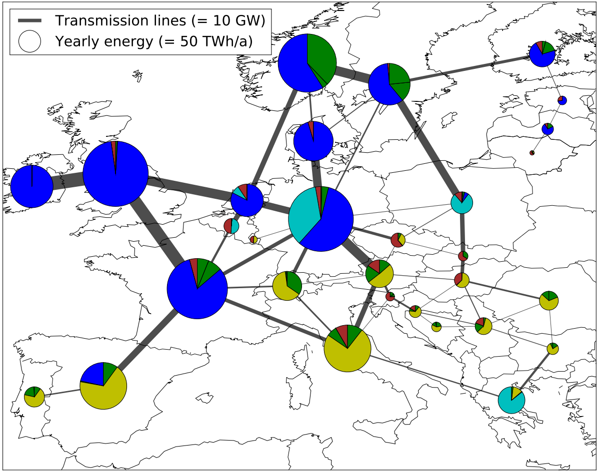


Technology by energy:



Average cost **€64/MWh**:

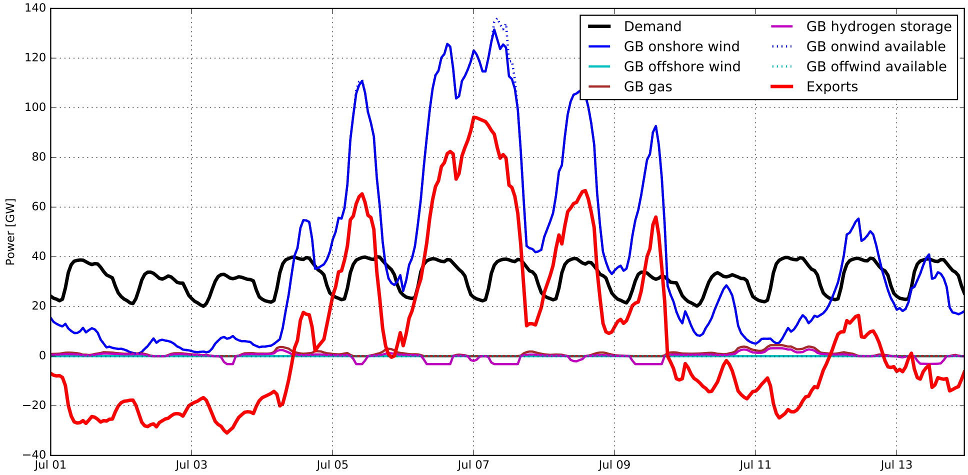




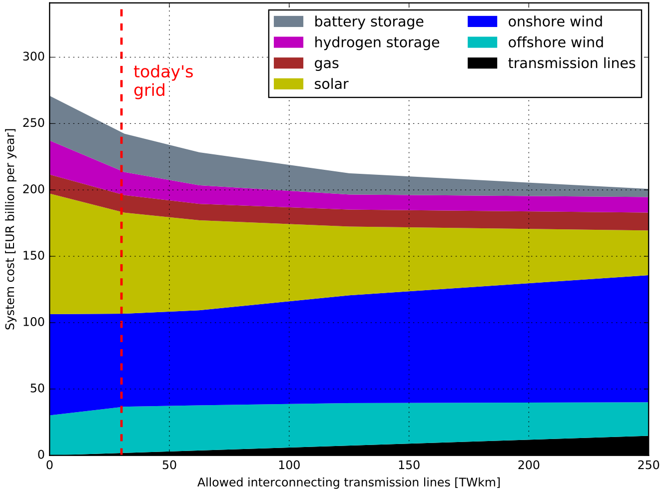
Large transmission expansion; onshore wind dominates. This optimal solution may run into public acceptance problems.

Dispatch with cost-optimal interconnecting transmission

Almost all excess wind can be now be exported:

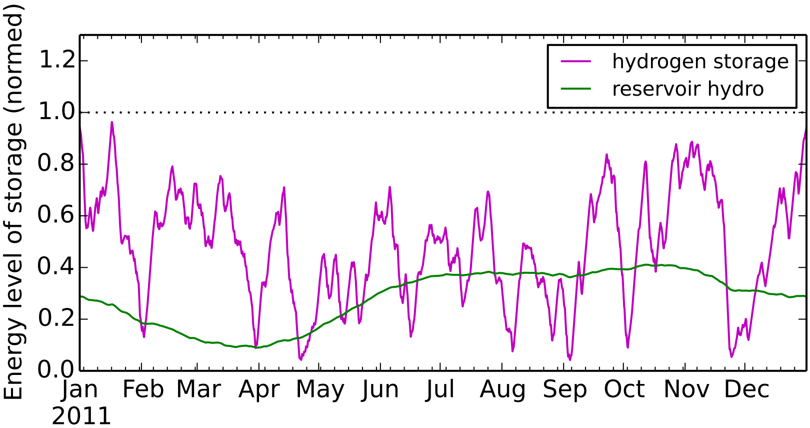


Electricity Only Costs Comparison

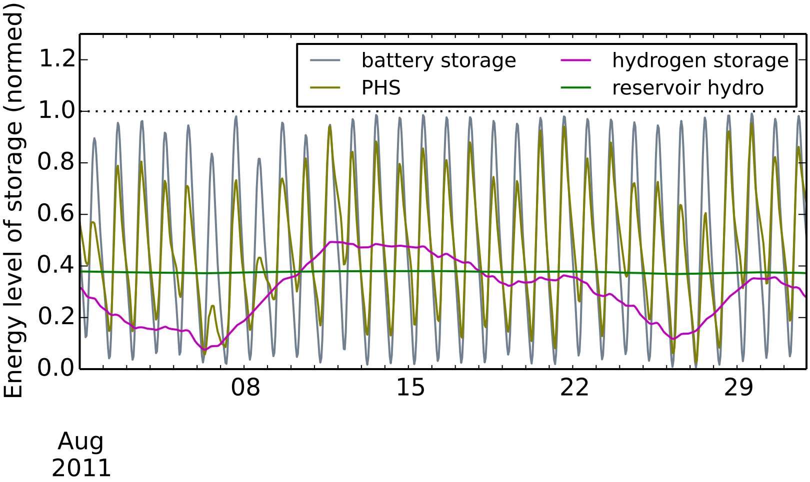


- Average total system costs can be as low as € 64/MWh
- Energy is dominated by wind (64% for the cost-optimal system), followed by hydro (15%) and solar (17%)
- Restricting transmission results in more storage to deal with variability, driving up the costs by up to 34%
- Many benefits already locked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



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

Features of this example

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**.