Synergies of sector coupling and transmission extension in a cost-optimised, highly renewable European energy system

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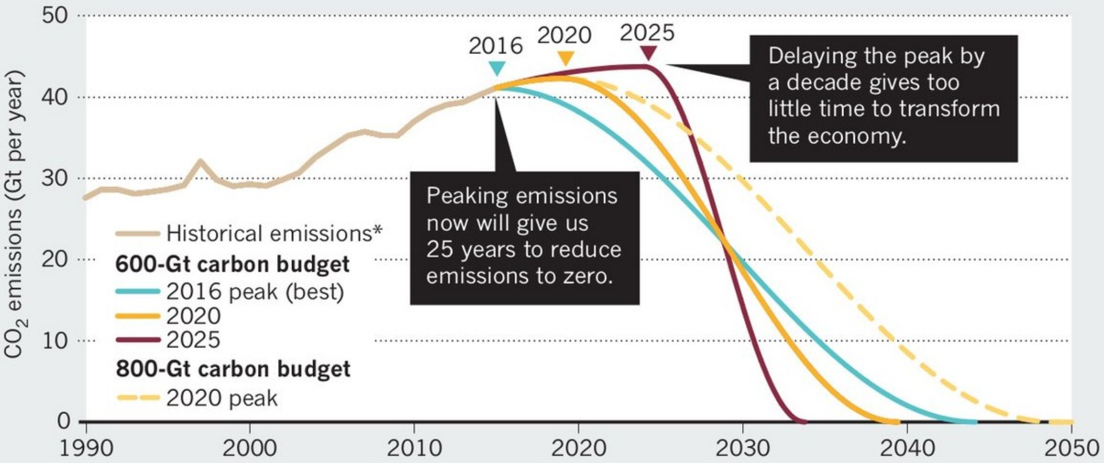
Table of Contents

Energy System Challenges

The Global Carbon Dioxide Challenge: Budgets from 2016

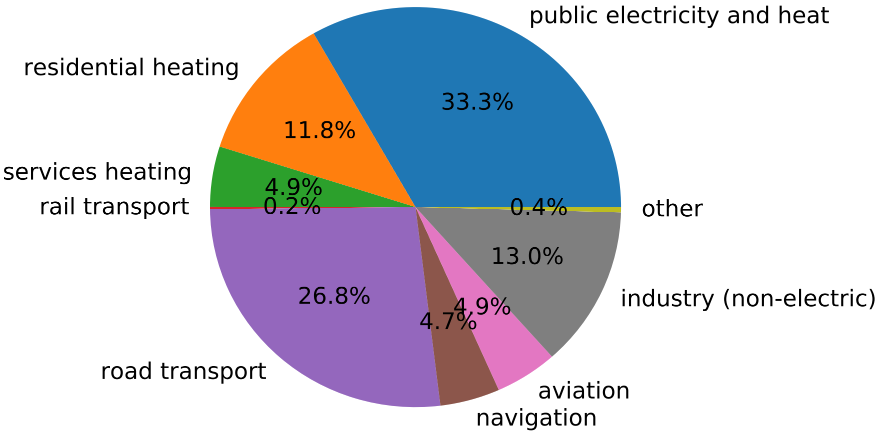
600 Gt budget gives 33% chance of 1.5°C (Paris: 'pursue efforts to limit [warming] to 1.5°C')
800 Gt budget gives 66% chance of 2°C (Paris: hold 'the increase...to well below 2°C')



Source: 'Three years to safeguard our climate,' Nature, 2017

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 electification of other sectors is critical for decarbonisation

Wind and solar dominate the expandable potentials for low-carbon energy provision, so **electrification is essential** to decarbonise sectors such as transport and heating.

Fortunately, these sectors can also offer crucial **flexibility** back to the electricity system.

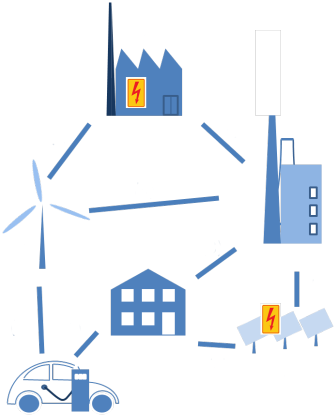
Source: Tesla; heat pump: Kristoferb at English Wikipedia

Energy System Design: Research Questions

- What **infrastructure** does a highly renewable energy system require?
- **Where** should it go? And **when**?
- Given a desired CO_2 reduction, how much will it **cost**?
- How to deal with the **variability** of wind and solar?

The answers to these questions affect **hundreds of billions** of euros of spending per year.

Researchers deal with these questions by solving large **optimisation** problems.



Take account of social and political constraints

The Energy Transition is not just a case of "cost optimisation under CO_2 constraints". There are also **social and political constraints**.

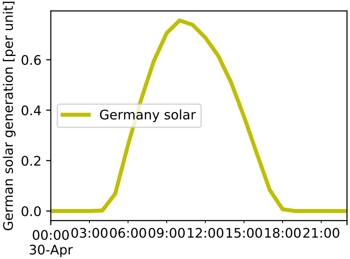
We need to assess:

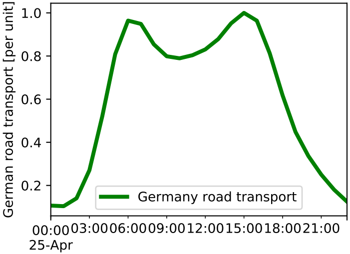
- Reducing need for transmission using **storage / sector coupling** (e.g. battery electric vehicles, thermal storage)
- **New technologies** that can minimise the landscape impact of transmission
- **Efficiency** and **sufficiency** to reduce demand

Transparency is critical for public acceptance.

Variability of Wind, Solar & Demand

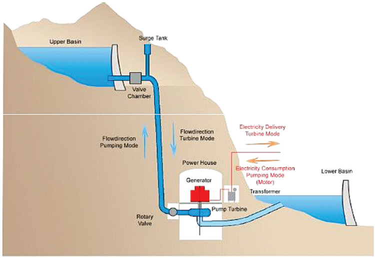
Daily variations: challenges and solutions



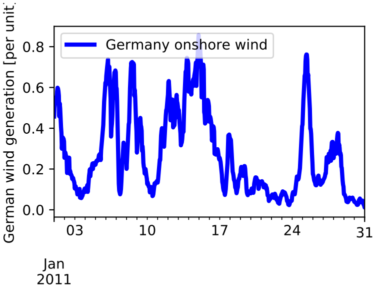


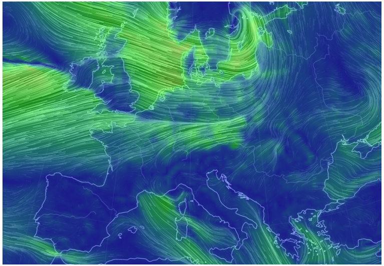
Daily variations in supply and demand can be balanced by

- **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**



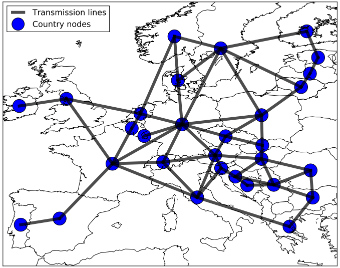
Synoptic variations: challenges and solutions



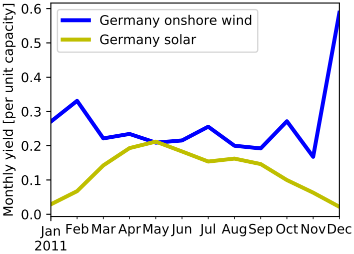


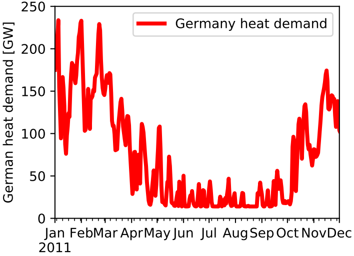
Synoptic variations in supply and demand can be balanced by

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



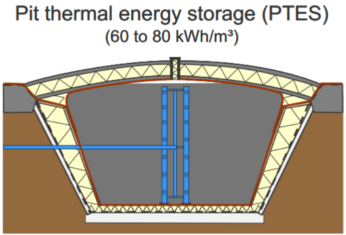
Seasonal variations: challenges and solutions





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**



Warm-Up Electricity Only

Linear optimisation of annual system costs

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

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

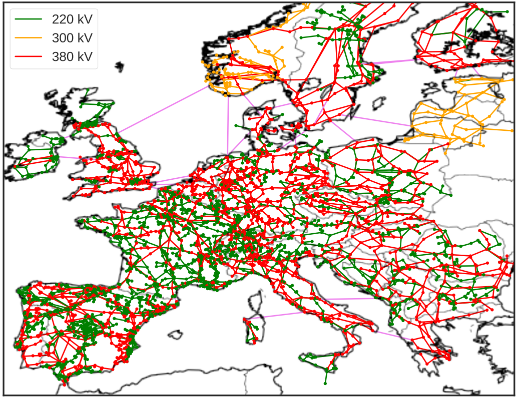
subject to

- meeting energy demand at each node n (e.g. region) and time t (e.g. hour of year)
- wind, solar, hydro (variable renewables) availability $\forall\, n, t$
- transmission constraints between nodes
- (installed capacity) $\leq$ (geographical potential for renewables)
- CO_2 constraint (95% reduction compared to 1990)

Generation, storage and transmission optimised **jointly** because they are **strongly interacting**.

Warm-up: Determine optimal electricity system

- Meet all electricity demand.
- Reduce CO_2 by 95% compared to 1990.
- **Generation** (where potentials allow): onshore and offshore wind, solar, hydroelectricity, backup from natural gas.
- **Storage**: batteries for short term, electrolyse hydrogen gas for long term.
- **Grid expansion**: simulate everything from no grid expansion (like a **decentralised solution**) to optimal grid expansion (with significant **cross-border trade**).



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

Global constraint on transmission volume

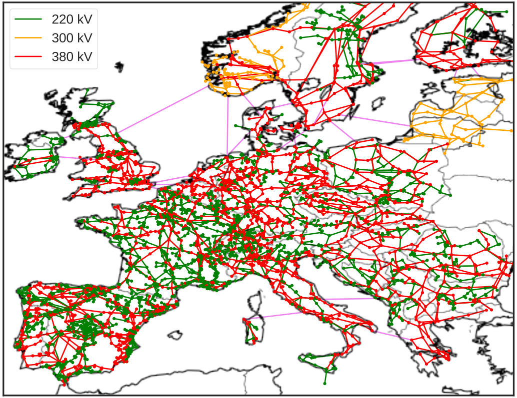
New transmission is **capped**, given length d_l and capacity $\bar{P}_\ell$ of each line:

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

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

The shadow price μ_{trans} [EUR/(aMWkm)] gives us the marginal value of new transmission capacity.

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/FRESNA/pypsa-eur`

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

Quantity	Overnight Cost [€]	Unit	FOM [%/a]	Lifetime [a]
Wind onshore	1182	kW_{el}	3	20
Wind offshore	2506	kW_{el}	3	20
Solar PV	600	kW_{el}	4	20
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.

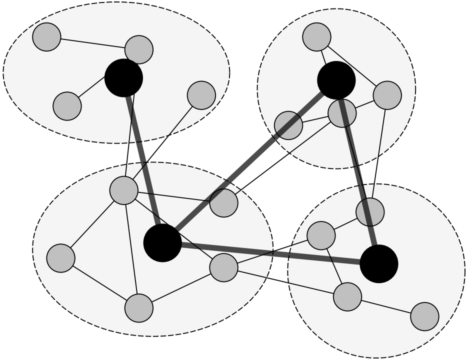
Batteries can store for 6 hours at maximal rating (efficiency 0.9×0.9), hydrogen storage for 168 hours (efficiency 0.75×0.58).

Reduce spatial resolution with clustering

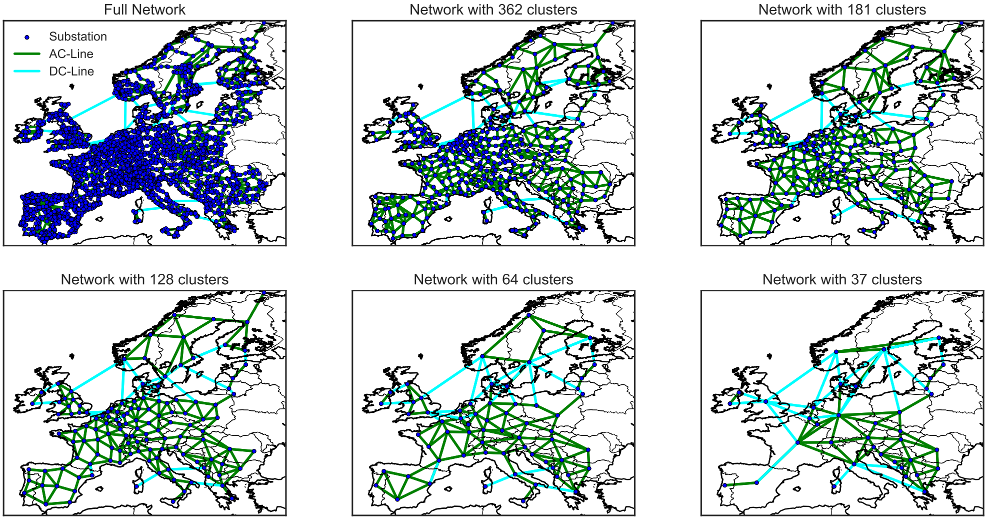
We need spatial resolution to:

- 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**

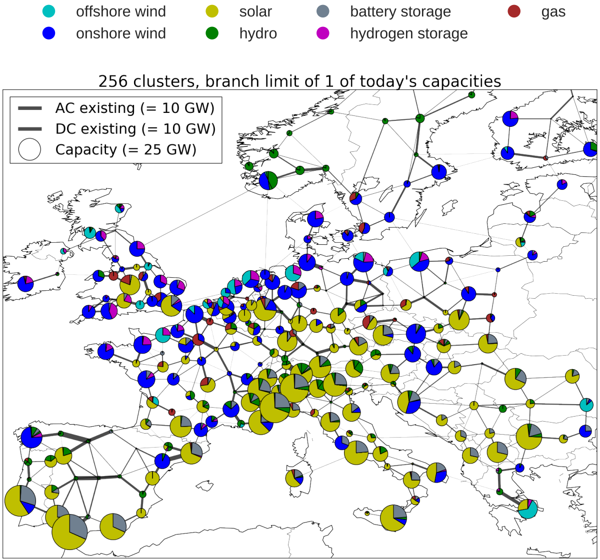
BUT we do not want to have to model all 5,000 network nodes of the European system.



Solution: k-means clustering



Electricity system with no grid expansion

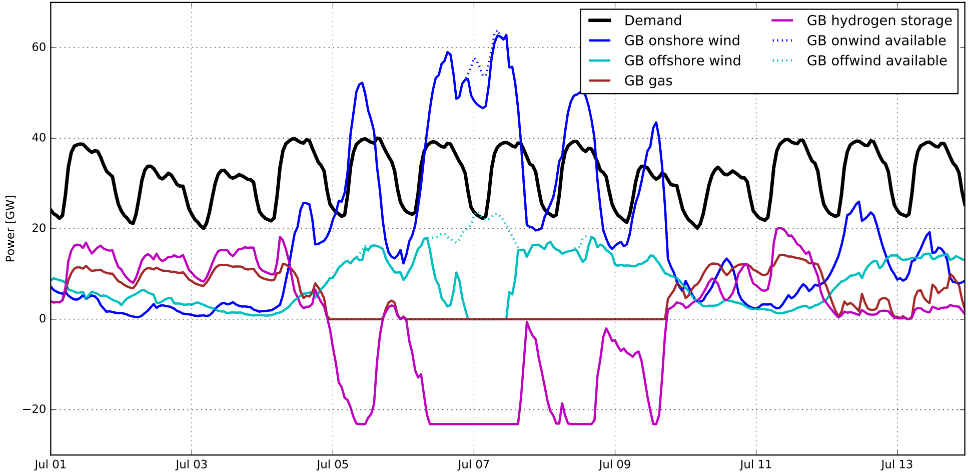


- Assume **nodal pricing**
- Wind built in North where grid capacity allows, solar in South
- With **no grid expansion**, lots of storage required to balance variability, **costs are high**
- Batteries pair with solar in South
- Hydrogen storages pairs with longer-term variations of wind in North

Source: Hörsch et al, 2017

Dispatch with no grid expansion

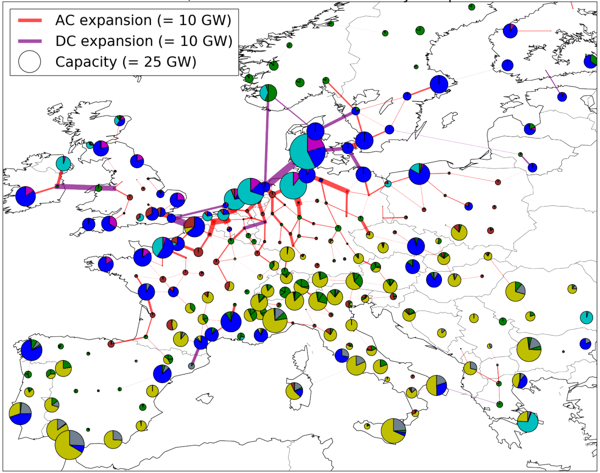
For Great Britain with limited interconnecting transmission, excess wind is either stored as hydrogen or curtailed:



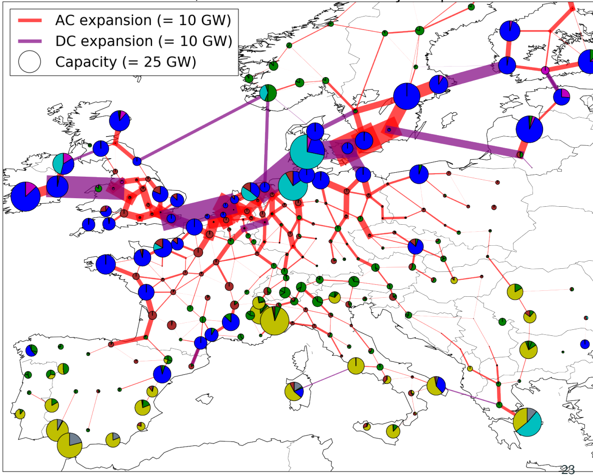
When grid expansion allowed: avoid costly storage

offshore wind · onshore wind · solar · gas · hydro · hydrogen storage · battery storage

256 clusters, branch limit of 1.5 of today's capacities

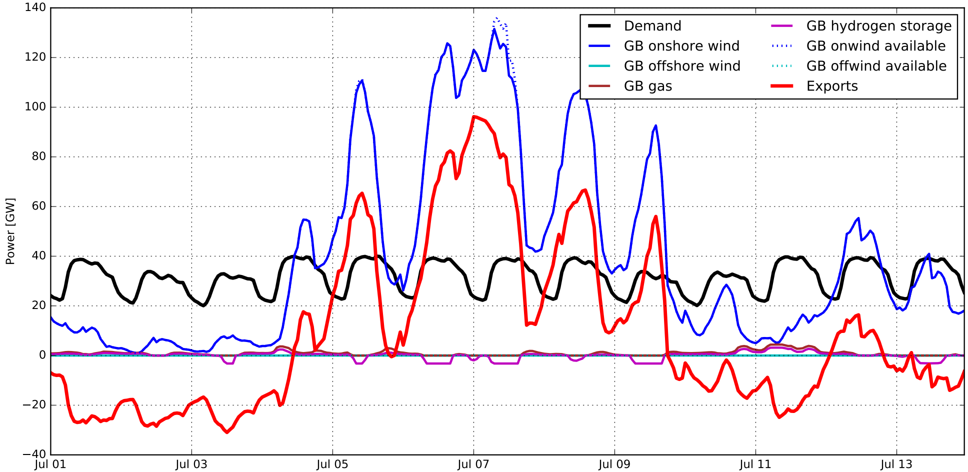


256 clusters, branch limit of 3 of today's capacities

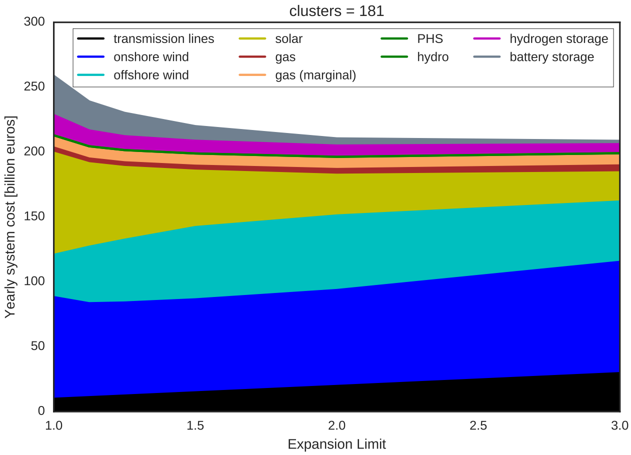


Dispatch with cost-optimal interconnecting transmission

Almost all excess wind can be now be exported:



Cost behaviour as transmission expansion is allowed

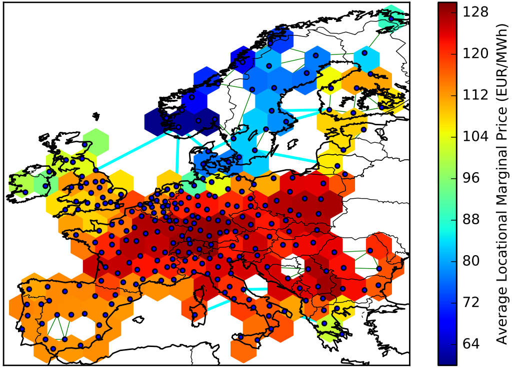


- Big **non-linear cost reduction** as grid is expanded
- Most of cost reduction happens with **25% grid expansion** compared to today's grid (25% corresponds to TYNDP)
- Costs comparable to today's system (around €200 billion/a)
- Investment in solar and batteries decrease significantly as grid expanded; with cost-optimal grid, system is dominated by wind

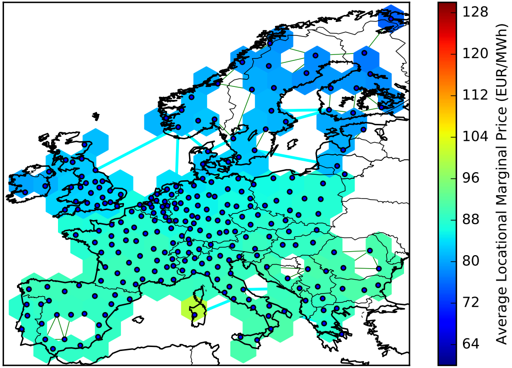
Source: Schlachtberger et al, 2017, Hörsch et al, 2017

Locational Marginal Prices CAP=1 versus CAP=3

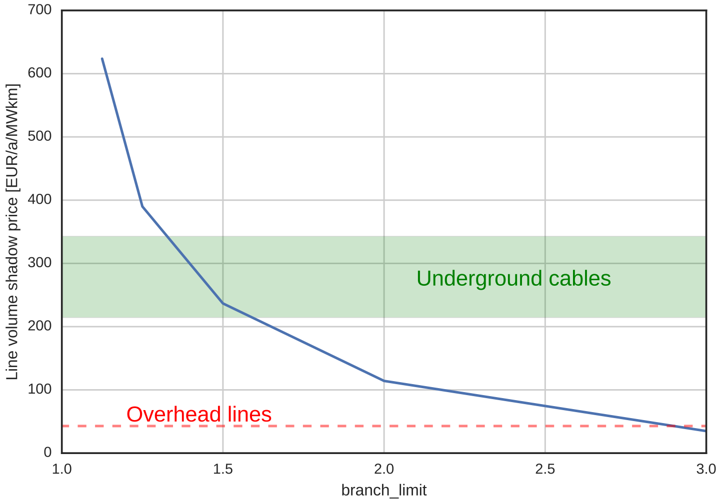
With today's capacities:



With three times today's grid:

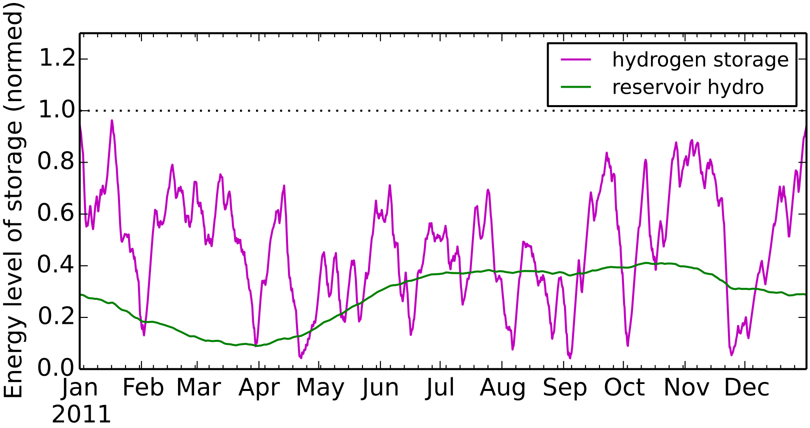


Grid expansion cap shadow price as cap is relaxed



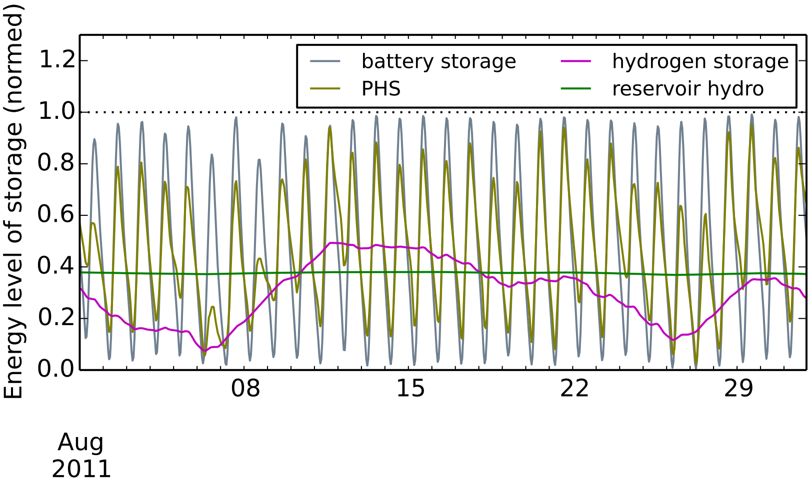
- With overhead lines the optimal system has around 3 times today's transmission volume
- With underground cables (5-8 times more expensive) the optimal system has around 1.3 to 1.6 times today's transmission volume

Different flexibility options have difference temporal scales



- Hydro reservoirs are **seasonal**
- Hydrogen storage is **synoptic**

Different flexibility options have difference temporal scales

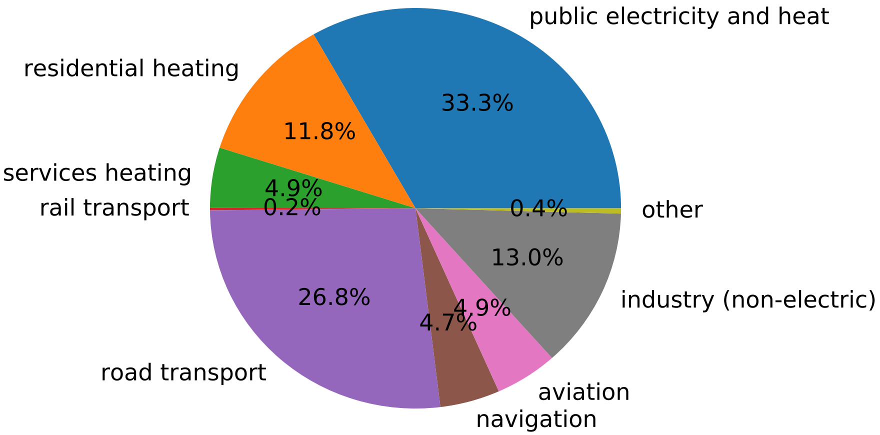


- Pumped hydro and battery storage are **daily**

Electricity, Heat and Transport

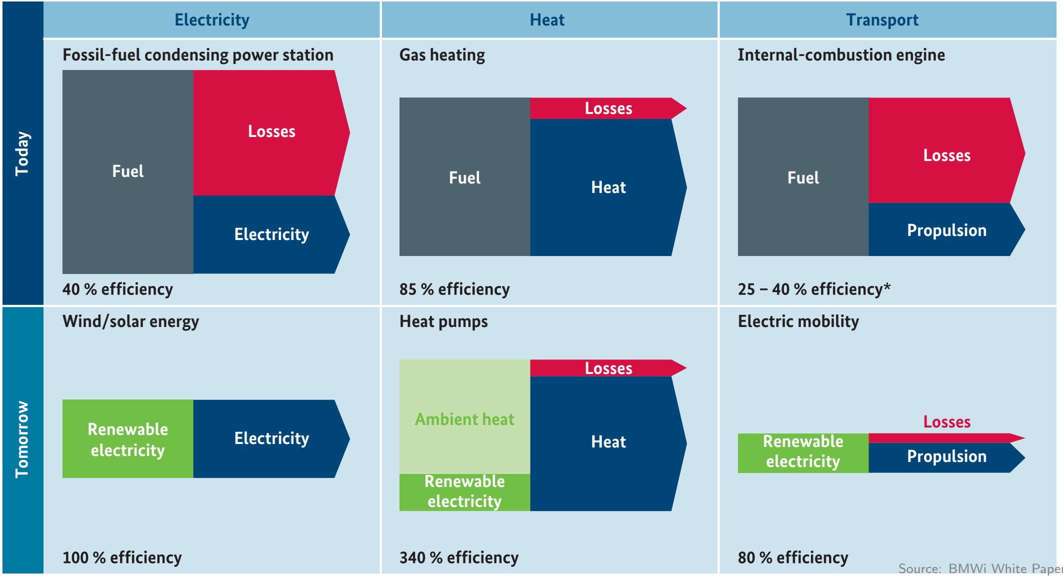
Include other sectors: heating and land transport

Electricity, (low-temperature) heating and land transport cover 77% of 2015 CO_2 emissions:



Source: Brown, data from EEA

Efficiency of renewables and sector coupling

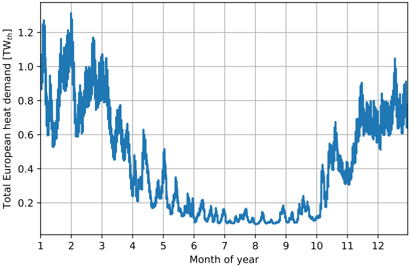


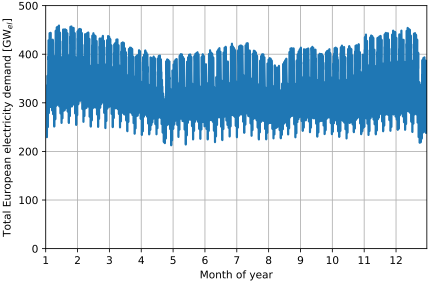
Source: BMWi White Paper 2015

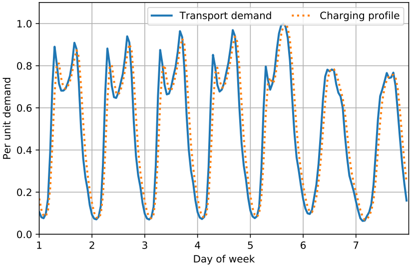
Challenge: Heating and transport demand highly peaked

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

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







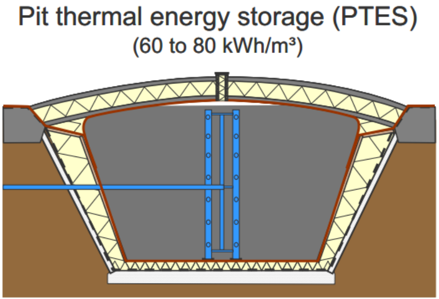
Sector Coupling

Idea: Couple the electricity sector to heating and mobility.

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

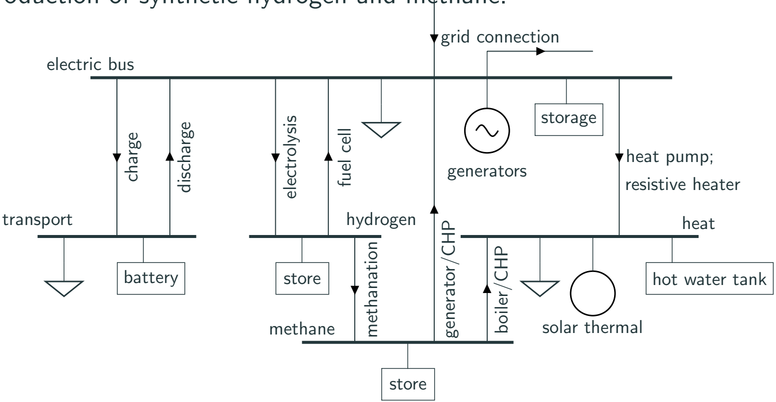
Battery electric vehicles can change their charging pattern to benefit the system and even feed back into the grid if necessary

Heat and **synthetic fuels** are easier and cheaper to store than electricity, even over many months



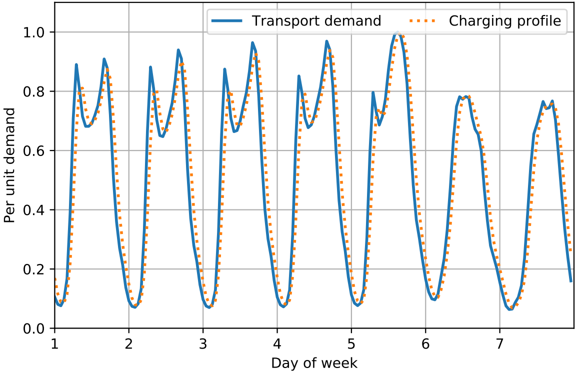
Sector coupling: A new source of flexibility

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.



[NB: Computational restrictions mean restricting to one-node-per-country for Europe.]

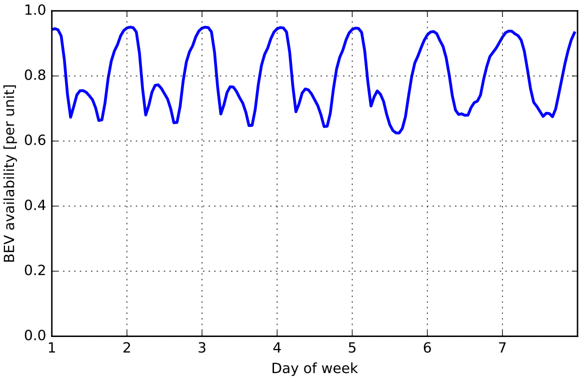
Transport sector: Electrification of Transport



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

- All road and rail transport in each country is electrified, where it is not already electrified
- Because of higher efficiency of electric motors, final energy consumption 3.5 times lower than today at 1102 $\mathrm{TWh}_{el}/\mathrm{a}$ for the 30 countries
- In model can replace Electric Vehicles (EVs) with Fuel Cell Vehicles (FCVs) consuming hydrogen. Advantage: hydrogen cheap to store. Disadvantage: efficiency of fuel cell only 60%, compared to 90% for battery discharging.

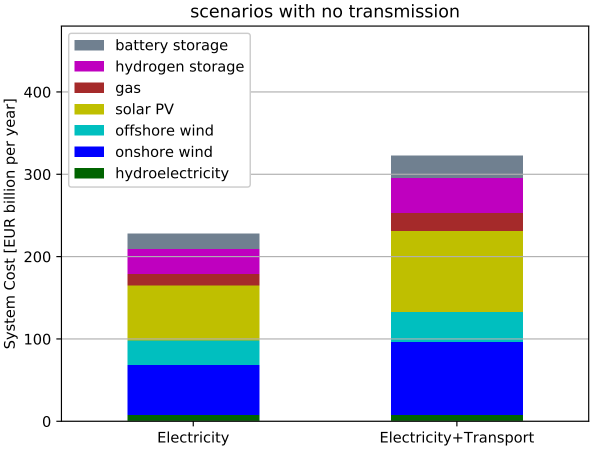
Transport sector: Battery Electric Vehicles



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

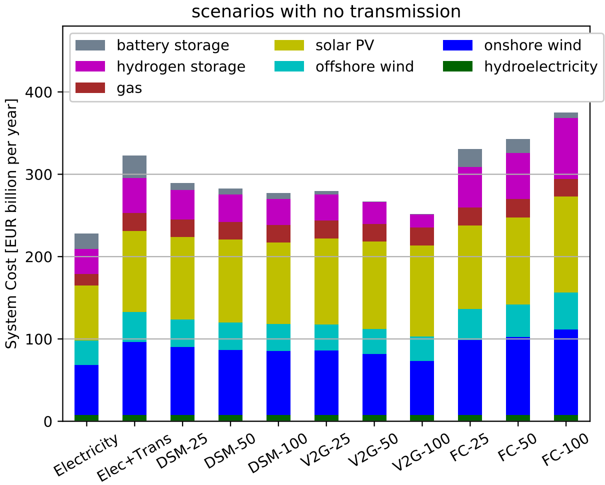
- Passenger cars to Battery Electric Vehicles (BEVs), 50 kWh battery available and 11 kW charging power
- Can participate in DSM and V2G, depending on scenario (state of charge returns to at least 75% every morning)
- All BEVs have time-dependent availability, averaging 80%, max 95% (at night)
- No changes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

Coupling Transport to Electricity



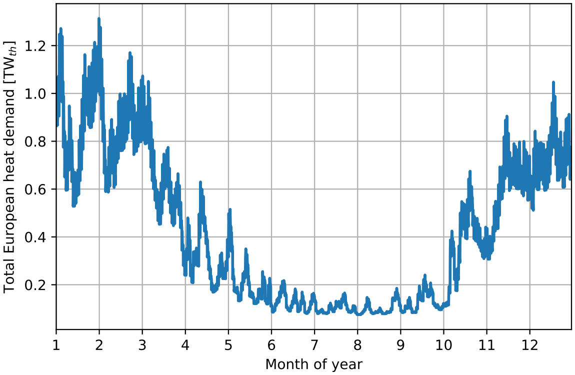
- If all road and rail transport is electrified, electrical demand increases 37%
- Costs increase 41% because charging profiles are very peaked (NB: distribution grid costs NOT included)
- Stronger preference for PV and storage in system mix because of daytime peak
- Can now use flexible charging

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.

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



Heat demand profile from 2011 in all 30 countries using population-weighted average daily T in each country, 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.

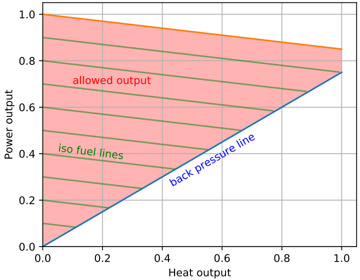
Decentral individual heating can be supplied by:

- 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:

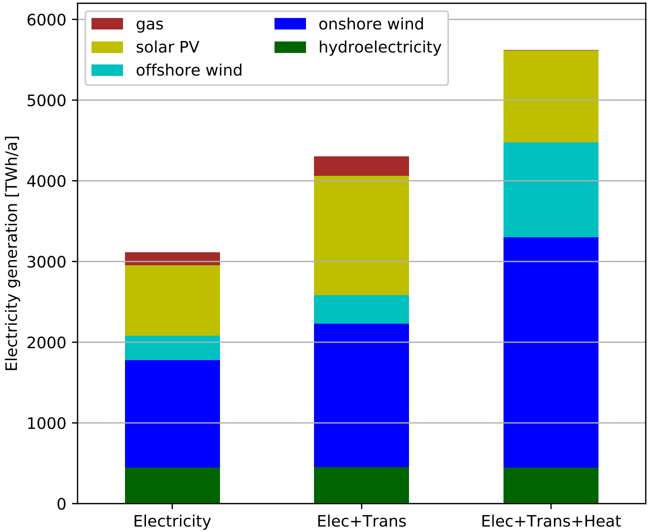


Cost and other assumptions

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

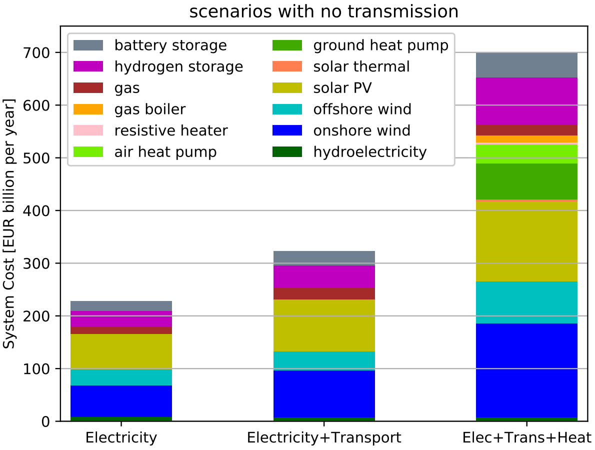
Costs oriented towards Henning & Palzer (2014, Fraunhofer ISE) and Danish Energy Database

Coupling Heating to Transport and Electricity: Electricity Demand



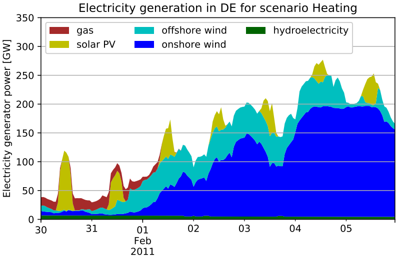
- To 4062 TWh_{el}/a demand from electricity and transport, 3585 TWh_{th}/a heating demand is added
- Much of the heating demand is met via electricity, but with high efficiency from heat pumps
- Electricity demand 80% higher than current electricity demand
- Efficiency savings can reduce this ...

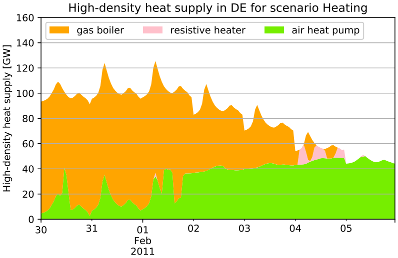
Coupling Heating to Transport and Electricity: Costs



- 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



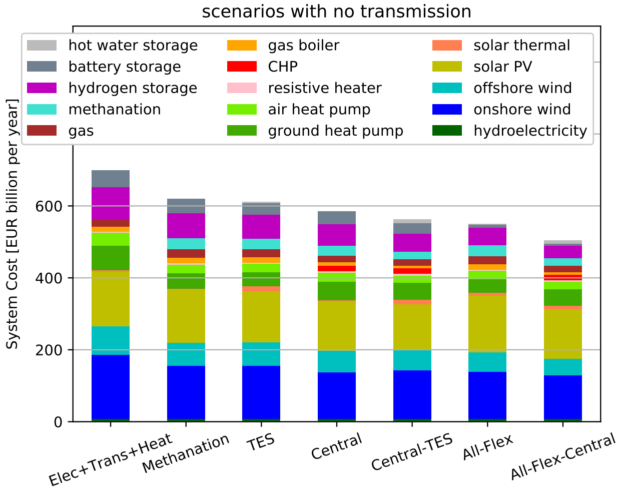


There are difficult periods in winter with:

- **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.

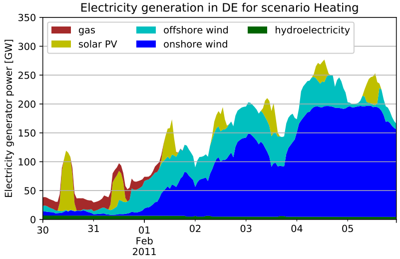
Using heating flexibility

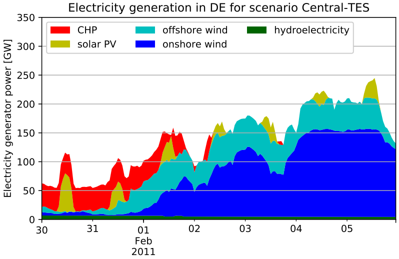


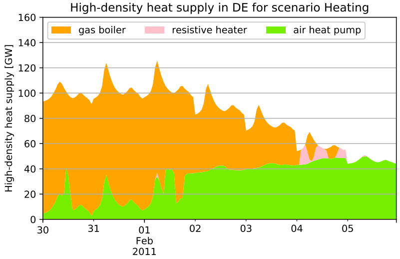
Successively activating couplings and flexibility **reduces costs** by 28%. These options include:

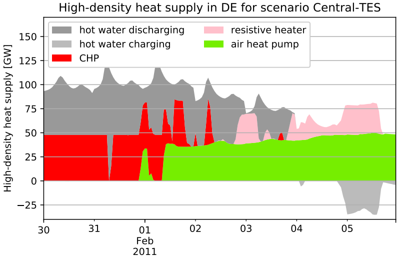
- production of **synthetic methane**
- centralised **district heating** in areas with dense heat demand
- long-term **thermal energy storage** (TES) in district heating networks
- **demand-side management** and vehicle-to-grid from battery electric vehicles (BEV)

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



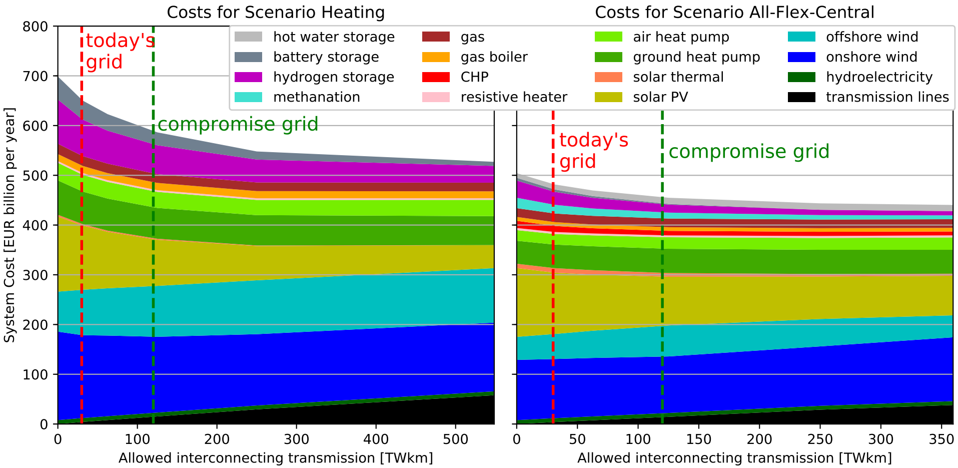






Sector Coupling with All Extra Flexibility (V2G and TES)

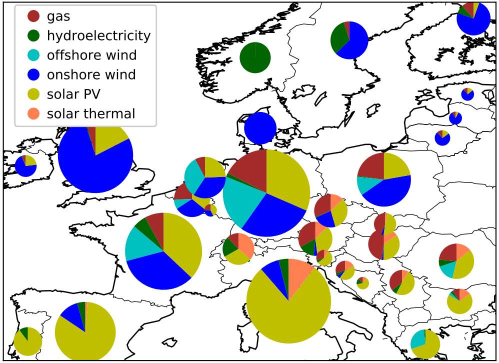
Benefit of cross-border transmission is weaker with full sector flexibility (right) than with inflexible sector coupling (left); comes close to today's costs of around € 377 billion per year



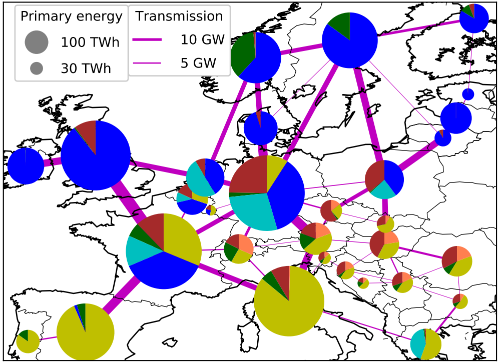
Spatial distribution of primary energy for All-Flex-Central

Including optimal transmission sees a shift of energy production to wind in Northern Europe.

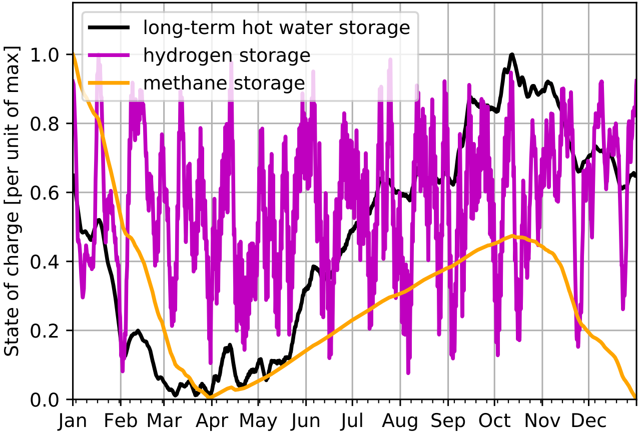
Scenario All-Flex-Central with no transmission



Scenario All-Flex-Central with optimal transmission

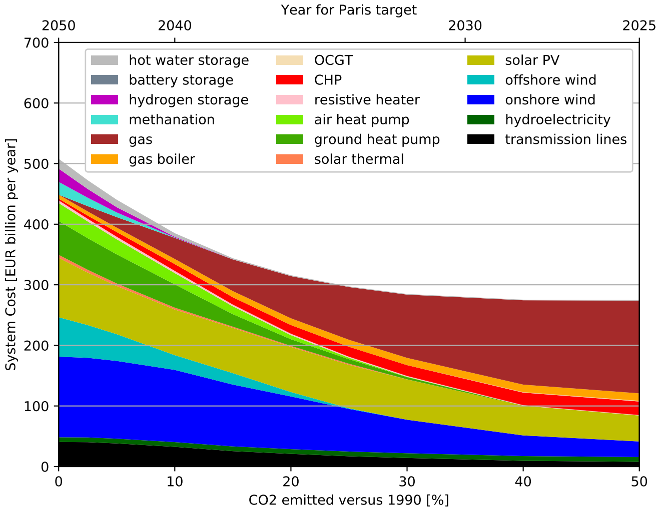


Storage energy levels: different time scales



- 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

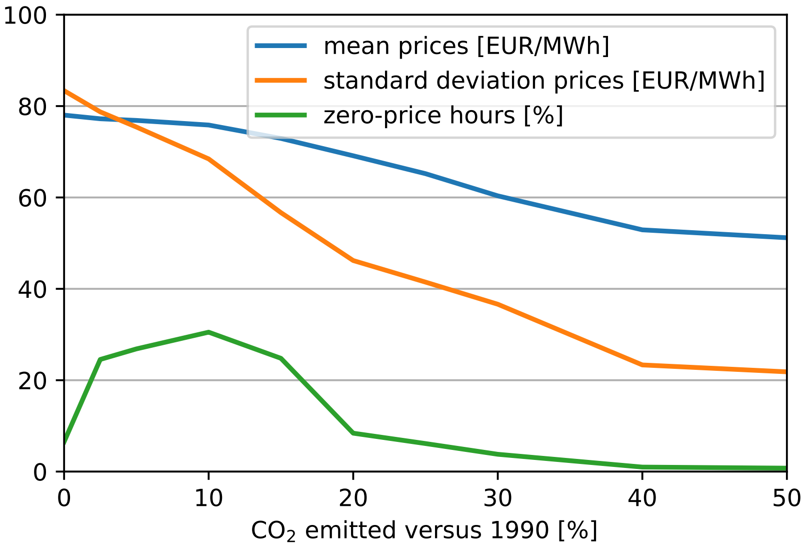
Pathway down to zero emissions in electricity, heating and transport



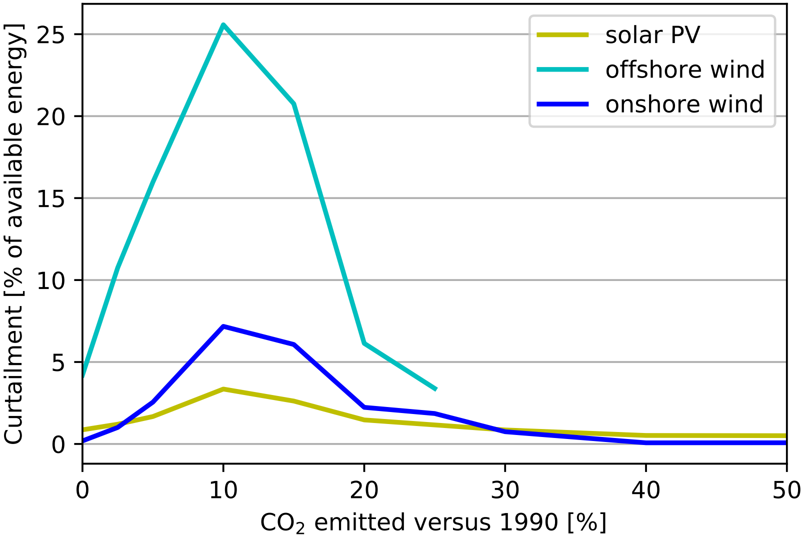
If we look at investments to eradicate CO_2 emissions in electricity, heating and transport we see:

- Electricity and transport are decarbonised first
- Transmission increasingly important below 30%
- Heating comes next with expansion of heat pumps below 20%
- Below 10%, power-to-gas solutions replace natural gas

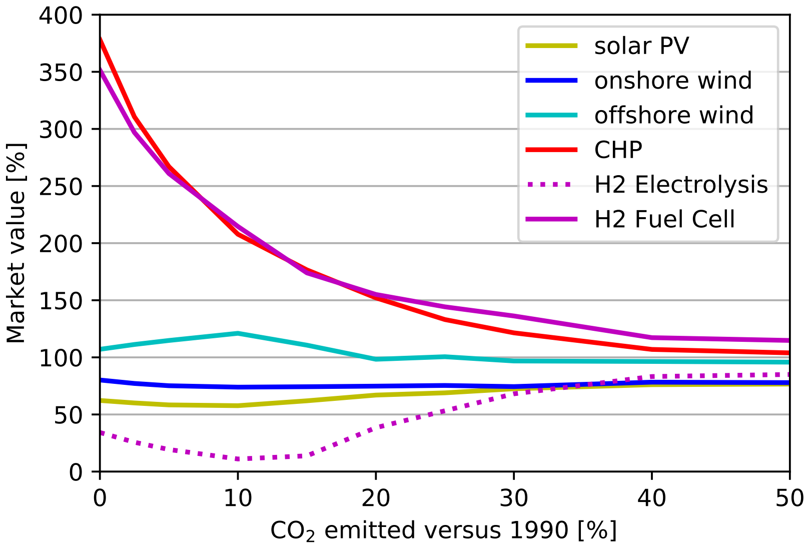
Electricity price statistics: zero-price hours gone thanks to P2G



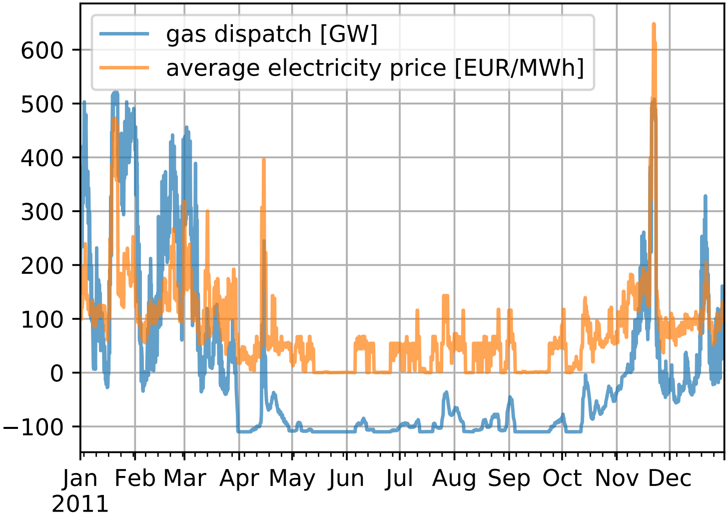
Curtailment also much reduced



Market values relative to average load-weighted price re-converge



Gas production/consumption tightly coupled to price



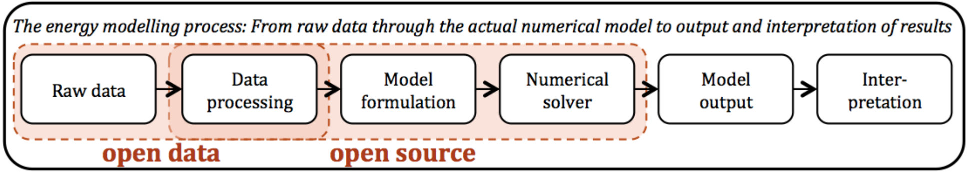
Outlook

- Develop improvements on algorithmic side to enable larger problems (clustering, improved optimisation routines)
- Apply sector coupling to 200-node European model (instead of one-node-per-country) to see real transmission bottlenecks with scope, scale and sectors
- Explore pathway from here to 2050 (is P2X cost-effective sooner for local transmission bottlenecks? - these are not seen in the one-node-per-country sector model)
- 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

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:

openmod open energy modelling initiative

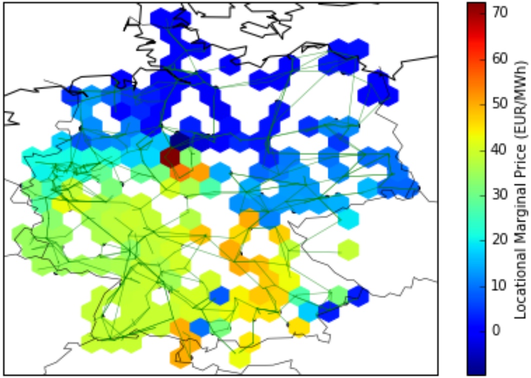
openmod-initiative.org

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
- There are **lots of cost-effective solutions** thanks to falling price of renewables
- **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**
- The energy system is complex and contains some uncertainty (e.g. cost developments, scaleability of power-to-gas, consumer behaviour), so **openness is critical**

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