

# Energy Systems, Summer Semester 2022

## Lecture 1: Organisation & Introduction

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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

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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](mailto:p.glaum@tu-berlin.de)).

Group website (with **open MA theses**): <https://www.ensys.tu-berlin.de/>

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=28764>

Course abbreviation: EnSys SoSe22

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

All lecture slides will be available here as PDFs shortly before each lecture:

<https://nworbmot.org/courses/es-22/>

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

- 'Energy Systems' Lectures + Tutorials + 90-minute Written Exam = 6 ECTS
- 'Energy Systems' as above + Seminar 'New Developments in Energy Markets' = 9 ECTS  
(Portfolioprüfung für Projekt EVT: Energiesysteme)

Registration:

- via MTS (up to one week before the exam)
- Erasmus: try via MTS, if that fails, email Philipp Glaum

- Written exam online via ISIS portal
- 90-minute exam 1430-1600 on Wednesday 3rd August 2022
- Open-book exam
- 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 7 points

- Students analyse a current topic in energy markets, prepare a 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 2022, presentations on 14-15th September 2022
- Example topics: getting off gas, market reform, EEG, European Green Deal, e-mobility, hydrogen economy, industrial decarbonisation, flexibility markets, etc.

The seminar has [its own ISIS page](#).



Due to the novel corona virus, this lecture course will take place online on [Zoom](#).

All lectures and tutorials will be recorded and videos will be available for the whole semester.

Day	Time	Event
Tuesday	1600-1800	Lecture
Wednesday	1600-1800	Tutorial
Thursday	1400-1600	Lecture

First lecture: Tuesday 19th April 2022, last lecture: Thursday 21st July 2022

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

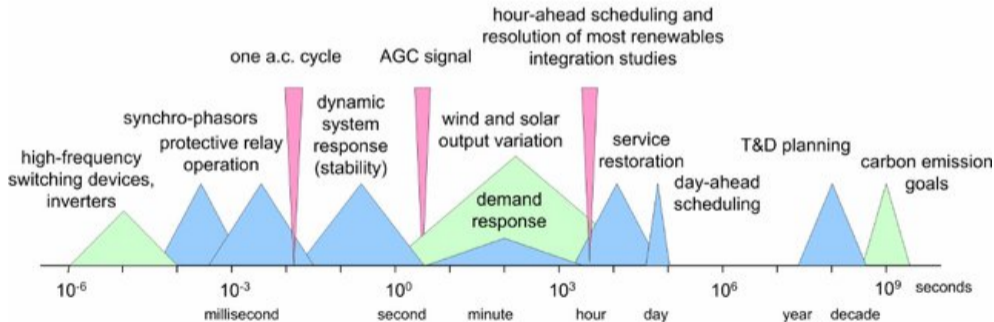
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Energy System Modelling requires methods and skills from several disciplines:

- **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, energy balances
- Input-output analysis
- 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
- Current research topics

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



# What is Energy System Modelling?

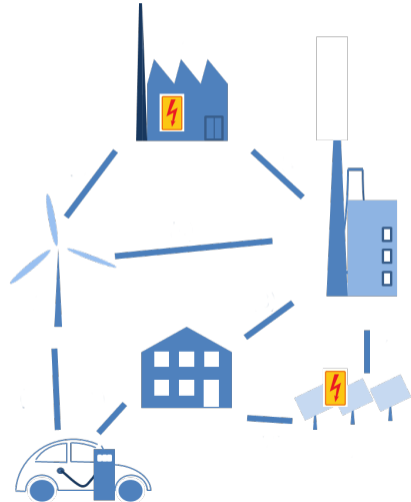
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**Energy System Modelling** is about the overall **design** and **operation** of the energy system.

- 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:



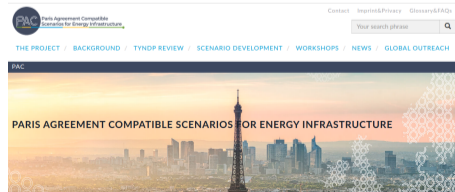
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Suchbegriff eingeben

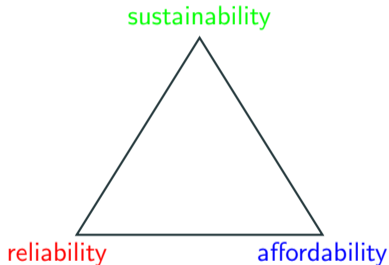


ARTIKEL [Energiedaten und -szenarien](#)

## Langfrist- und Klimaszenarien



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

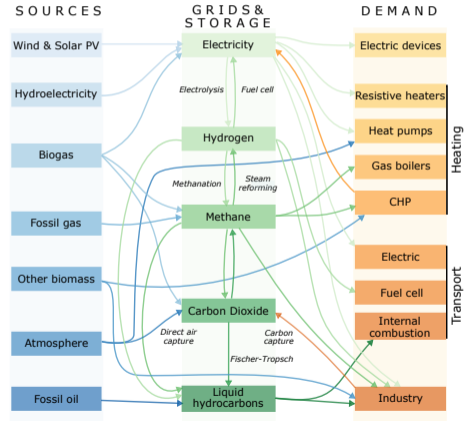
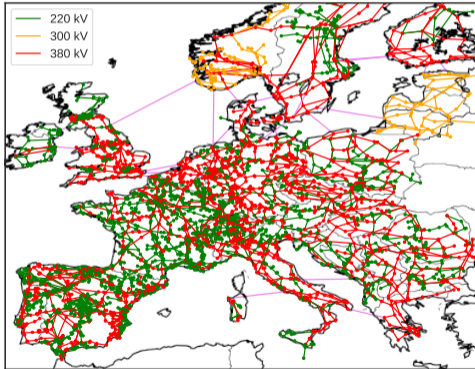


- **Sustainability:** Respect environmental constraints (greenhouse gases, air quality, preservation of wildlife), social and political constraints (geopolitics, public acceptance of transmission lines, onshore wind, nuclear power)
- **Reliability:** Ensure energy services are delivered whenever needed,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

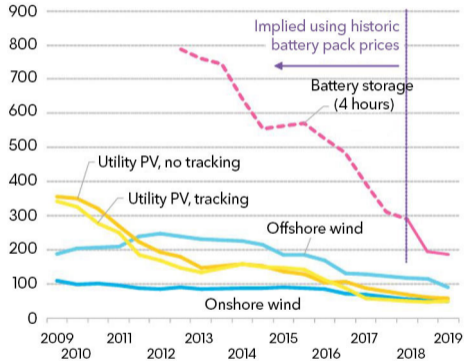
Need to model: (at least) all of Europe for market integration; enough spatial and temporal detail to capture all important effects; all interactions between energy sectors; correct physics.



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

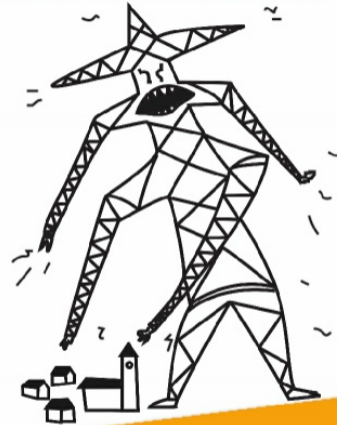
Global benchmarks - PV, wind and batteries

LCOE (\$/MWh, 2018 real)



Source: BloombergNEF. Note: The global benchmark is a country weighed-average using the latest annual capacity additions. The storage LCOE is reflective of a utility-scale Li-ion battery storage system running at a daily cycle and includes charging costs assumed to be 60% of whole sale base power price in each country.

[www.berngau-gegen-monstertrasse.de](http://www.berngau-gegen-monstertrasse.de)

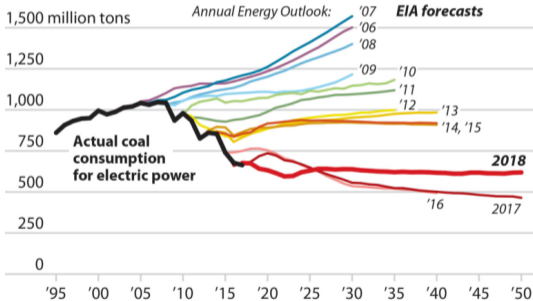


**Nein!** ZUR MONSTERTRASSE!

# Not everyone gets it right...

## EIA Coal Consumption Forecasts, 2006-2018

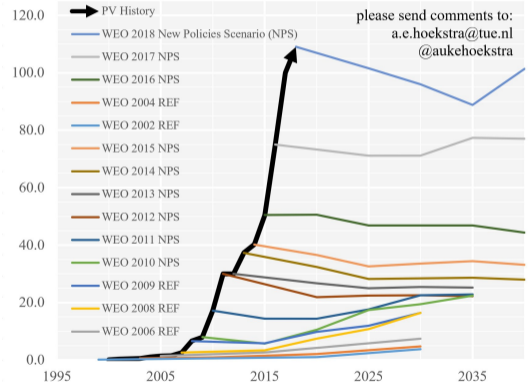
Each year, the Energy Information Administration releases its Annual Energy Outlook, which includes a long-term forecast for U.S. coal consumption for electric power generation. However, the forecasts have been wildly inaccurate, even in the near term.



Source: Energy Information Administration

## 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

[TWITTER](#) [FACEBOOK](#) [LINKEDIN](#) [WHATSAPP](#) [EMAIL](#) [PRINT](#)



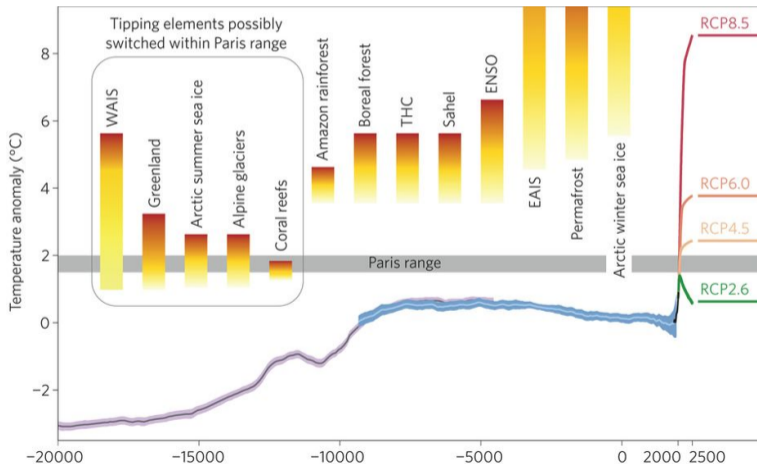
Sinn's study was [debunked](#), shown to use cherry-picked assumptions

# **The Greenhouse Gas Challenge & The Energy System**

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# 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 (⇒ 5m sea level rise)

Greenland (7m)

THC: thermohaline circulation (warms Europe)

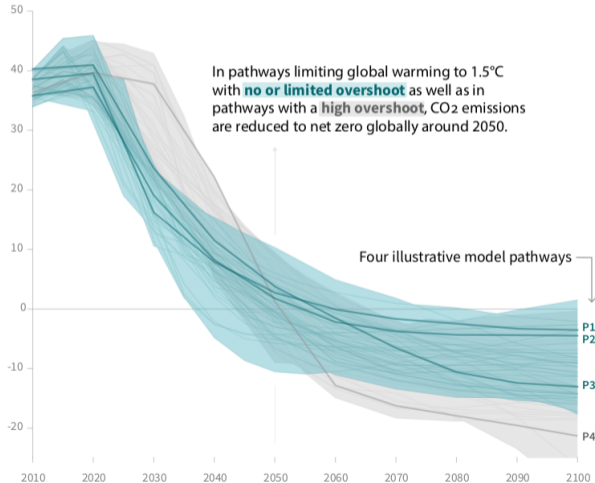
ENSO: El Niño–Southern Oscillation (extreme weather)

EAIS: East Antarctic Ice Sheet (> 50 m)



## Global total net CO<sub>2</sub> emissions

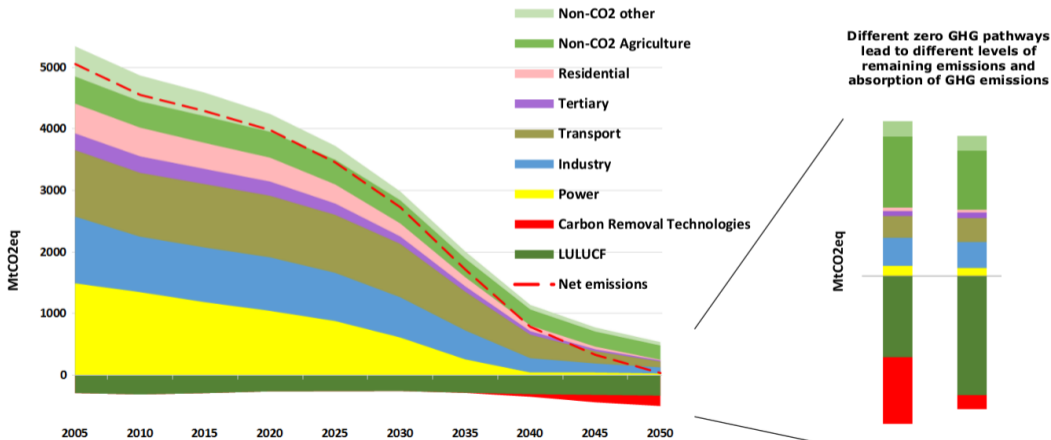
Billion tonnes of CO<sub>2</sub>/yr



- Scenarios for global CO<sub>2</sub> 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**

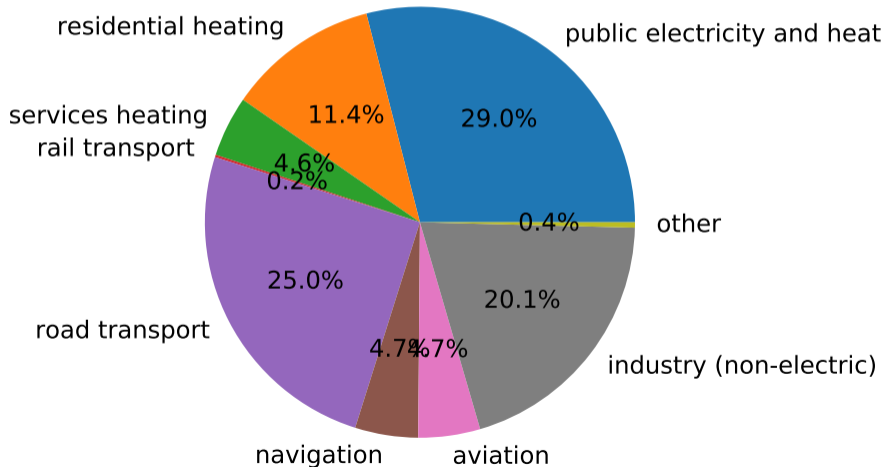
# The Greenhouse Gas Challenge: Net-Zero Emissions by 2050

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 CO<sub>2</sub> emissions in 2016 (total 3.5 Gt CO<sub>2</sub>, 9.7% of global):

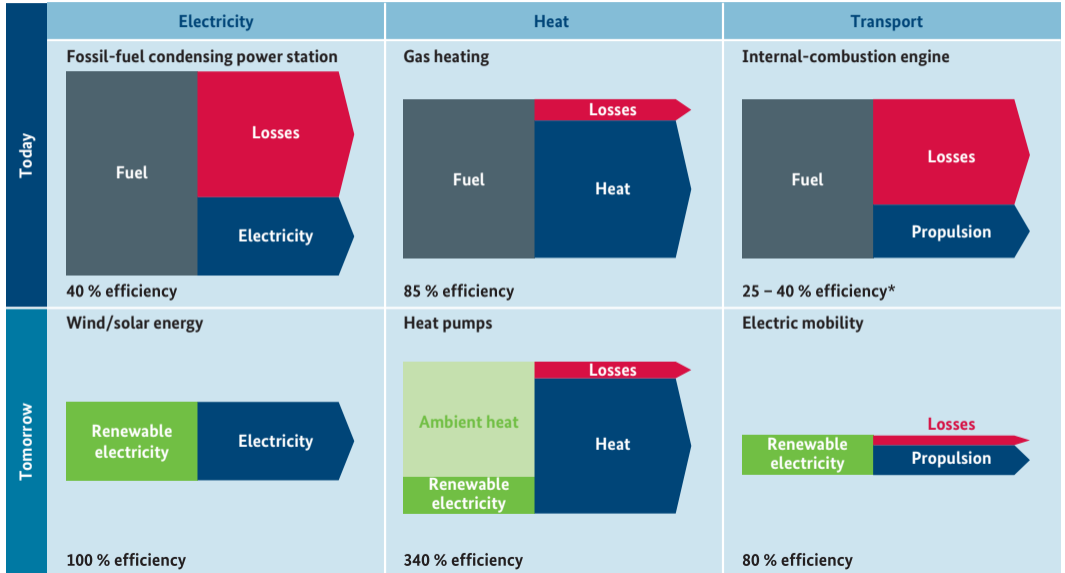


**Electrification is essential** to decarbonise sectors such as transport, heating and industry, since we can use low-emission electricity from e.g. wind and solar to displace fossil-fuelled transport with electric vehicles, and fossil-fuelled heating with electric heat pumps.

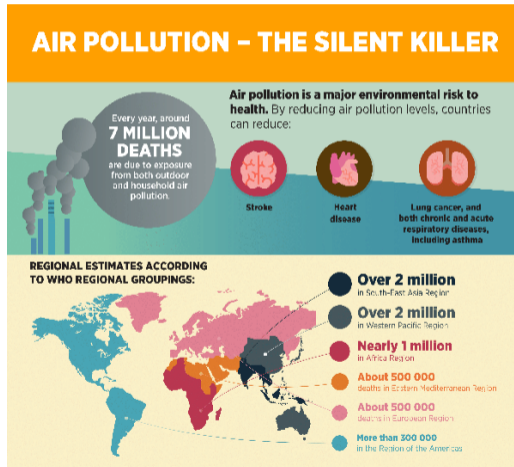
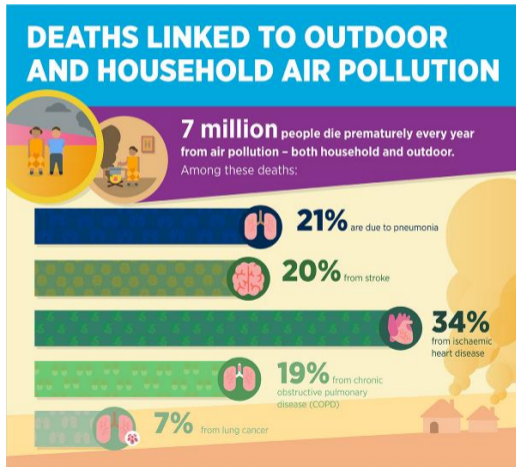
Some scenarios show a **doubling or more of electricity demand**.



# Efficiency of renewables and sector coupling

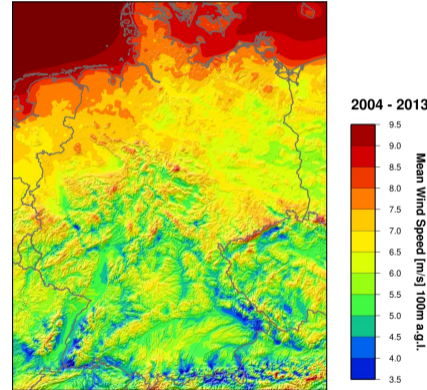
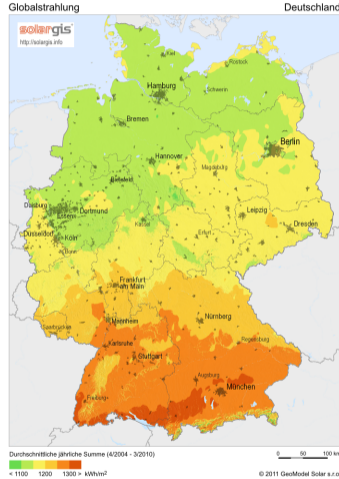


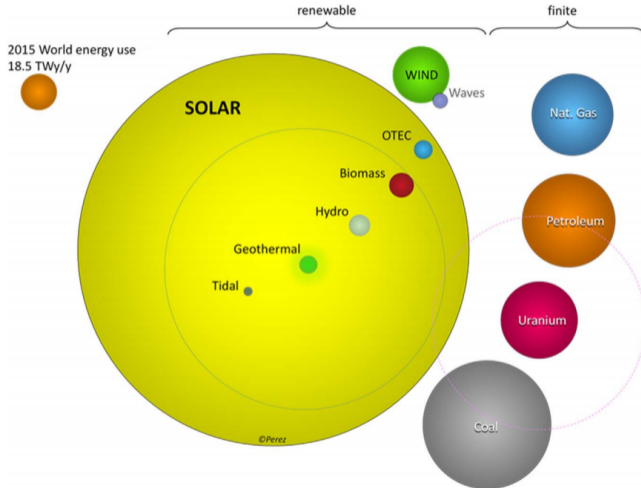
Air pollution from fossil fuel burning is linked to higher mortality (deaths) and morbidity (diseases, e.g. aggravation of asthma).



# 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





## 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

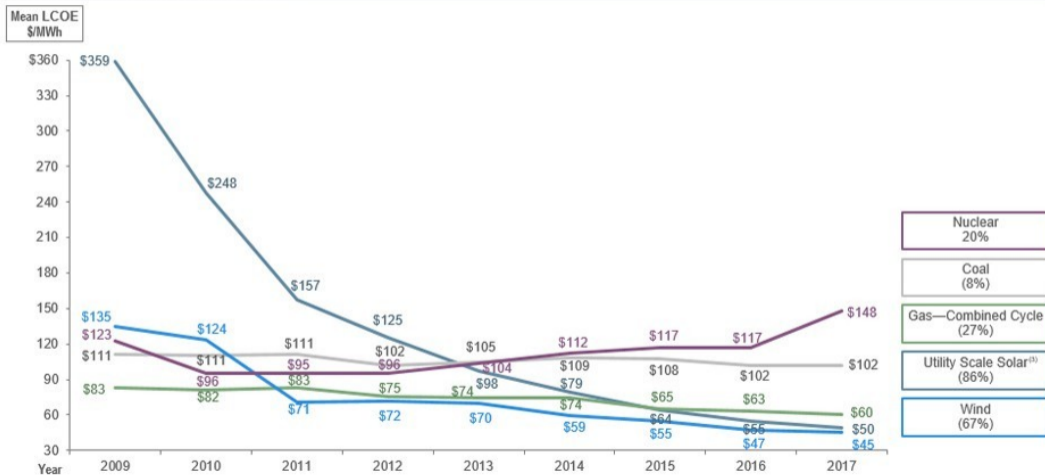
- Potentials for wind and solar exceed current demand by many factors (ignoring variability)
- Other renewable sources include wave, tidal, geothermal, biomass and hydroelectricity
- Uranium depends on the reactor: conventional thermal reactors can extract 50-70 times less than fast breeders



# Low cost of wind & solar per MWh in 2017 (NB: ignores variability)

$$\text{LCOE} = \text{Levelised Cost of Energy} = \text{Total Costs} / \text{Energy Output}$$

Selected Historical Mean LCOE Values<sup>(2)</sup>

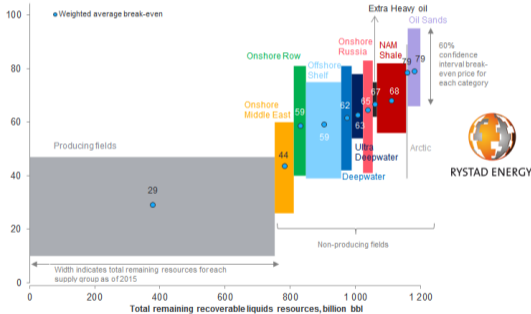


# Fundamental shift from scarce exhaustible to renewable energy

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

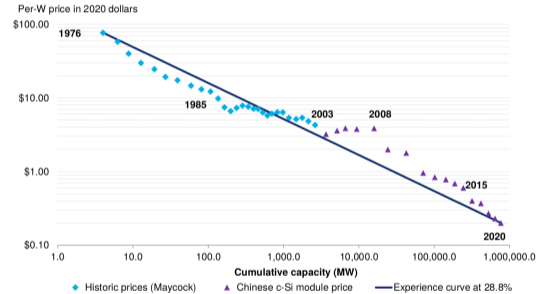
Solar and wind costs drop with innovation (can rise locally where land is scarce)

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

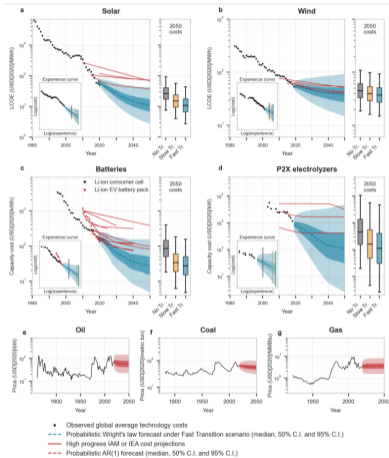
PV module experience curve (2020\$/W, MW)



(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.

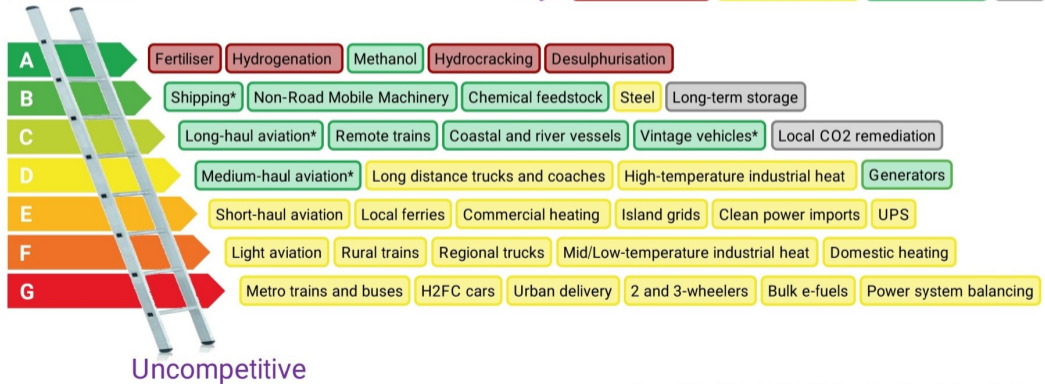
- **Low-cost electricity** from wind and solar.
- **Batteries** for mobility and balancing applications.
- **Electrolytic hydrogen** (splitting water) for everything else: long-duration storage, aviation, shipping, industry.
- **Heat pumps** (missing from graphic) for building comfort and some low-temperature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

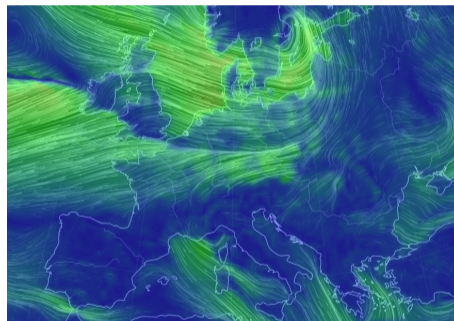
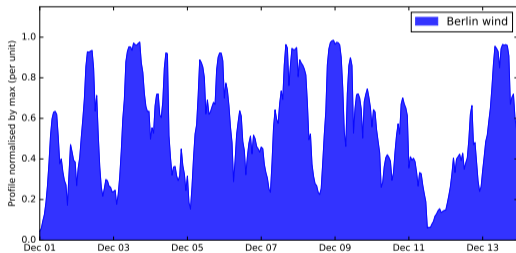
Key: No real alternative Electricity/batteries Biomass/biogas Other



\* 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](https://creativecommons.org/licenses/by/3.0/)

# But must take account of variability...



[WWW.BERNGAU-GEGEN-MONSTERTRASSE.DE](http://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.



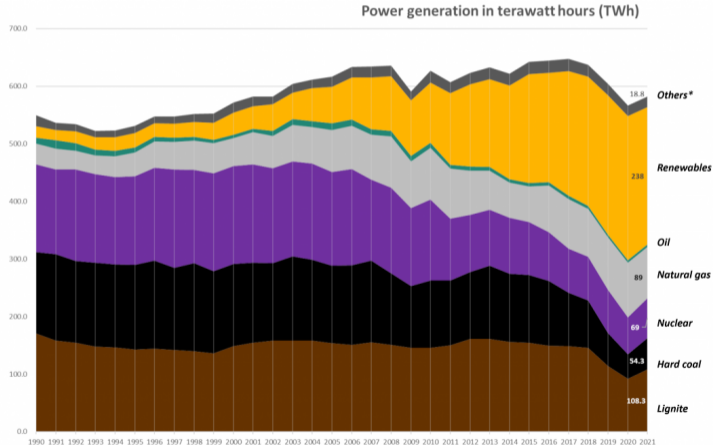
**Energiewende:** The Energy Transition, consists of several parts:

- 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 41% of gross electricity in Germany in 2021

## Gross power production in Germany 1990 - 2021, by source.

Data: BDEW 2021, data preliminary.



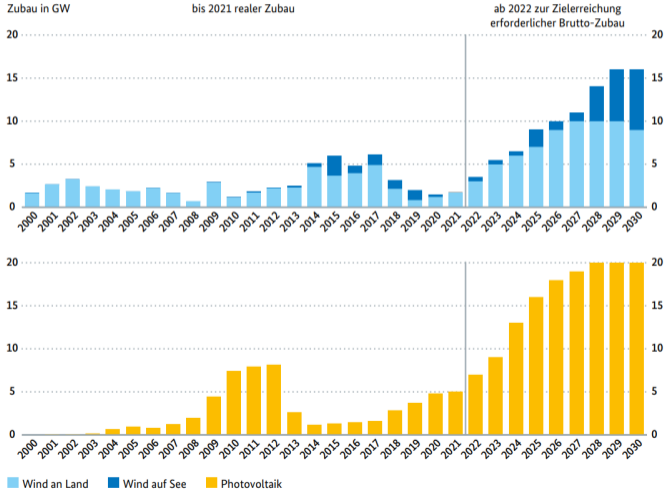
\* Without power generation from pumped storage.



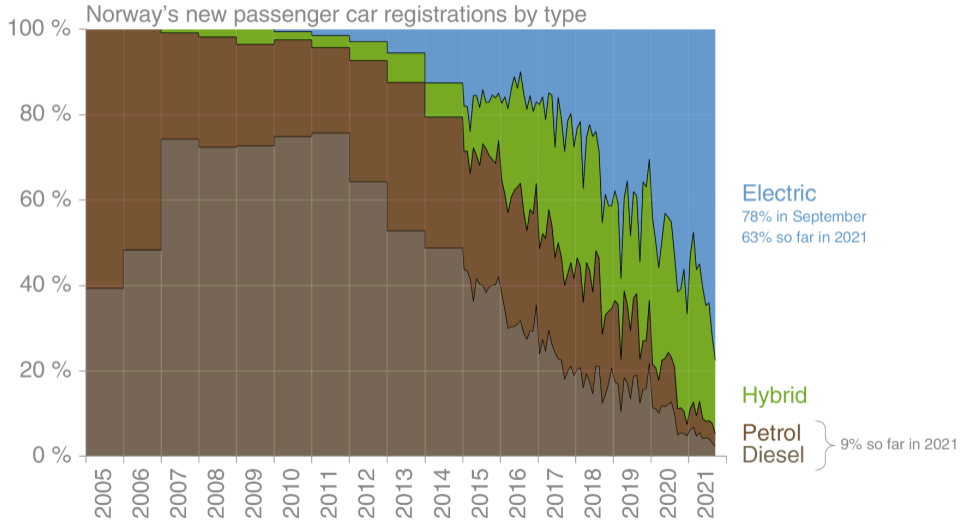
# Build-out rates for wind and solar need to increase rapidly

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

## Ausbau Wind und Photovoltaik

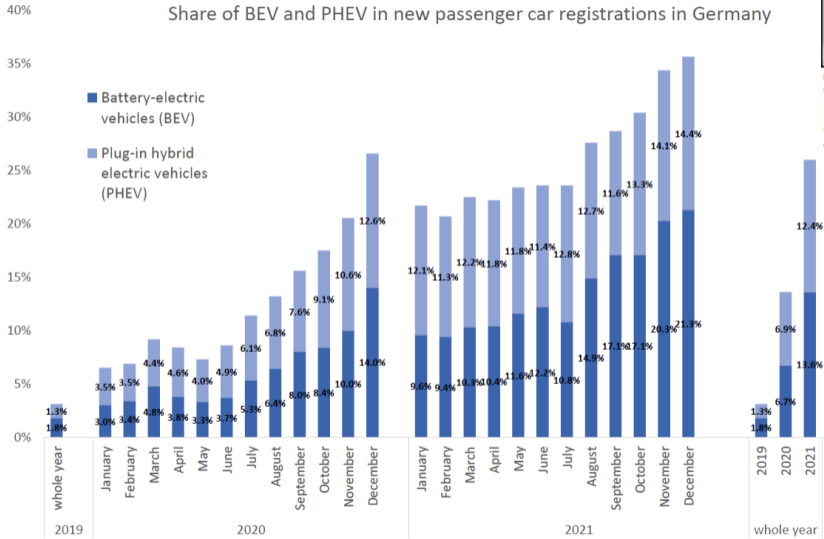


# Electric vehicles take off, first in Norway



© @robbie\_andrew • Data: OFV • Through September 2021

# Electric vehicles: Germany catching up



Based on Kraftfahrt-Bundesamt data  
#energy\_graph @WPSchill

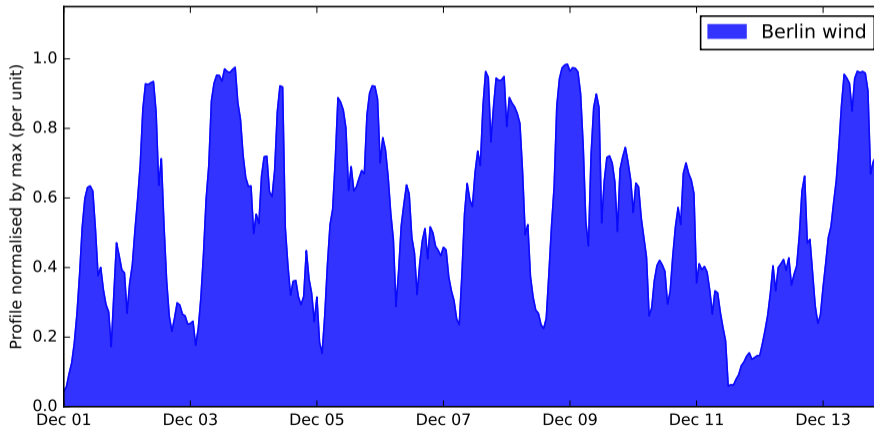
# **Invitation: Balancing Variable Renewable Energy in Europe**

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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<sub>2</sub> 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?

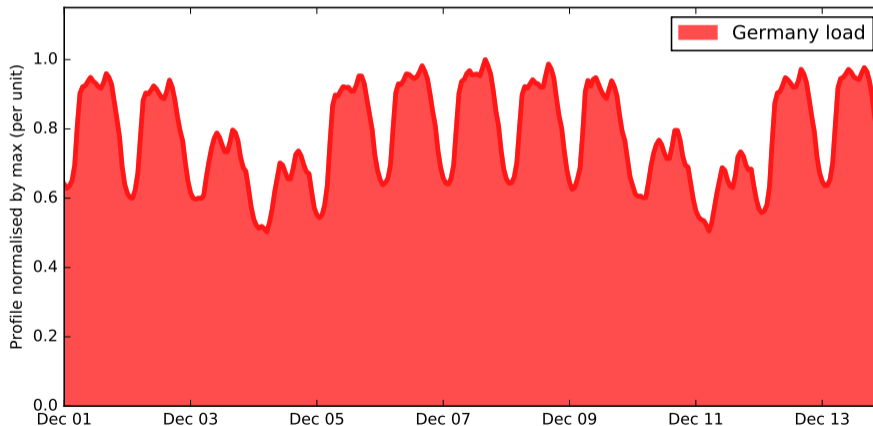
## Variability: Single wind site in Berlin

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.



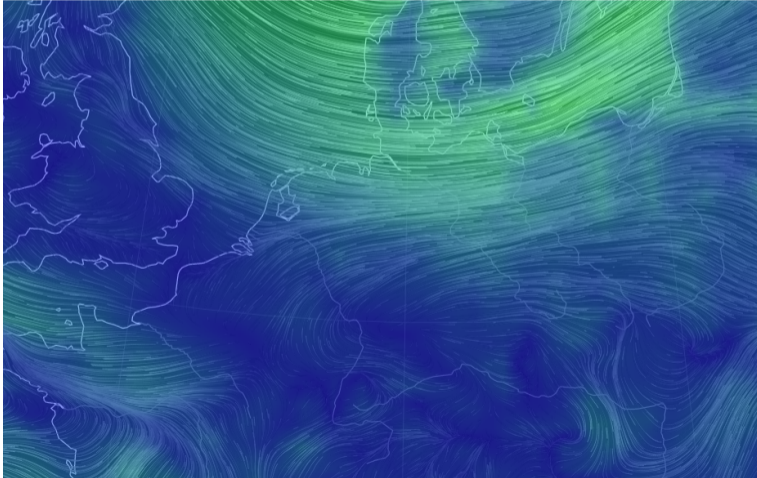
# Electricity consumption is much more regular

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...



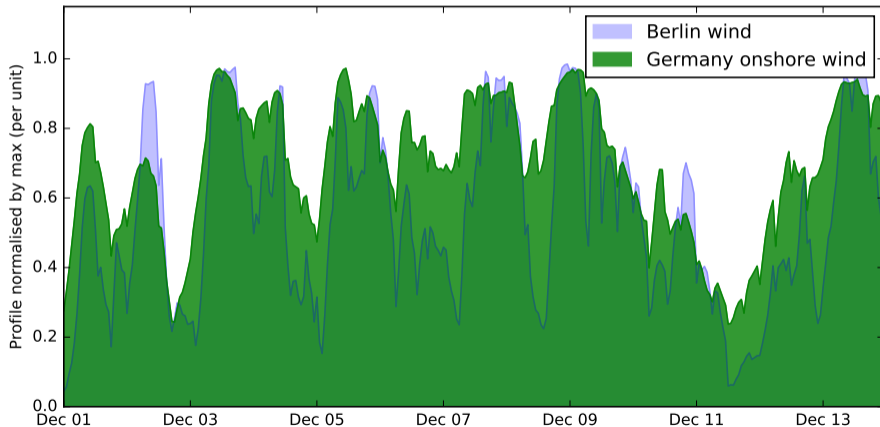
## Variability: Different wind conditions over Germany

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**.



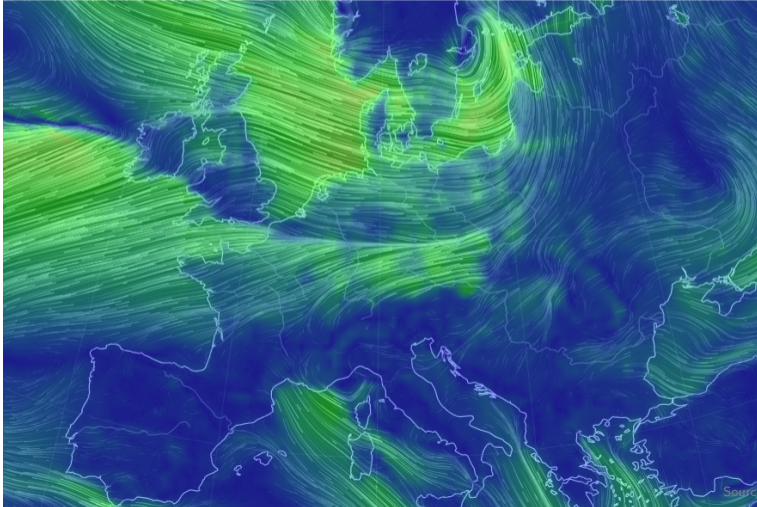


For a whole country like Germany this results in valleys and peaks that are somewhat smoother, but the profile still frequently drops close to zero.

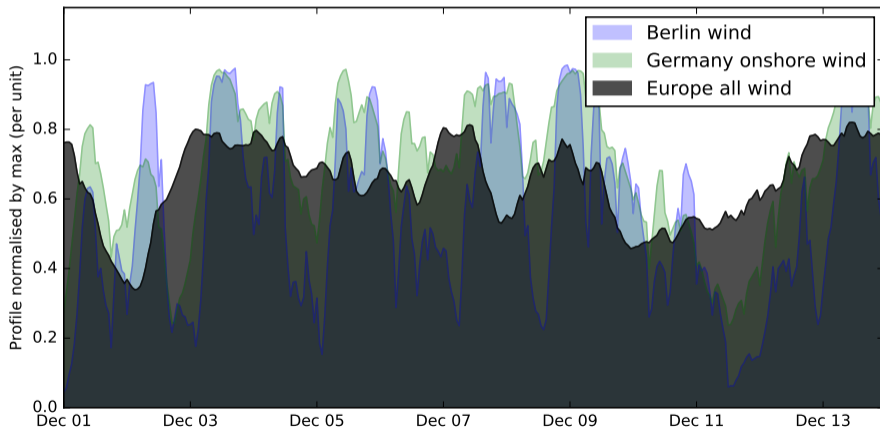


## Variability: Different wind conditions over Europe

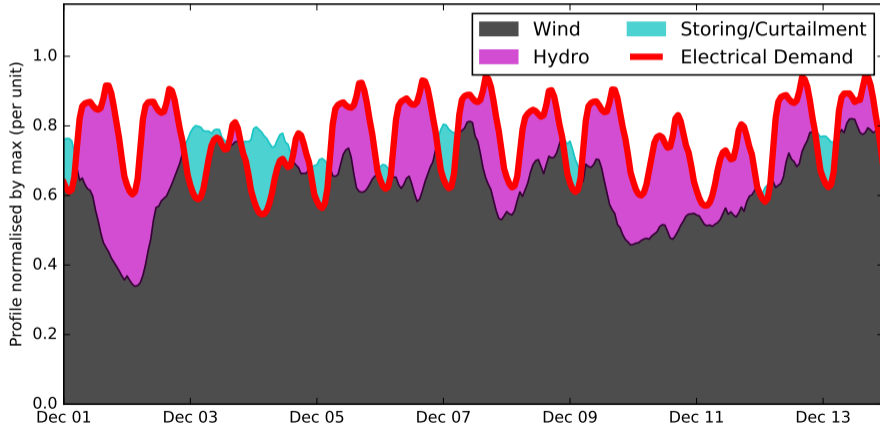
The scale of the weather systems are bigger than countries, so to leverage the full smoothing effects, you need to integrate wind at the **continental scale**.

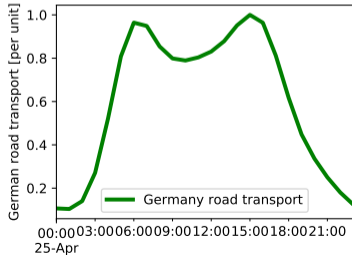
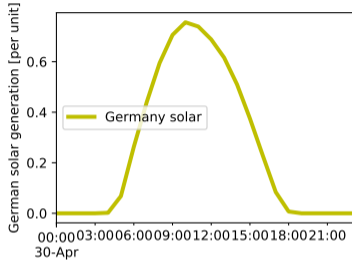


If we can integrate the feed-in of wind turbines across the European continent, the feed-in is considerably smoother: we've eliminated most valleys and peaks.



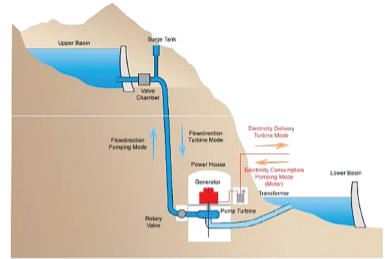
Flexible, renewable hydroelectricity from storage dams in Scandinavia and the Alps can fill many of the valleys; excess energy can either be curtailed (spilled) or stored.

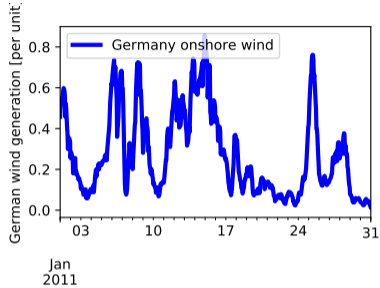




Daily variations in supply and demand can be balanced by

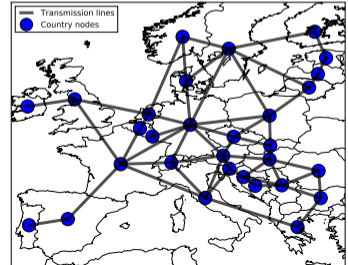
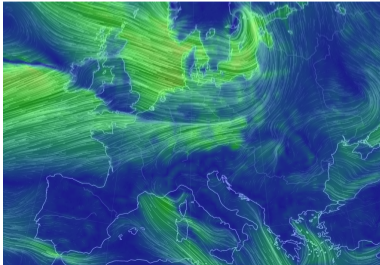
- **short-term storage** (e.g. batteries, pumped-hydro, small thermal storage)
- **demand-side management** (e.g. battery electric vehicles, industry)
- **east-west grids over multiple time zones**

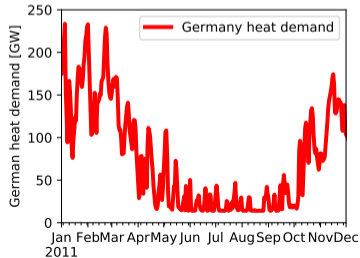
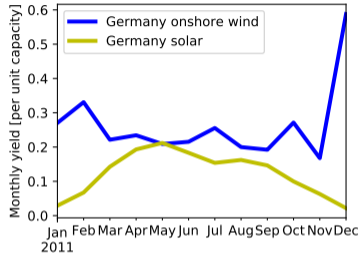




Weekly variations in supply and demand can be balanced by

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



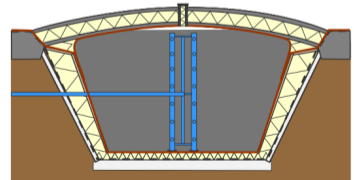


**Seasonal** variations in supply and demand can be balanced by

- **long-term storage** (e.g. chemically with 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/m<sup>3</sup>)



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

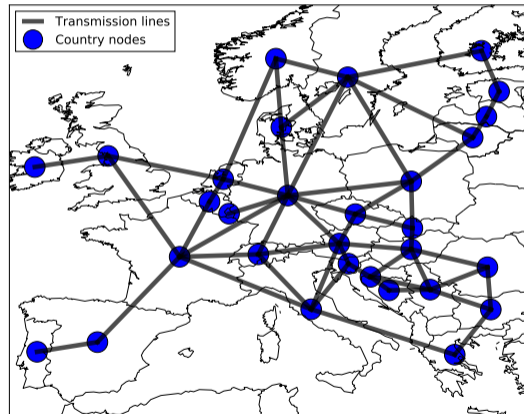
- Meet demand for energy services
- Reduce CO<sub>2</sub> emissions
- Conservative predictions for cost developments
- No/minimal/optimal grid expansion

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 CO<sub>2</sub> 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:

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

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<sub>2</sub> 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.

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<b>Inputs</b>	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
$\eta_*$	Storage efficiencies
$C_{i,s}$	Generator capital costs
$O_{i,s,t}$	Generator marginal costs
$c_\ell$	Line costs

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<b>Outputs</b>	Description
$G_{i,s}$	Generator capacities
$g_{i,s,t}$	Generator dispatch
$F_\ell$	Line capacities
$f_{\ell,t}$	Line flows
$\lambda_*, \mu_*$	Lagrange/KKT multipliers of all constraints
f	Total system costs

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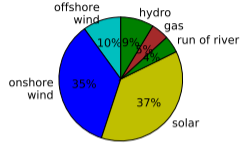
Quantity	Overnight Cost [€]	Unit	FOM [%/a]	Lifetime [a]
Wind onshore	1182	kW <sub>el</sub>	3	20
Wind offshore	2506	kW <sub>el</sub>	3	20
Solar PV	600	kW <sub>el</sub>	4	20
Gas	400	kW <sub>el</sub>	4	30
Battery storage	1275	kW <sub>el</sub>	3	20
Hydrogen storage	2070	kW <sub>el</sub>	1.7	20
Transmission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

Interest rate of 7%, storage efficiency losses, only gas has CO<sub>2</sub> emissions, gas marginal costs.

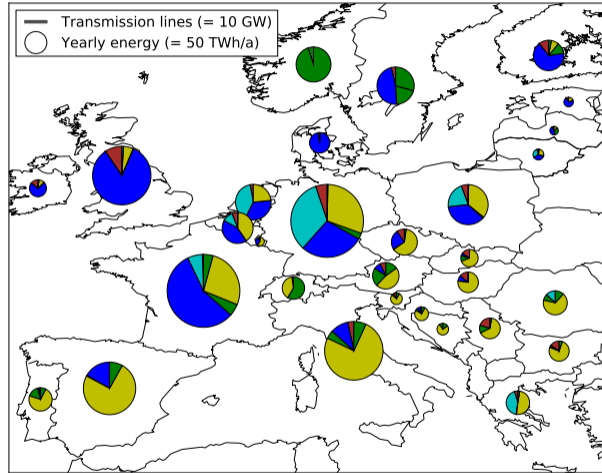
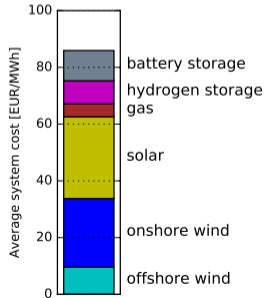
Batteries can store for 6 hours at maximal rating (efficiency  $0.9 \times 0.9$ ), hydrogen storage for 168 hours (efficiency  $0.75 \times 0.58$ ).

# Costs: No interconnecting transmission allowed

## Technology by energy:



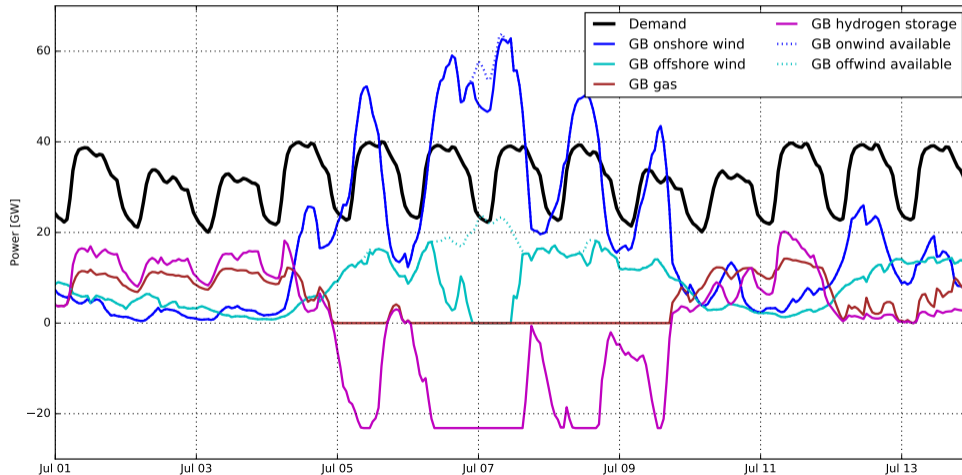
## Average cost €86/MWh:



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

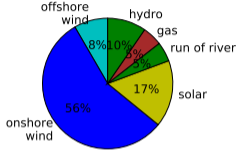
# Dispatch with no interconnecting transmission

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

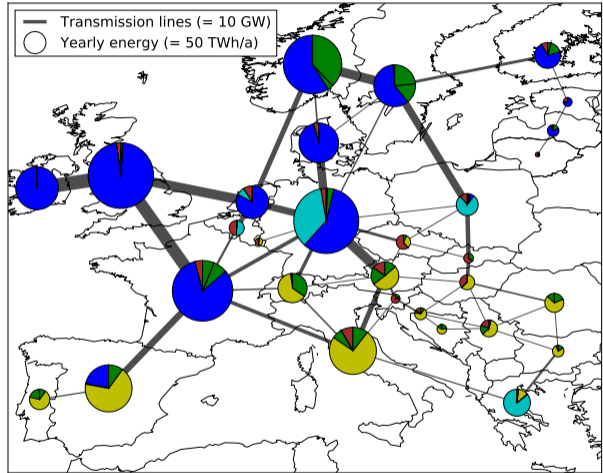
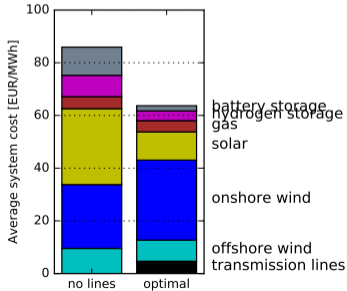


# Costs: Cost-optimal expansion of interconnecting transmission

## Technology by energy:



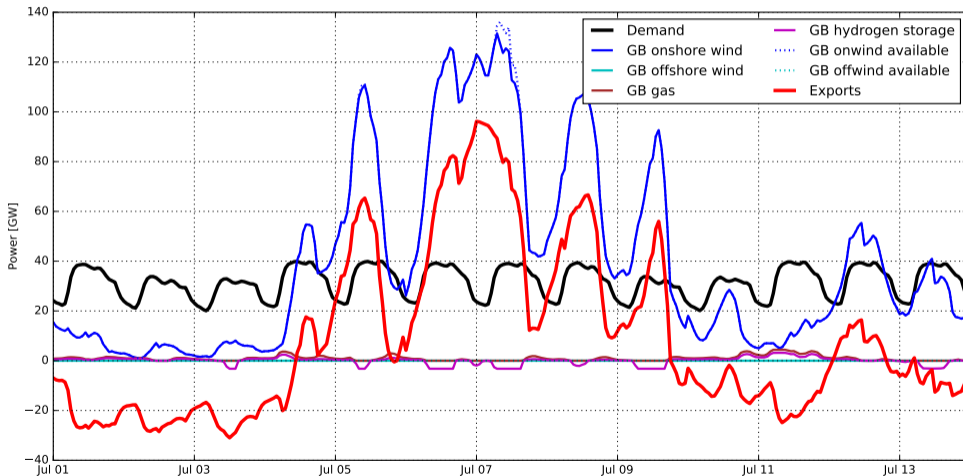
## Average cost €64/MWh:



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

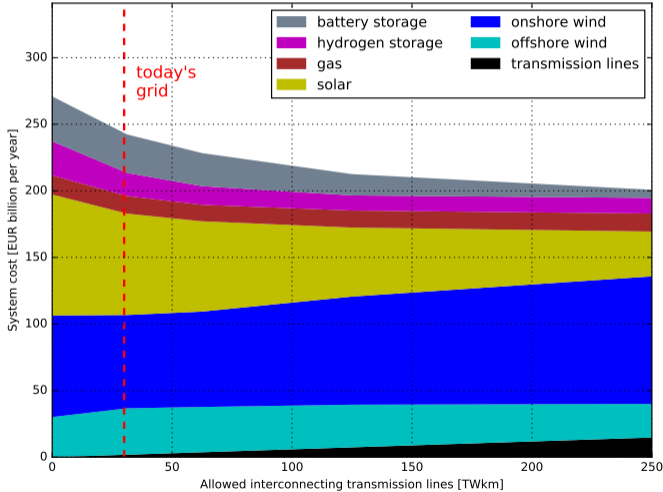
# Dispatch with cost-optimal interconnecting transmission

Almost all excess wind can be now be exported:



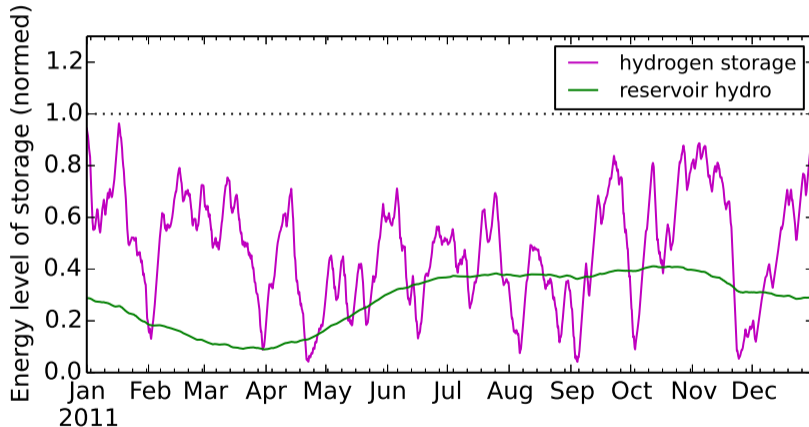


# Electricity Only Costs Comparison



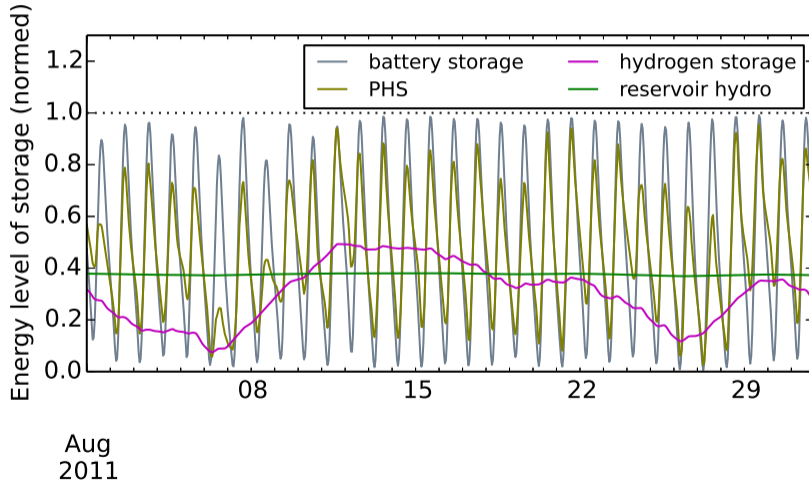
- Average total system costs can be as low as € 64/MWh
- Energy is dominated by wind (64% for the cost-optimal system), followed by hydro (15%) and solar (17%)
- Restricting transmission results in more storage to deal with variability, driving up the costs by up to 34%
- Many benefits already locked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

# 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).