Integrated Modelling of Energy Systems and Transmission Networks

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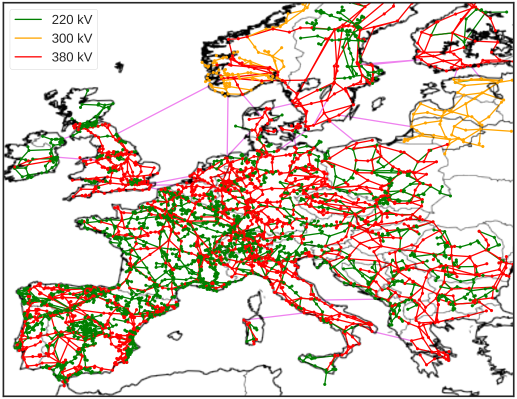
The Challenges: Complexity in Energy System Models



To **decarbonise** the energy system by 2050:

- Need to model **capacity investments** and **operation** of all generators, storage, grids and heating/transport/industry.
- Need **European scope** for smoothing renewables and energy markets.
- Need **detailed grid model** to capture network bottlenecks.
- Need **all energy sectors** to leverage potential flexibility.

Source: PyPSA-Eur, based on ENTSO-E map

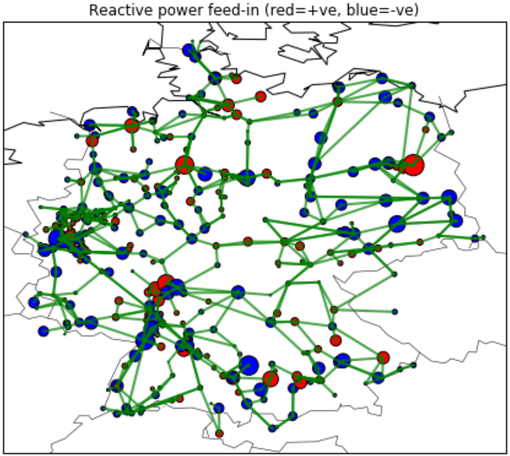
Some solutions from FIAS, Frankfurt

- **Openness** and **cooperation** in the community: engagement with Open Energy Modelling Initiative, development of free software (PyPSA) and open data (PyPSA-Eur).
- **Clustering algorithms** to reduce the size of the grid model while maintaining important bottlenecks.
- **Iterative algorithms for network expansion** that are only near-optimal but fast and stable.
- **New formulations of linear OPF problems** that also enhance speed.

These solutions and techniques will be further expanded and developed in a Helmholtz Young Investigator Group starting at KIT Institut für Angewandte Informatik (IAI) from April 2018.

Python for Power System Analysis (PyPSA)

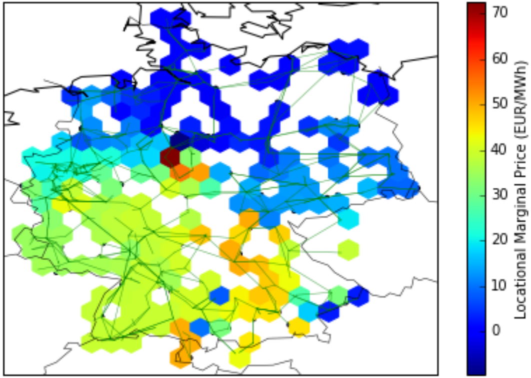
- Developed at Frankfurt Institute of Advanced Studies by Tom Brown, Jonas Hörsch and David Schlactberger for the CoNDyNet project.
- Fills missing gap between **load flow software** (e.g. MATPOWER, PowerFactory) and **energy system simulation software** (e.g. OSeMOSYS, PLEXOS, TIMES).
- Good grid modelling is increasingly important, for integration of renewables and possible electrification of transport and heating.



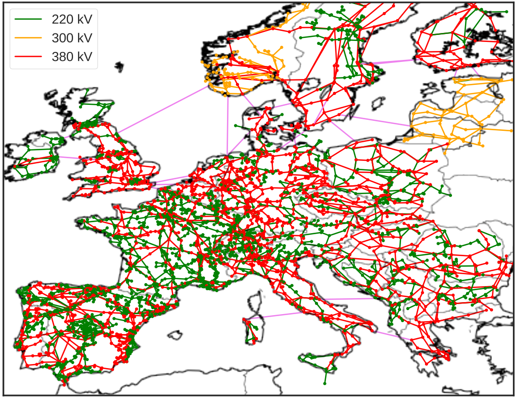
Python for Power System Analysis (PyPSA)

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

- Static **power flow**
- **Linear optimal power flow** (multiple periods, unit commitment, storage, coupling to other sectors)
- **Security-constrained linear optimal power flow**
- Total electricity system **investment optimisation**



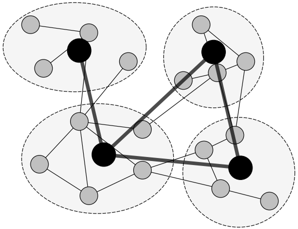
PyPSA-Eur: Open Model of European Transmission System

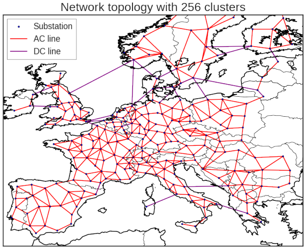


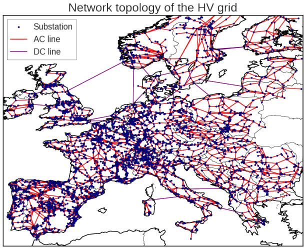
- Grid data based on **GridKit** extraction of ENTSO-E interactive map.
- FIAS **powerplantmatching** database of power plants in Europe.
- Renewable energy time series from open **atlite**, based on Aarhus University REatlas.
- Geographic **potentials** for RE from land use.
- Basic **validation** described in Hörsch et al 'PyPSA-Eur: An Open Optimisation Model of the European Transmission System'.
- `https://github.com/FRESNA/pypsa-eur`

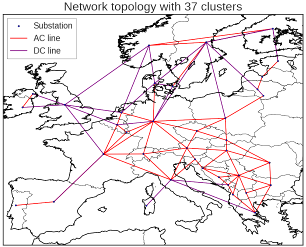
Network Clustering

Can cluster down the network, to reduce resolution while retaining important transmission lines:









Clustering: Many algorithms in the literature

There are lots of algorithms for 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). Not always tested on real network data.

Question of spatial resolution

If we do a **joint optimisation** of generation, storage and transmission with a 95% CO_2 reduction compared to 1990, how is the solution affected by an **increase of spatial resolution** in each country?

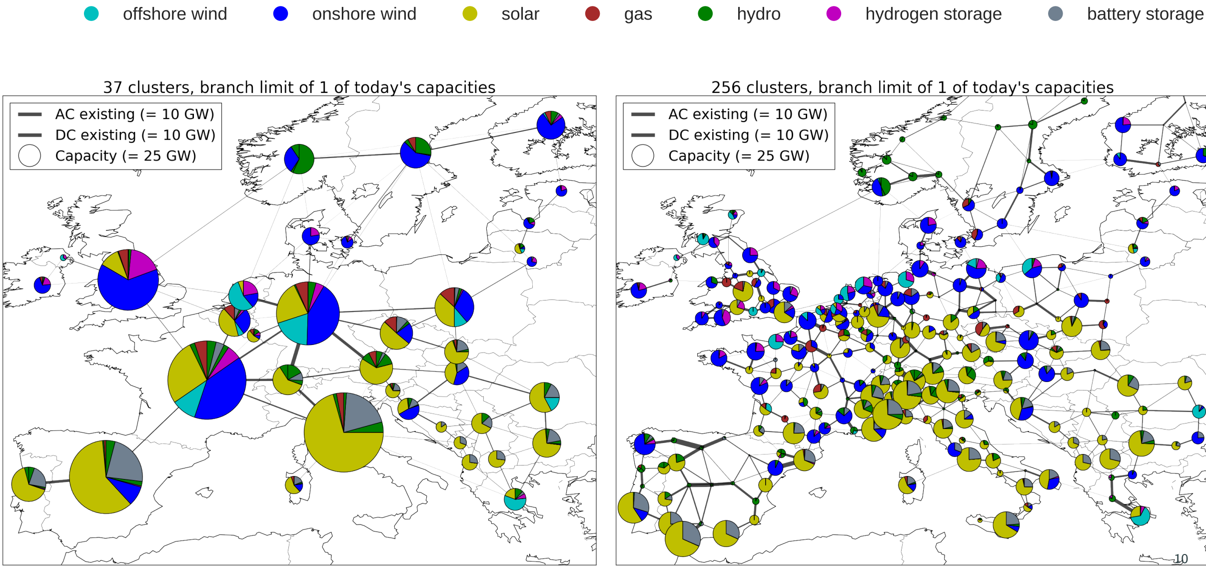
We expect

- **Better representation of existing internal bottlenecks** that will prevent the transport of e.g. offshore wind to the South of Germany.
- **Better local exploitation of good renewable resources**, e.g. local areas of good wind can be better exploited by the optimisation.

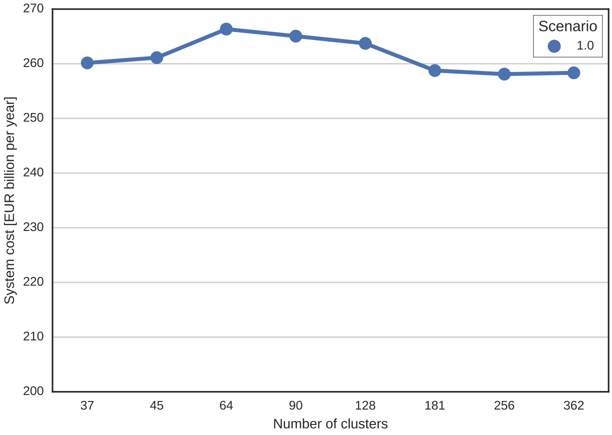
Which effect will win?

First we only optimize the gas, wind and solar generation capacities, the long-term and short-term storage capacities and their economic dispatch including the available hydro facilities **without grid expansion**.

Nodal capacities per technology (w/o grid expansion)

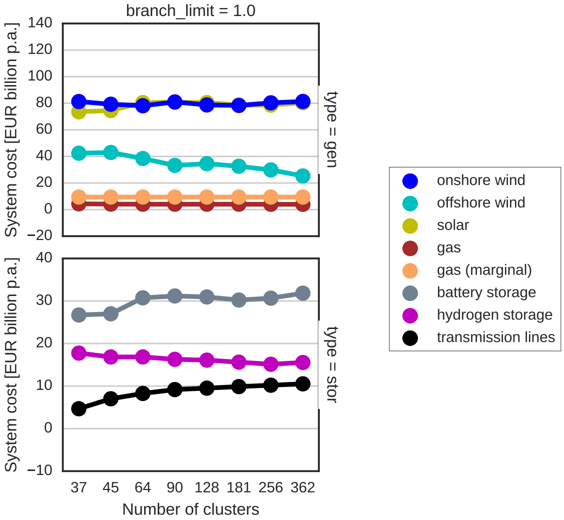


Costs: System cost w/o grid expansion



- Steady total system cost at € 260 billion per year
- This translates to € 82/MWh (compared to today of € 50/MWh to € 60/MWh)

Costs: System cost and break-down into technologies (w/o grid expansion)



If we break this down into technologies:

- 37 clusters captures around half of total network volume
- Redistribution of capacities from offshore wind to solar
- Increasing solar share is accompanied by an increase of battery storage
- Single countries do not stay so stable

Interaction between network expansion, cost and spatial scale

To investigate how **public acceptance problems** for transmission lines impact on the cost-effectiveness, we introduce **transmission volume limits**.

If each line ℓ has length d_ℓ and capacity $\bar{P}_\ell$ then:

$$\begin{aligned} \bar{P}_\ell &\geq \bar{P}_\ell^{\text{today}} \\ \sum_\ell d_\ell \bar{P}_\ell &\leq \mathrm{CAP}_{\text{trans}} \qquad \leftrightarrow \qquad \mu_{\text{trans}} \end{aligned}$$

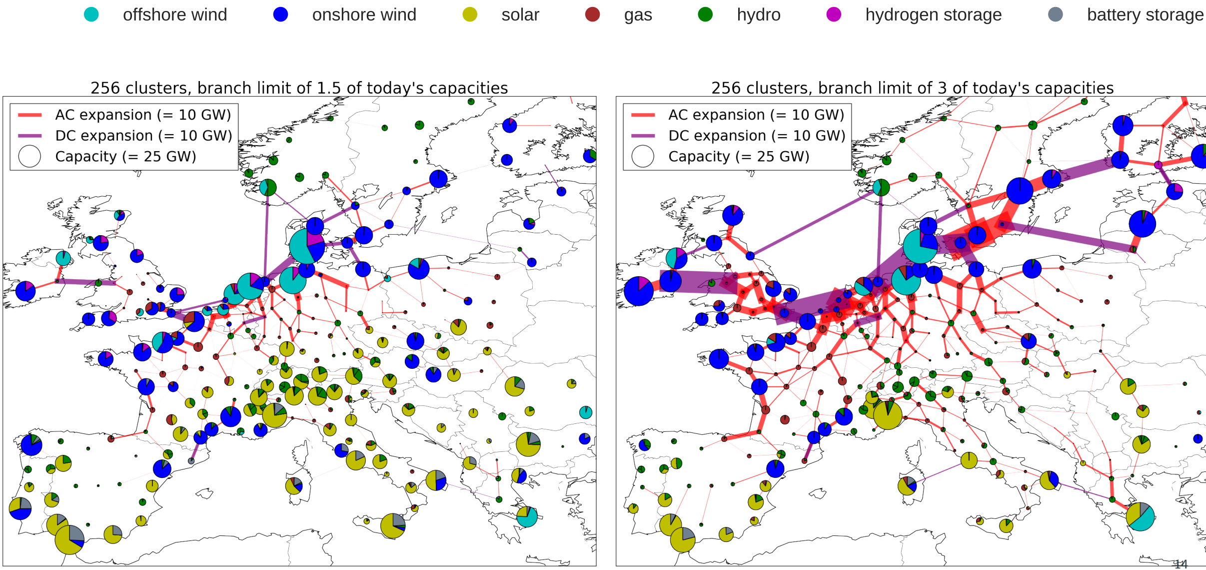
We constrain the overall transmission line volume in relation to today's line volume $\mathrm{CAP}_{\text{trans}}^{\text{today}}$:

$$\mathrm{CAP}_{\text{trans}} = x\,\mathrm{CAP}_{\text{trans}}^{\text{today}}$$

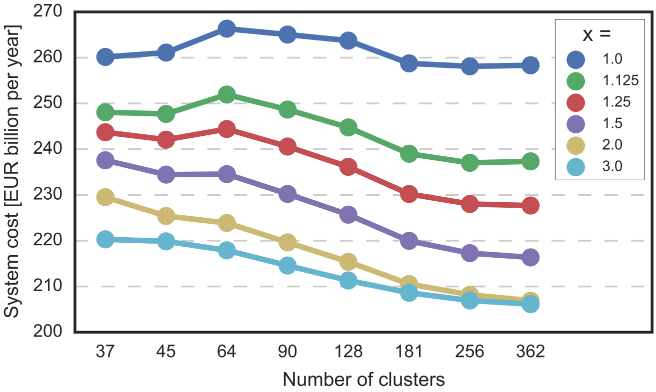
for $x = 1$ (today's grid) $x = 1.125, 1.25, 1.5, 2, x = 3$.

This allows us to assess the costs of balancing power in time (i.e. storage) versus space (i.e. inter-connecting transmission networks).

When grid expansion allowed: avoid costly storage

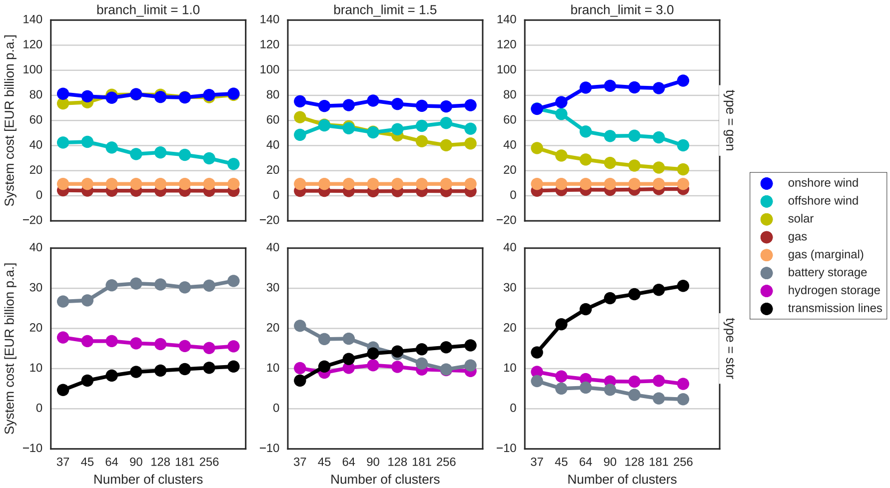


Costs: Total system cost

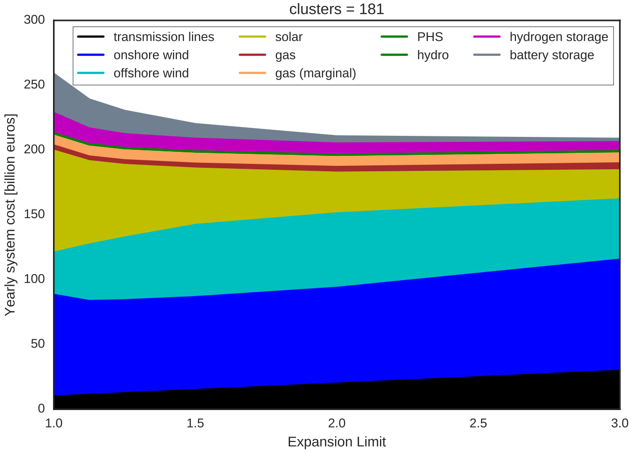


- Steady cost for No Expansion (1)
- For expansion scenarios, as clusters increase, the better expoitation of good sites decreases costs faster than transmission bottlenecks increase them
- Decrease in cost is v. non-linear as grid expanded (25% grid expansion gives 50% of optimal cost reduction)
- Only a moderate 20 – 25% increase in costs from the Optimal Expansion scenario (3) to the No Expansion scenario (1).

Costs: Break-down into technologies



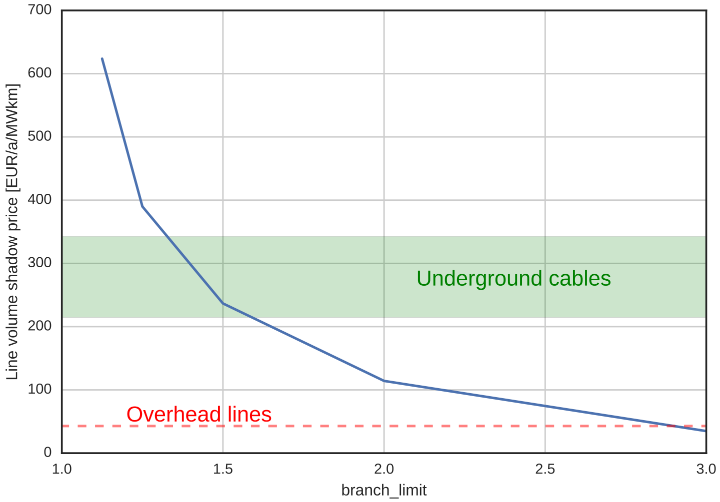
Behaviour as transmission expansion is allowed



- Big **non-linear cost reduction** as grid is expanded, from 82€/MWh to 66€/MWh (drop of 50 bill. €/a)
- Most of cost reduction happens with **25% grid expansion** compared to today's grid; costs rather flat once capacity has doubled
- Need for solar and batteries decrease significantly as grid expanded; with cost-optimal grid, system is dominated by wind

Source: Schlachtberger et al, 2017, Hörsch et al, 2017

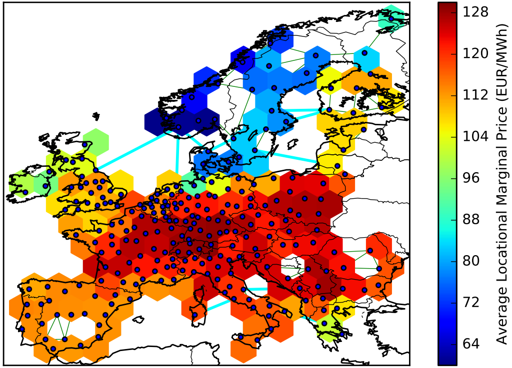
Grid expansion CAP shadow price for 181 nodes as CAP relaxed



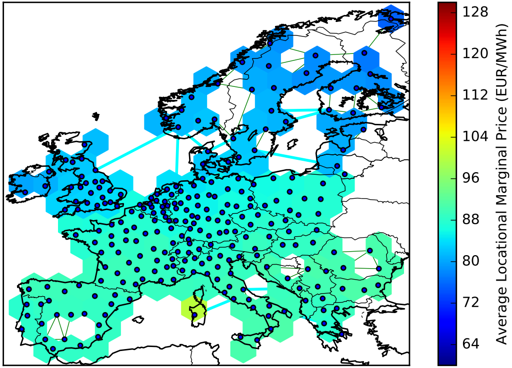
- With overhead lines the optimal system has around 3 times today's transmission volume
- With underground cables (5-8 times more expensive) the optimal system has around 1.3 to 1.6 times today's transmission volume

Locational Marginal Prices CAP=1 versus CAP=3

With today's capacities:



With three times today's grid:



Iterative grid expansion optimisation

The full grid expansion problem has to take account of:

- Non-linear equations for active and reactive power flow ($S_i = \sum_j V_i Y_{ij}^* V_j^*$)
- Non-linear expansion equations (coupling between changing Y_{ij} and V_i)
- Integer variables for each additional circuit
- Non-convexity of feasible space
- Reactive power compensation
- Optimal switching
- Contingencies ($n-1$, etc.)

In practice, this level of detail is **redundant** for long-term planning at an aggregated level of detail. There are bigger uncertainties elsewhere...

Even linearisation is too complex for large grids

Many transmission planning models use a linearized power flow approximation, but even this results in an expansion problem which is both **bilinear** and **integer**:

$$f_\ell = b_\ell \cdot \eta_l \cdot (\theta_i - \theta_j)$$
$$|f_\ell| \leq \eta_l \cdot F_\ell$$

where b_ℓ is the fixed susceptance per circuit, θ_i is the nodal voltage angle and $\eta_\ell \in \{0, 1, 2, \dots\}$ is the integer number of circuits.

This can be converted to a MILP using a big-M disjunctive relaxation. This has been implemented in PyPSA by a researcher from TU Delft, but it's very slow.

There are also MISOC and MISD variants which use convex quadratic flow approximations to get more of the physics.

Iterative grid expansion optimisation

Our approach: allow each corridor to expand **continuously**, i.e. fuse

$$b_\ell \cdot \eta_l \rightarrow \tilde{b}_\ell \in \mathbb{R}$$
$$\eta_l \cdot F_\ell \rightarrow \tilde{F}_\ell \in \mathbb{R}$$

to continuous variables. This removes the **discreteness**.

Algorithm: Fix $\tilde{b}_\ell$ for the simulation, allow $\tilde{F}_\ell$ to be optimised, then update $\tilde{b}_\ell$ with the value corresponding to the optimised $\tilde{F}_\ell$ ($\tilde{b}_\ell \propto \tilde{F}_\ell$). Repeat until there is convergence. This removes the **bilinearity**.

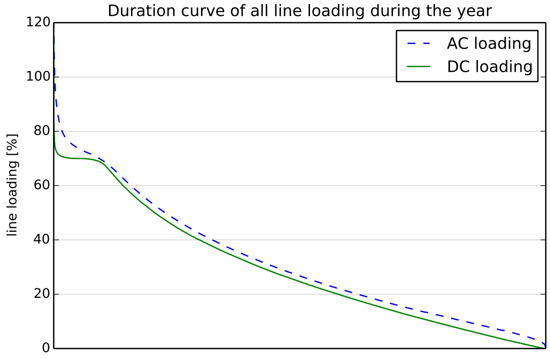
Approach tested in Hagspiel et al, Energy (2014).

The **good**: fast, stable, convergent, feasible, optimal for small networks.

The **bad**: no guarantee of optimality, must do discretisation into circuits 'post facto', tricky to build new network topologies.

Non-linear check of linear results

In Brown et al, IET RPG (2016) we ran the results of a linear grid capacity optimisation through a non-linear 'AC' power flow:

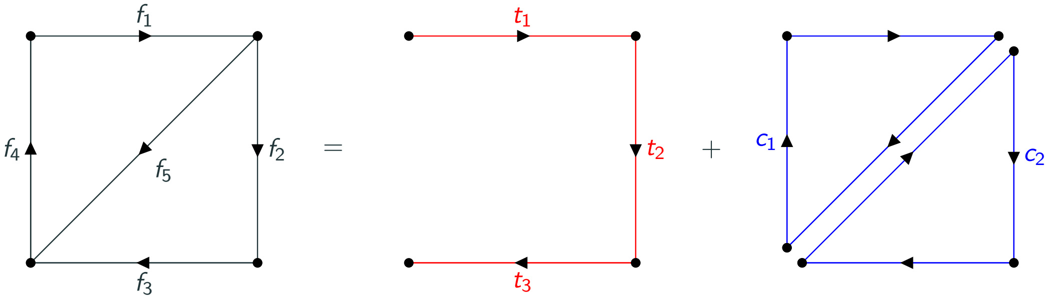


- The 'DC' results plateau at 70% because this was our chosen contingency buffer
- 70% is the natural loading level of a typical transmission line, which explains the 'AC' results: below 70% the line is a capacitor, whereas above 70% the line behaves like an inductor and the loading increases $\propto I^2$.
- Conclusion: keeping 70% contingency limit also solves problems with over-loading due to reactive power currents.

Cycle formulation of linear power flow

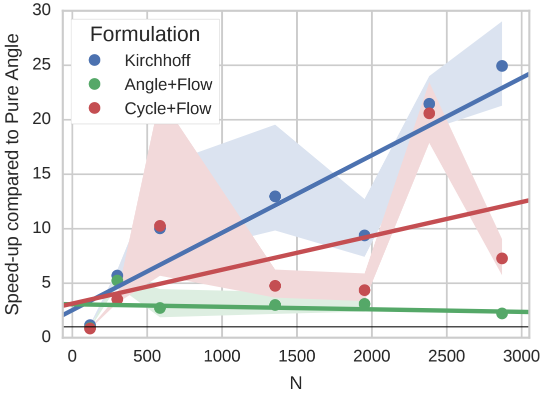
We can use dual graph theory to decompose the flows in the network into two parts:

1. A flow on a spanning tree of the network, uniquely determined by nodal **p** (ensuring KCL)
2. Cycle flows, which don't affect KCL; their strength is fixed by enforcing KVL



$$f_\ell \quad = \quad t_\ell \quad + \quad \sum_k C_{\ell,k} c_k$$

LOPF speedup with cycle flows



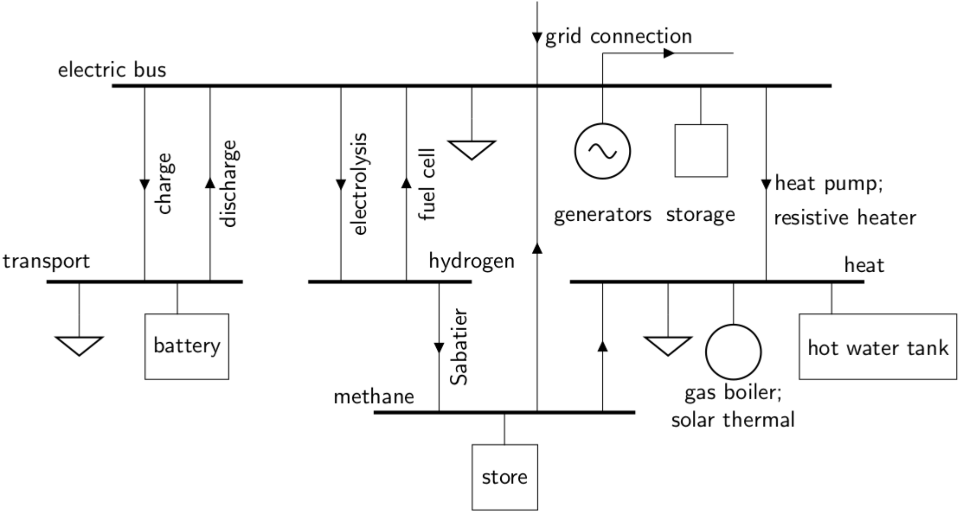
Using **cycle flows instead of voltage angles** we found for generation expansion optimisation (fixed grid):

- A speed-up of up to **200 times**
- Average speed-up of **factor 12**
- Speed-up is highest for **large networks with lots of renewables**

H. Ronellenfitsch, D. Manik, J. Hörsch, **T. Brown, D. Witthaut**, *"Dual theory of transmission line outages,"* 2017, IEEE Transactions on Power Systems

J. Hörsch, H. Ronellenfitsch, **D. Witthaut, T. Brown**, *"Linear Optimal Power Flow Using Cycle Flows,"* 2017

Coupling to Other Energy Sectors



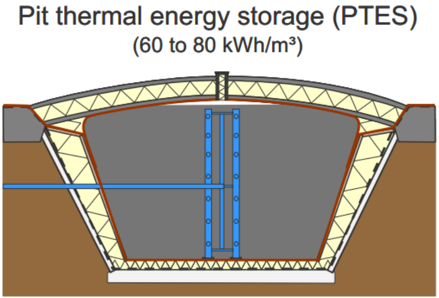
Coupling to Other Energy Sectors

Idea: Couple the electricity sector to heating and mobility.

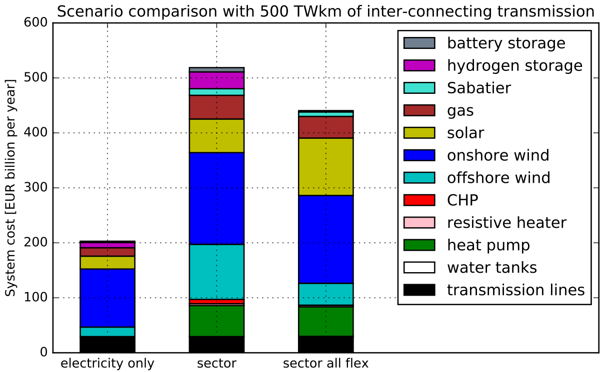
This enables decarbonisation of these sectors **and** offers more flexibility to the power system.

Battery electric vehicles can change their charging pattern to benefit the system and even feed back into the grid if necessary

Heat is much easier and cheaper to store than electricity, even over many months



Coupling to Other Energy Sectors



- Not just electricity: transport, heating and industrial must be considered to meet **Paris targets**
- Electrifying land-based transport and low-temperature heating would **increase electricity demand** by up to 60%, with strong seasonality
- However, these other sectors also offer significant **flexibility**: smart battery electric vehicle charging and thermal storage can play a big role

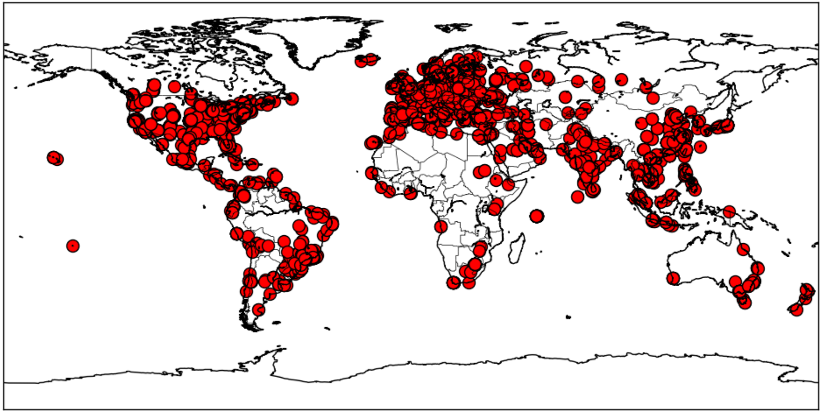
PyPSA users

PyPSA is being actively used by more than a dozen research institutions and companies (that we know of...). Those whose activity is visible online:

- FIAS: Optimisation of European energy system
- FIAS+CSIR: Optimisation of South African energy system
- RLI, DLR VE, Flensburg, Magdeburg: open_Ego for open grid optimization
- Forschungszentrum Jülich: Optimisation of European energy system
- Aarhus University: Optimisation of European energy system
- TU Delft: European Northern Seas offshore grid
- ewi Energy Research & Scenarios: Incentives for wind placement in Germany
- Saudi Aramco: High renewable scenarios for Saudia Arabia
- Edison Energy, Spire in United States

PyPSA users

The website has been visited by people from 120+ countries:



PyPSA development

- Improvements to power flow: distributed slack, reactive power limits
- Improvements to OPF: investment over multiple years, non-linear constraints
- Workflow: integrate with snakemake
- Pyomo: persistent gurobipy solver interface for repeated solution of similar problems
- Julia interface port: testing JuMP for more performant problem building

Links

Python for Power System Analysis (PyPSA):

a free software toolbox for simulating and optimising modern power systems

- **Documentation** and **examples** showcasing open data: `https://pypsa.org/`
- **Github**: `https://github.com/FRESNA/PyPSA`
- **Mailing list**: `https://groups.google.com/forum/#!forum/pypsa`
- **Research paper description**: `https://arxiv.org/abs/1707.09913`

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