The impact of sector-coupling on transmission reinforcement needs in a highly-renewable European energy scenario

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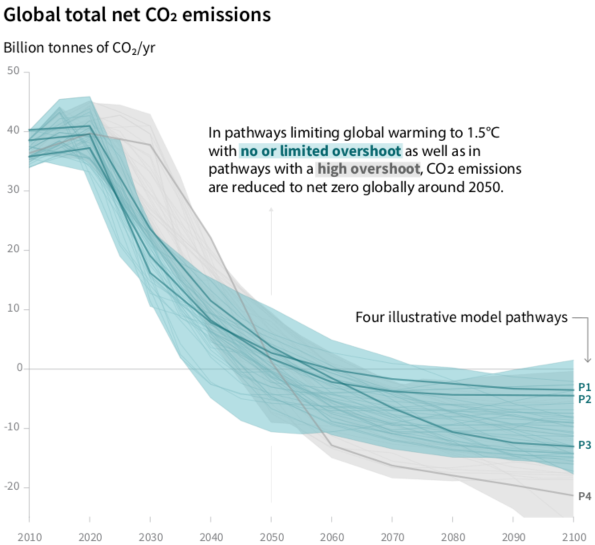
The Challenge

The Global Carbon Dioxide Challenge: Net-Zero Emissions by 2050

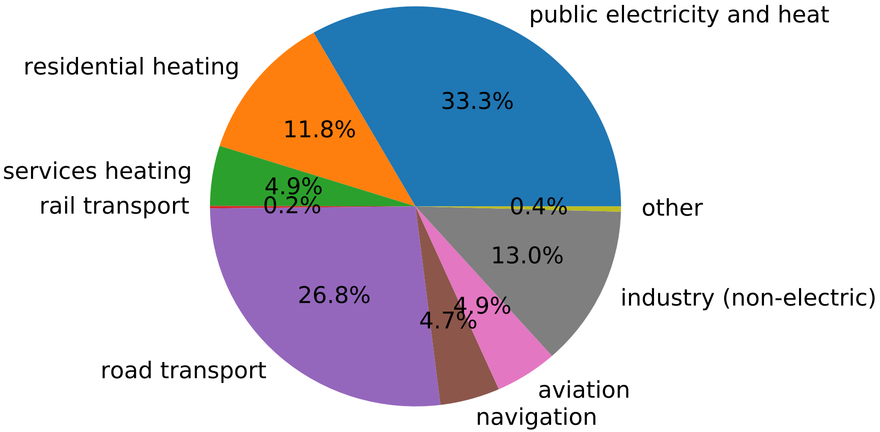


- Line widths represent 5-95th percentile of scenarios
- Level of use of negative emission technologies (NET) depends on rate of progress
- 2C target without NET also needs rapid fall by 2050
- Common theme: **net-zero by 2050**

Source: IPCC SR15 on 1.5C, 2018

It's not just about electricity demand...

EU28 CO_2 emissions in 2015 (total 3.2 Gt CO_2, 8% 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 and heating.

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

Source: Tesla; heat pump: Kristoferb at English Wikipedia

Take account of social and political constraints

However, there are **social and political constraints**, particularly for transmission grid and onshore wind development. Fortunately:

- Other sectors can offer **flexibility** back to the grid (e.g. battery electric vehicles, power-to-gas, thermal storage)
- **New technologies** can minimise the landscape impact of transmission

Sectoral coupling with spatial resolution, European scope

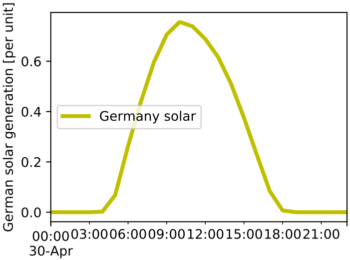
The Problem: Most cross-sectoral studies are at country level, but don't have the resolution to resolve transmission bottlenecks or the variations of renewables

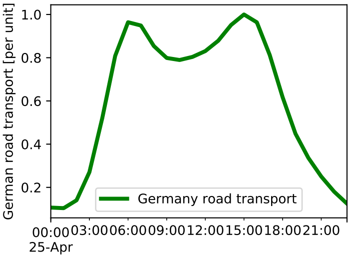
Our Goal: Model full energy system over Europe with enough resolution to understand the need and cost-benefits of transmission reinforcement

Today: Some preliminary results

Variability of Renewables, Demand and Flexibility

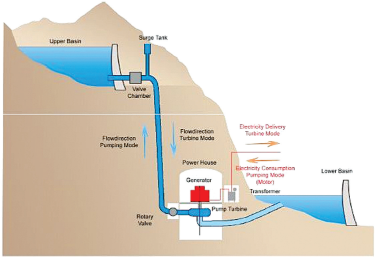
Daily variations: challenges and solutions



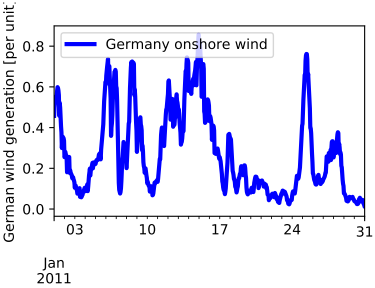


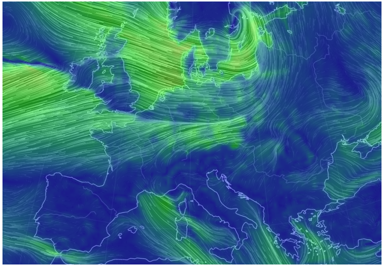
Daily variations in supply and demand can be balanced by

- **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**



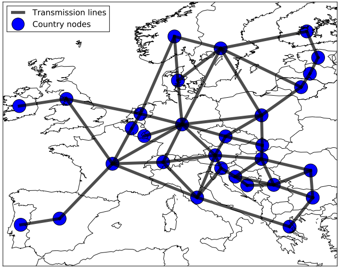
Synoptic variations: challenges and solutions



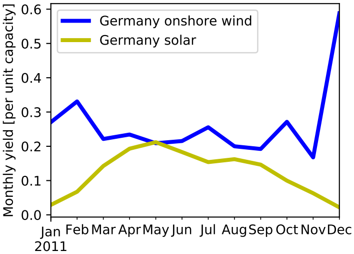


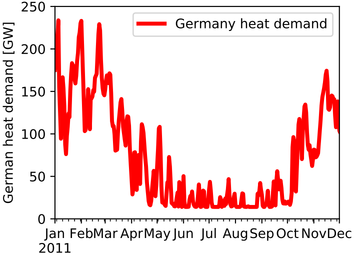
Synoptic variations in supply and demand can be balanced by

- **medium-term storage** (e.g. compressed air, chemically with hydrogen or methane, thermally, hydro reservoirs)
- **continent-wide grids**



Seasonal variations: challenges and solutions

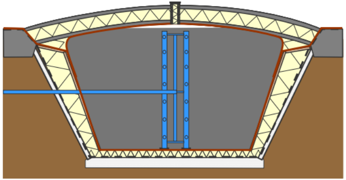




Seasonal variations in supply and demand can be balanced by

- **long-term storage** (e.g. chemically with hydrogen or methane storage, long-term thermal energy storage, hydro reservoirs)
- **north-south grids over multiple latitudes**

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



The model

Linear 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.

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 some fraction of 1990 levels.

Optimal transmission capacities $\bar{P}_\ell$ cannot be reduced compared to today's capacities $\bar{P}_\ell^{\mathrm{today}}$:

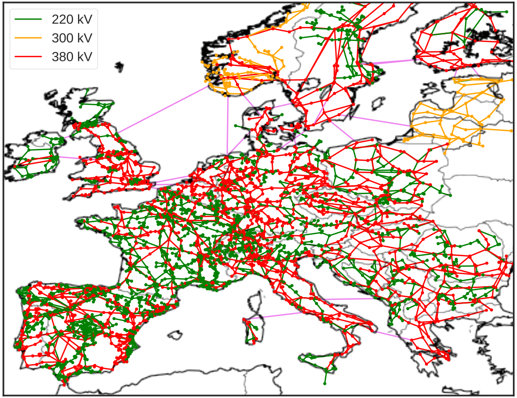
$$\bar{P}_\ell \geq \bar{P}_\ell^{\mathrm{today}}$$

But we can also limit total new transmission volume in MWkm (d_ℓ is line length in km):

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

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

PyPSA-Eur: Open Model of European Transmission System



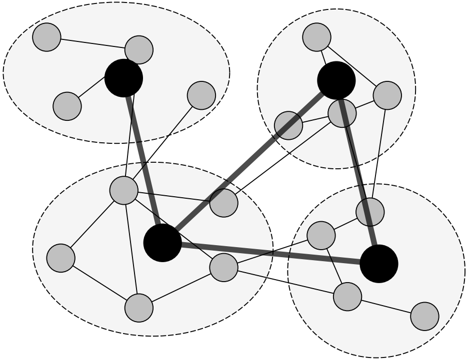
- Grid data based on **GridKit** extraction of ENTSO-E interactive map
- **powerplantmatching** tool combines open databases using matching algorithm DUKE
- Renewable energy time series from open **atlite**, based on Aarhus University REatlas
- Geographic **potentials** for RE from land use
- Basic **validation**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

Reduce spatial resolution with clustering

We need spatial resolution to:

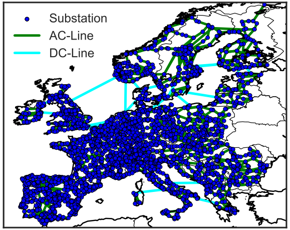
- capture the **geographical variation** of renewables resources and the load
- capture **spatio-temporal effects** (e.g. size of wind correlations across the continent)
- represent important **transmission constraints**

BUT we do not want to have to model all 5,000 network nodes of the European system.

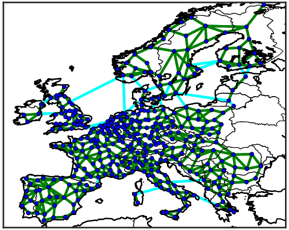


Solution: *k*-means clustering

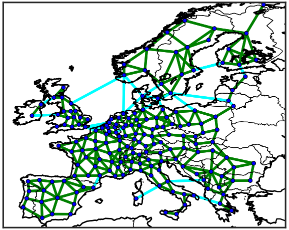
Full Network



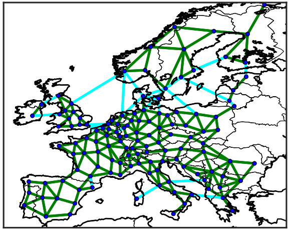
Network with 362 clusters



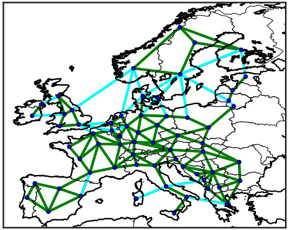
Network with 181 clusters



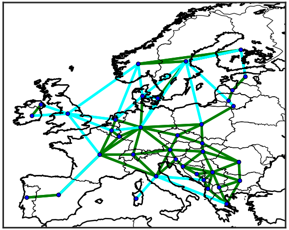
Network with 128 clusters



Network with 64 clusters

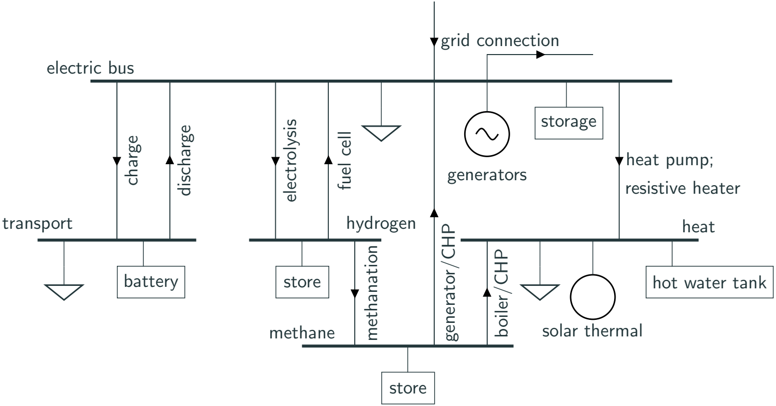


Network with 37 clusters



Sector coupling: A new source of flexibility

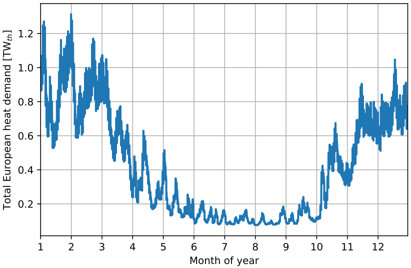
Couple the electricity sector (electric demand, generators, electricity storage, grid) to electrified transport and low-T heating demand (model covers 75% of final energy consumption in 2014). Also allow production of synthetic hydrogen and methane.

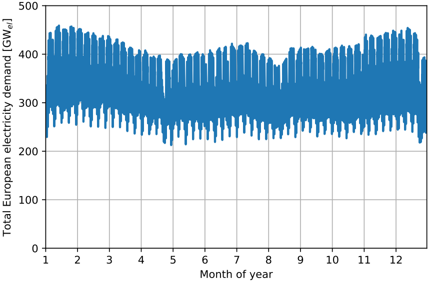


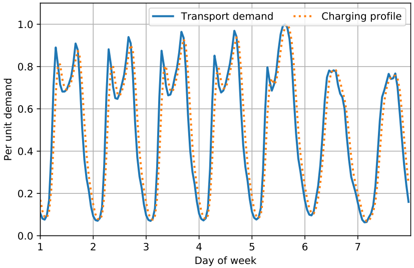
Challenge: Heating and transport demand strongly peaked

Compared to electricity, heating and transport are **strongly peaked**.

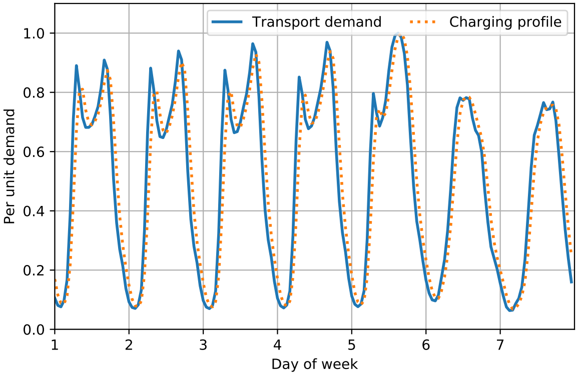
- Heating is strongly seasonal, but also with synoptic variations.
- Transport has strong daily periodicity.







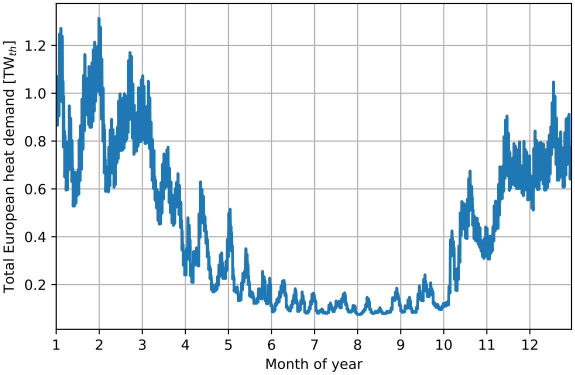
Transport sector: Electrification of Transport



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.

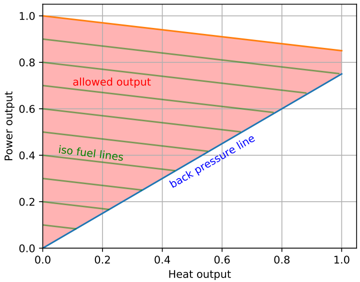
Decentral individual heating can be supplied by:

- 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:



Results

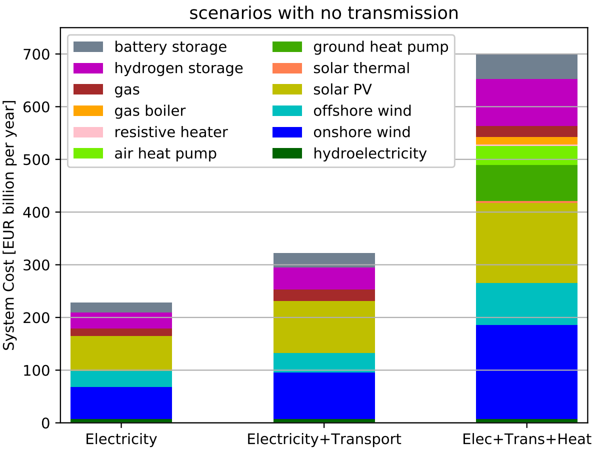
Introduction to results

In the first few slides we'll sequentially turn on different demand sectors and flexibility options to assess their effects on total system costs and balancing in the **temporal dimension**.

This was done in a one-node-per-country model for Europe in **Brown et al 2018** for a 95% CO_2 reduction target (compared to 1990).

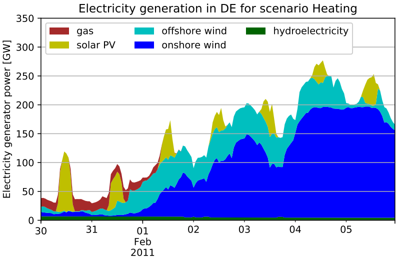
Then we'll upgrade to a 128-node model and explore the effects of transmission expansion and different CO_2 targets, and how they interact - the **spatial dimension**.

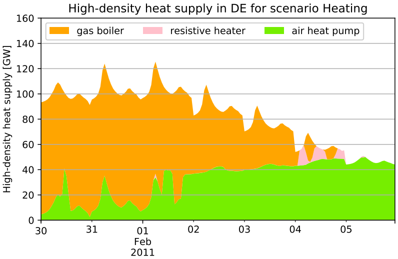
Coupling Heating and Transport to Electricity: Limited Use of Flexibility



- Costs jump by 117% to cover new energy supply and heating infrastructure
- 95% CO_2 reduction means most heat is generated by heat pumps using renewable electricity
- Cold winter weeks with high demand, low wind, low solar and low heat pump COP mean backup gas boilers required

Cold week in winter



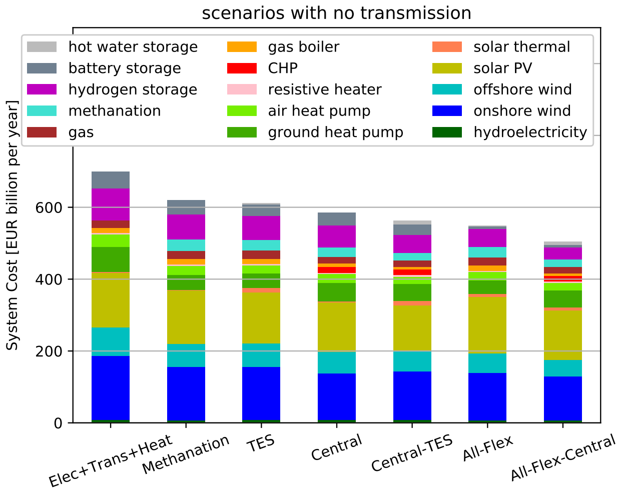


There are difficult periods in winter with:

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

Solution: **backup gas boilers** burning either natural gas, or synthetic methane.

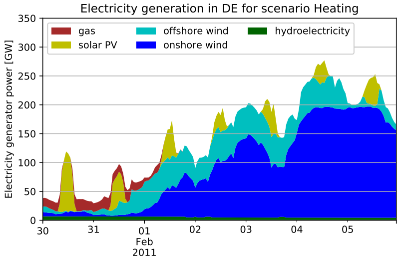
Using heating flexibility

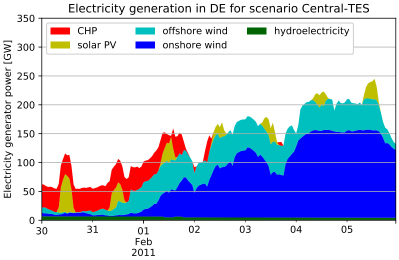


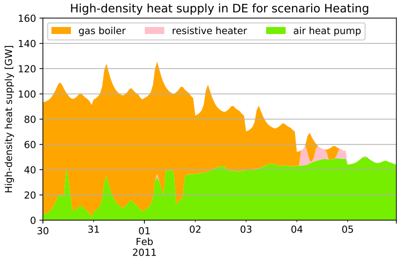
Successively activating couplings and flexibility **reduces costs** by 28%. These options include:

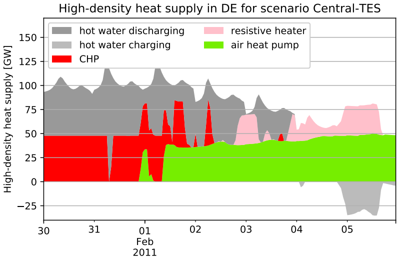
- production of **synthetic methane**
- centralised **district heating** in areas with dense heat demand
- long-term **thermal energy storage** (TES) in district heating networks
- **demand-side management** and vehicle-to-grid for 50% of battery electric vehicles (BEV)

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

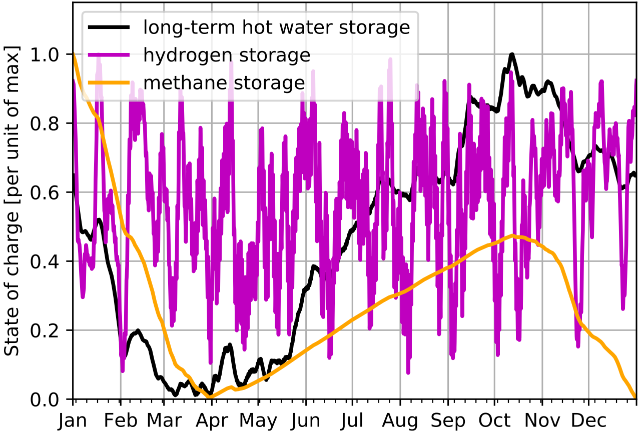








Storage energy levels: different time scales

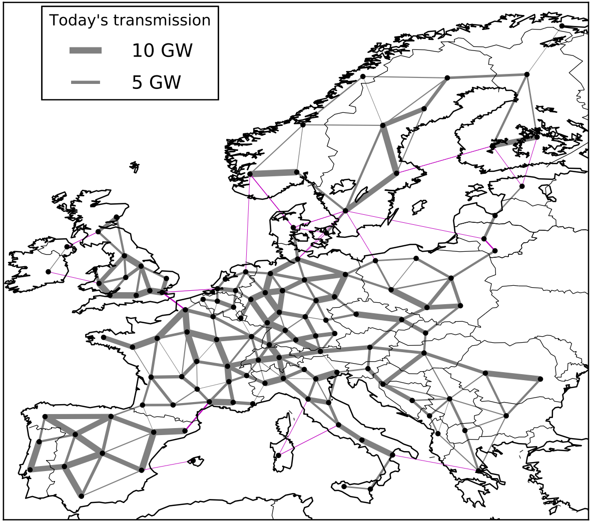


- Methane storage is depleted in winter, then replenished throughout the summer with synthetic methane
- Hydrogen storage fluctuates every 2–3 weeks, dictated by wind variations
- Long-Term Thermal Energy Storage (LTES) has a dominant seasonal pattern, with synoptic-scale fluctuations are super-imposed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

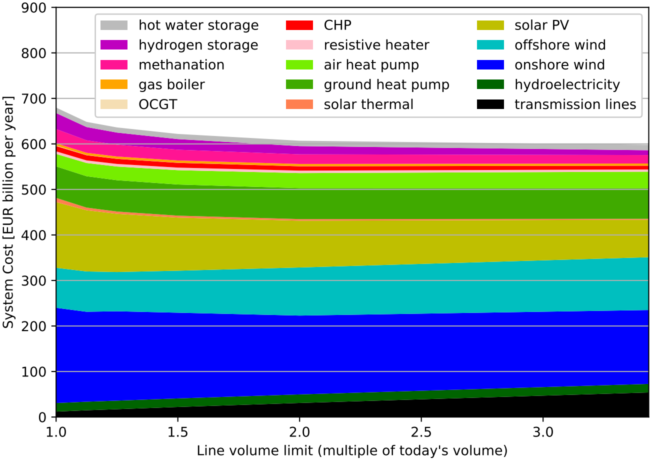
Application to 128-node transmission model

The previous sector coupling results come from a model with one node power country described in Brown et al 2018, for the case with no interconnecting transmission.

Now we apply the smart flexibility model to a 128-node model of Europe.

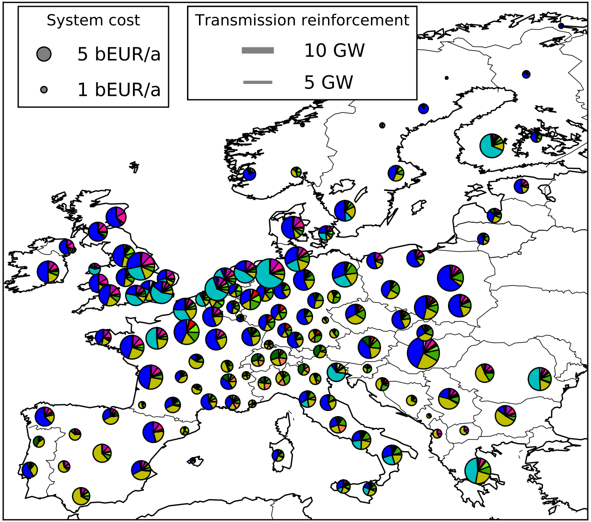


Benefit of grid expansion for sector-coupled system



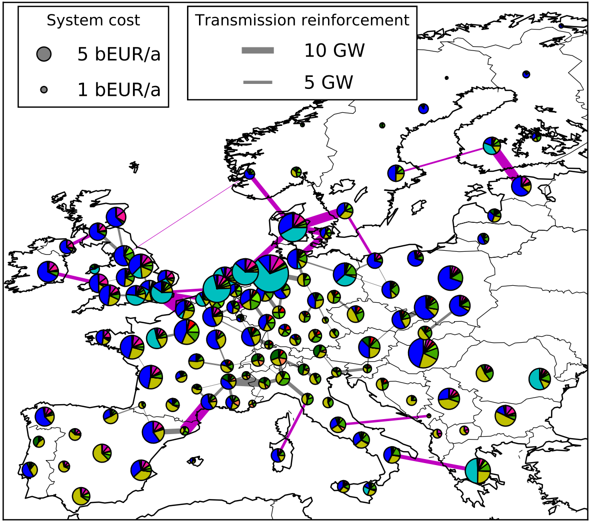
- The optimal volume (in MWkm) of transmission is around factor 3 bigger than today's grid
- Costs reduce from solar and power-to-gas; more offshore wind
- Costlier than today's system (380 billion €/a with same assumptions)
- Total cost benefit of extra grid: $\sim$ 80 billion €/a
- **Over half of benefit available at 25% expansion** (like TYNDP)

Distribution of technologies: No grid expansion



- Mix of solar and wind at almost all locations
- Capacities of offshore wind limited by grid restrictions
- Large share of power-to-gas paired with on- and offshore wind, particularly at periphery of network

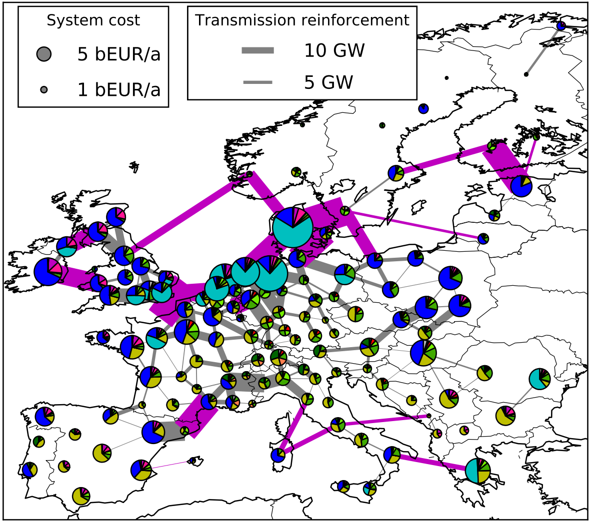
Distribution of technologies: 25% more grid volume



- Wind predominates in North
- Solar predominates in South
- P2G near wind and at periphery of network
- Grid expansion mostly around North Sea, to bring offshore to load centres, and East-West to smooth weather coming from Atlantic

(HVDC in purple, HVAC in grey)

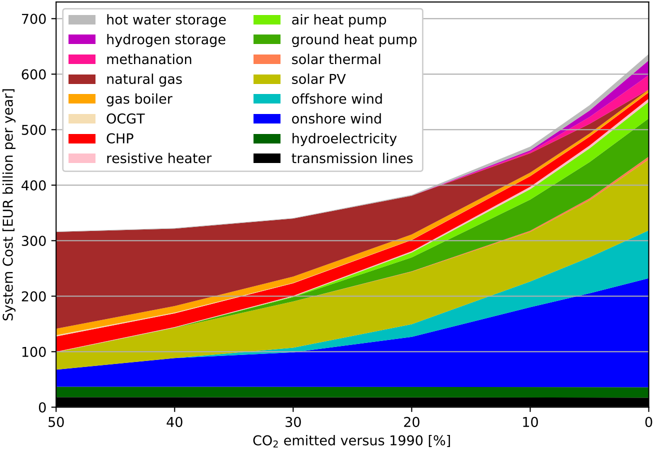
Distribution of technologies: 100% more grid volume



- Further expansion of off- and onshore wind in North
- Grid expansion focuses again on North and East-West axis

(HVDC in purple, HVAC in grey)

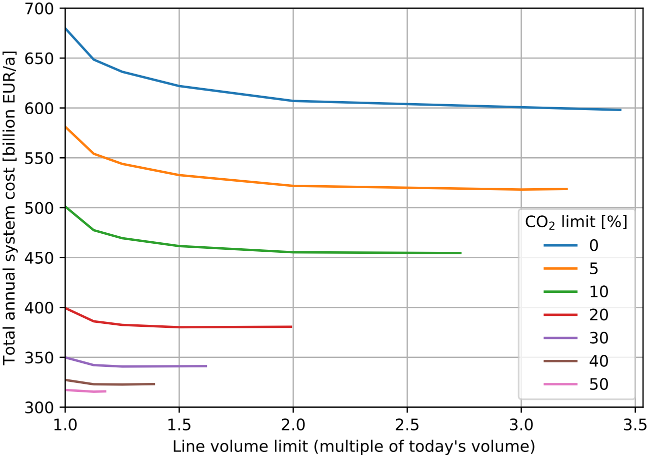
Pathway down to zero emissions in electricity, heating and transport



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

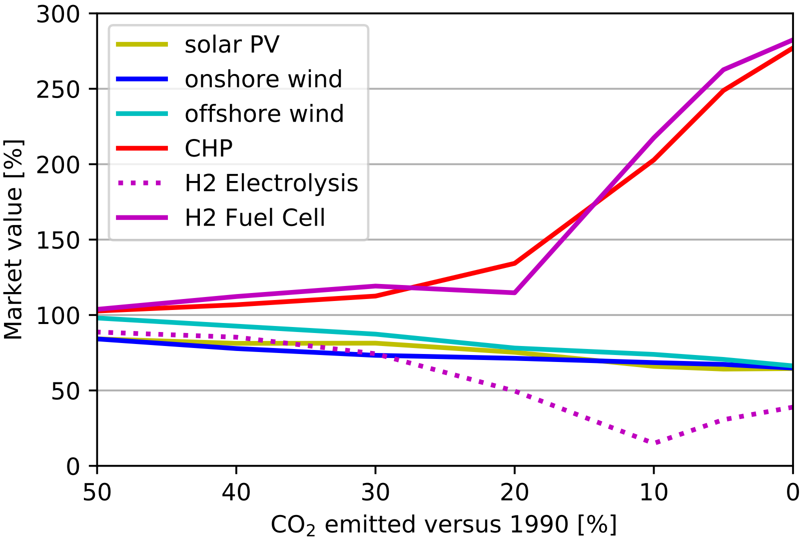
- Electricity and transport are decarbonised first
- Heating comes next with expansion of heat pumps below 30%
- Below 10%, power-to-gas solutions replace natural gas

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



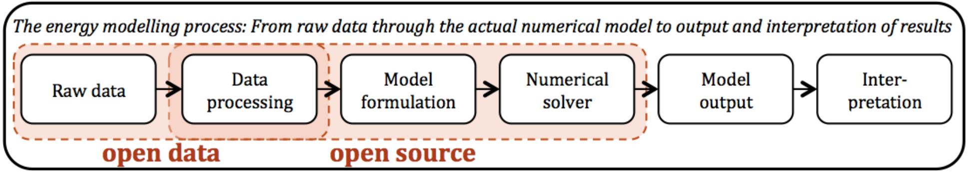
Outlook

- Develop **improvements on algorithmic side** to enable larger problems (clustering, improved optimisation routines)
- Explore **pathways** from here to 2050 more rigorously
- Improve **technology palette**: bioenergy, waste heat, CCS, DAC, more synthetic electrofuels
- Complete **sectoral coverage**: aviation, shipping, process heat in industry
- Explore more **grid optimisation** options: HTC, DLR, PST, SPS with storage/DSM
- Improve representation of **thermal loads** (e.g. to assess building insulation)
- Co-optimise **distribution grids** in a simplified manner
- Develop **model simplifications** that reproduce features of bigger model

Open Energy Modelling

Idea of Open Energy Modelling

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



Open data + free software $\Rightarrow$ Transparency + Reproducibility

There's an initiative for that! Sign up for the mailing list / come to the next workshop at Aarhus University, Denmark, 22-24 May 2019:

openmod open energy modelling initiative

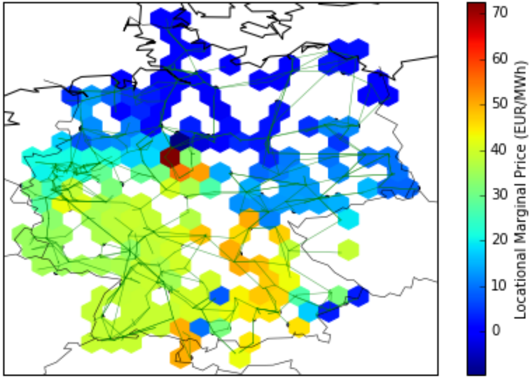
openmod-initiative.org

Source: openmod initiative

Python for Power System Analysis (PyPSA)

Our free software PyPSA is 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.

Conclusions

Conclusions

- Meeting **Paris targets** is much more urgent than widely recognised
- **Electrification of other energy sectors** like heating and transport is important, since wind and solar will dominate low-carbon primary energy provision
- **Grid helps** to make CO2 reduction easier = cheaper
- **Cross-sectoral** approaches are important to reduce CO2 emissions **and** for flexibility
- **Policy prerequisites**: high, increasing and transparent **price for CO_2 pollution**; to manage grid congestion better: **smaller bidding zones** and **more dynamic pricing**
- The energy system is complex and contains some uncertainty (e.g. cost developments, scaleability of power-to-gas, consumer behaviour), so **openness is critical**

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 $\ell \in \{1, \ldots L\}$ 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:

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

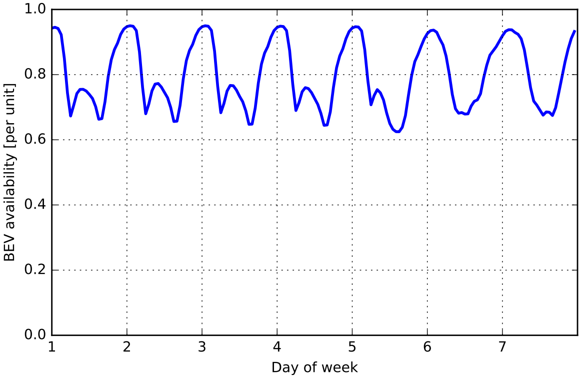
This solves faster and more stably than the angle formulation using commercial LP solvers.

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.

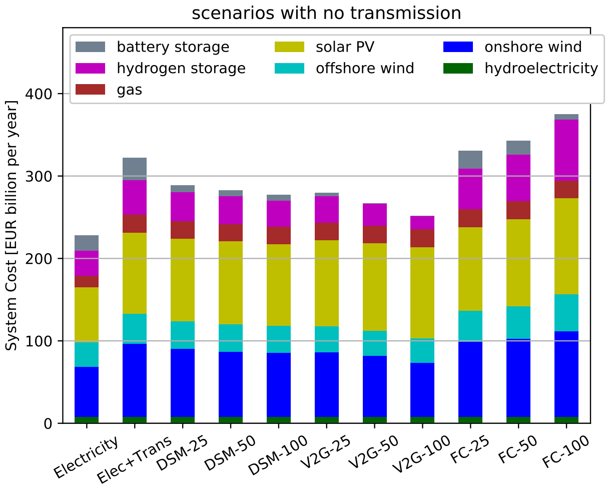
Transport sector: Battery Electric Vehicles



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)

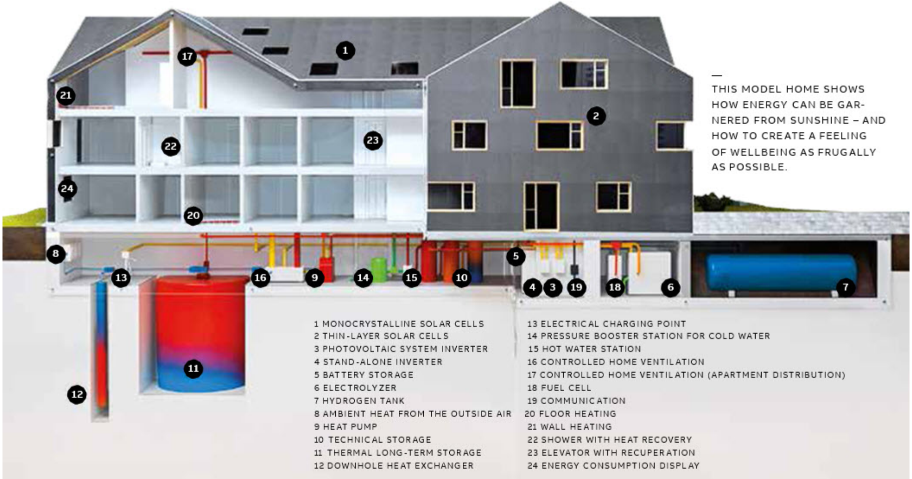
Using Battery Electric Vehicle Flexibility



- 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.

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).



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