Building a Secure Energy System with Variable Renewables: Challenges and Solutions

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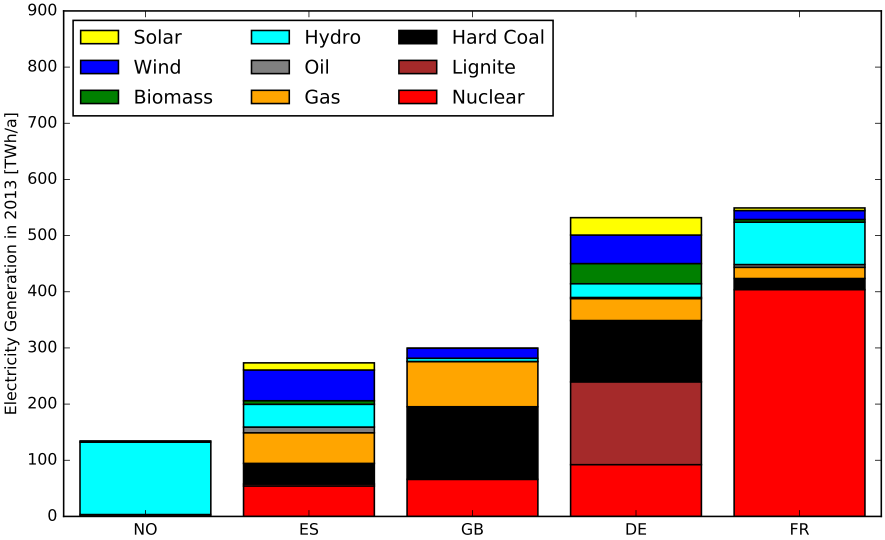
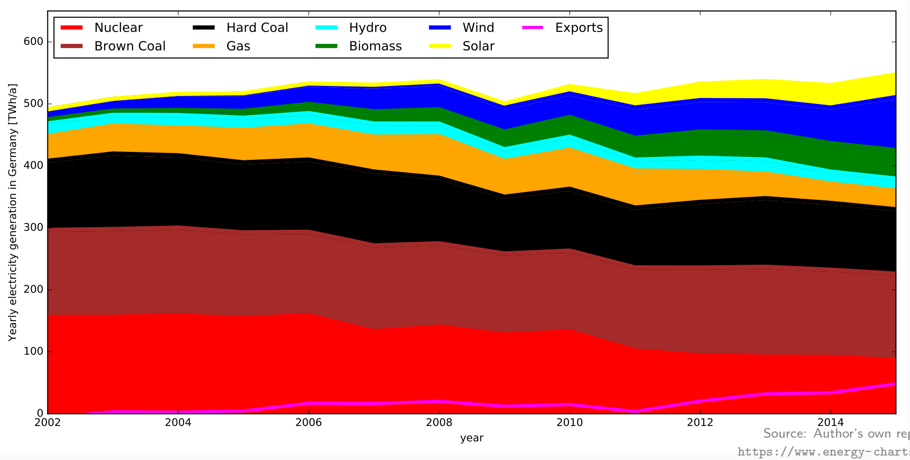
The Challenges of Optimising a Renewable Energy System

Where we are: electricity generation across major EU countries in 2013



Where we're going: electricity generation in Germany per year

In 15 years Germany has gone from a system dominated by nuclear and fossil fuels, to one with 33% renewables in electricity consumption.



Source: Author's own representation based on `https://www.energy-charts.de/energy_en.htm`

Goal: understand the destination, so we can steer towards it

Want to answer (at least) two questions:

1. What infrastructure (wind, solar, hydro generators, storage and networks) does a highly renewable electricity system require and where should it go?
2. Given a desired CO_2 reduction (e.g. 95% compared to 1990), what is the cost-optimal combination of infrastructure (including all capital and marginal costs) that can guarantee security of supply?

Interesting Questions

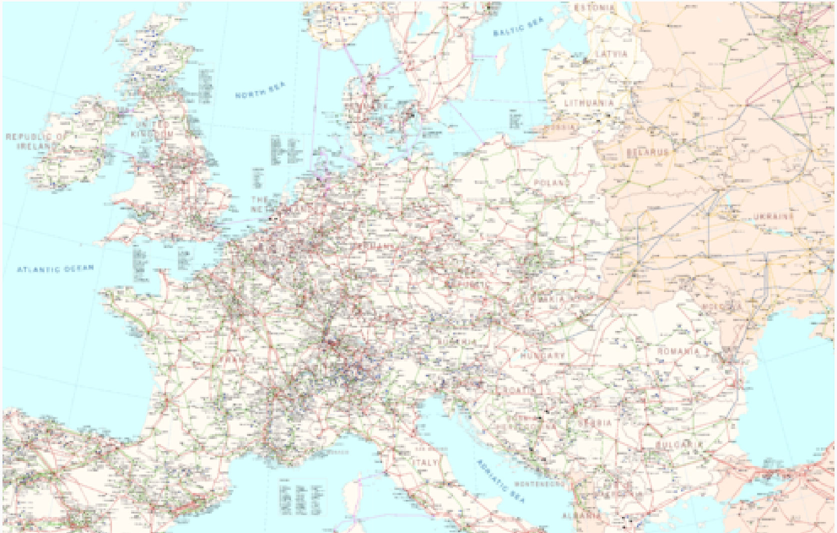
How do system characteristics and costs change as we ...

- ... restrict transmission expansion (i.e. due to public acceptance)?
- ... impose import/export balance constraints (i.e. due to politics)?
- ... relax CO_2 constraint?
- ... include non-pumped-hydro storage?
- ... include meshed overlay direct current network and/or more phase-shifting transformers?
- ... couple electricity sector to heating and transport?

Some of these questions are driven by politics/social factors: compromises that take us away from economic optimum.

Problem 1: Spatial resolution

Need high spatial resolution to represent VRE variations and transmission constraints.

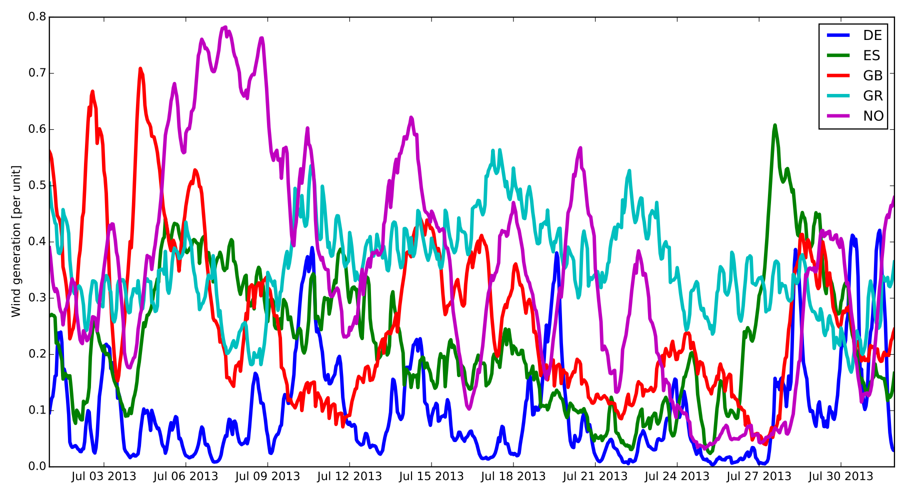


Source: ENTSO-E

Problem 2: Temporal resolution

Need high temporal resolution to represent load and VRE resource variability and correlations.

Wind generation in Europe in July 2013:



Problem 3: Model complexity

Modelling all sectors of the energy system involves lots of interdependencies

Example: Improving building insulation:

- increases capital expenditure (bad)
- reduces heating demand (good)
- reduces electricity demand if heating is provided via heat pumps (good)
- may reduce flexibility provision by reducing the need/availability of thermal storage (bad)

Beyond sector coupling: Nexus of energy, water, agriculture and biodiversity.

Problem 3: Model complexity

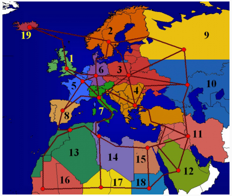
Modelling must respect physics

- How much detail in the input data do we need?
- Optimise transmission simultaneously with generation capacity?
- Optimise electricity, heating and transport together?
- How bad are linear approximations?
- Can we make the algorithms faster, to add detail in other areas?
- By looking at static situations, do we miss dynamic effects?

Examples from literature of energy system optimisation

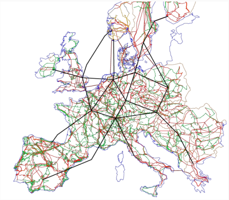
Study	Scope	Spatial resolution	Temporal resolution	What?	Flow physics
Czisch (2005)	MENA	low	high	electricity (gen and grid)	transport
Hagspiel et al. (2014)	EU	medium	low	electricity (gen and grid)	linear
Egerer et al. (2014)	EU	high	low	electricity (gen only)	linear
Fraunhofers ISE, IWES	DE	none	high	electricity, heating, transport	none

Czisch



Hagspiel et al.

Egerer et al.



Problem 4: Flatness of solution space near the optimum

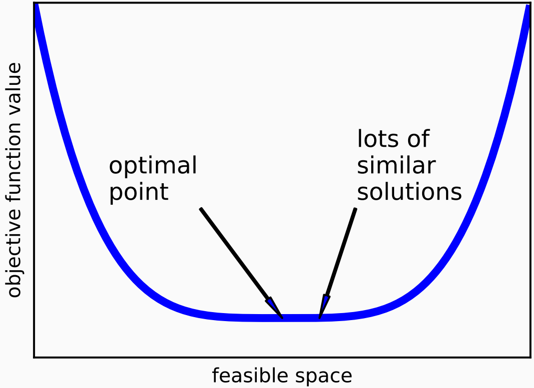
Once we've formulated our optimisation problem and solved it, we're not done.

How sensitive is our solution to small changes in the inputs?

In which directions do the costs explode?

Typical energy optimisation results are very flat around the optimum, i.e. there are many similar configurations with similar costs.

It is very important for policy-makers to know what freedom there is to adjust the solution, without exploding the costs.



Overarching goal

Find the “sweet spot” where:

- Computation time is finite (i.e. a week)
- Temporal resolution is “good enough”
- Spatial resolution is “good enough”
- Model detail is “good enough”

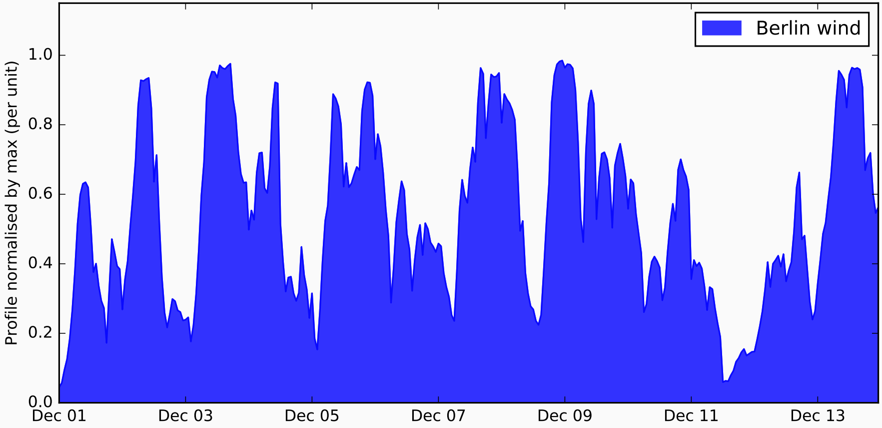
AND quantify the error we make by only being “good enough” (e.g. are important metrics $\pm 10\%$ or $\pm 50\%$ correct?)

AND be sure we’re got a handle on all sectoral interdependencies that might affect the results.

Introduction: Dealing with Renewable Intermittency

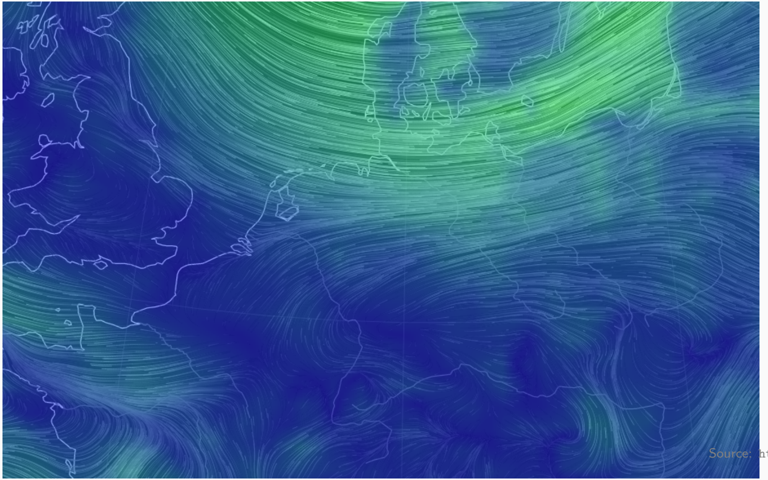
Variability: Single wind site in Berlin

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

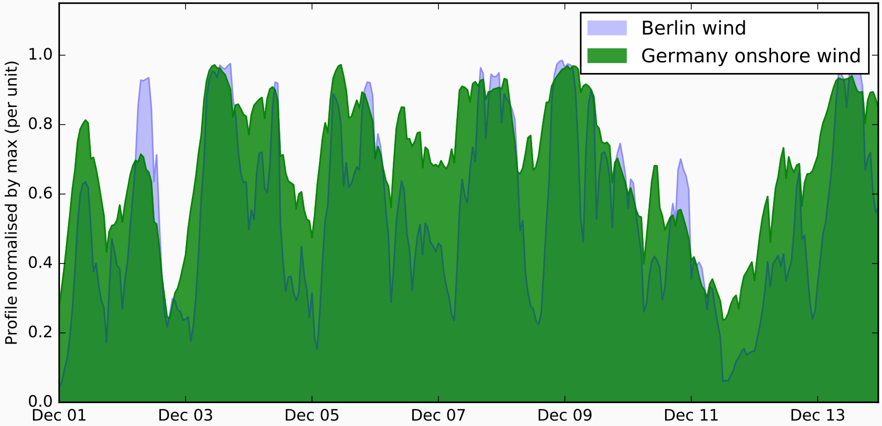
But the wind does not blow the same at every site at every time: at a given time there are a variety of wind conditions across Germany. These differences balance out over time and space.



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

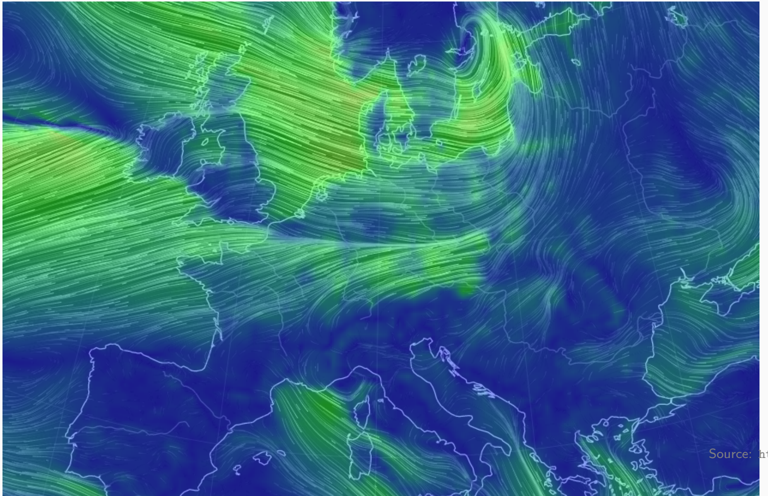
Variability: Single country: Germany

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

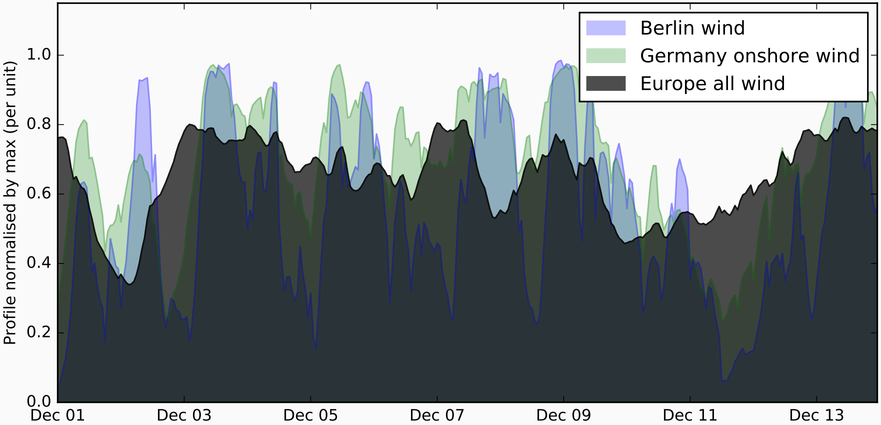
The scale of the weather systems are bigger than countries, so to leverage the full smoothing effects, you need to integrate wind at the continental scale.



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: Flexible hydroelectricity

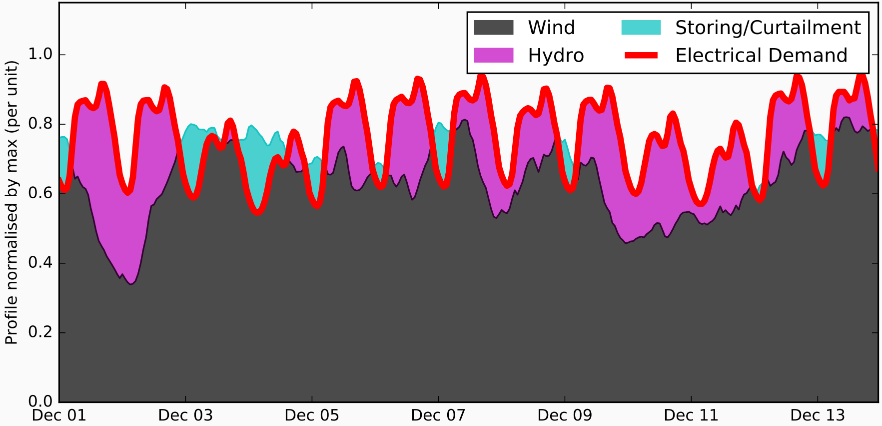
Existing hydroelectric plants can provide much of the backup. Hydro has several attractive properties:

- It is renewable
- It is flexible - water can be stored until needed and then dispatched very quickly
- It has no fuel costs
- It already covers 15-18% of Europe's electricity demand, depending on rain conditions

Source: Wikipedia

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.



Cost Optimisation: Balancing Renewable Intermittency in Space versus Time

Goal

Given a desired CO_2 reduction, what is the most cost-effective energy system?

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

subject to

- meeting energy demand at each node n (e.g. countries) and time t (e.g. hours of year)
- wind, solar, hydro (variable renewables) availability $\forall\, n, t$
- electricity/gas transmission constraints between nodes
- (installed capacity) $\leq$ (geographical potential for renewables)
- CO_2 constraint

Optimisation problem

Optimisation problems take the following form:

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.):

$$f(\bar{P}_\ell, \bar{g}_{n,s}, g_{n,s,t}) = \sum_\ell c_l \bar{P}_\ell + \sum_{n,s} c_{n,s}\bar{g}_{n,s} + \sum_{n,s,t} w_t o_{n,s} g_{n,s,t}$$

We optimise for n nodes (30 European countries in this case), representative times t and transmission lines l:

- the transmission capacity $\bar{P}_\ell$ of all the lines ℓ
- the generation and storage capacities $\bar{g}_{n,s}$ of all technologies (wind/solar/gas etc.) s at each node n
- the dispatch $g_{n,s,t}$ of each generator and storage unit at each point in time t

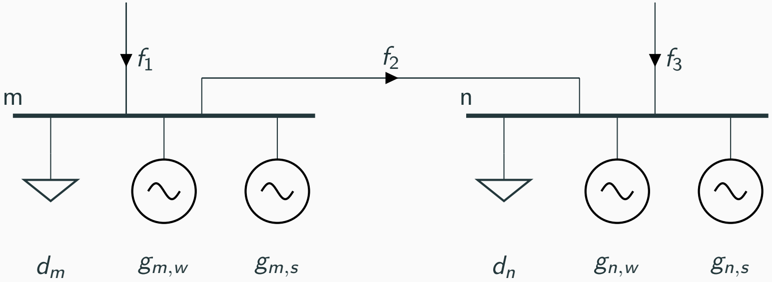
Representative time points are weighted w_t such that $\sum_t w_t = 365 * 24$ and the capital costs c_* are annualised, so that the objective function represents the annual system cost.

Constraints 1/6: Nodal energy balance

Demand $d_{n,t}$ at each node n and time t is always met by generation/storage units $g_{n,s,t}$ at the node or from transmission flows $f_{\ell,t}$ on lines attached at the node:

$$d_{n,t} = \sum_{s} g_{n,s,t} + \sum_{\ell \in n} f_{\ell,t} \qquad \leftrightarrow \qquad \lambda_{n,t}$$

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

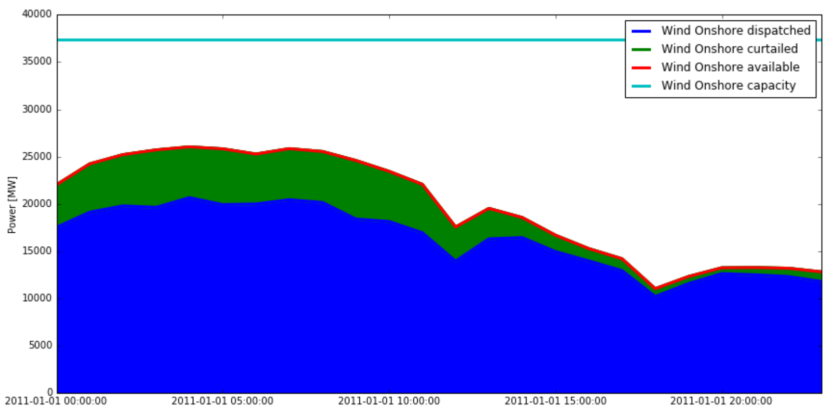


$$d_m = g_{m,w} + g_{m,s} + f_1 - f_2 \qquad\qquad d_n = g_{n,w} + g_{n,s} + f_2 + f_3$$

Constraints 2/6: Generation availability

Generator/storage dispatch $g_{n,s,t}$ cannot exceed availability $\bar{g}_{n,s,t}$, which is bounded by capacity $\bar{g}_{n,s}$ and installable potential $\hat{g}_{n,s}$. Both the dispatch $g_{n,s,t}$ and the capacity $\bar{g}_{n,s}$ are subject to optimisation.

$$0 \leq g_{n,s,t} \leq \bar{g}_{n,s,t} \leq \bar{g}_{n,s} \leq \hat{g}_{n,s}$$



Constraints 3/6: Storage consistency

Storage units such as batteries or hydrogen storage can work in both storage and dispatch mode. They have a limited energy capacity. The amount of energy stored is called the state of charge.

$$soc_{n,t} = \eta_0 soc_{n,t-1} + \eta_1 g_{n,t,\mathrm{store}} - \eta_2^{-1} g_{n,t,\mathrm{dispatch}}$$

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 $\ell \in \{1, \ldots L\}$ in an AC network are determined by the reactances x_ℓ of the transmission lines and the net power injection at each node p_n for $n \in \{1, \ldots N\}$. (Assume voltage magnitudes $|V_n|$ are constant and redefine $x_\ell \to |V_\ell|^{-2} x_\ell$.)

The flows f_ℓ are linked to the x_ℓ via the voltage angles θ_n for each node by $f_\ell = \frac{\theta_i - \theta_j}{x_\ell}$.

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) and the diagonal matrix of the x_l, $X = \mathrm{diag}(x_1, \ldots, x_L) \in \mathbb{R}^{L \times L}$.

- Kirchoff's Current Law: $\mathbf{p} = K\mathbf{f}$
- Kirchoff's Voltage Law: $C^t \theta = C^t X \mathbf{f} = 0$

We can satisfy these using:

$$\mathbf{f} = X^{-1} K^t \theta \qquad (\sim E = -\nabla \phi)$$

$$\mathbf{p} = K X^{-1} K^t \theta \qquad (\sim \rho = \Delta \phi)$$

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):

$$|f_{\ell,t}| \leq \bar{P}_\ell$$

However, since the $\bar{P}_\ell$ are subject to optimisation, we can always expand the capacity of the lines at a cost which appears in the objective function (and a computational cost, because it introduces non-linearities...).

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

CO_2 limits are respected, given emissions $e_{n,s}$ for each fuel source s:

$$\sum_{n,s,t} g_{n,s,t} e_{n,s} \leq \mathrm{CAP}_{\mathrm{CO}_2} \qquad \leftrightarrow \qquad \mu_{\mathrm{CO}_2}$$

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 $\bar{P}_\ell$ of each line:

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

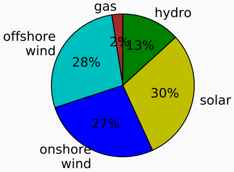
We successively change the transmission limit, to assess the costs of balancing power in time (i.e. storage) versus space (i.e. transmission networks).

Cost and other assumptions

Quantity	Cost	Unit
Wind onshore capital	1000	€/kW
Wind offshore capital	2000	€/kW
Solar capital	1000	€/kW
Gas capital	900	€/kW
Gas marginal	75	€/MWh
Battery storage	200	€/kWh
Hydrogen storage	2000	€/kW
Transmission line	400	€/MW/km
Gas CO_2 emissions	0.2	$t/MWh_{thermal}$
Gas plant efficiency	40	%
Interest rate	7	%
Line lifetime	40	years
Generators lifetime	20	years

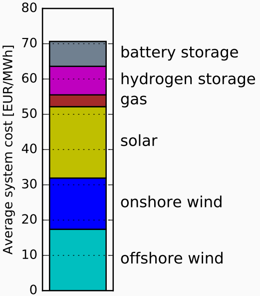
Costs: No interconnecting transmission allowed

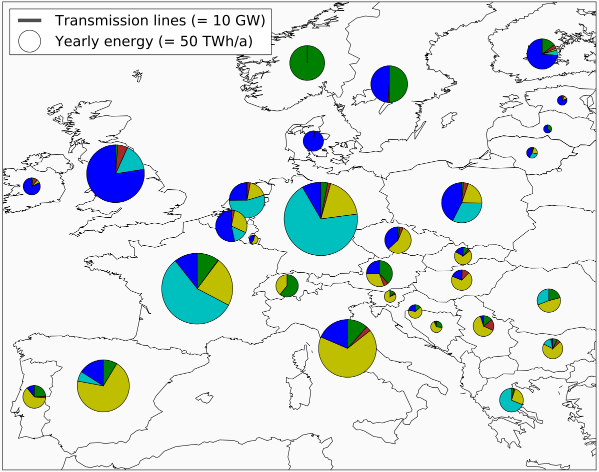
Technology by energy:



$$\mu_{\mathrm{CO_2}} = 168$$
$$\mu_{\mathrm{trans}} = 4800$$

Average cost €71/MWh:

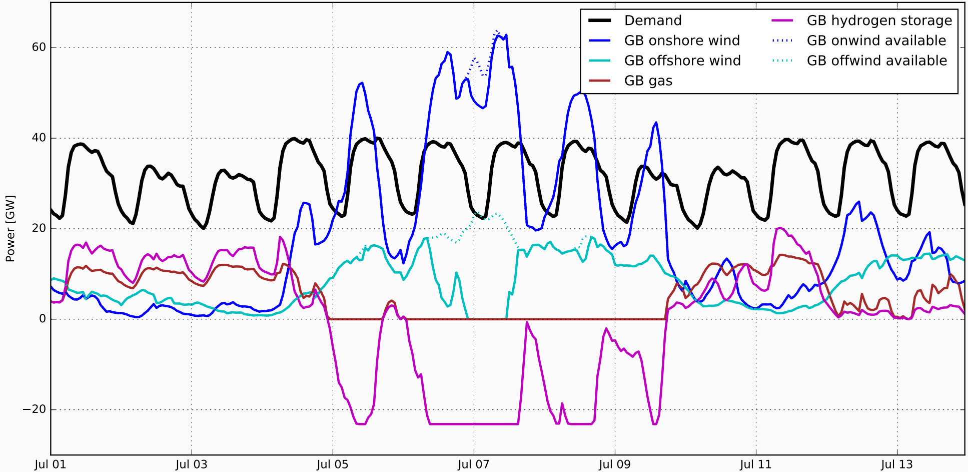




Countries must be self-sufficient at all times; lots of storage and some gas to deal with fluctuations of wind and solar.

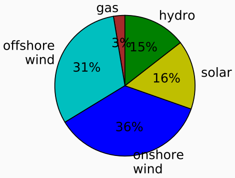
Dispatch with no interconnecting transmission

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



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

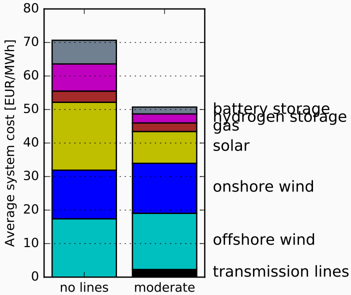
Technology by energy:

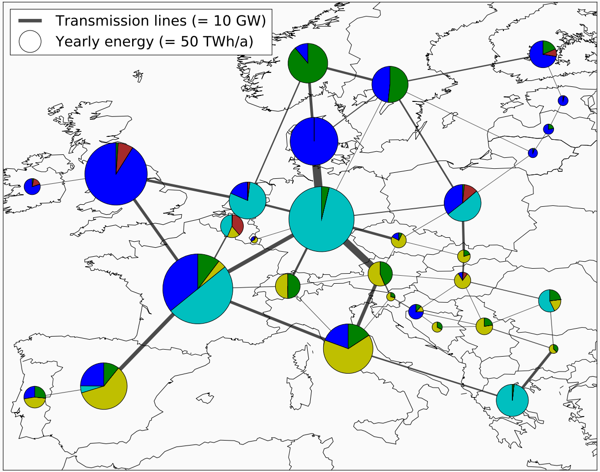


$\mu_{\mathrm{CO}_2} = 65$

$\mu_{\mathrm{trans}} = 235$

Average cost €51/MWh:

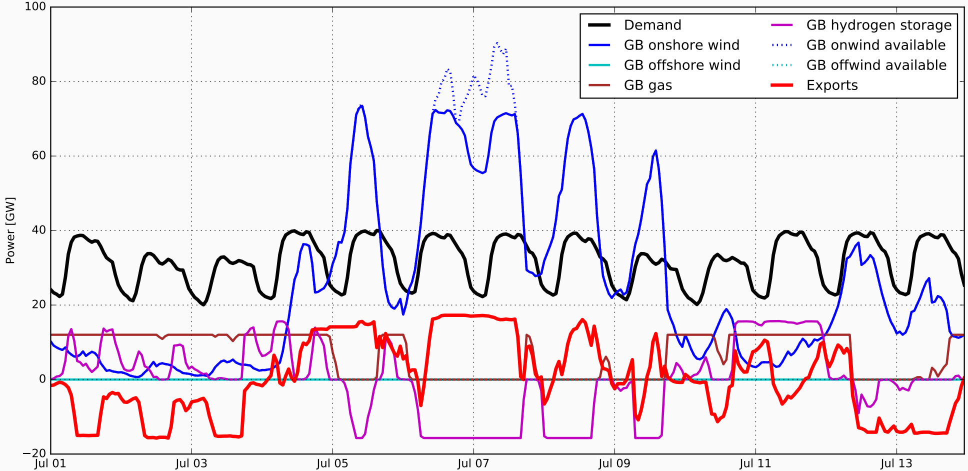




A restricted extension of interconnection goes a long way to reduce the costs. More onshore wind, less solar and storage.

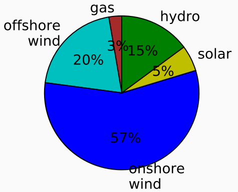
Dispatch with moderate interconnecting transmission

For Great Britain with moderate interconnecting transmission, excess wind can be exported instead of being curtailed:



Costs: Cost-optimal expansion of interconnecting transmission

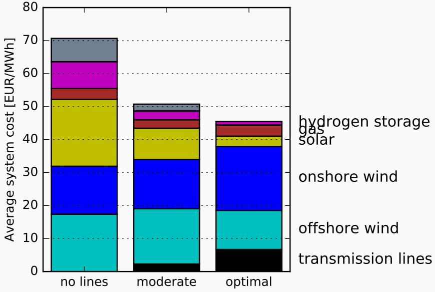
Technology by energy:

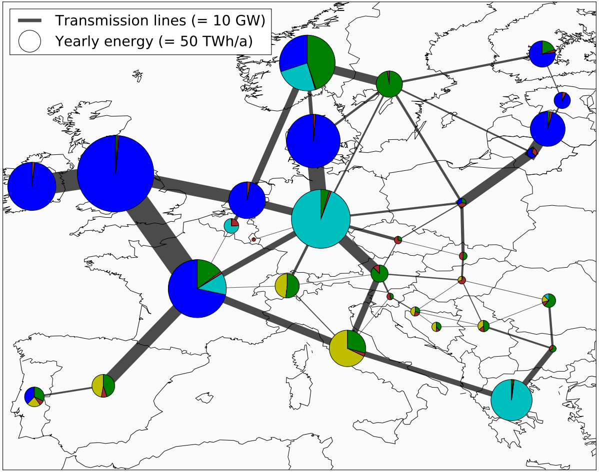


$\mu_{CO_2} = 42$

$\mu_{trans} = 0$

Average cost €45/MWh:

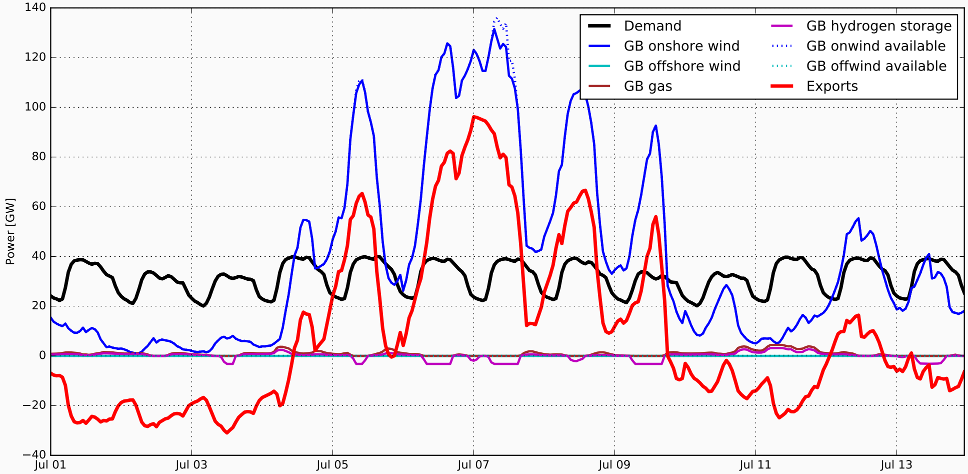




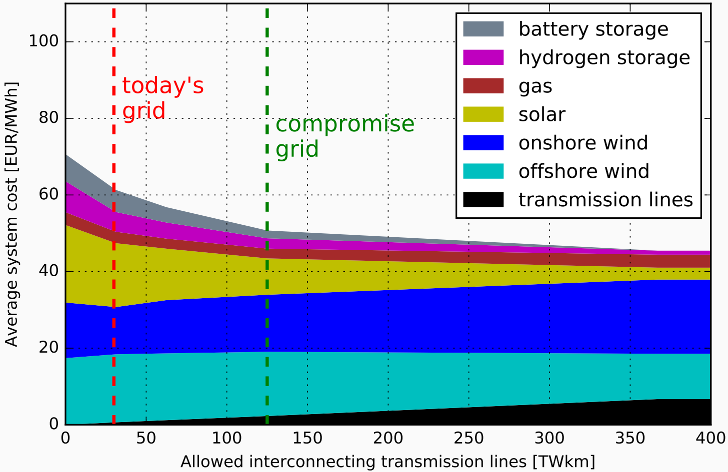
Large transmission expansion; onshore wind dominates. This optimal solution may run into public acceptance problems.

Dispatch with cost-optimal interconnecting transmission

Almost all excess wind can be now be exported:

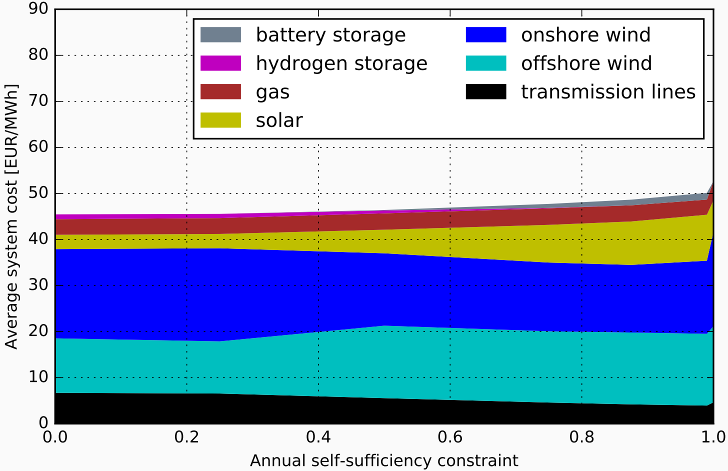


Costs: Comparison



- Total system costs can be as cheap as today's system (down to €45/MWh)
- Energy is dominated by wind (77% 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 55%
- Compromise locks in many benefits of transmission

Costs: Comparison for Changing heterogeneity

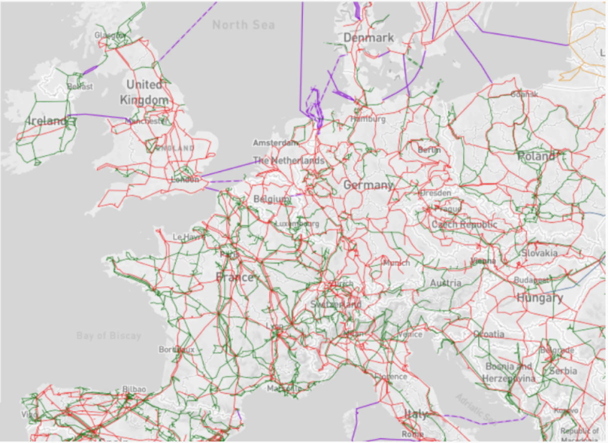


- For the optimal solution try varying the heterogenity, e.g. for self-sufficiency parameter k, country must generate annually between $1/k$ and k of its annual load.
- $k = 0$ on left is unconstrained; $k = 1$ means on balance self-sufficient over the year

Trade-Offs in Spatial Resolution

Spatial resolution

In reality network has much more detail. Need high spatial resolution to represent VRE resource variation and transmission constraints in electricity and gas networks.



Source: ENTSO-E

Changing spatial resolution

We need spatial resolution to:

- capture the geographical variation of renewables resources and the load
- capture spatio-temporal effects (e.g. size of wind correlations across the continent)
- represent important transmission constraints

BUT we do not want to have to model all 10,000 network nodes of the European system.

Many algorithms in the literature

There are lots of algorithms for clustering/aggregating networks, particularly in the engineering literature:

- k-means clustering on (electrical) distance
- k-means on load distribution
- Community clustering (e.g. Louvain)
- Spectral analysis of Laplacian matrix
- Clustering of Locational Marginal Prices with nodal pricing (sees congestion and RE generation)
- PTDF clustering
- Cluster nodes with correlated RE time series

The algorithms all serve different purposes (e.g. reducing part of the network on the boundary, to focus on another part).

Our metrics of interest

What we want from a network aggregation algorithm:

1. Preservation of major flows within original network
2. Preservation of overall volume of flows
3. For capacity optimisation: representative capacity extensions with aggregated network
4. Preservation of spatial distribution of generation capacity

k-means clustering on load or load & conventional generation

Cluster nodes based on load using k-means.

I.e. find k centroids and the corresponding k-partition of the original nodes that minimises the sum of squared distances from each centroid to its nodal members:

$$\min_{\{x_c\}} \sum_{c=1}^{k} \sum_{n \in N_c} w_n ||x_c - x_n||^2 \tag{1}$$

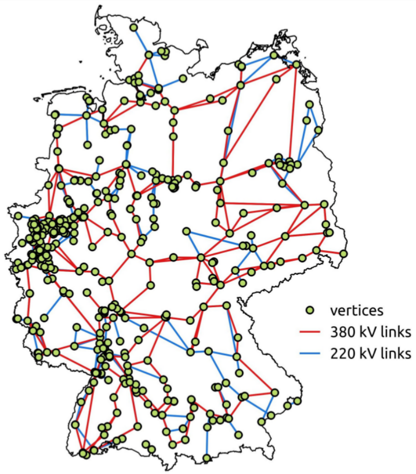
where each node is weighted w_n by the average load there.

NB: Totally ignores grid topology. It works because network is principally laid out to serve the load (with exception of large conventional power plants situated near e.g. mines/rivers).

Take an open grid: SciGRID for Germany

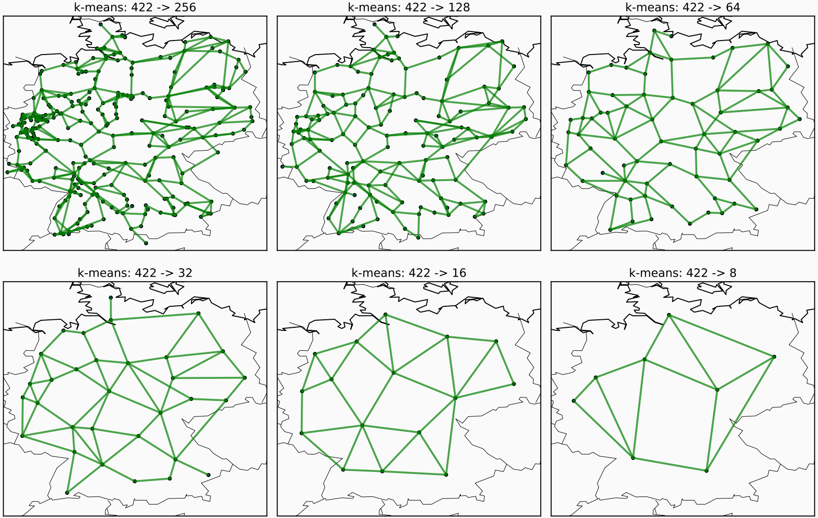
`http://scigrid.de/` (NEXT Energy)

- Uses OpenStreetMap (OSM) relations (ordered lists of nodes, ways and other relations) to generate an open network dataset
- So far only Germany, because relations for transmission lines are sparse outside Germany
- Only transmission lines in dataset, no trafos, load or generation data, these have been added as a PyPSA advertising example and a few tweaks to the grid



Source: NEXT Energy, OSM

k-means clustering (stubs are reduced in pre-processing)



Question of spatial resolution

If we take our “worst case” from before of no interconnection (€ 71/MWh), we still assumed each country had no internal bottlenecks.

How is this result affected by an increase of spatial resolution in each country?

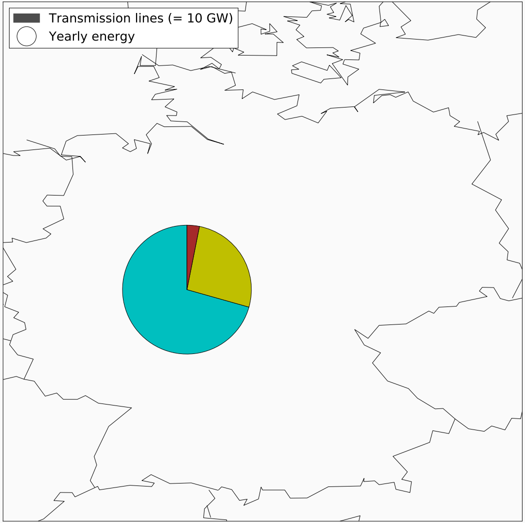
We expect

- A better representation of existing internal bottlenecks will prevent the transport of e.g. offshore wind to the south.
- Localised areas of e.g. good wind can be better exploited by the optimisation.

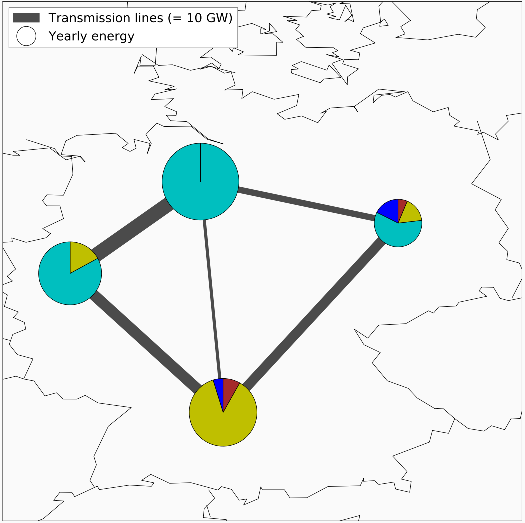
Which effect wins?

Clustering nodes

1 nodes:

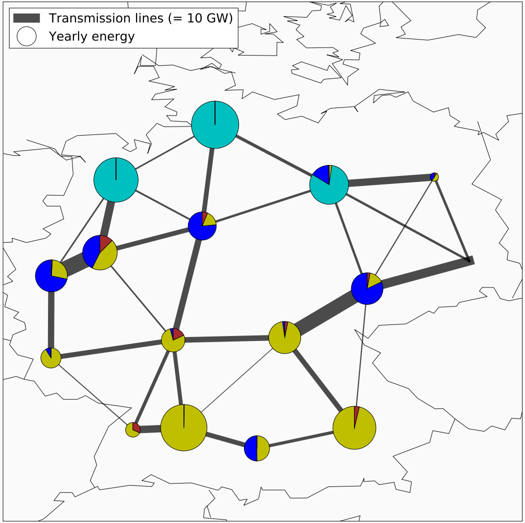


4 nodes:

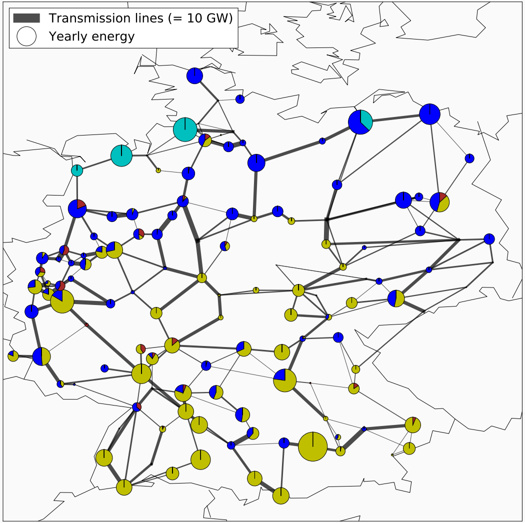


Clustering nodes

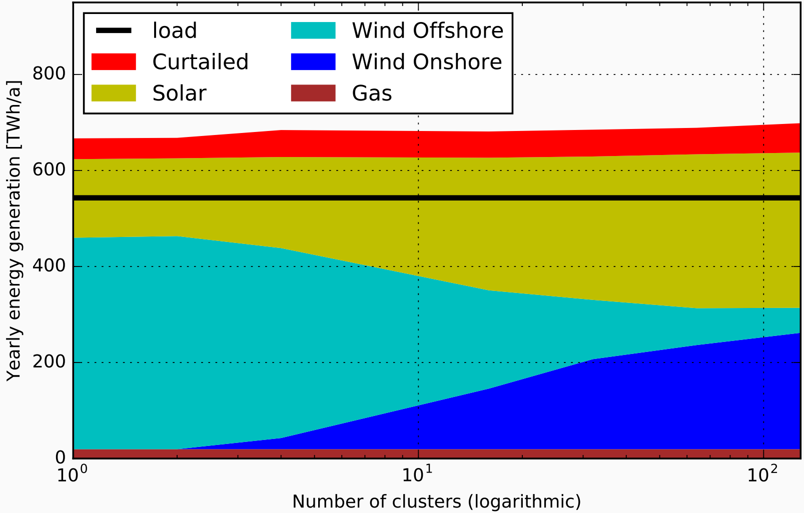
16 nodes:



128 nodes:

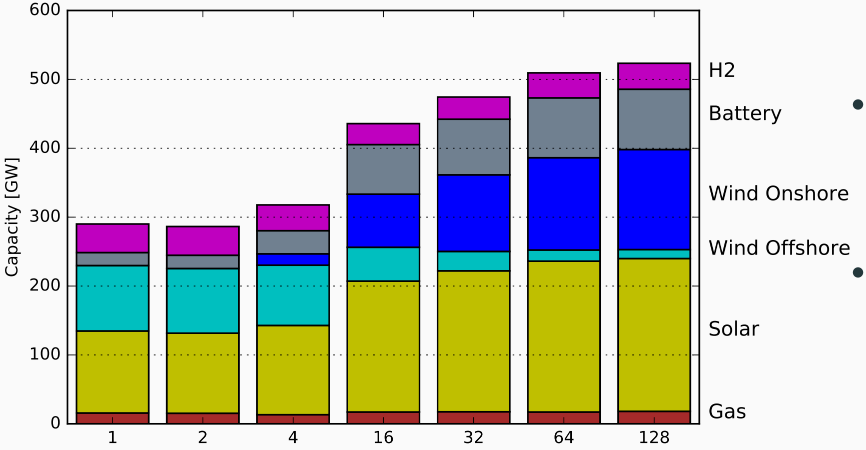


Comparison of results: energy



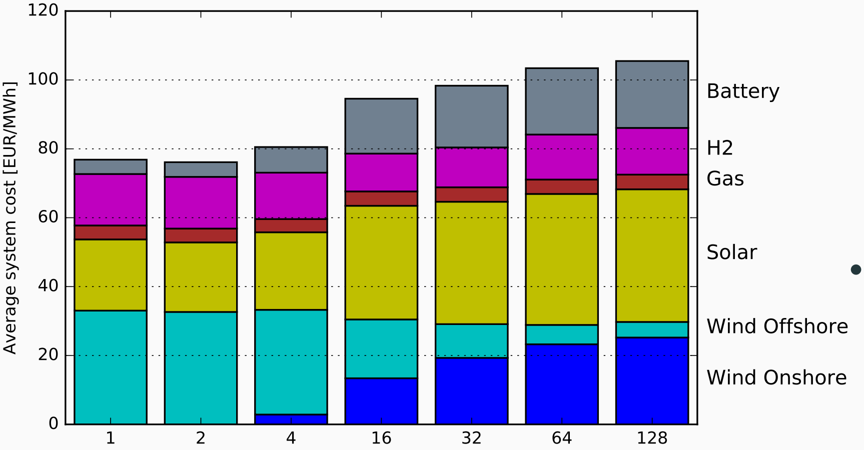
- As resolution increases, we trade offshore wind for consumer-near wind and solar energy.
- 94 TWh/a is lost in storage efficiency losses
- 61 TWh/a of renewables are curtailed

Comparison of results: power



- Big increase in total capacity as we shift from offshore to onshore and solar
- Big increase in storage capacity

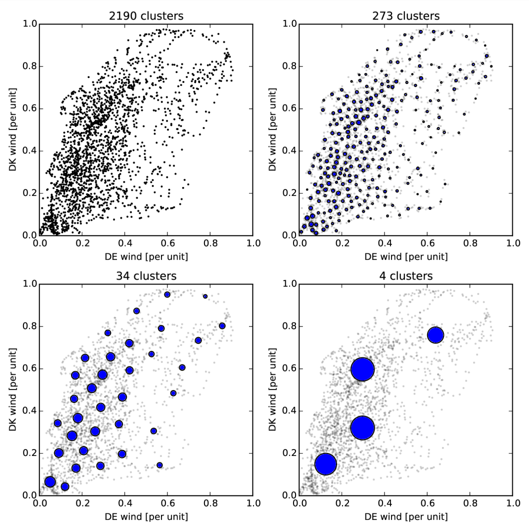
Comparison of results: cost



- As spatial resolution increases, cost of generation increases from € 77/MWh to € 105/MWh due to grid bottlenecks, an increase of 37%
- NB: This is without any grid extensions and without interconnection; with both of these the solution would be considerably cheaper

Optimisation Outlook: Temporal Resolution and Sector Coupling

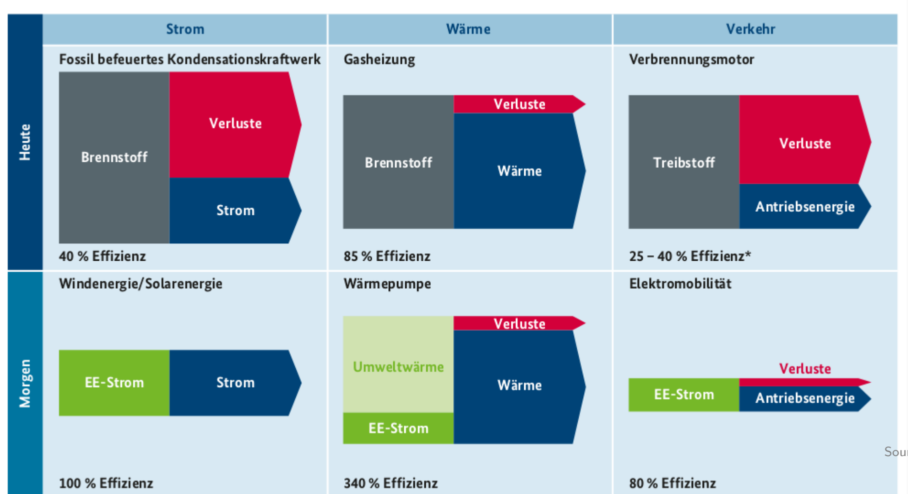
Time series reduction example: wind production in Germany and Denmark



- Want to capture correlations in time series (load, wind and solar) and spatio-temporal patterns without taking whole year of hourly data
- k-means clustering creates k clusters
- Centroids chosen to minimise the sum of squared distances between the centroids and the original points
- Weighting $w(s) \propto$ number of points assigned to each cluster
- Convex hull not so well captured

Sector integration

Replacing heating and transport fossil fuels with renewable sources and renewable electricity increases efficiency and reduces emissions of GHG.



Source: BMWi Weißbuch

Sector Coupling: Additional Flexibility

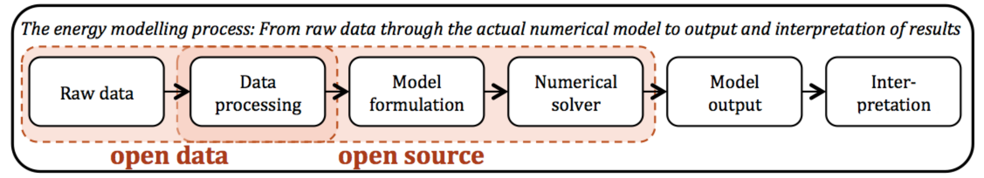
Example from Germany of final energy consumption reduction and increased flexibility through electrifying other energy sectors:

Sector	Today's final energy [TWh/a]	Electrification	Future final energy [TWh/a]	Extra flexibility
Traditional electric	550	Efficiency	400	None
Transport	800	Electric vehicles	150	Batteries
Low-T Heating	900	Heat pumps	300	Thermal storage
Total	2250		850	

Industrial process heat, aviation, shipping and agricultural emissions are more tricky...

Idea of Open Energy Modelling

The whole chain from raw data to modelling results should be open:



Open data + free software ⇒ Transparency + Reproducibility

There's an initiative for that, with a wiki, a lively mailing list and regular workshops:

openmod open energy modelling initiative

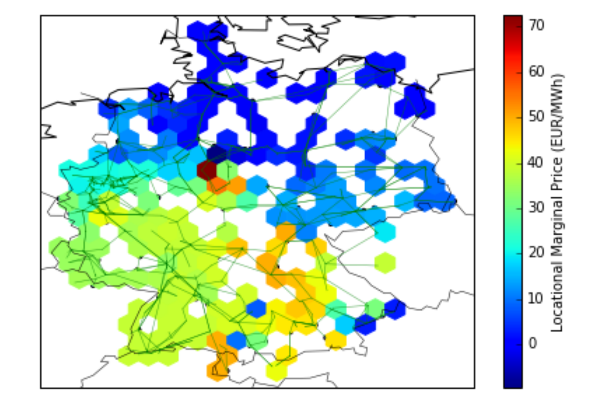
openmod-initiative.org

Source: openmod initiative

Python for Power System Analysis (PyPSA)

The FIAS software PyPSA is online at `http://pypsa.org/` and on github. It can do:

- Static power flow
- Linear optimal power flow
- Security-constrained linear optimal power flow
- Total electricity system investment optimisation



It has models for storage, meshed AC grids, meshed DC grids, hydro plants, variable renewables,...
Coming soon: heat and gas sectors

Conclusions

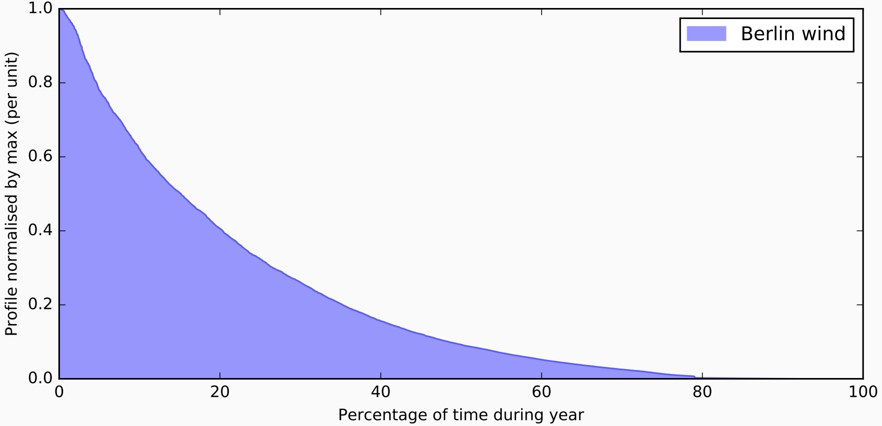
Conclusions

- 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 55% - the price of non-cooperation.
- Network bottlenecks internal to the countries could increase the costs by another 40%.
- Major challenges for modelling: getting more grid detail, while retaining European scope; sector coupling with transport and heating; reducing model complexity.

Copyright

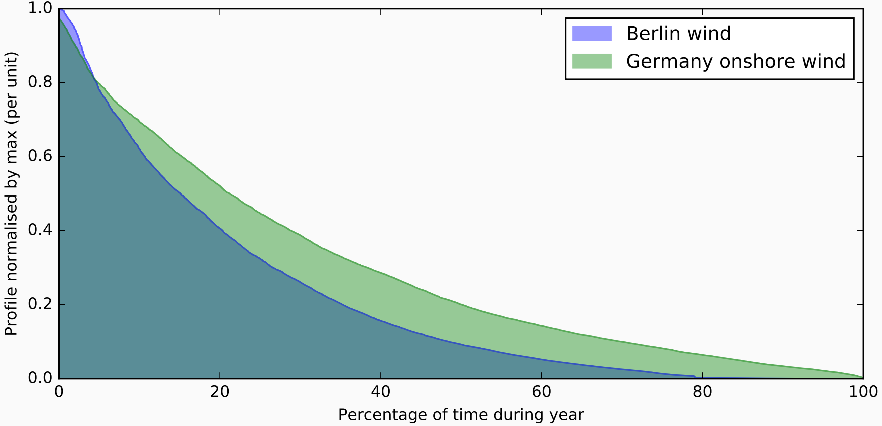
Duration curve: Berlin

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.