The Price of Non-Cooperation in a Highly Renewable European Energy System

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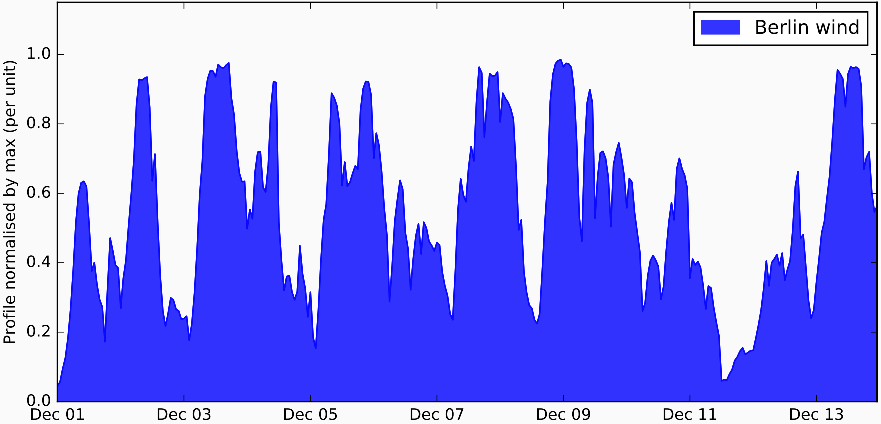
Two Main Points

1. Renewable resources are best when shared internationally.
   - The best wind and solar resources can be fully exploited
   - Grids smooth fluctuations over large areas
   - Flexible, renewable hydroelectricity plugs the gaps
2. Highly renewable systems can be cheap *if* countries cooperate.
   - Total system costs can be comparable to today's
   - Integrating renewables on a purely national basis requires storage, driving up costs

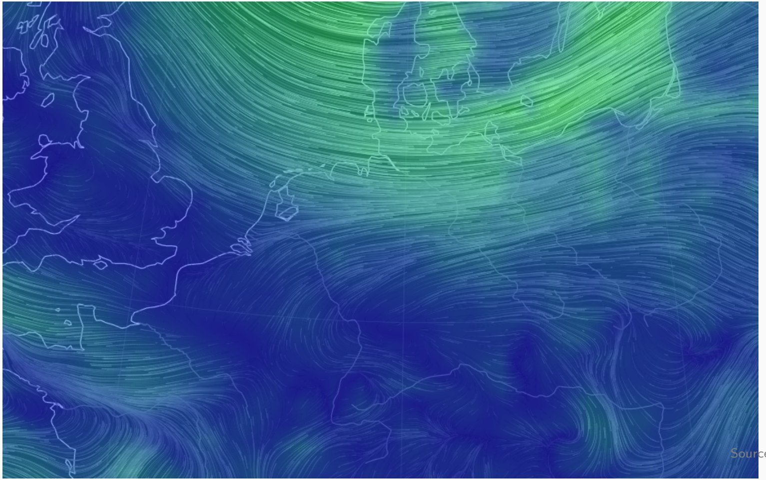
Variability: Single wind site in Berlin

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.



Variability: Different wind conditions over Germany

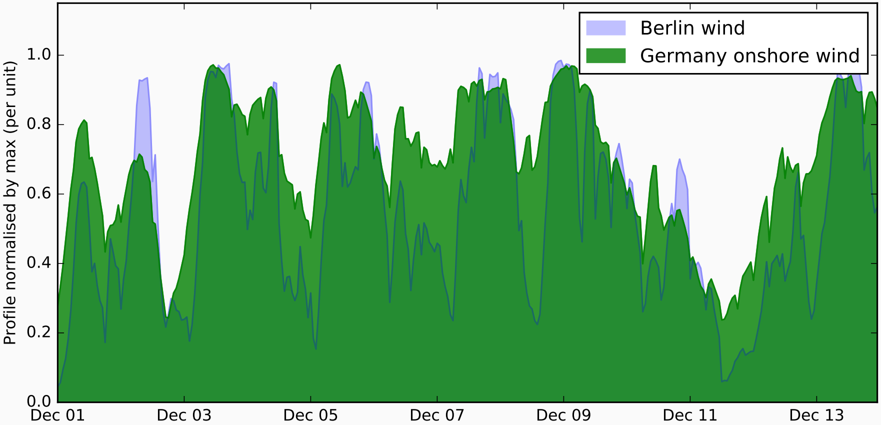
But the wind does not blow the same at every site at every time: at a given time there are a variety of wind conditions across Germany. These differences balance out over time and space.



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

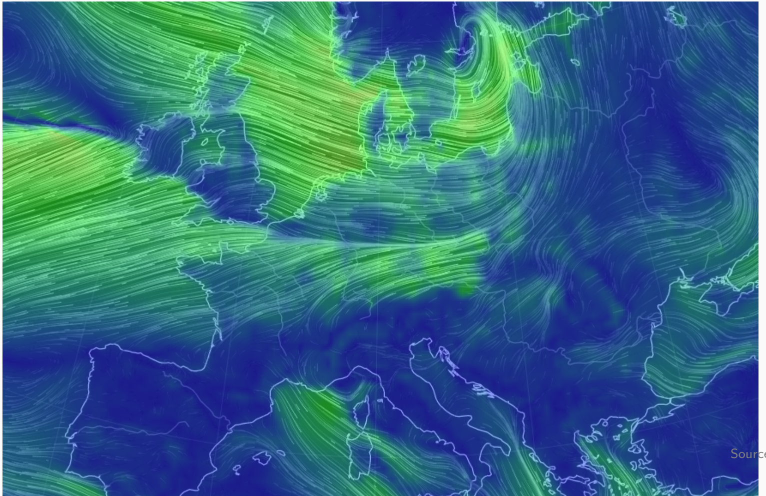
Variability: Single country: Germany

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

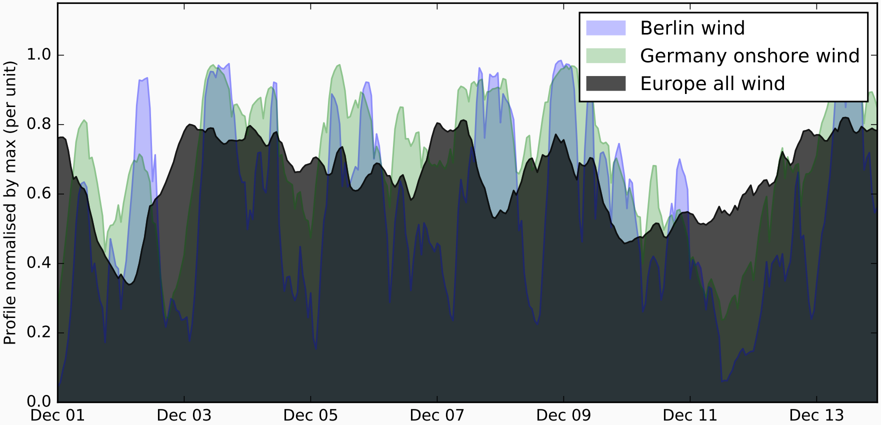
The scale of the weather systems are bigger than countries, so to leverage the full smoothing effects, you need to integrate wind at the continental scale.



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

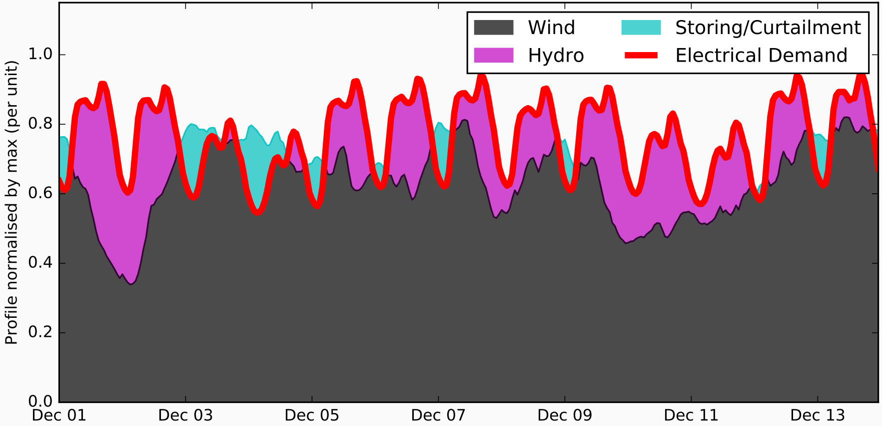
Variability: A continent: Europe

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.



Costs: Introduction to Optimisation

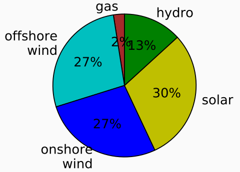
Want to answer three questions:

1. What infrastructure does a highly renewable electricity system require?
2. What will all the generators, storage and transmission lines cost (including all capital and marginal costs)?
3. How does the answer change if we add restrictions on e.g. transmission expansion due to public acceptance issues?

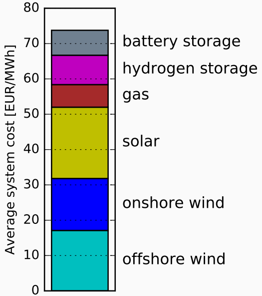
Run a technico-economic cost optimisation for 95% CO_2 reduction compared to 1990 over a full historical year of weather and electricity demand for 30 European countries. Demand must be met at every hour and every node, to ensure security of supply; all possible weather conditions and restrictions on land use must be taken into account.

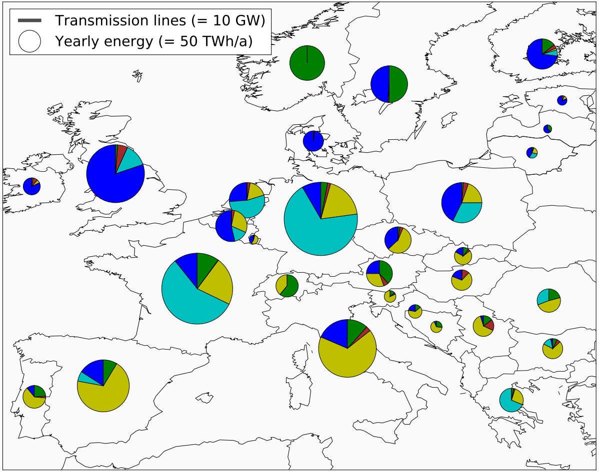
Costs: No interconnecting transmission allowed

Technology by energy:



Average cost €74/MWh:

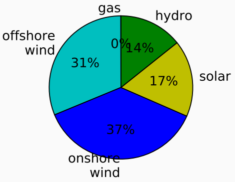




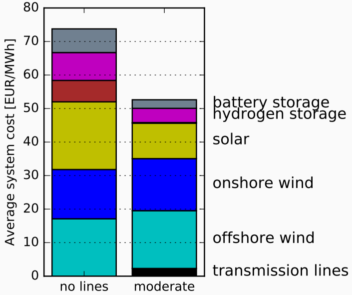
Countries must be self-sufficient at all times; lots of storage and some gas to deal with fluctuations of wind and solar.

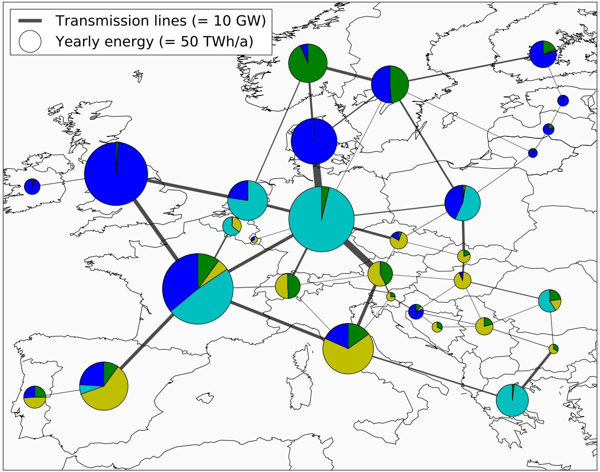
Costs: Moderate amount of interconnection (3-4 times today's)

Technology by energy:



Average cost €53/MWh:

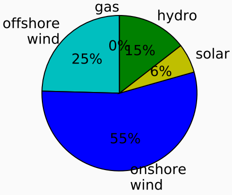




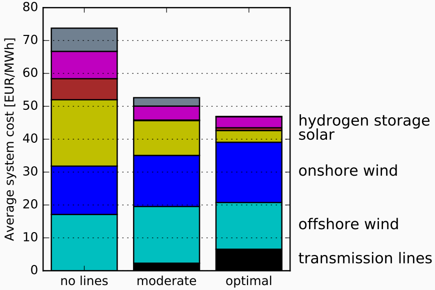
A restricted extension of interconnection goes a long way to reduce the costs. More onshore wind, less solar and storage.

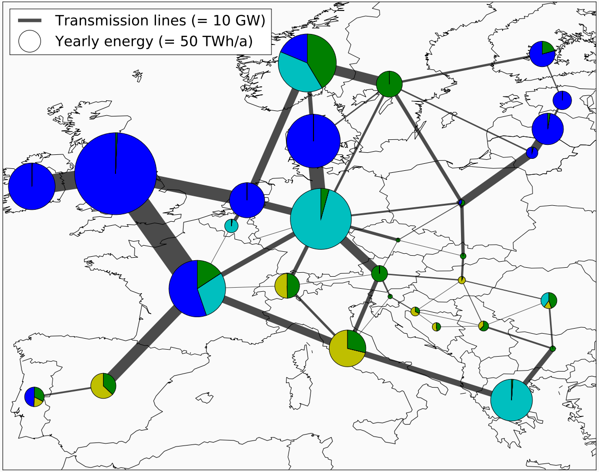
Costs: Cost-optimal expansion of interconnecting transmission

Technology by energy:



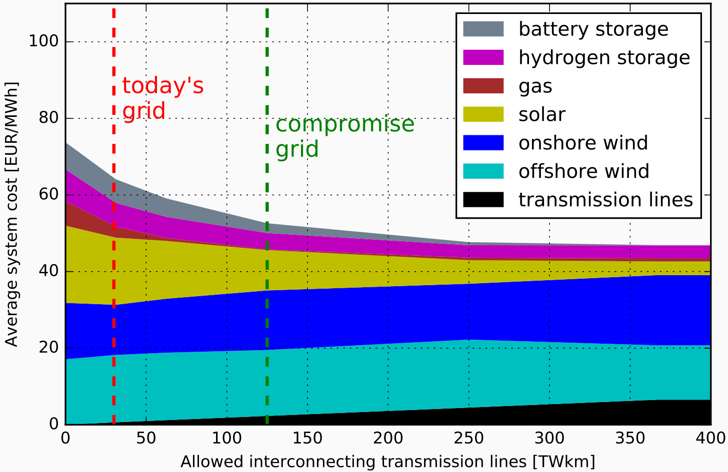
Average cost €47/MWh:





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

Costs: Comparison

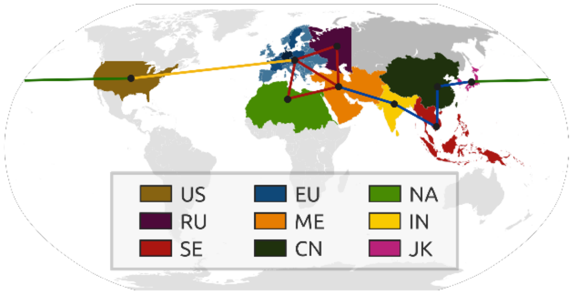


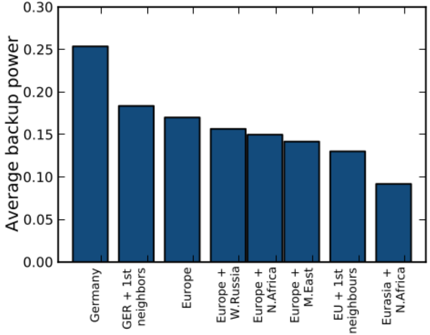
- Total system costs can be as cheap as today's system (down to €47/MWh)
- Energy is dominated by wind (80% for the cost-optimal system), followed by hydro (15%) and solar (5%)
- Restricting transmission requires more storage to deal with variability, driving up the costs by up to 60%
- Compromise locks in many benefits of transmission

Beyond the EU: A Worldwide Grid

In the longer term there is no reason to stop at Europe's borders.

Smoothing at a global scale reduces the need for backup even further, but this is counter-balanced by higher transmission costs.





"Infrastructure Estimates for a Highly Renewable Global Electricity Grid", M. Dahl, R. Rodriguez, A. Sondergaard, T. Zeyer, G. Andresen, M. Greiner (Aarhus University), 2016.

A Contribution to Public Acceptance: Open Modelling

Any big change in society needs public consent.

The public can only consent when the modelling and future planning is done in an open and transparent manner.

Open data + free software ⇒ Transparency + Reproducibility

There's an initiative for that:

openmod-initiative.org

Our systems-modelling software can be downloaded here:

pypsa.org

Conclusions

- The questions are no longer *whether a renewable system is possible* or *whether it can be affordable*; rather it is what compromises will we make and how much will they cost?
- The cost-optimal system has lots of onshore wind and international network expansion, with costs comparable to today's.
- If countries do not cooperate on grid expansion, storage becomes necessary to deal with the variability of renewables, driving up costs by 60% - the price of non-cooperation.
- Decisions about the future energy system require public consent; openness and transparency are critical.
- Challenges for modelling: getting more grid detail, while retaining European scope; sector coupling with transport and heating; incorporating political restrictions.

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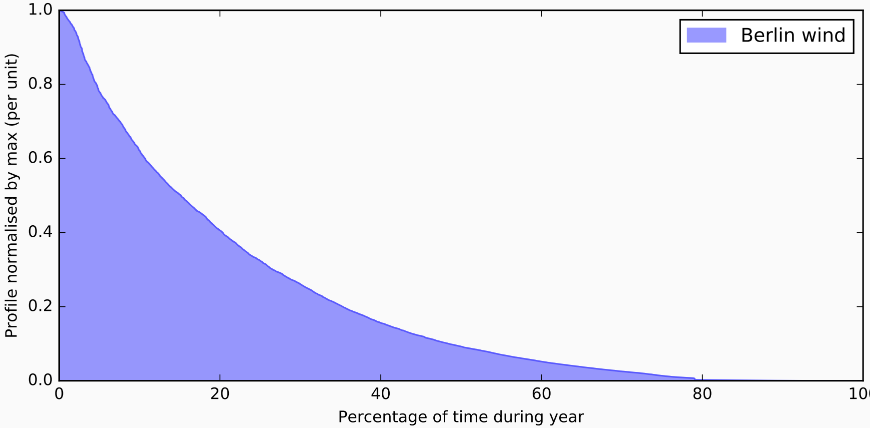
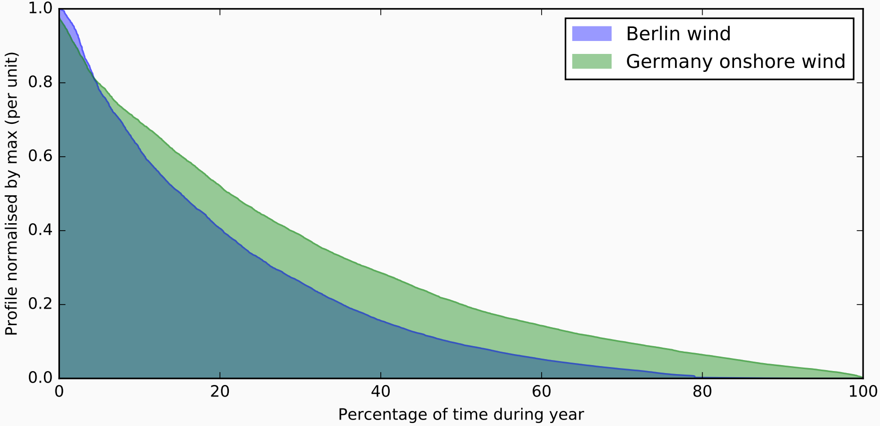
Duration curve: Berlin

A duration curve shows the feed-in for the whole year, re-ordered by from highest to lowest value. For a single location there are many hours with no feed-in.



Duration curve: Germany

For a whole country there are fewer peaks and fewer hours with no feed-in.



Duration curve: Europe

For the whole of Europe there are no times with zero feed-in.