The European Energy Transition: Fulfilling the Paris Agreement While Maintaining Public Acceptance of Energy Infrastructure

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5th International Conference on Smart Energy Systems, Copenhagen, 11th September 2019

Karlsruhe Institute of Technology

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

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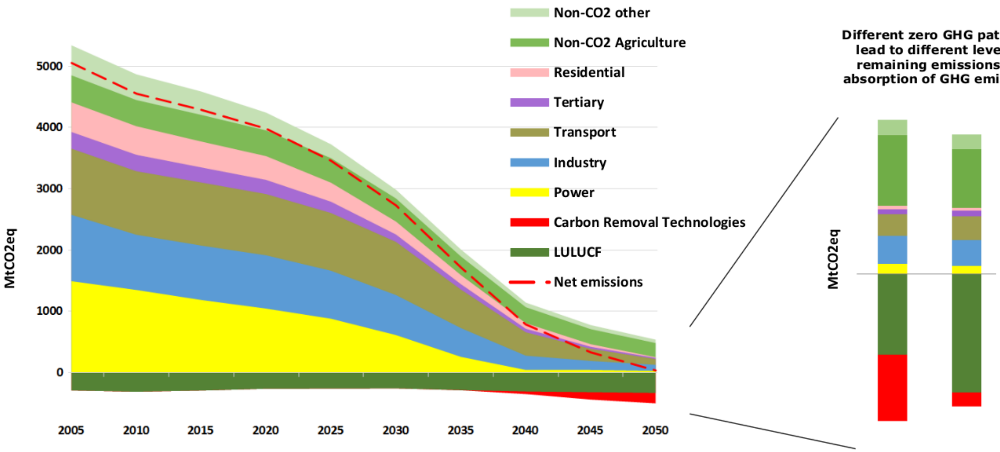
Research Challenge

The Greenhouse Gas Challenge: Net-Zero Emissions in Europe by 2050

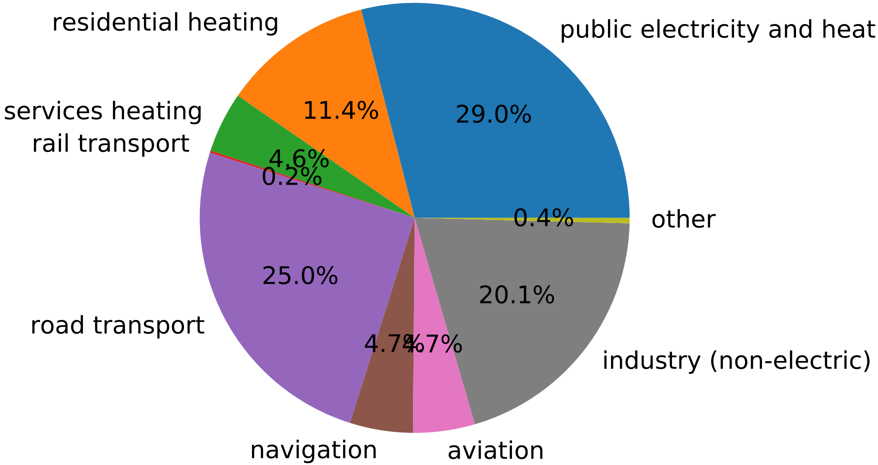
Paris-compliant 1.5° C scenarios from European Commission - **net-zero GHG in EU by 2050**



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.

Some scenarios show a **doubling or more of electricity demand**.

Source: Tesla; heat pump: Kristoferb at English Wikipedia

Must take account of variabilility & social & political constraints

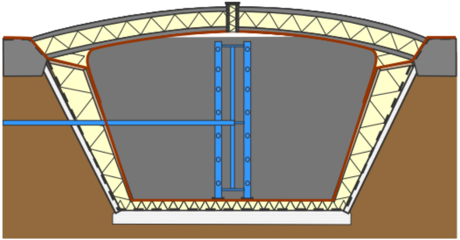
Sustainability doesn't just mean taking account of environmental constraints.

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

Fortunately other sectors offer flexibility back to grid

Other sectors offer **flexibility** (e.g. battery electric vehicles, power-to-gas, thermal storage), enabling energy to be **stored cheaply** and **transported easily** (e.g. using natural gas network).

Pit thermal energy storage (PTES)
(60 to 80 kWh/m³)



Sectoral coupling with spatial resolution, European scope

The Issue: Most cross-sectoral studies are at country level, but don't have the resolution to resolve transmission bottlenecks or the variability of renewables

Our Goal: Model full energy system over Europe with enough resolution to understand the effects of congestion and the cost-benefits of transmission reinforcement

The Challenge: Enormous datasets, computability, complexity

Today: Some preliminary results from my group and our cooperation partners

The Model

Optimisation of annual system costs

Find the long-term cost-optimal energy system, including investments and short-term costs:

$$\text{Minimise}\left(\begin{array}{c}\textbf{Yearly}\\ \textbf{system costs}\end{array}\right)=\sum_{n}\left(\begin{array}{c}\textbf{Annualised}\\ \textbf{capital costs}\end{array}\right)+\sum_{n,t}\left(\begin{array}{c}\textbf{Marginal}\\ \textbf{costs}\end{array}\right)$$

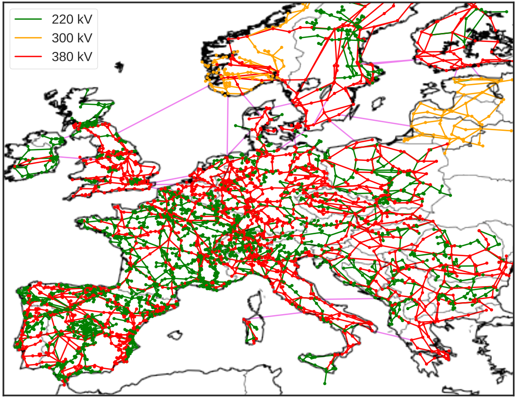
subject to

- 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.

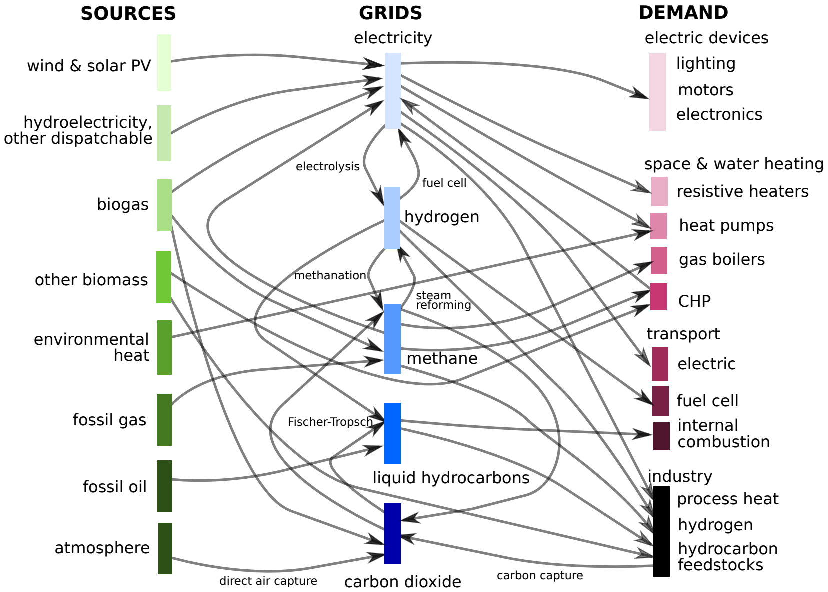
PyPSA-Eur: Open Model of European Energy System



Basic **validation** of grid model in Hörsch et al (Energy Strategy Reviews (ESR), 2018), github.com/PyPSA/pypsa-eur

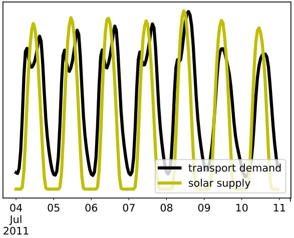
- Grid data based on **GridKit** extraction of ENTSO-E interactive map
- **powerplantmatching** tool combines open databases using matching algorithm DUKE
- Renewable energy time series from open **atlite**, which processes terabytes of weather data from e.g. new ERA5 global reanalysis
- Geographic **potentials** for RE from land use GIS availability
- All energy demand and supply options (power, transport, heating and industry)

Sector coupling: A new source of flexibility

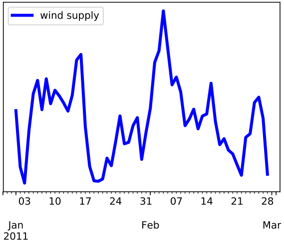


Key to Understand Flexibility: Different Time and Spatial Scales

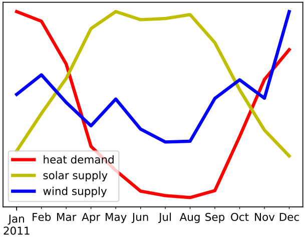
Daily Scale (↔ East-West in Space)



Weekly Scale ↔ Continental in Scale



Seasonal Scale (↔ North-South in Space)

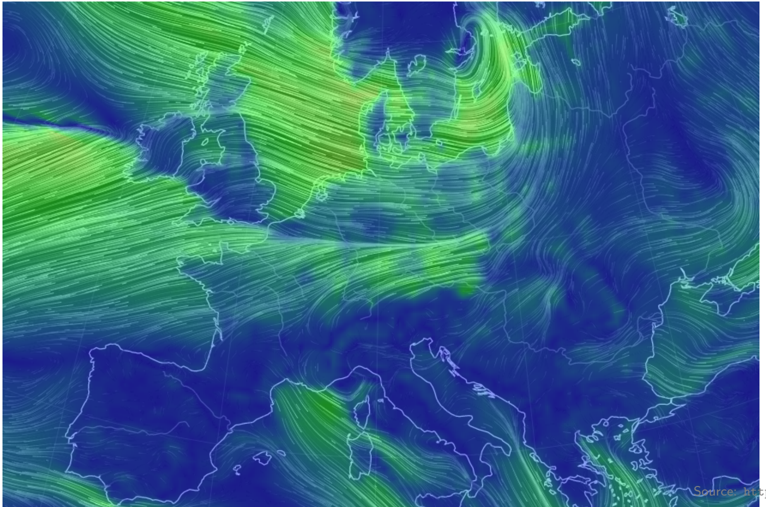


Match scales to flexibility options, e.g.:

- **Daily**: shift demand or battery storage
- **Weekly**: H_2/CH_4 storage or big grids
- **Seasonal**: H_2/CH_4 storage

Solve wind variability in space instead of time with grids

Weekly variations in wind are caused by big weather systems. Can also **smooth in space** with **continent-spanning power grids**.



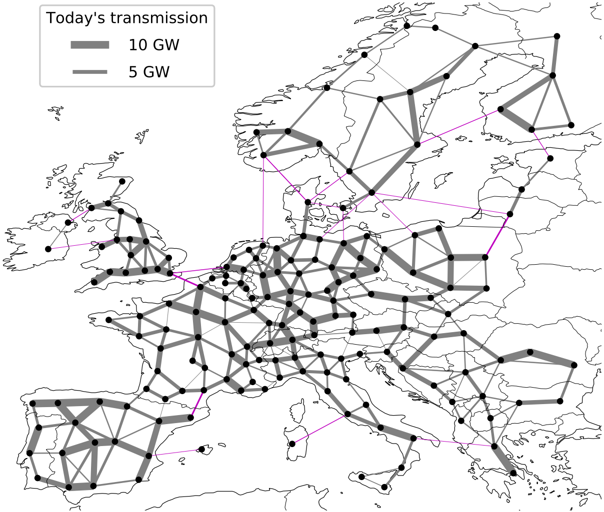
Source: https://earth.nullschool.net/

Results

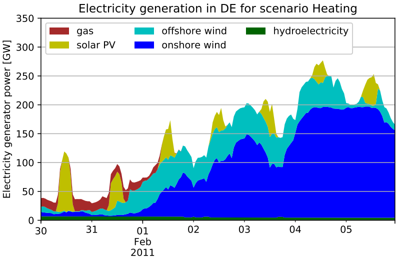
181-node model of European energy system

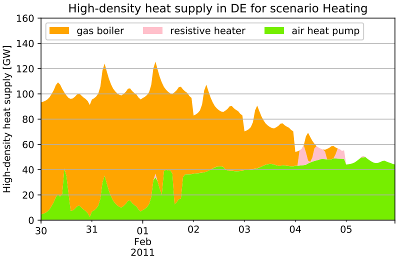
Some brief, preliminary results from our sector-coupled, 181-node model of the European energy system.

- Couple **all energy sectors** (power, heat, transport industry)
- Reduce CO_2 emissions **to zero**
- Assume **smaller bidding zones** and **widespread dynamic pricing**
- **Conservative** technology assumptions
- Examine effect of **acceptance** for **grid expansion** and **onshore wind**



Example problem with balancing: Cold week in winter





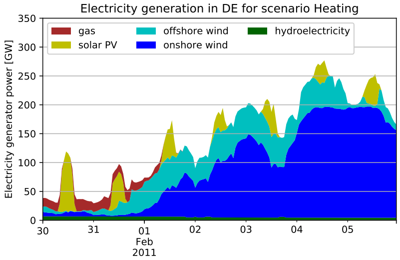
There are difficult periods in winter with:

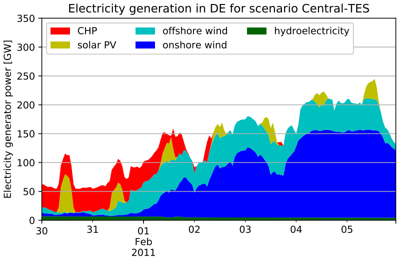
- **Low** wind and solar generation
- **High** space heating demand
- **Low** air temperatures, which are bad for air-sourced heat pump performance

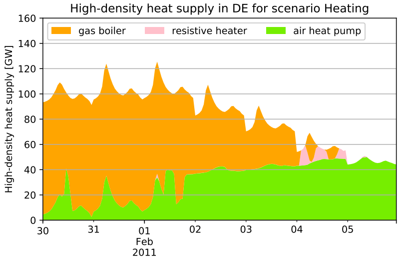
Less-smart solution: **backup gas boilers** burning either natural gas, or synthetic methane.

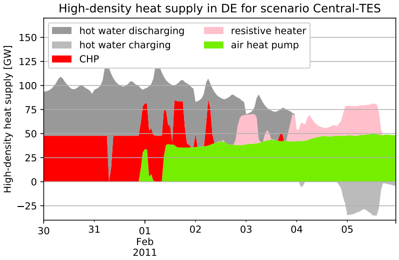
Smart solution: **long-term thermal energy storage** in **district heating networks** and efficient **combined-heat-and-power plants**.

Cold week in winter: inflexible (left); smart (right)

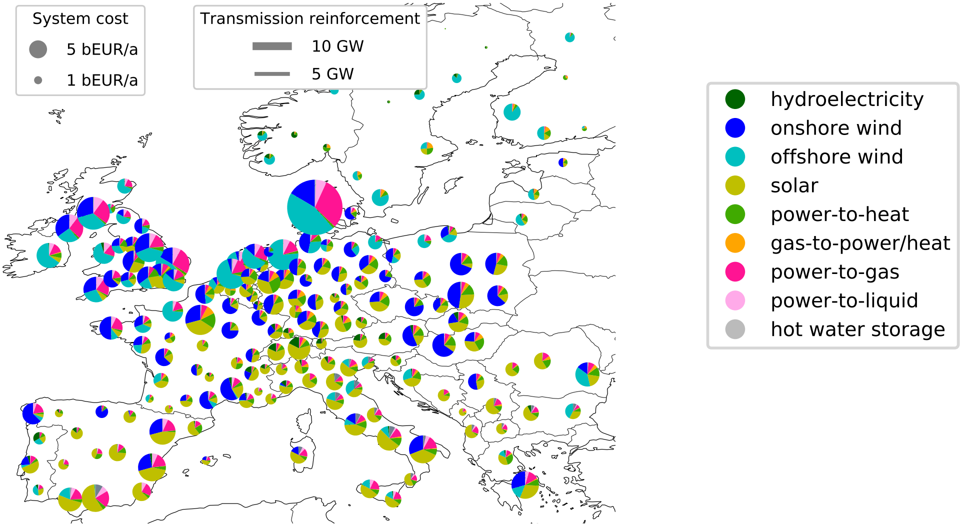




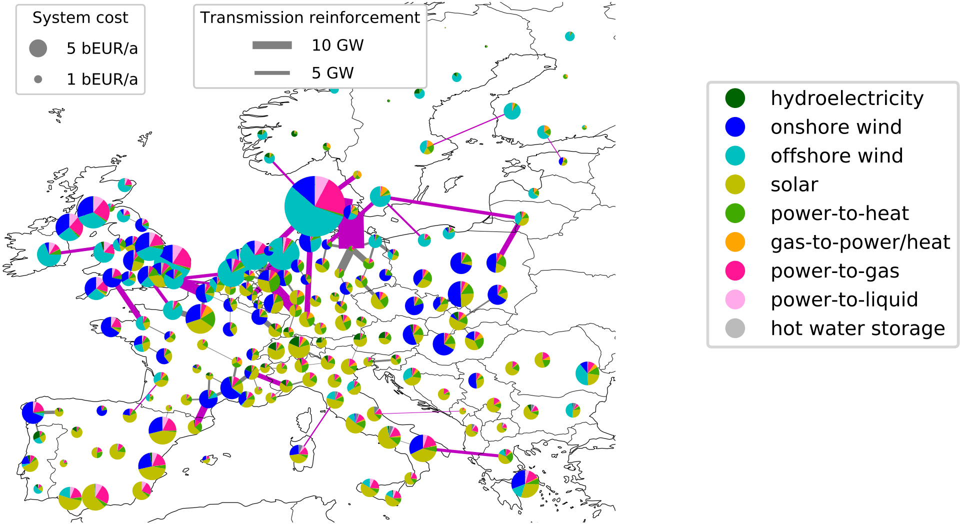




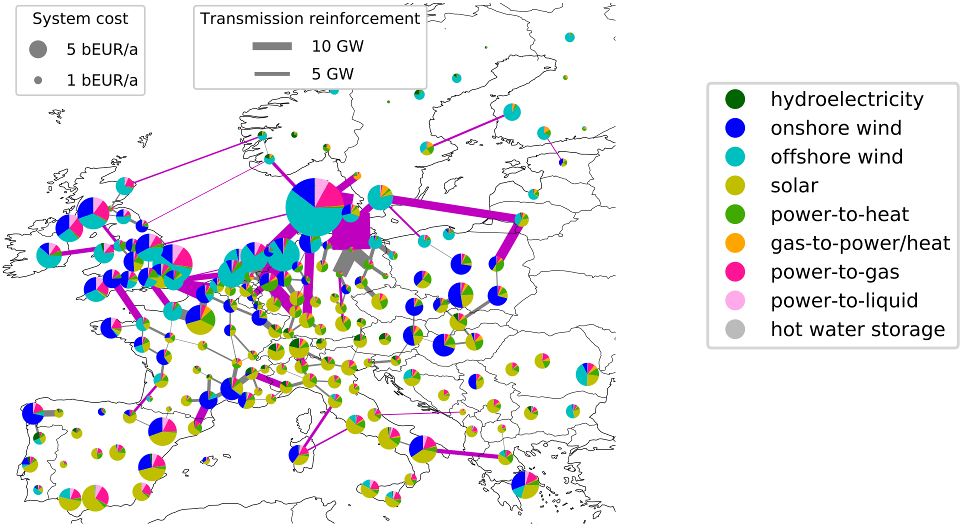
Distribution of technologies: No grid expansion



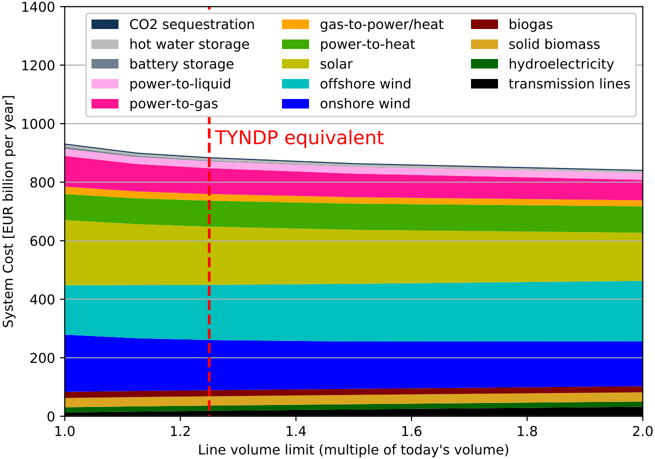
Distribution of technologies: 25% more grid volume - similar to TYNDP



Distribution of technologies: 50% more grid volume - double the TYNDP

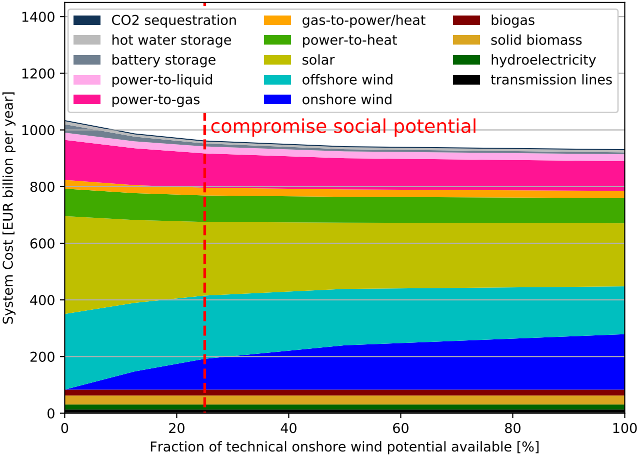


Benefit of grid expansion for sector-coupled system



- Direct system costs **higher than today's system** (€ 700 billion per year with same assumptions)
- Systems **without grid expansion** are feasible, but more costly
- As grid is expanded, **costs reduce** from solar and power-to-gas; more offshore wind
- Total cost benefit of extra grid: $\sim$ € 90 billion per year
- **Over half of benefit available at 25% expansion** (like TYNDP)

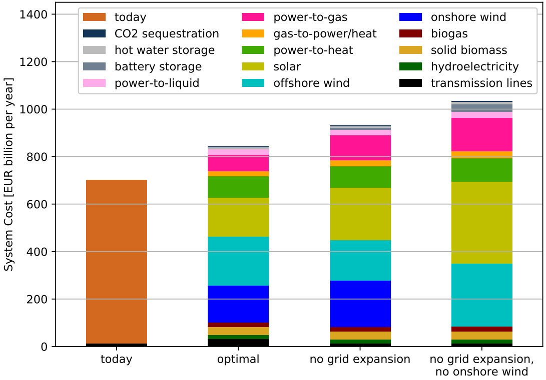
Benefit of full onshore wind potentials



- **Technical potentials** for onshore wind respect land usage
- However, they do not represent the **socially-acceptable potentials**
- Technical potential of ∼ 400 GW in Germany is **unlikely to be built**
- Costs rise by ∼ € 100 billion per year as we **eliminate onshore wind** (with no grid expansion)
- Rise is only ∼ € 30 billion per year if we **allow a quarter of technical potential** (∼ 100 GW for Germany)

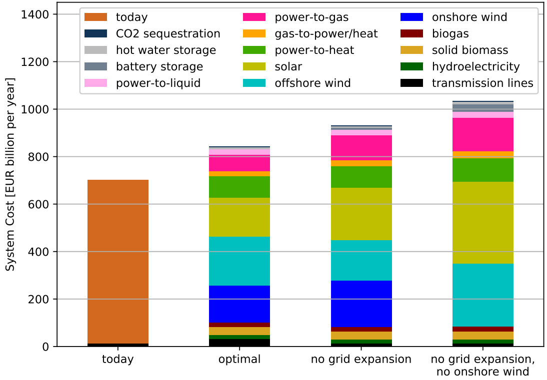
Should also consider indirect costs, which change the picture

Costs increase as we reduce emissions and accommodate public acceptance...

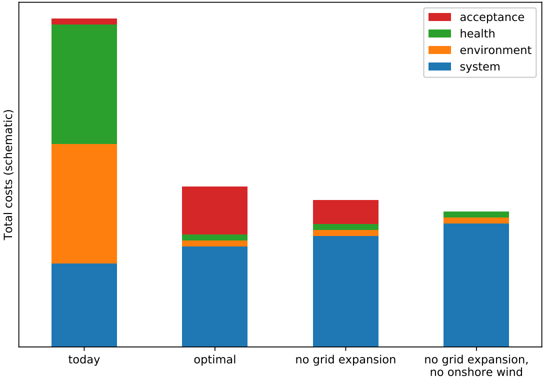


Should also consider indirect costs, which change the picture

Costs increase as we reduce emissions and accommodate public acceptance...



but not if we include indirect environmental, health and social costs (schematic example)



Conclusions

Conclusions

- Meeting Paris targets is **urgent** and requires addressing **all energy sectors**
- **Cross-sectoral** approaches are important to reduce CO2 emissions **and** for flexibility
- Without grid expansion, deep CO_2 reductions are possible but **expensive**
- In our model, TYNDP-level expansion delivers $\sim$ **€40-50 billion per year benefit**; a bigger expansion could deliver double the benefit, but is unlikely to find public acceptance
- **Policy prerequisites**: high, increasing and transparent **price for CO_2 pollution** (or second-best policies); to manage grid congestion better: **smaller bidding zones** and **more dynamic pricing**
- All results depend strongly on assumptions and modelling approach - therefore **openness and transparency are critical**, guaranteed by open licences for data and code

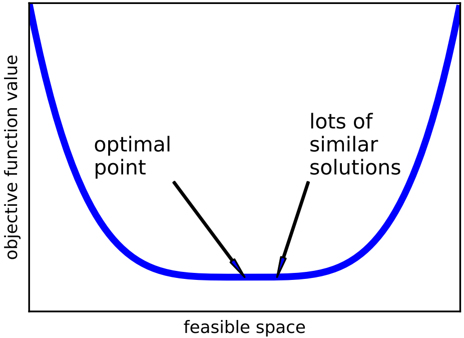
Research Outlook

- Demonstrate feasibility of **energy system pathway to 2050** at **high spatial resolution**
- Prerequisites: **GIS modelling** of buildings, transport and industrial processes
- Understand role of **spatial scale** in energy system optimisations
- Incorporate **distribution grid** interactions and non-linear expansion functions
- Demonstrate benefits of **smart, digital, IT-aware** grid operation (more price signals, SPS, DSM, RONTs, etc.)
- Explore impact of **complexity reduction** and **uncertainty** of long-term assumptions
- Explore **near-optimal solutions** with higher public acceptance (using the Method to Generate Alternatives, among others)

Optimisation with Different Goals

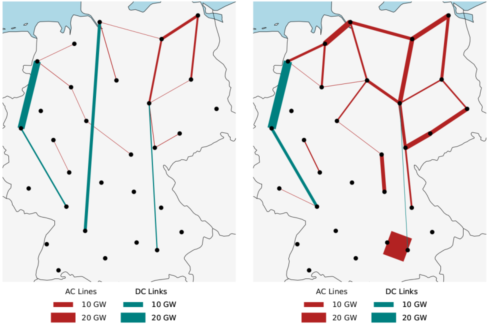
Often the pure economic optimum is **neither realistic nor desirable**.

There are other important considerations, such as public acceptance, environmental protection and politics (distribution of capital and jobs)

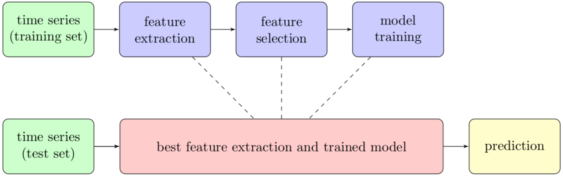


To do this rigourously, use the **Method to Generate Alternatives**: look at space of solutions within x% of the optimum.

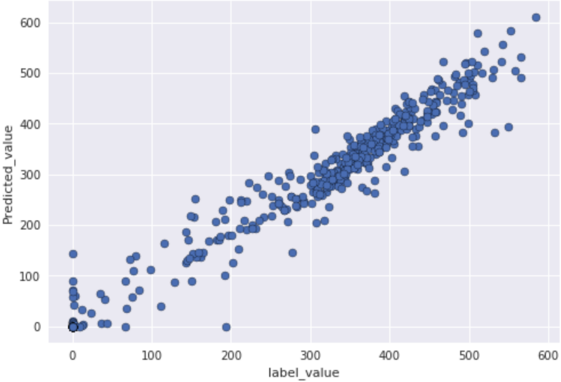
Fabian Neumann (IAI): min and max transmission expansion for a 95% emissions reduction target and an cost increase of 1%



Machine Learning to Reproduce Optimisation Results



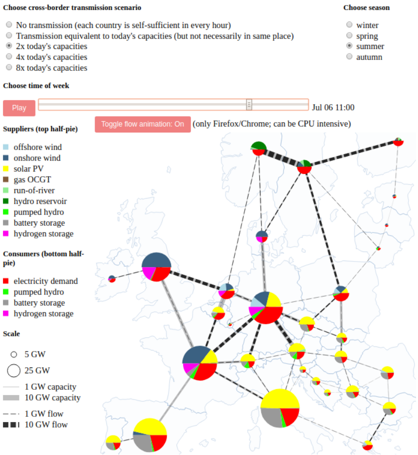
We've been exploring using **feature identification** and **supervised machine learning** to understand what inputs (statistics of time series, technology parameters, costs) influence optimisation results most strongly (see left for a neural network predicting wind capacities).



Public Outreach: Online Visualisations and Interactive 'Live' Models

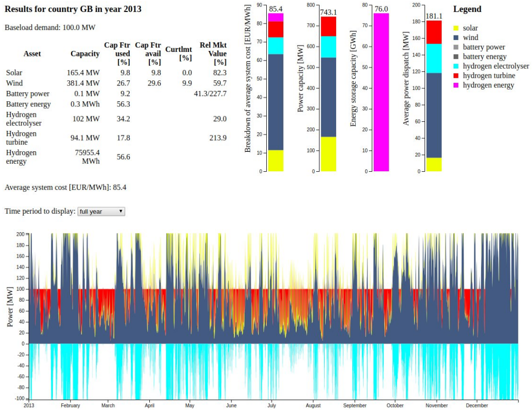
Online animated simulation results:

`pypsa.org/animations/`



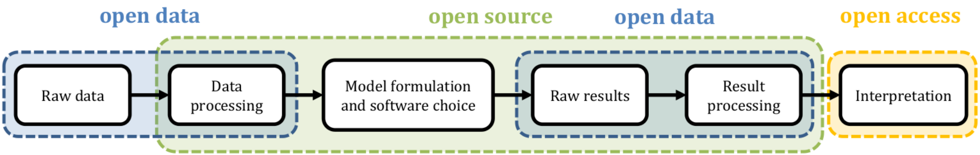
Live user-driven energy optimisation:

`model.energy`



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! Sign up for the mailing list / come to the next workshop (Berlin, 15-17 January 2020):

openmod open energy modelling initiative

openmod-initiative.org

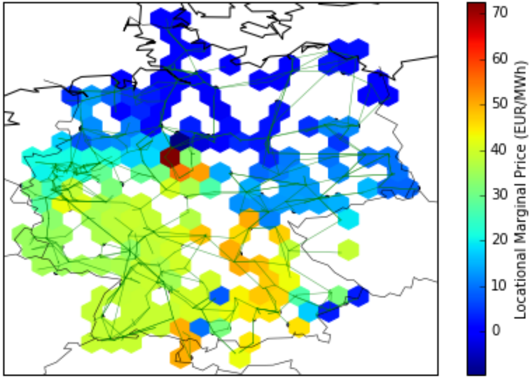
Source: openmod initiative

Python for Power System Analysis (PyPSA)

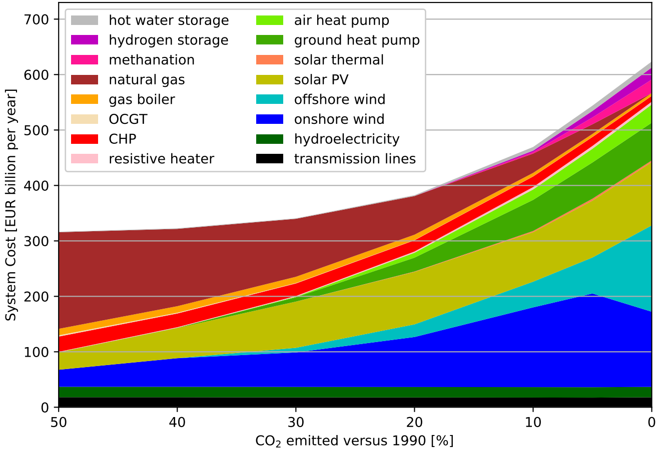
Our free software PyPSA is available online at `https://pypsa.org/` and on github. It can do:

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

It has models for storage, meshed AC grids, meshed DC grids, hydro plants, variable renewables and sector coupling.



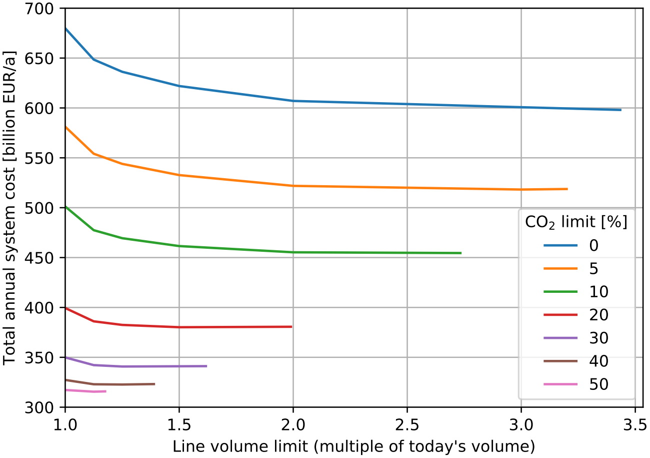
Pathway down to zero emissions in electricity, heating and transport



If we look at investments to eradicate CO_2 emissions in electricity, heating and transport we see:

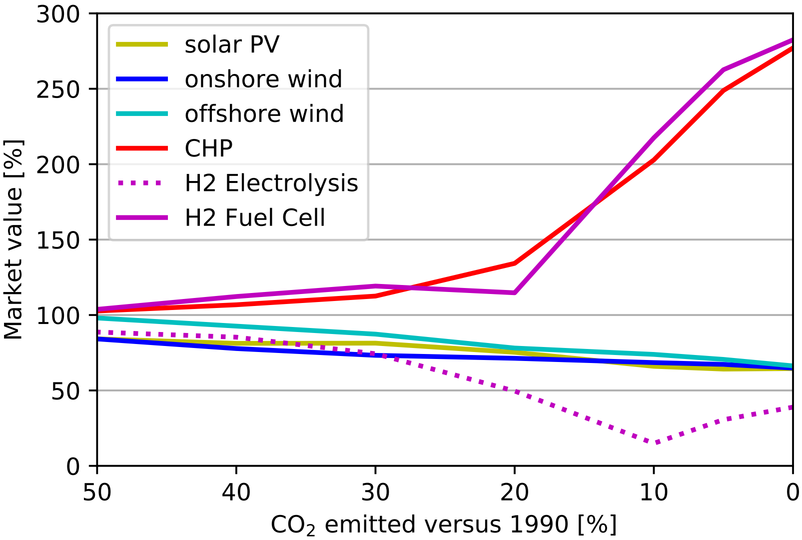
- Electricity and transport are decarbonised first
- Heating comes next with expansion of heat pumps below 30%
- Below 10%, power-to-gas solutions replace natural gas

Benefit of grid depends on level of carbon dioxide reduction



- Optimal grid (rightmost point of each curve) grows successively larger
- Benefit of grid expansion grows with depth of CO_2 reduction
- Can still get away with no transmission reinforcement (if the system is operated flexibly)

Relative market values drop, but not drastically



Costs and assumptions for the electricity sector (projections for 2030)

Quantity	Overnight Cost [€]	Unit	FOM [%/a]	Lifetime [a]
Wind onshore	1182	kW_{el}	3	25
Wind offshore	2506	kW_{el}	3	25
Solar PV	600	kW_{el}	4	25
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).

Cost and other assumptions

Quantity	O'night cost [€]	Unit	FOM [%/a]	Lifetime [a]	Efficiency
GS Heat pump decentral	1400	kW_{th}	3.5	20	
AS Heat pump decentral	1050	kW_{th}	3.5	20	
AS Heat pump central	700	kW_{th}	3.5	20	
Resistive heater	100	kW_{th}	2	20	0.9
Gas boiler decentral	175	kW_{th}	2	20	0.9
Gas boiler central	63	kW_{th}	1	22	0.9
CHP	650	kW_{el}	3	25	
Central water tanks	30	m^3	1	40	$\tau = 180$d
District heating	220	kW_{th}	1	40	
Methanation+DAC	1000	kW_{H_2}	3	25	0.6

Costs oriented towards Henning & Palzer (2014, Fraunhofer ISE) and Danish Energy Database

Linear power flow

The linearised **power flows** f_ℓ for each line $\ell \in \{1, \dots L\}$ in an AC network are determined by the nodal power injections p_i, the **reactances** x_ℓ of the transmission lines by enforcing Kirchhoff's Current Law (energy conservation), then Voltage Law (angle differences around closed cycles) **directly on cycles** $C_{\ell c}$ rather than using auxilliary angle variables θ_i:

$$\sum_\ell C_{\ell c} K_{i\ell} \theta_i = \sum_\ell C_{\ell c} x_\ell f_\ell = 0$$

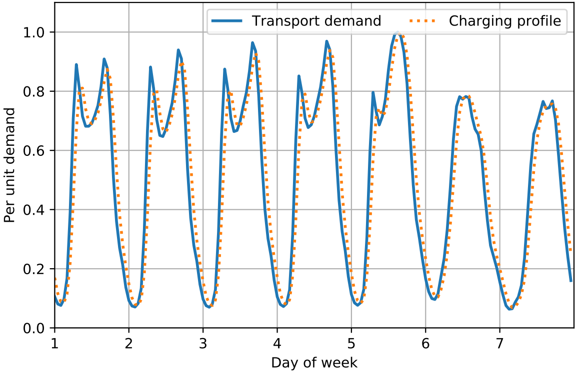
This solves faster and more stably than the angle formulation using commercial LP solvers.

Transmission flows cannot exceed the capacities $\bar{P}_\ell$ of the transmission lines (with buffer $s_{N-1} = 0.7$ to approximate $N-1$ security):

$$|f_{\ell,t}| \leq s_{N-1} \cdot \bar{P}_\ell$$

Since the impedances x_ℓ change as capacity $\bar{P}_\ell$ is added, we do multiple runs and iteratively update the x_ℓ after each run, rather than risking a non-linear (or MILP) optimisation.

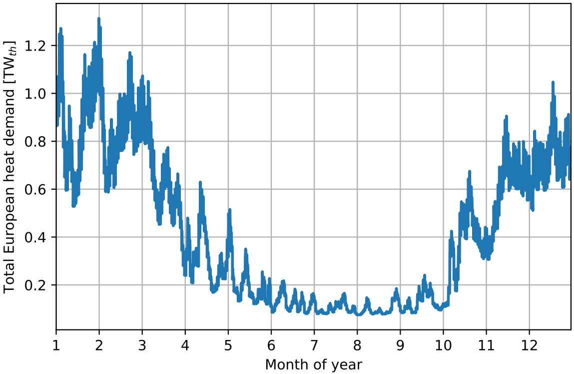
Transport sector: Electrification of Transport



Weekly profile for the transport demand based on statistics gathered by the German Federal Highway Research Institute (BASt).

- Road and rail transport is fully electrified (vehicle costs are not considered)
- Because of higher efficiency of electric motors, final energy consumption 3.5 times lower than today at 1100 TWh_{el}/a for Europe
- In model can replace Battery Electric Vehicles (BEVs) with Fuel Cell Electric Vehicles (FCEVs) consuming hydrogen. Advantage: hydrogen cheap to store. Disadvantage: efficiency of fuel cell only 60%, compared to 90% for battery discharging.

Heating sector: Many Options with Thermal Energy Storage (TES)



Heat demand profile from 2011 in each region using population-weighted average daily T in each region, degree-day approx. and scaled to Eurostat total heating demand.

- All space and water heating in the residential and services sectors is considered, with no additional efficiency measures (conservative) - total heating demand is 3585 TWh_{th}/a.
- Heating demand can be met by heat pumps, resistive heaters, gas boilers, solar thermal, Combined-Heat-and-Power (CHP) units. No industrial waste heat.
- Thermal Energy Storage (TES) is available to the system as hot water tanks.

Centralised District Heating versus Decentralised Heating

We model both fully decentralised heating and cases where up to 45% of heat demand is met with district heating in northern countries.

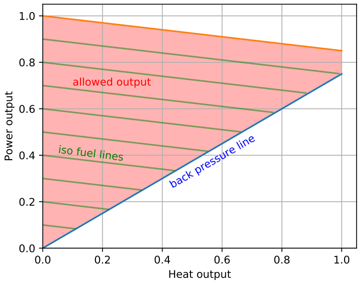
Decentral individual heating can be supplied by:

- Air- or Ground-sourced heat pumps
- Resistive heaters
- Gas boilers
- Small solar thermal
- Water tanks with short time constant $\tau = 3$ days

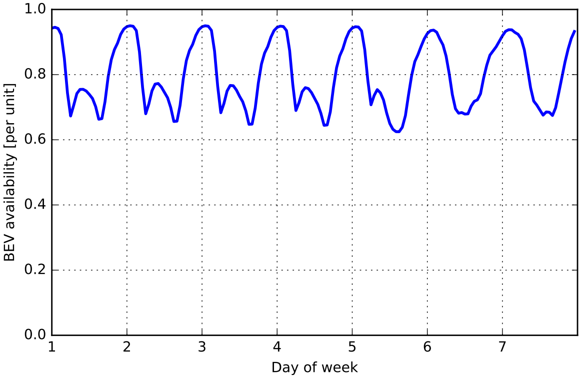
Central heating can be supplied via district heating networks by:

- Air-sourced heat pumps
- Resistive heaters
- Gas boilers
- Large solar thermal
- Water tanks with long time constant $\tau = 180$ days
- CHPs

CHP feasible dispatch:



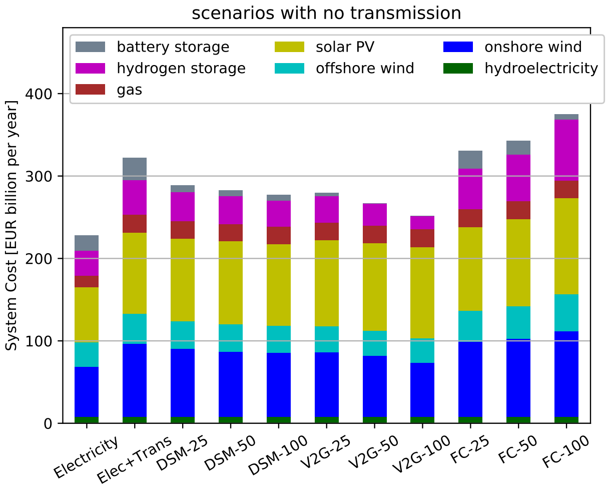
Transport sector: Battery Electric Vehicles



Availability (i.e. fraction of vehicles plugged in) of Battery Electric Vehicles (BEV).

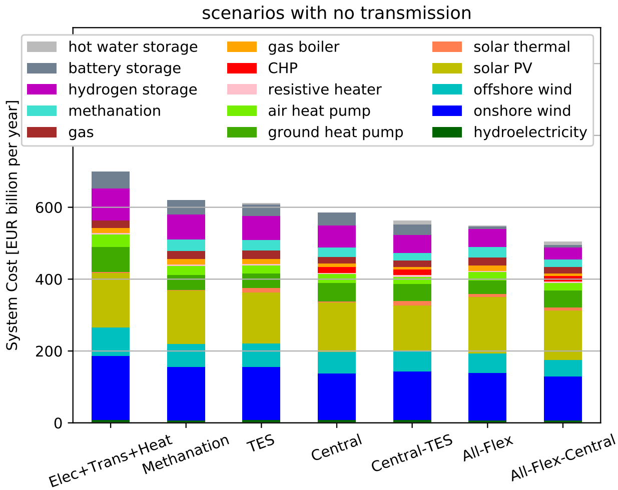
- Passenger cars to Battery Electric Vehicles (BEVs), 50 kWh battery available and 11 kW charging power
- Can participate in DSM and V2G, depending on scenario (state of charge returns to at least 75% every morning)
- All BEVs have time-dependent availability, averaging 80%, max 95% (at night)
- No changes in consumer behaviour assumed (e.g. car-sharing/pooling)
- BEVs are treated as exogenous (capital costs NOT included in calculation)

Using Battery Electric Vehicle Flexibility



- Shifting the charging time can reduce system costs by up to 14%.
- If only 25% of vehicles participate: already a 10% benefit.
- Allowing battery EVs to feed back into the grid (V2G) reduces costs by a further 10%.
- This removes case for stationary batteries and allows more solar.
- If fuel cells replace electric vehicles, hydrogen electrolysis increases costs because of conversion losses.

Using heating flexibility

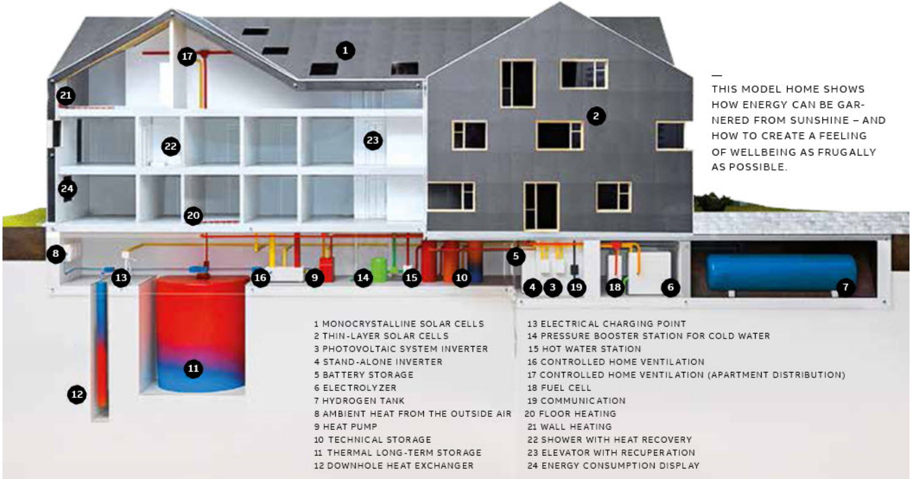


Successively activating couplings and flexibility **reduces costs** by 28%. These options include:

- production of **synthetic methane**
- centralised **district heating** in areas with dense heat demand
- long-term **thermal energy storage** (TES) in district heating networks
- **demand-side management** and vehicle-to-grid for 50% of battery electric vehicles (BEV)

LTES and P2G in autarkic (self-sufficient) apartment block

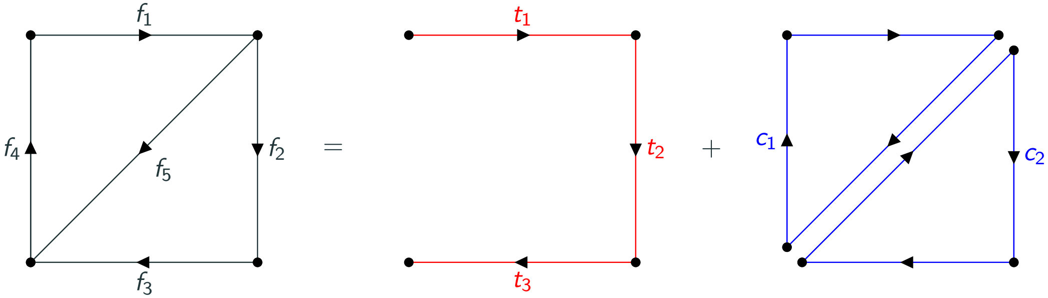
LTES and H2 storage enable **complete self-sufficiency** for an apartment block in Brütten, Switzerland. All its energy comes from solar panels and a heat pump (no grid connections).



Cycle formulation of linear power flow

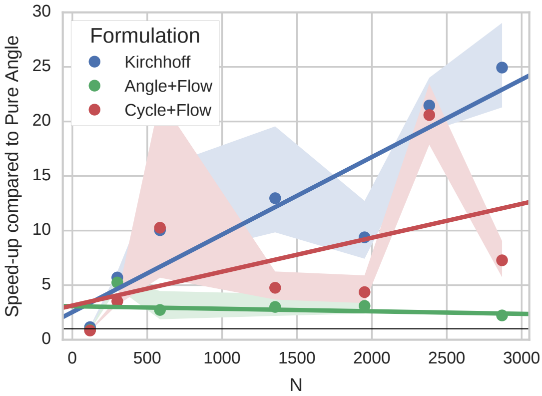
We can use dual graph theory to decompose the flows in the network into two parts:

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**

In his PhD thesis, **Fabian Neumann** will be looking at similar algorithmic improvements.

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

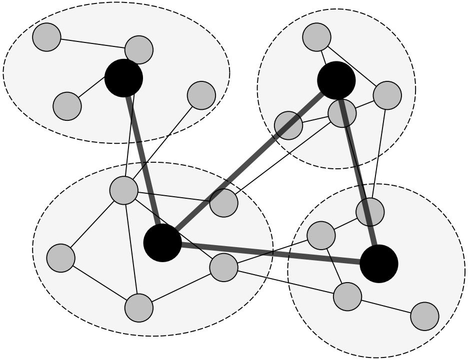
J. Hörsch, H. Ronellenfitsch, **D. Witthaut, T. Brown**, *"Linear Optimal Power Flow Using Cycle Flows,"* 2017

Reduce spatial resolution with clustering

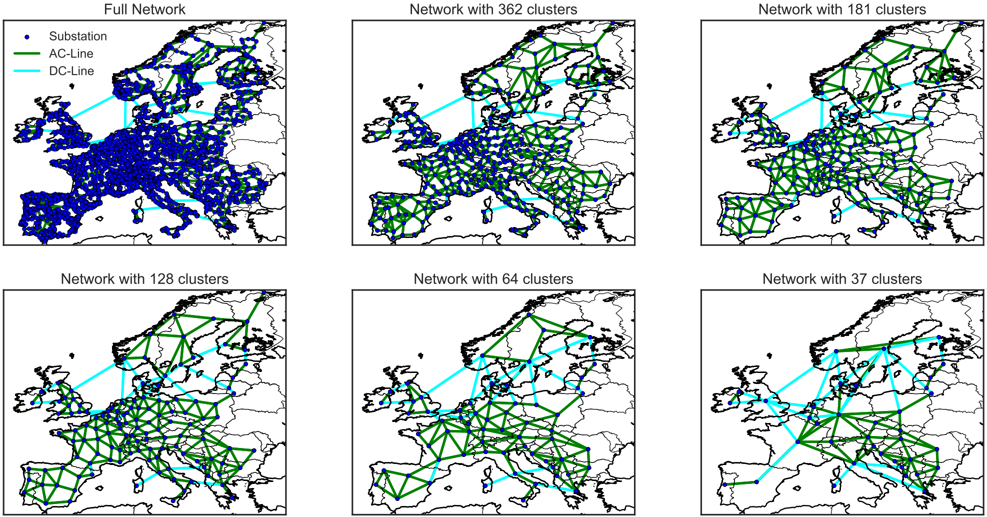
We need spatial resolution to:

- 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 5,000 network nodes of the European system.



Solution: k-means clustering



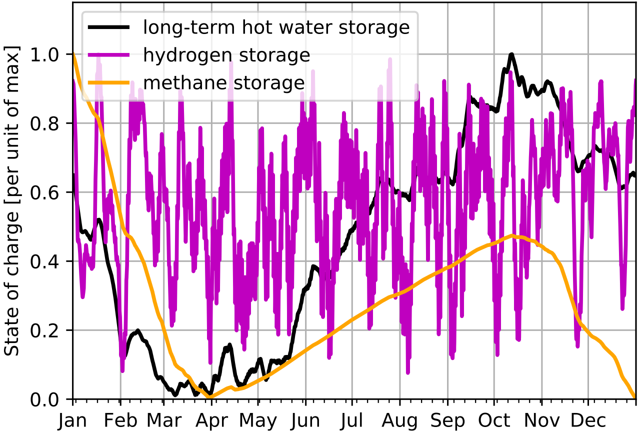
Remaining sectors: non-electric industry processes, aviation, shipping

For ‘hard-to-defossilise’ sectors, we assume some process- and fuel-switching (under review):

Iron & Steel	70% from scrap, rest from direct reduction with 1.7 $MWhH_2$/tSteel + electric arc (process emissions 0.03 tCO_2/tSteel)
Aluminium	80% recycling, for rest: methane for high-enthalpy heat (bauxite to alumina) followed by electrolysis (process emissions 1.5 tCO_2/tAl)
Cement	Waste and solid biomass
Ceramics & other NMM	Electrification
Chemicals	Synthetic methane, synthetic naphtha and hydrogen
Other industry	Electrification; process heat from biomass
Shipping	Liquid hydrogen (could be replaced by other liquid fuels)
Aviation	Kerosene from Fischer-Tropsch

Carbon is tracked through system: 90% of industrial emissions are captured; direct air capture (DAC); synthetic methane and liquid hydrocarbons; transport and sequestration 20 €/tCO_2

Storage energy levels: different time scales



- Methane storage is depleted in winter, then replenished throughout the summer with synthetic methane
- Hydrogen storage fluctuates every 2–3 weeks, dictated by wind variations
- Long-Term Thermal Energy Storage (LTES) has a dominant seasonal pattern, with synoptic-scale fluctuations are super-imposed
- Battery Electric Vehicles (BEV) and battery storage vary daily

More details?

For more details, see publications, code and data listed at:

`https://www.nworbmot.org`

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