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)

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1. Administration

2. What is Energy System Modelling?

3. The Greenhouse Gas Challenge

4. Invitation: Balancing Variable Renewable Energy in Europe
Administration
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.
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:

<table>
<thead>
<tr>
<th>time</th>
<th>session</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00 - 12:00</td>
<td>Live Q &amp; A on lectures on MS Teams (please watch the lectures for this day beforehand)</td>
</tr>
<tr>
<td>13:00 - 14:30</td>
<td>Live tutorial on MS Teams (please do the exercise sheet beforehand)</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Dates</th>
<th>lectures uploaded by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thu 04.06.2020</td>
<td>21.05.2020</td>
</tr>
<tr>
<td>Fri 05.06.2020</td>
<td>28.05.2020</td>
</tr>
<tr>
<td>Fri 19.06.2020</td>
<td>05.06.2020</td>
</tr>
<tr>
<td>Thu 25.06.2020</td>
<td>11.06.2020</td>
</tr>
<tr>
<td>Fri 26.06.2020</td>
<td>19.06.2020</td>
</tr>
</tbody>
</table>

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

- Göran Andersson Skript, “Elektrische Energiesysteme: Vorlesungsteil Energieübertragung,” online
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 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

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.
Not everyone gets it right...

EIA Coal Consumption Forecasts, 2006-2018

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

annual energy outlook:

- 1,500 million tons
- 1,250
- 1,000
- 750
- 500
- 250
- 0

EIA forecasts:

- '07
- '06
- '08
- '09
- '10
- '11
- '12
- '13
- '14, '15

Actual coal consumption for electric power:

- '16
- 2017
- 2018

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

Please send comments to:
a.e.hockstra@tue.nl
@aukehockstra
Sinn’s study was debunked using an open model (he exaggerated storage requirements by ‘up to two orders of magnitude’).

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 $1.5\,^\circ\mathrm{C}$’ and hold ‘the increase...to well below $2\,^\circ\mathrm{C}$’. These targets were chosen to avoid potentially irreversible tipping points in the Earth’s systems.

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

Global total net CO₂ emissions

In pathways limiting global warming to 1.5°C with no or limited overshoot as well as in pathways with a high overshoot, CO₂ emissions are reduced to net zero globally around 2050.

Source: IPCC SR15 on 1.5C, 2018
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 CO₂ emissions in 2016 (total 3.5 Gt CO₂, 9.7% of global):

- Public electricity and heat: 29.0%
- Residential heating: 11.4%
- Services heating: 4.6%
- Rail transport: 0.2%
- Road transport: 25.0%
- Navigation: 4.7%
- Aviation: 4.7%
- Industry (non-electric): 20.1%
- Other: 0.4%

Source: Brown, data from EEA
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

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Today</th>
<th>Tomorrow</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electricity</strong></td>
<td>Fossil-fuel condensing power station</td>
<td>Wind/solar energy</td>
</tr>
<tr>
<td>Losses</td>
<td><strong>Electricity</strong></td>
<td>Renewable electricity</td>
</tr>
<tr>
<td>40 % efficiency</td>
<td><strong>Heat</strong></td>
<td><strong>Transport</strong></td>
</tr>
<tr>
<td>Gas heating</td>
<td>Heat pumps</td>
<td>Internal-combustion engine</td>
</tr>
<tr>
<td>Fuel</td>
<td>Losses</td>
<td>Losses</td>
</tr>
<tr>
<td>85 % efficiency</td>
<td>340 % efficiency</td>
<td>25 - 40 % efficiency*</td>
</tr>
<tr>
<td>Heat</td>
<td>Propulsion</td>
<td>Propulsion</td>
</tr>
<tr>
<td>Fuel</td>
<td>Renewable electricity</td>
<td>Renewable electricity</td>
</tr>
<tr>
<td>100 % efficiency</td>
<td><strong>Electricity</strong></td>
<td>Propulsion</td>
</tr>
</tbody>
</table>

*Efficiency of internal-combustion engines (e.g. internal-combustion engines on a boat) ranges from 25% to 40%.

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
• 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)

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

Source: Lazard’s LCOE Analysis V11
Must take account of variability...
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

Gross power production in Germany 1990 - 2019, by source.
Data: AG Energiebilanzen 2019, data preliminary.

* Without power generation from pumped storage.
Invitation: Balancing Variable Renewable Energy in Europe
1. What **infrastructure** (wind, solar, hydro generators, heating/cooling units, storage and networks) does a highly renewable energy system require and **where** should it go?

2. Given a desired 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 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.
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 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
Avoid too many assumptions. Fix the **boundary conditions**:

- Meet demand for energy services
- Reduce CO\textsubscript{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:

Minimise \( \text{Yearly system costs} = \sum_n (\text{Annualised capital costs}) + \sum_{n,t} (\text{Marginal costs}) \)

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** $f : \mathbb{R}^k \rightarrow \mathbb{R}$ which is to be either maximised or minimised:

$$\max_x f(x)$$

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

$$g_i(x) = c_i \leftrightarrow \lambda_i \quad i = 1, \ldots n$$

$$h_j(x) \leq d_j \leftrightarrow \mu_j \quad j = 1, \ldots m$$

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

We introduce KKT multipliers $\lambda_i$ and $\mu_j$ 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.
Objective is the minimisation of total annual system costs, composed of capital costs $c_*$ (investment costs) and operating costs $o_*$ (fuel, etc.):

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

We optimise for $i$ nodes, representative times $t$ and transmission lines $\ell$:

- the transmission capacity $F_{\ell}$ of all the lines $\ell$
- the flows $f_{\ell,t}$ on each line $\ell$ 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 $\sum_t w_t = 365 \times 24$ 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):

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

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

$$d_i + g_{i,w} + g_{i,s} - d_i = f_2 - f_1$$

$$d_j + g_{j,w} + g_{j,s} - d_j = -f_2 - f_3$$
Constraints 2/6: Generation availability

Generator/storage dispatch $g_{i,s,t}$ cannot exceed availability $G_{i,s,t} \times G_{i,s}$, 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 $\hat{G}_{i,s}$.

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

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

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 $\eta$; hydroelectric dams can also have a river inflow.
The linearised **power flows** $f_\ell$ for each line $\ell \in \{1, \ldots L\}$ in an AC network are determined by the **reactances** $x_\ell$ of the transmission lines and the **net power injection** at each node $p_i$ for $i \in \{1, \ldots N\}$.

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**: $\sum_\ell C_{\ell c} x_\ell f_\ell = 0$
Transmission flows cannot exceed the thermal capacities of the transmission lines (otherwise they sag and hit buildings/trees):

\[ |f_{\ell,t}| \leq F_{\ell} \]
CO₂ limits are respected, given emissions $\varepsilon_{i,s}$ for each fuel source $s$:

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

We enforce a reduction of CO₂ emissions by 95% compared to 1990 levels, in line with German and EU targets for 2050.

Transmission volume limits are respected, given length $d_\ell$ and capacity $F_\ell$ of each line:

$$\sum_{\ell} d_\ell F_\ell \leq \text{CAP}_{\text{trans}} \quad \leftrightarrow \quad \mu_{\text{trans}}$$

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

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{i,t}$</td>
<td>Demand (inelastic)</td>
</tr>
<tr>
<td>$G_{i,s,t}$</td>
<td>Per unit availability for wind and solar</td>
</tr>
<tr>
<td>$\hat{G}_{i,s}$</td>
<td>Generator installable potentials</td>
</tr>
<tr>
<td>various</td>
<td>Existing hydro data</td>
</tr>
<tr>
<td>various</td>
<td>Grid topology</td>
</tr>
<tr>
<td>$\eta^*$</td>
<td>Storage efficiencies</td>
</tr>
<tr>
<td>$c_{i,s}$</td>
<td>Generator capital costs</td>
</tr>
<tr>
<td>$o_{i,s,t}$</td>
<td>Generator marginal costs</td>
</tr>
<tr>
<td>$c_{\ell}$</td>
<td>Line costs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{i,s}$</td>
<td>Generator capacities</td>
</tr>
<tr>
<td>$g_{i,s,t}$</td>
<td>Generator dispatch</td>
</tr>
<tr>
<td>$F_{\ell}$</td>
<td>Line capacities</td>
</tr>
<tr>
<td>$f_{\ell,t}$</td>
<td>Line flows</td>
</tr>
<tr>
<td>$\lambda^<em>, \mu^</em>$</td>
<td>Lagrange/KKT multipliers of all constraints</td>
</tr>
<tr>
<td>$f$</td>
<td>Total system costs</td>
</tr>
</tbody>
</table>
## Costs and assumptions for the electricity sector (projections for 2030)

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

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 × 0.9), hydrogen storage for 168 hours (efficiency 0.75 × 0.58).
Costs: No interconnecting transmission allowed

Technology by energy:

- offshore wind: 10%
- onshore wind: 35%
- solar: 37%
- run of river: 4%
- gas: 5%
- hydrogen: 9%

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:

- Offshore wind: 8%
- Onshore wind: 56%
- Solar: 17%
- Run of river: 5%
- Gas: 5%
- Hydro: 10%

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 different 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.