Energy System Modelling
Summer Semester 2020, Lecture 1

Dr. Tom Brown, tom.brown@kit.edu, https://nworbmot.org/
Karlsruhe Institute of Technology (KIT), Institute for Automation and Applied Informatics (IAI)

Table of Contents

Administration

Contact Details

Dr. Tom Brown

Leader of ‘Energy System Modelling’ Research Group

Institute for Automation and Applied Informatics (IAI)

KIT, North Campus

Associate Fellow of KIT’s Department of Informatics

tom.brown@kit.edu

Group website (with **open MA theses**): `https://www.iai.kit.edu/english/ESM.php`

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

I specialise in the optimisation of energy systems and the interactions of complex networks. I work at the intersection of informatics, economics, engineering, mathematics, meteorology and physics.

Lectures, Q & A and Exercise Classes

Due to the novel corona virus, this lecture course will take place online. Instead of lectures on Campus Nord, lectures will be pre-recorded and released as video along with the slides.

For each of the five days of the course there are 3 roughly hour-long lecture videos.

On each day there will an online Q & A on the pre-recorded lectures as well as a tutorial:

time	session
10:00 - 12:00	Live Q & A on lectures on MS Teams (please watch the lectures for this day beforehand)
13:00 - 14:30	Live tutorial on MS Teams (please do the exercise sheet beforehand)

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.

Lectures, Q & A and Exercise Classes

The lectures will be recorded and uploaded to YouTube well before the online live sessions to give you a chance to view the material in advance. Similarly the exercise sheets will be uploaded beforehand.

Dates		lectures uploaded by
Thu	04.06.2020	21.05.2020
Fri	05.06.2020	28.05.2020
Fri	19.06.2020	05.06.2020
Thu	25.06.2020	11.06.2020
Fri	26.06.2020	19.06.2020

If you want to download the videos to watch them offline, the utility youtube-dl is your friend.

Course Website

You can find the course website here:

`https://nworbmot.org/courses/esm-2020/`

by following the links from:

`https://nworbmot.org/`

Course notes, lecture slides, links to videos, exercise sheets and other links can be found there.

Registration for Oral Exam

To get an evaluation at the end of the course, you need to register online for the oral examination.

The oral examinations will take place some time in July on a single date. The date will be decided during the final lecture, based on when we are all available.

The course has 4 ECTS points.

MA Theses

We have some exciting opportunities in the Energy System Modelling group at IAI to do MA Theses, see the list here:

`https://www.iai.kit.edu/english/2552.php`

We are also open to new suggestions and themes if they fit with our research programme.

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:

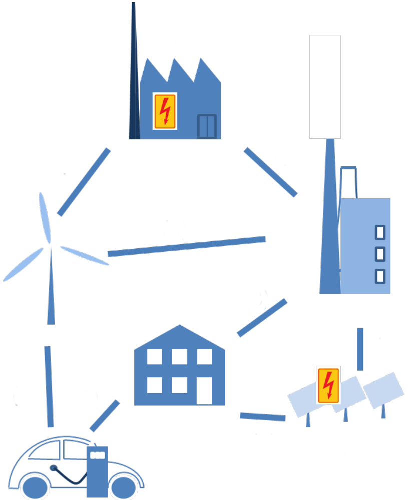
- Joshua Adam Taylor, "Convex Optimization of Power Systems", Cambridge University Press, 2018
- Volker Quashning, "Regenerative Energiesysteme", Carl Hanser Verlag München, 2015
- Leon Freris, David Infield, "Renewable Energy in Power Systems", Wiley, 2006
- Göran Andersson Skript, "Elektrische Energiesysteme: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

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.

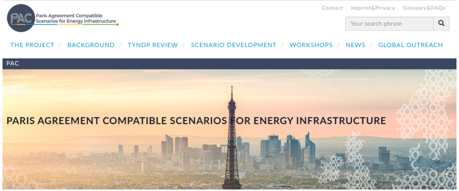
Researchers deal with these questions by **building computer models** of the energy system and then, for example, **optimizing** its design and operation.

Energy System Modelling: Who is it for?

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

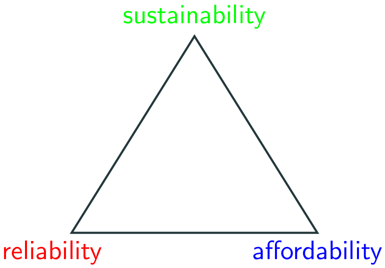
Government agencies commission studies to look at possible future scenarios:

But also companies and non-governmental organisations:



Guildelines: Energy Trilemma

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

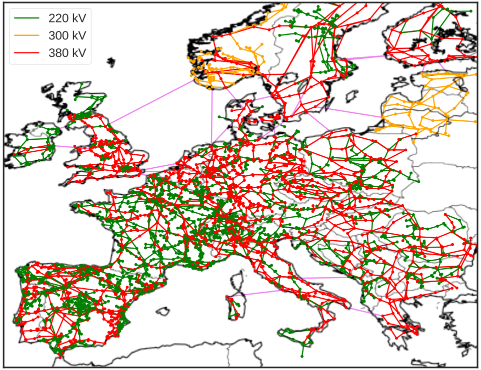


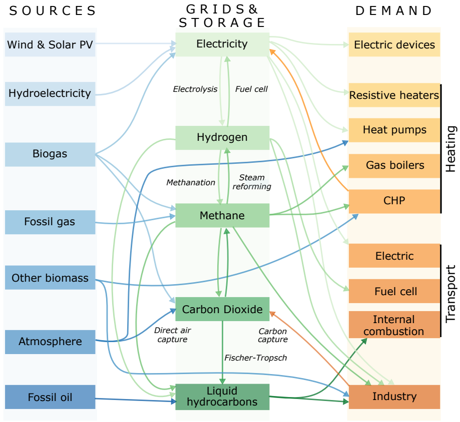
- **Sustainability**: Respect environmental constraints (greenhouse gas emissions, preservation of wildlife), as well as social and political constraints (public acceptance of transmission lines, onshore wind, nuclear power)
- **Reliability**: Ensure energy services are delivered whenever needed, even 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** (see EI1).

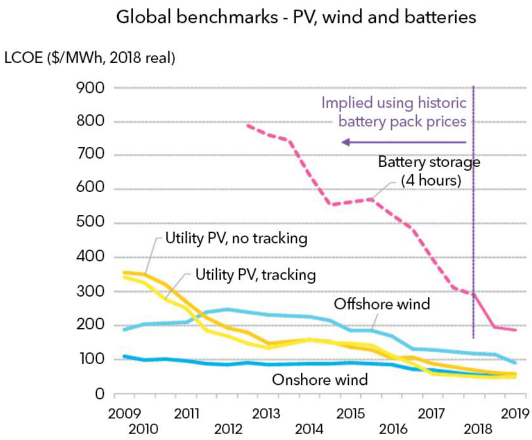
Why it's computationally hard: many components and interactions

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.



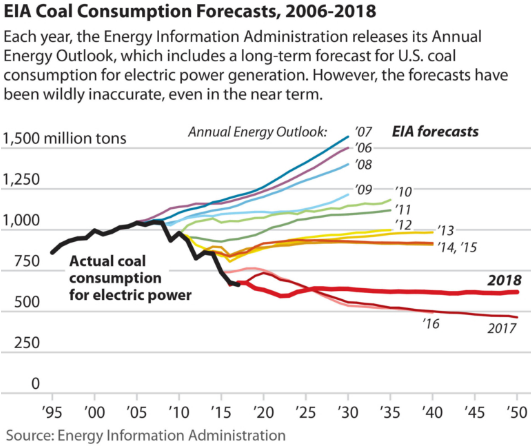


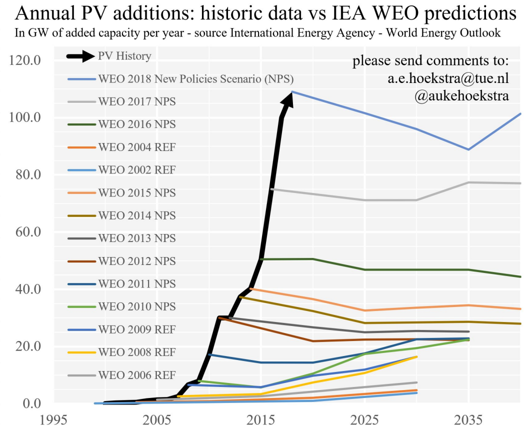
Why it's hard: non-linearities and social effects



Source: BloombergNEF. 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.

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

What can informatics contribute?

Informatics can contribute on the **data side**:

- Processing and analysing enormous weather datasets
- Geographical potential analysis with GIS tools
- Visualisation of results

and on the **algorithmic side**:

- New optimization routines for speed and accuracy
- Data reduction and feature identification
- Information theory to trace interdependencies

Build on informatics' **interdisciplinary** links to engineering, economics, meteorology, mathematics and physics.

Course outline

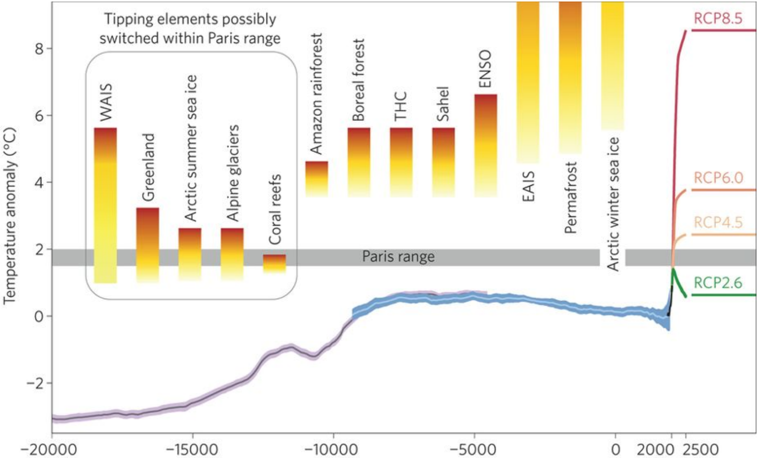
This course will cover the following topics:

- General properties of renewable power, time series analysis
- Backup generation, curtailment
- Network modelling in power systems
- Storage modelling
- Optimization theory
- Energy system economics
- Complex network techniques for renewable energy networks (flow tracing, etc.)
- Current research topics

The Greenhouse Gas Challenge

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)

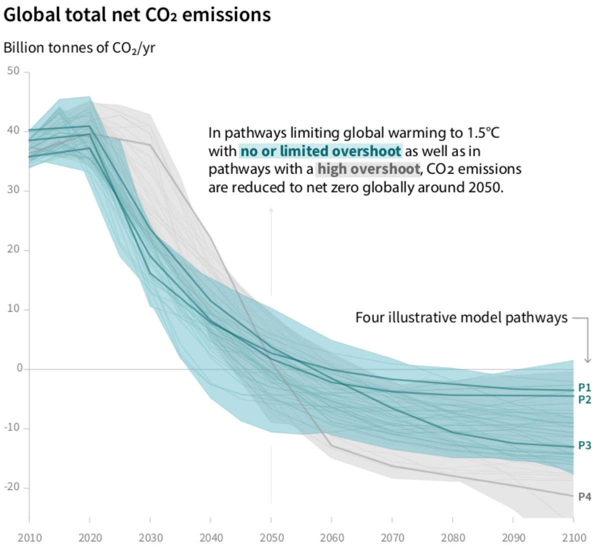
THC: thermohaline circulation (warms Europe)

ENSO: El Niño–Southern Oscillation (extreme weather)

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

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

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

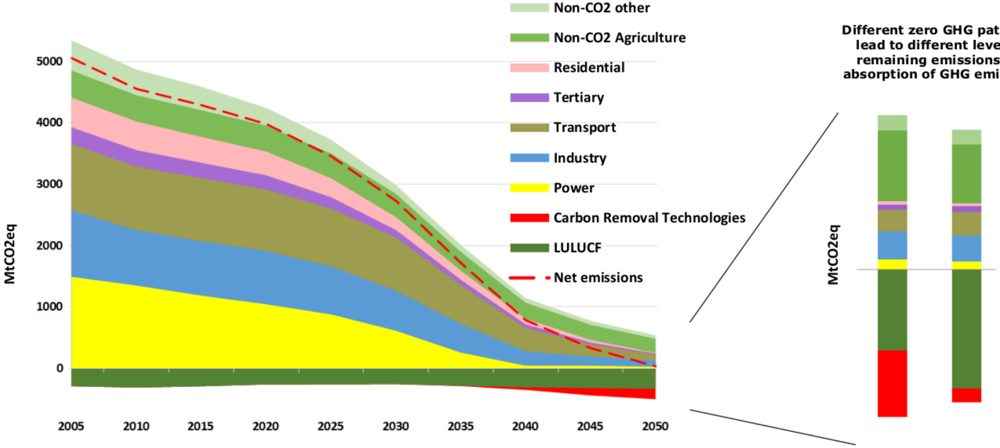


- Scenarios for global CO_2 emissions that limit warming to 1.5°C about industrial levels (**Paris agreement**)
- Today emissions **still rising**
- Level of use of negative emission technologies (NET) depends on rate of progress
- 2°C target without NET also needs rapid fall by 2050
- Common theme: **net-zero by 2050**

Source: IPCC SR15 on 1.5C, 2018

The Greenhouse Gas Challenge: Net-Zero Emissions by 2050

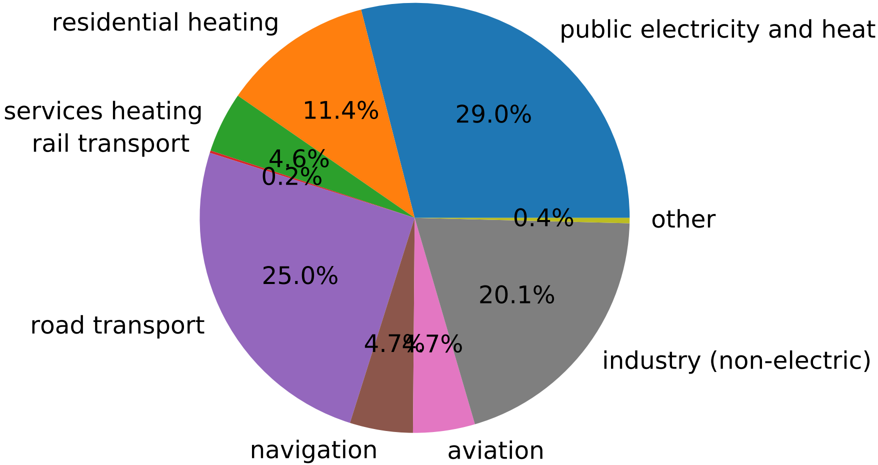
Paris-compliant 1.5° C scenarios from European Commission - **net-zero GHG in EU by 2050**



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

It's not just about electricity demand...

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



Source: Brown, data from EEA

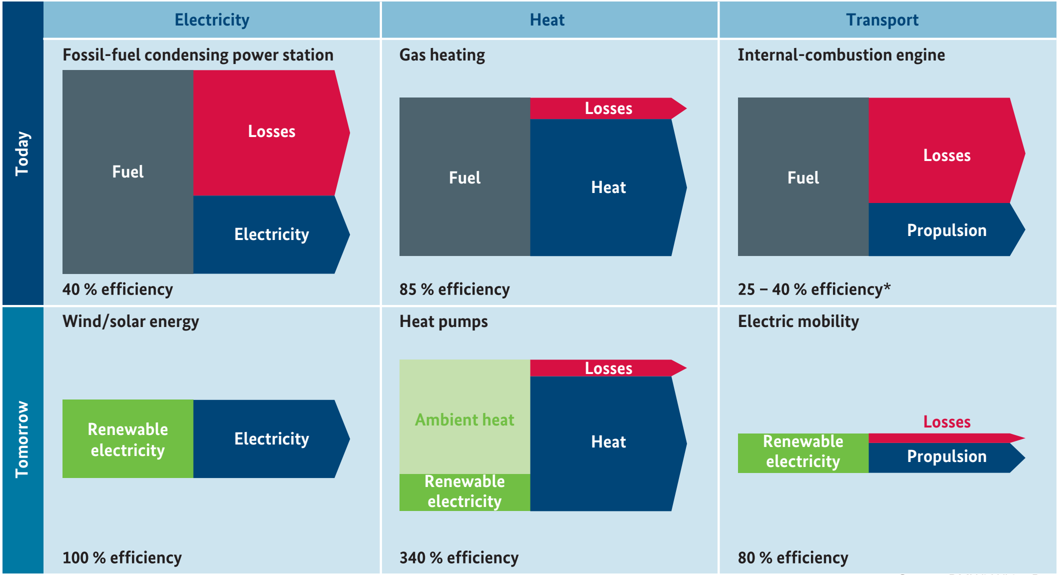
...but electrification of other sectors is critical for decarbonisation

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

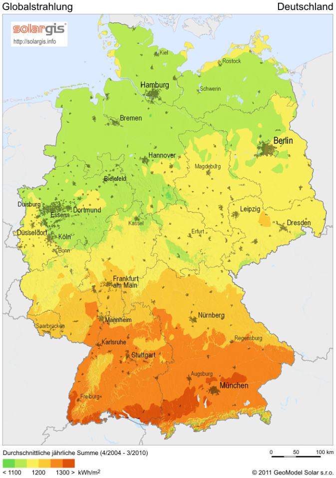
Efficiency of renewables and sector coupling

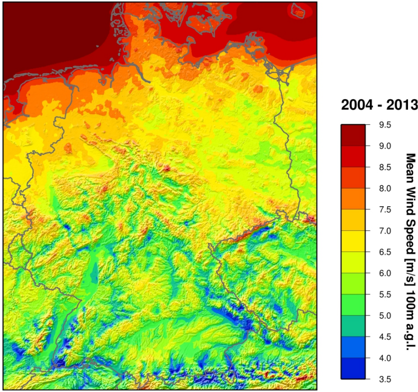


Source: BMWi White Paper 2015

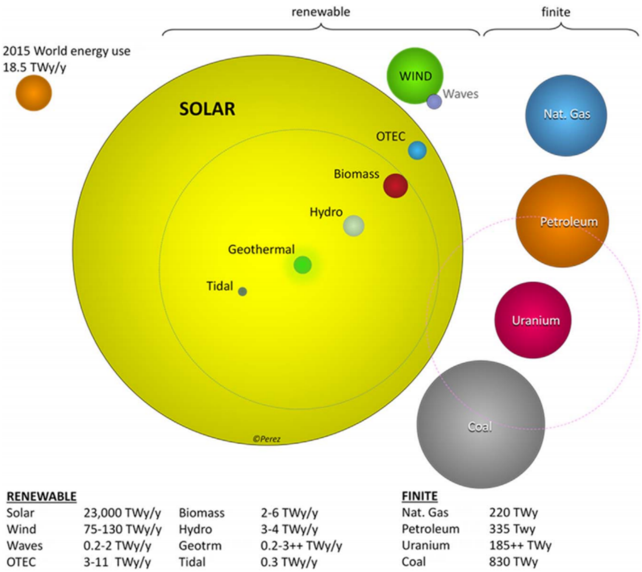
Why focus on wind and solar for electricity generation?

- 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





Worldwide potentials

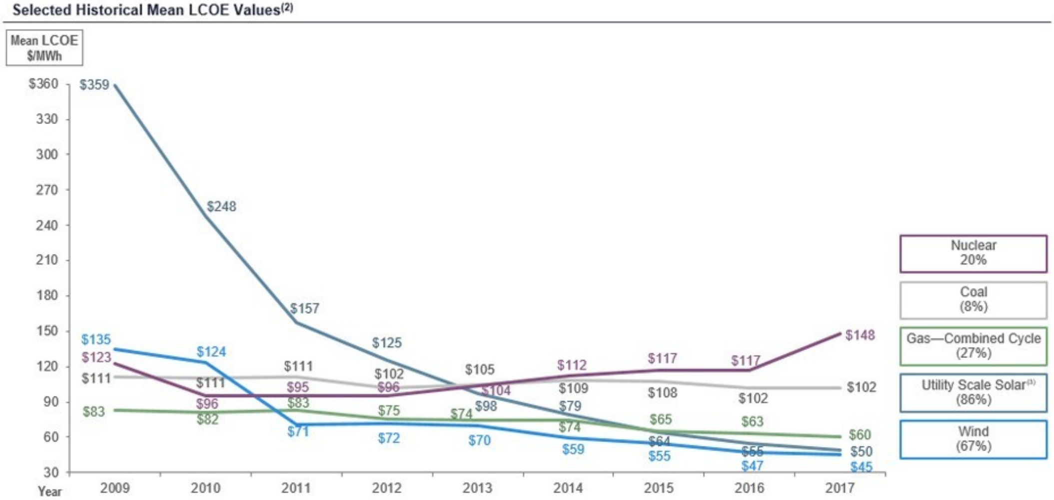


- Potentials for wind and solar exceed current demand by many factors (ignoring variability)
- Other renewable sources include wave, tidal, geothermal, biomass and hydroelectricity
- Uranium depends on the reactor: conventional thermal reactors can extract 50-70 times less than fast breeders

Source: Perez et al, Applied Policy, 2016

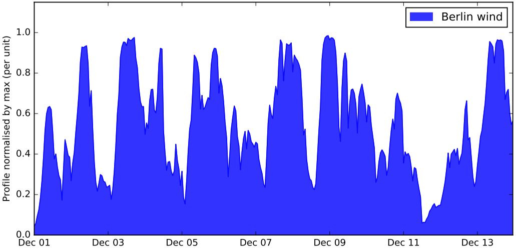
Low cost of wind & solar per MWh in 2017 (NB: ignores variability)

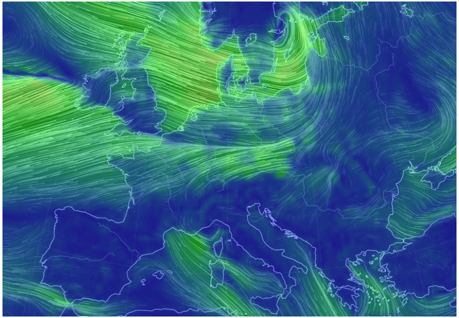
LCOE = **Levelised Cost of Energy** = Total Costs / Energy Output



Source: Lazard's LCOE Analysis V11

Must take account of variability...





...and social & political constraints

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

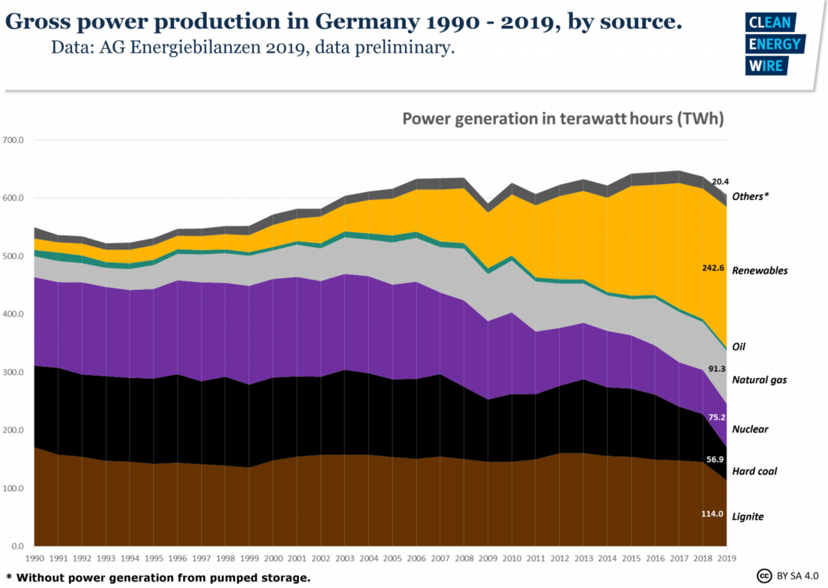
There are also **social and political constraints**, particularly for transmission grid and onshore wind development.

Energy Transition: Several changes happening simultaneously

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 40% of gross electricity generation in Germany in 2019



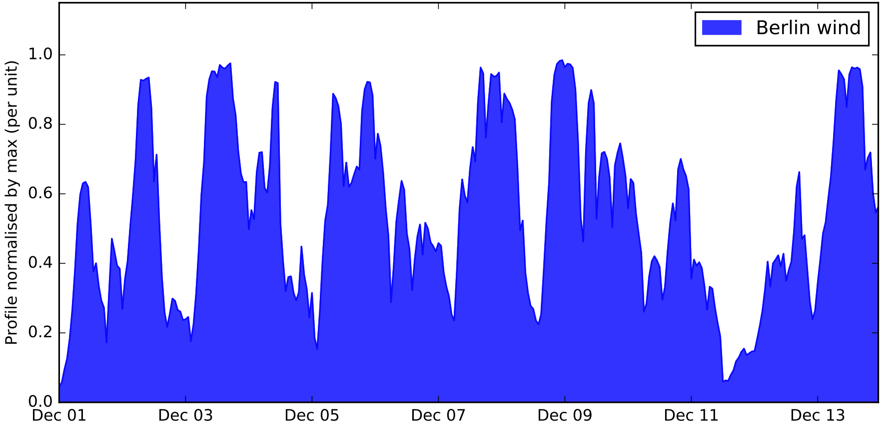
Invitation: Balancing Variable Renewable Energy in Europe

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?

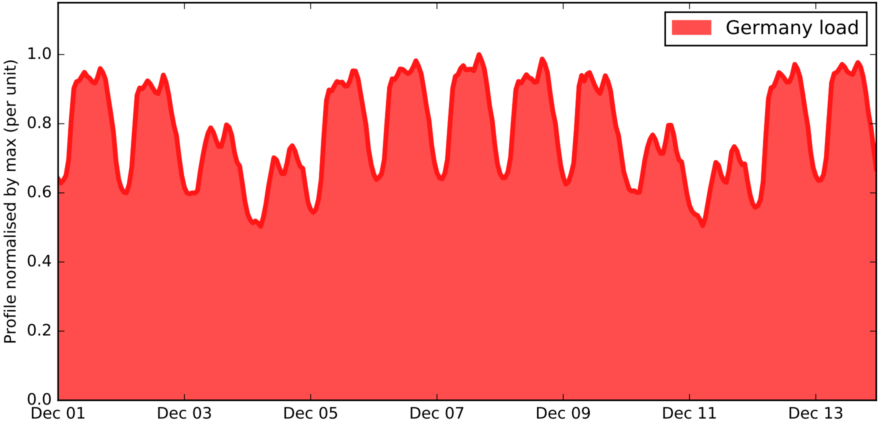
Variability: Single wind site in Berlin

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.



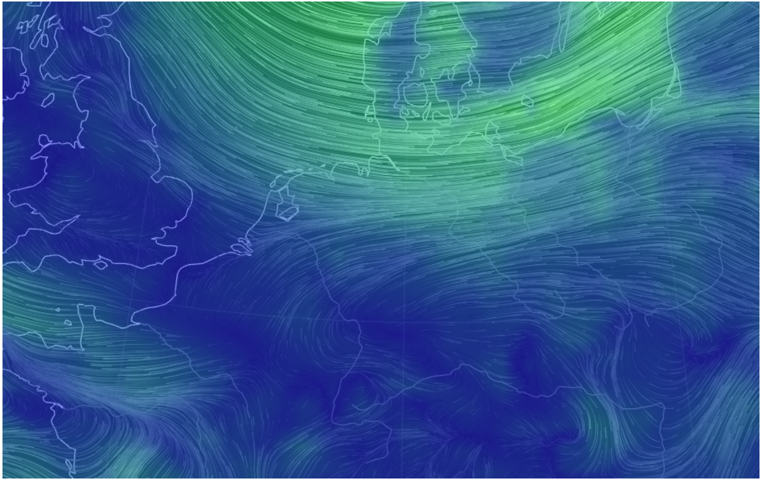
Electricity consumption is much more regular

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

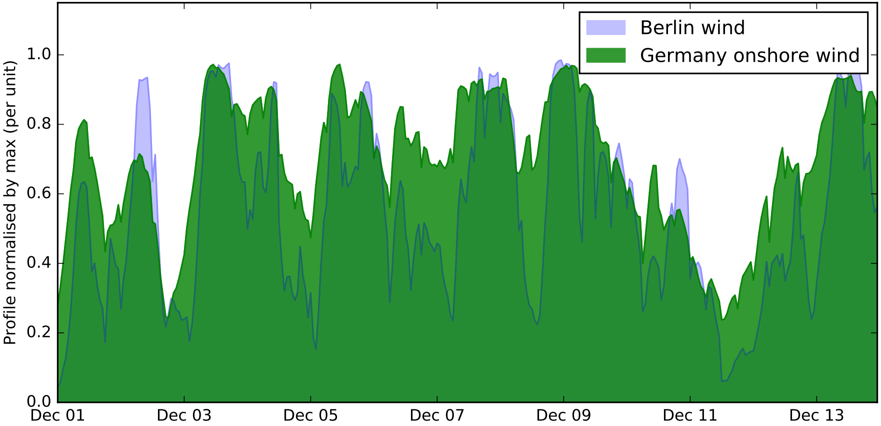
The wind does not blow the same at every site at every time: at a given time there are a variety of wind conditions across Germany. These differences **balance out over time and space**.



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

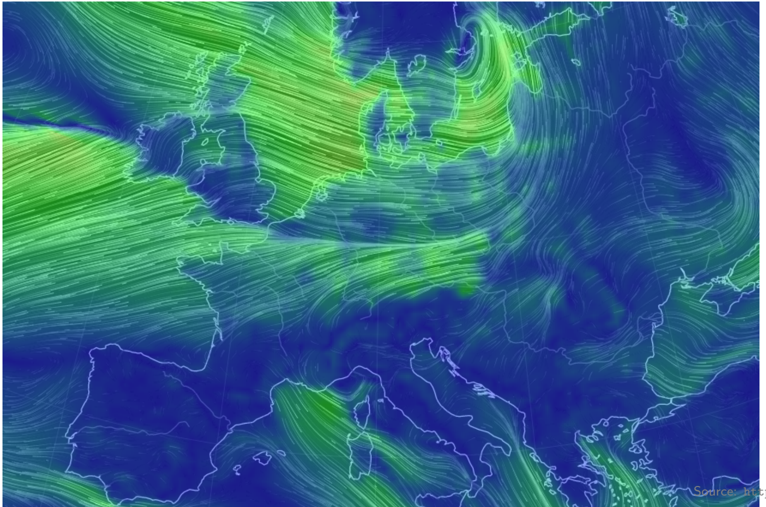
Variability: Single country: Germany

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

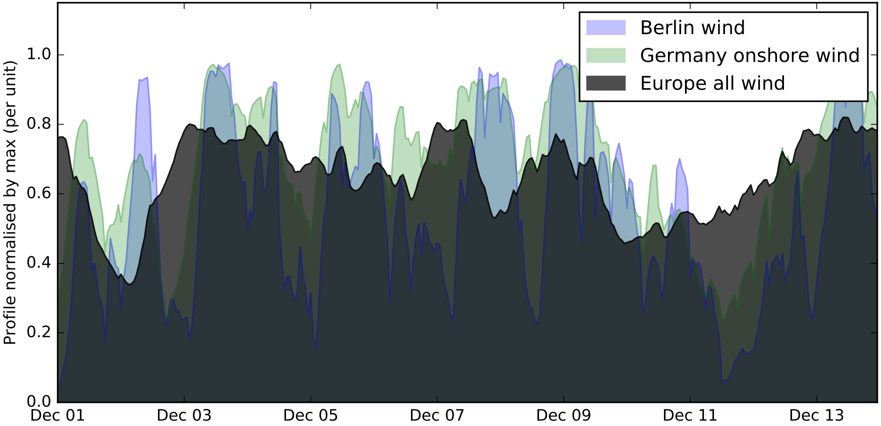
The scale of the weather systems are bigger than countries, so to leverage the full smoothing effects, you need to integrate wind at the **continental scale**.



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

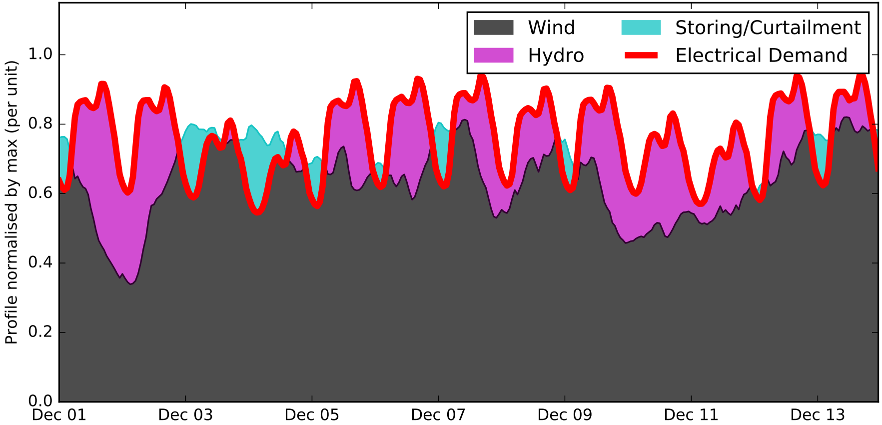
Variability: A continent: Europe

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.

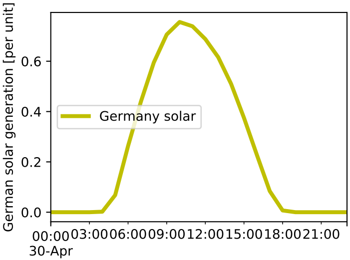


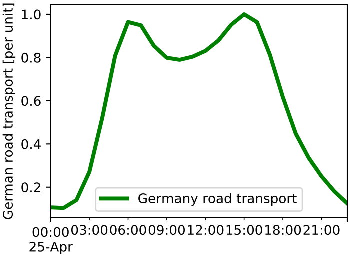
Variability: A continent: Wind plus Hydro

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.



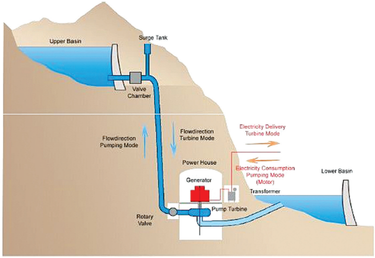
Daily variations: challenges and solutions



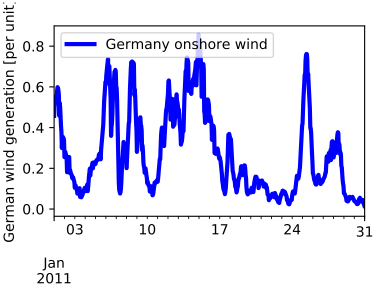


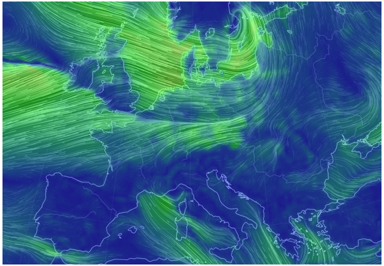
Daily variations in supply and demand can be balanced by

- **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**



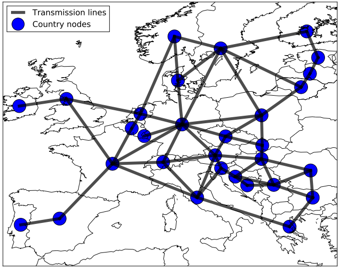
Weekly variations: challenges and solutions



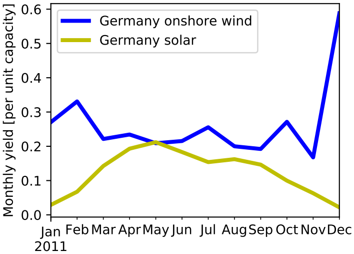


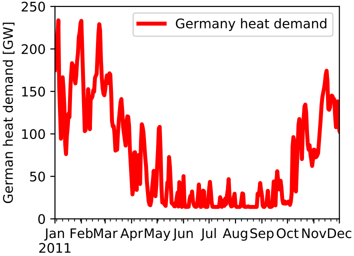
Weekly variations in supply and demand can be balanced by

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



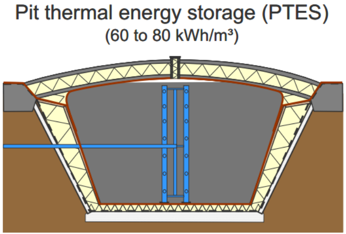
Seasonal variations: challenges and solutions





Seasonal variations in supply and demand can be balanced by

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



Research approach

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

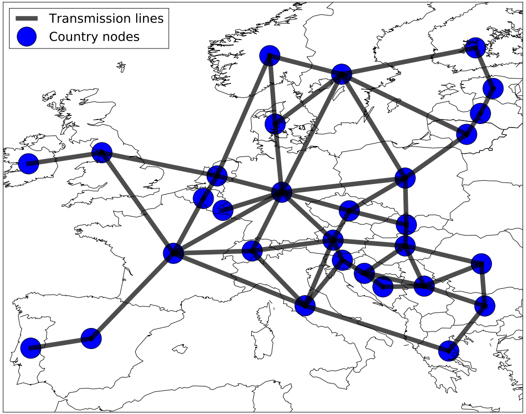
- Meet demand for energy services
- Reduce CO_2 emissions
- Conservative predictions for cost developments
- No/minimal/optimal grid expansion

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.

Optimization problem

This has the general form of an **optimization problem** for which there are specialized algorithms. For **continuous linear problems** these solve in **polynomial time**.

We have an **objective function** $f : \mathbb{R}^k \to \mathbb{R}$ which is to be either maximised or minimised:

$$\max_x f(x)$$

$[x = (x_1, \ldots x_k)]$ subject to some **constraints** within $\mathbb{R}^k$:

$$\begin{array}{cccc} g_i(x) = c_i & \leftrightarrow & \lambda_i & i = 1, \ldots n \\ h_j(x) \leq d_j & \leftrightarrow & \mu_j & j = 1, \ldots m \end{array}$$

The constraints define a **feasible space** within $\mathbb{R}^k$.

We introduce KKT multipliers λ_i and μ_j for each constraint equation, which have an economic interpretation as the **shadow prices** of the constraints. They tell us how the value of the objective function $f(x^*)$ changes as we relax/tighten the corresponding constraints.

Linear optimisation problem

Objective is the minimisation of **total annual system costs**, composed of **capital costs** c_* (investment costs) and **operating costs** o_* (fuel ,etc.):

$$\min f(F_\ell, f_{\ell,t}, G_{i,s}, g_{i,s,t}) = \sum_\ell c_l F_\ell + \sum_{i,s} c_{i,s} G_{i,s} + \sum_{i,s,t} w_t o_{i,s} g_{i,s,t}$$

We optimise for i nodes, representative times t and transmission lines l:

- the transmission capacity F_ℓ of all the lines ℓ
- the flows $f_{\ell,t}$ on each line ℓ at each time t
- the generation and storage capacities $G_{i,s}$ of all technologies (wind/solar/gas etc.) s at each node i
- the dispatch $g_{i,s,t}$ of each generator and storage unit at each point in time t

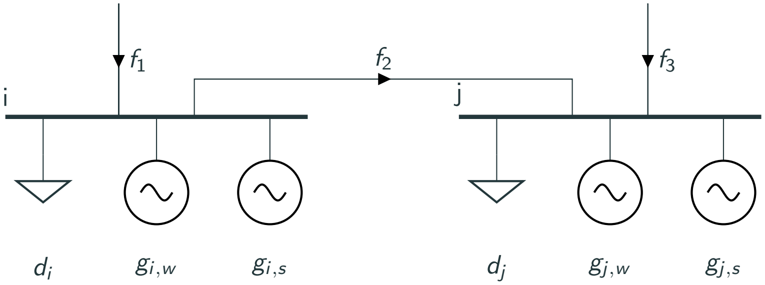
Representative time points are weighted w_t such that $\sum_t w_t = 365 * 24$ and the capital costs c_* are annualised, so that the objective function represents the annual system cost.

Constraints 1/6: Nodal energy balance

Demand $d_{i,t}$ at each node i and time t is always met by generation/storage units $g_{i,s,t}$ at the node or from transmission flows $f_{\ell,t}$ on lines attached at the node (Kirchhoff's Current Law):

$$\sum_s g_{i,s,t} - d_{i,t} = \sum_\ell K_{i\ell} f_{\ell,t} \qquad \leftrightarrow \qquad \lambda_{i,t}$$

Nodes are shown as thick busbars connected by transmission lines (thin lines):

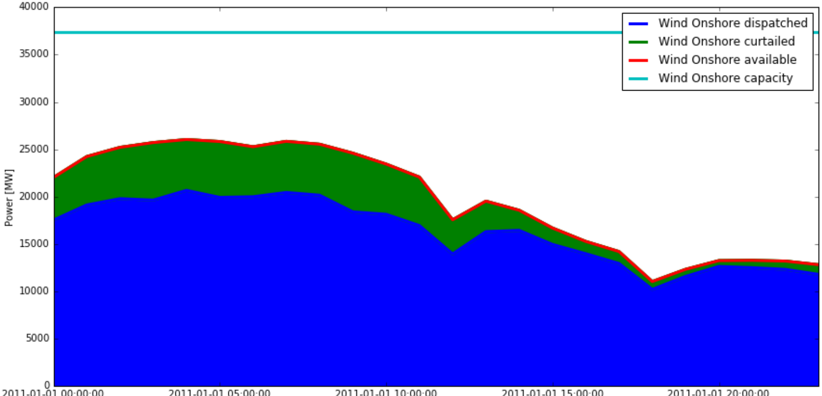


$g_{i,w} + g_{i,s} - d_i = f_2 - f_1$ $\qquad$ $g_{j,w} + g_{j,s} - d_j = -f_2 - f_3$

Constraints 2/6: Generation availability

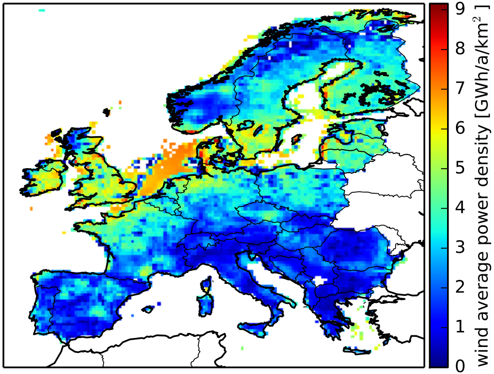
Generator/storage dispatch $g_{i,s,t}$ cannot exceed availability $G_{i,s,t} * G_{i,s}$, made up of per unit availability $0 \leq G_{i,s,t} \leq 1$ multiplied by the capacity $G_{i,s}$. The capacity is bounded by the installable potential $\hat{G}_{i,s}$.

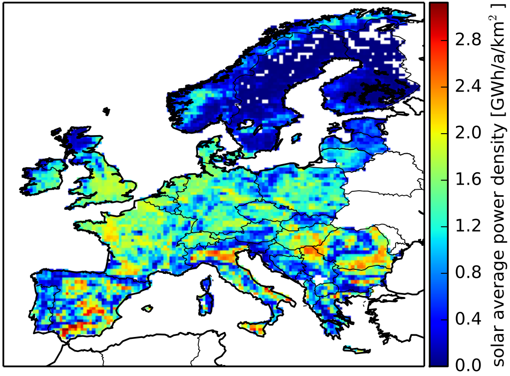
$$0 \leq g_{i,s,t} \leq G_{i,s,t} * G_{i,s} \leq G_{i,s} \leq \hat{G}_{i,s}$$



Installation potentials limited by geography

Expansion potentials are limited by **land usage** and **conservation areas**; potential yearly energy yield at each site limited by **weather conditions**:





Constraints 3/6: Storage consistency

Storage units such as batteries or hydrogen storage can work in both storage and dispatch mode. This has to be consistent with the state of charge $e_{i,s,t}$:

$$e_{i,s,t} = \eta_0 e_{i,s,t-1} + \eta_1 g_{i,s,t,\mathrm{store}} - \eta_2^{-1} g_{i,s,t,\mathrm{dispatch}}$$

The state of charge is limited by the energy capacity $E_{i,s}$:

$$0 \leq e_{i,s,t} \leq E_{i,s} \quad \forall i, s, t$$

There are efficiency losses η; hydroelectric dams can also have a river inflow.

Constraints 4/6: Kirchoff's Laws for Physical Flow

The linearised **power flows** f_ℓ for each line $\ell \in \{1, \dots L\}$ in an AC network are determined by the **reactances** x_ℓ of the transmission lines and the **net power injection** at each node p_i for $i \in \{1, \dots N\}$.

We have to satisfy Kirchoff's Laws, which can be compactly expressed using the **incidence matrix** $K \in \mathbb{R}^{N \times L}$ (boundary operator in homology theory) of the graph and the **cycle basis** $C \in \mathbb{R}^{L \times (L-N+1)}$ (kernel of K)

- Kirchoff's Current Law: $p_i = \sum_\ell K_{i\ell} f_\ell$
- Kirchoff's Voltage Law: $\sum_\ell C_{\ell c} x_\ell f_\ell = 0$

Constraints 5/6: Transmission Line Thermal Limits

Transmission flows cannot exceed the thermal capacities of the transmission lines (otherwise they sag and hit buildings/trees):

$$|f_{\ell,t}| \leq F_\ell$$

Constraints 6/6: Global constraints on CO_2 and transmission volumes

CO_2 limits are respected, given emissions $\varepsilon_{i,s}$ for each fuel source s:

$$\sum_{i,s,t} g_{i,s,t} \frac{\varepsilon_{i,s}}{\eta_s} \leq \mathrm{CAP}_{\mathrm{CO}_2} \qquad \leftrightarrow \qquad \mu_{\mathrm{CO}_2}$$

We enforce a reduction of CO_2 emissions by 95% compared to 1990 levels, in line with German and EU targets for 2050.

Transmission volume limits are respected, given length d_ℓ and capacity F_ℓ of each line:

$$\sum_{\ell} d_\ell F_\ell \leq \mathrm{CAP}_{\mathrm{trans}} \qquad \leftrightarrow \qquad \mu_{\mathrm{trans}}$$

We successively change the transmission limit, to assess the costs of balancing power in time (i.e. storage) versus space (i.e. transmission networks).

Model Inputs and Outputs

Inputs	Description
$d_{i,t}$	Demand (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)

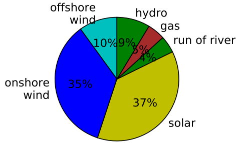
Quantity	Overnight Cost [€]	Unit	FOM [%/a]	Lifetime [a]
Wind onshore	1182	kW_{el}	3	20
Wind offshore	2506	kW_{el}	3	20
Solar PV	600	kW_{el}	4	20
Gas	400	kW_{el}	4	30
Battery storage	1275	kW_{el}	3	20
Hydrogen storage	2070	kW_{el}	1.7	20
Transmission line	400	MWkm	2	40

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

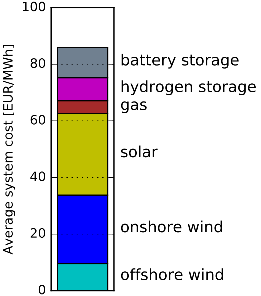
Batteries can store for 6 hours at maximal rating (efficiency 0.9×0.9), hydrogen storage for 168 hours (efficiency 0.75×0.58).

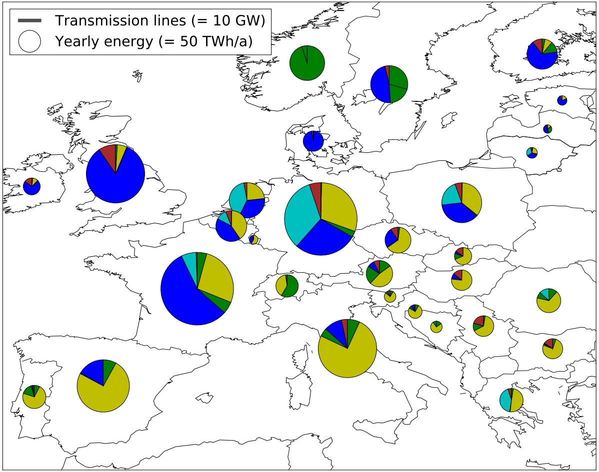
Costs: No interconnecting transmission allowed

Technology by energy:



Average cost **€86/MWh**:

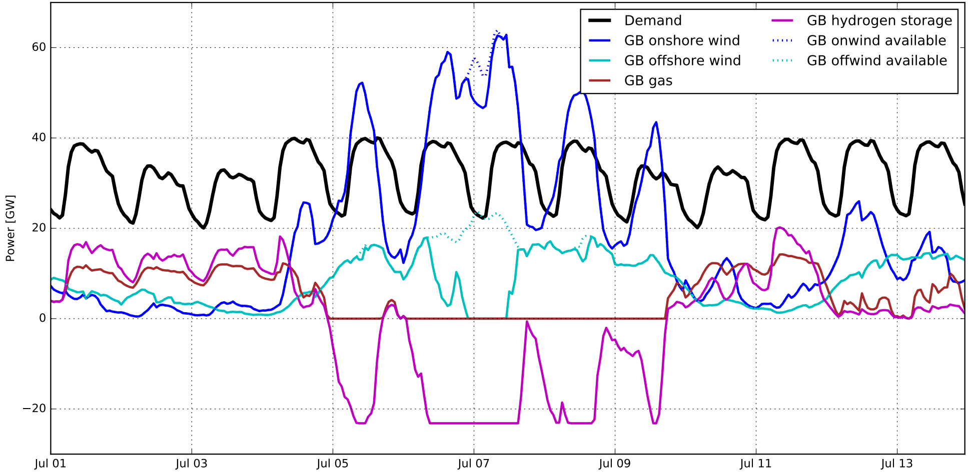




Countries must be self-sufficient at all times; lots of storage and some gas to deal with fluctuations of wind and solar.

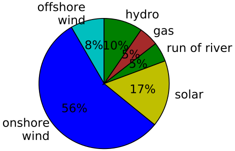
Dispatch with no interconnecting transmission

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

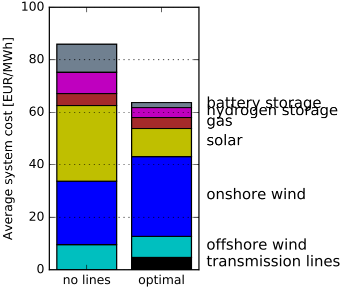


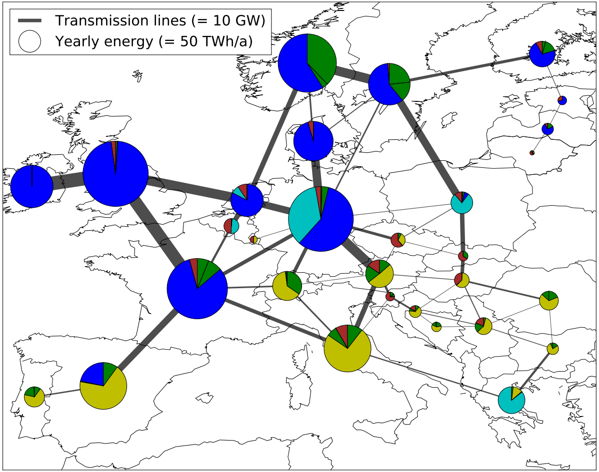
Costs: Cost-optimal expansion of interconnecting transmission

Technology by energy:



Average cost **€64/MWh**:

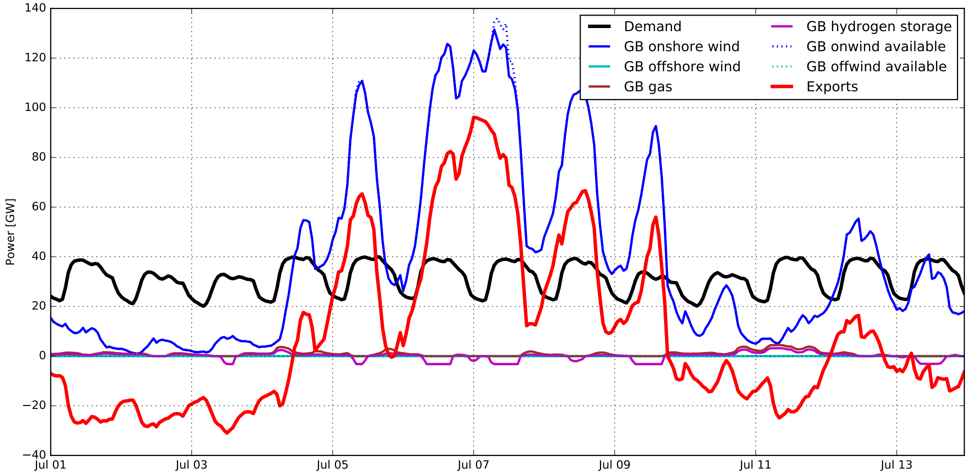




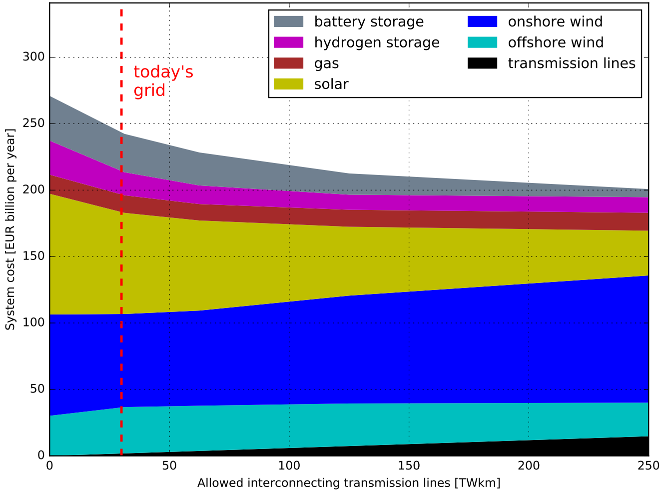
Large transmission expansion; onshore wind dominates. This optimal solution may run into public acceptance problems.

Dispatch with cost-optimal interconnecting transmission

Almost all excess wind can be now be exported:

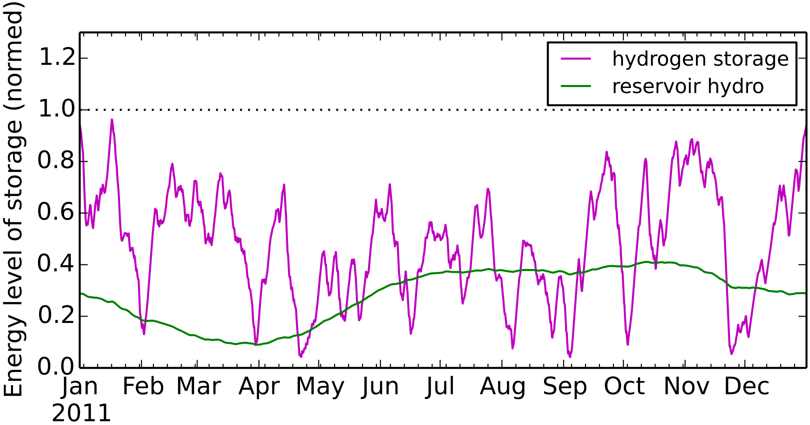


Electricity Only Costs Comparison



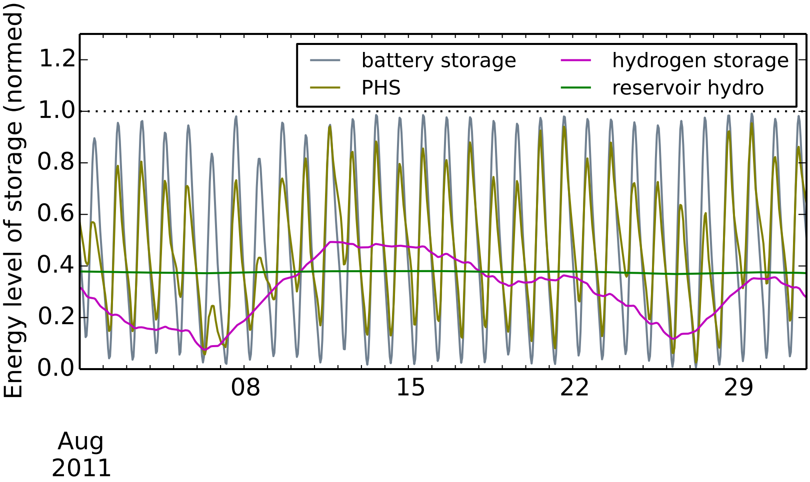
- Average total system costs can be as low as € 64/MWh
- Energy is dominated by wind (64% for the cost-optimal system), followed by hydro (15%) and solar (17%)
- Restricting transmission results in more storage to deal with variability, driving up the costs by up to 34%
- Many benefits already locked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

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.