Modelling Paris: Scenarios for the electricity grid, heating and transport in Europe with 95% carbon dioxide emission reductions

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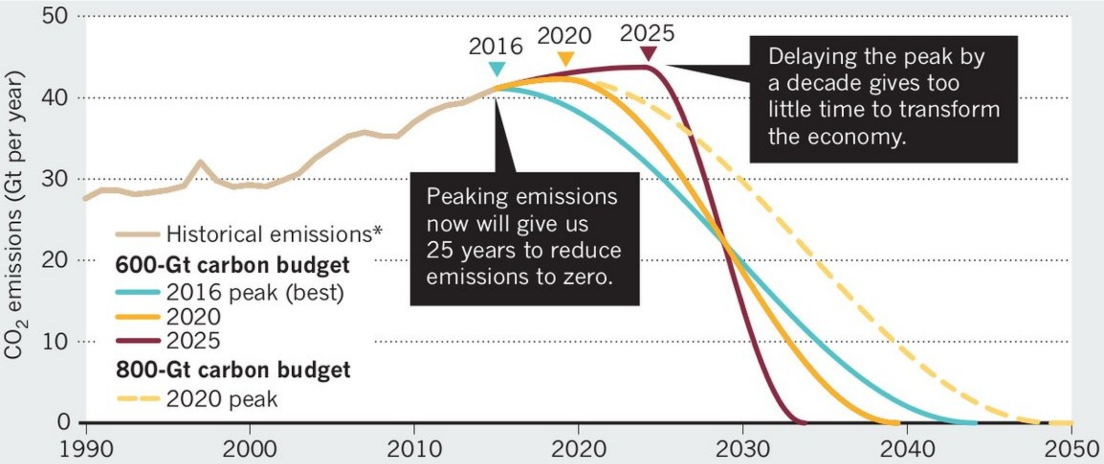
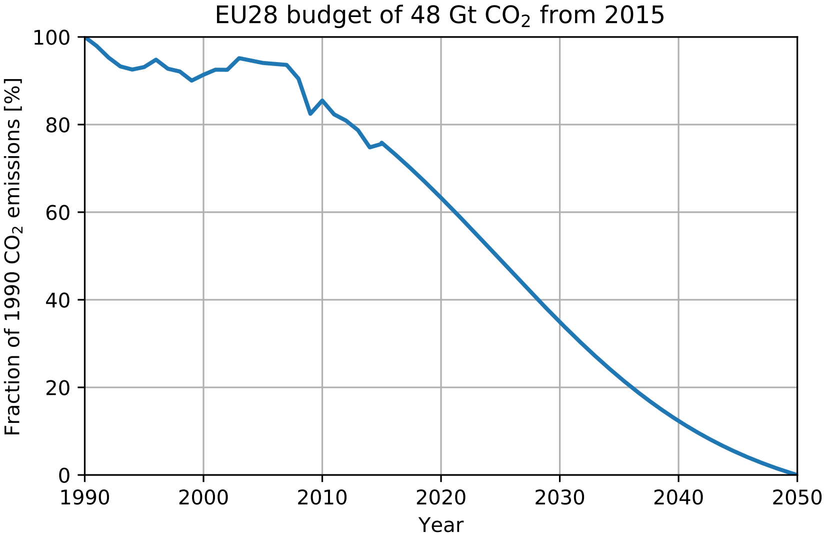
The Global Carbon Dioxide Challenge: Budgets from 2016

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')



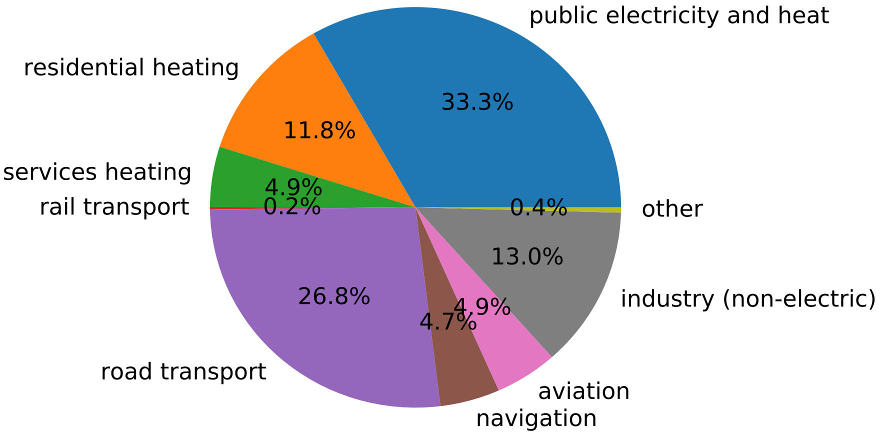
Source: 'Three years to safeguard our climate,' Nature, 2017

A Paris-compliant scenario: EU28 gets 8% of global 600 Gt budget



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

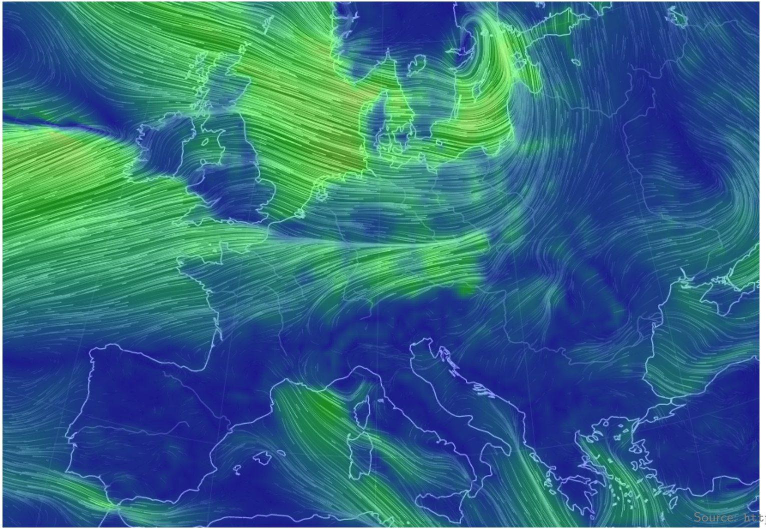
Wind and solar dominate the expandable potentials for low-carbon energy provision, so **electrification is essential** to decarbonise sectors such as transport and heating.

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

Source: Tesla; heat pump: Kristoferb at English Wikipedia

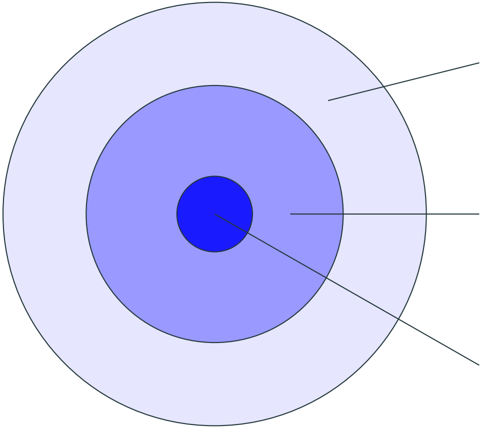
The Wind and Solar Variability Challenge

Wind and solar power **vary over time and space**. Wind at 3am on 30.11.2015:



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

Different levels of planning



Researchers: bold modelling with wide scope, but rough on details

Network Development Plan: more precise, but restricted scope

Specific construction project: very concrete, no additional scope

Research approach

Avoid too many assumptions. Fix the **boundary conditions**:

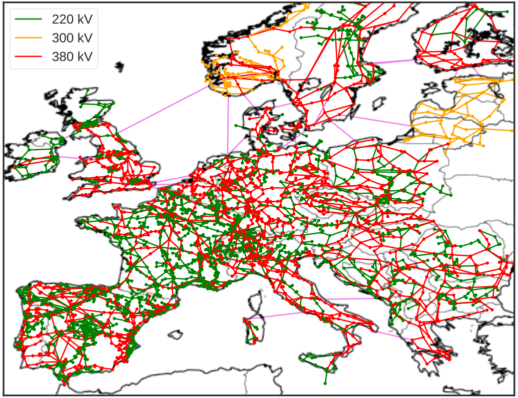
- Meet demand for energy services
- Reduce CO_2 emissions
- Conservative predictions for cost developments
- No/minimal/optimal grid expansion

Then **let the math decide the rest**, i.e. choose the number of wind turbines / solar panels / storage units / transmission lines to minimise total costs.

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

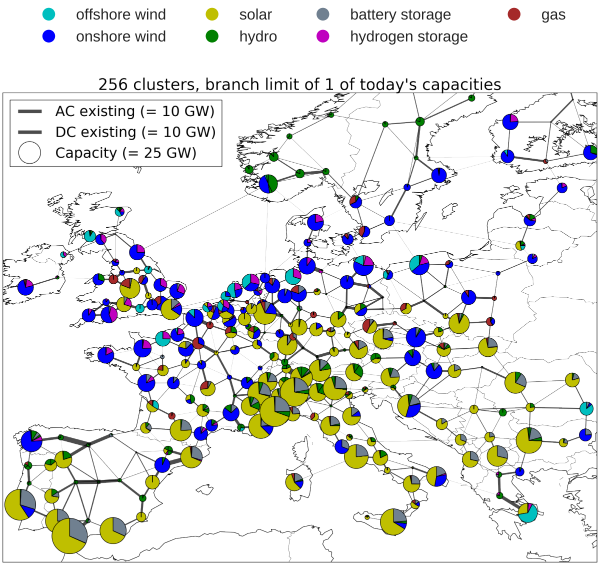
Warm-up: Determine optimal electricity system

- 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

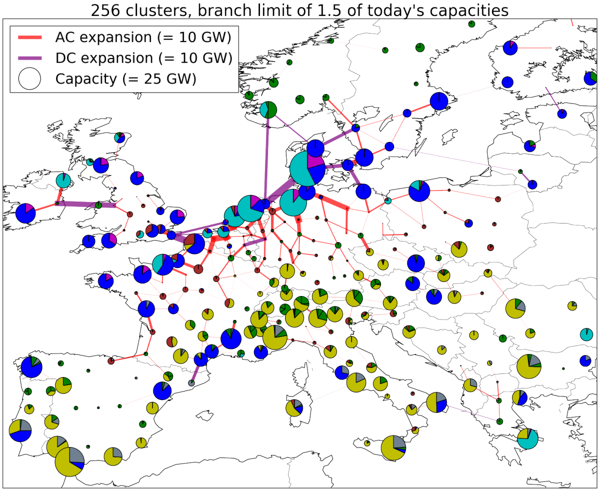
Electricity system with no grid expansion

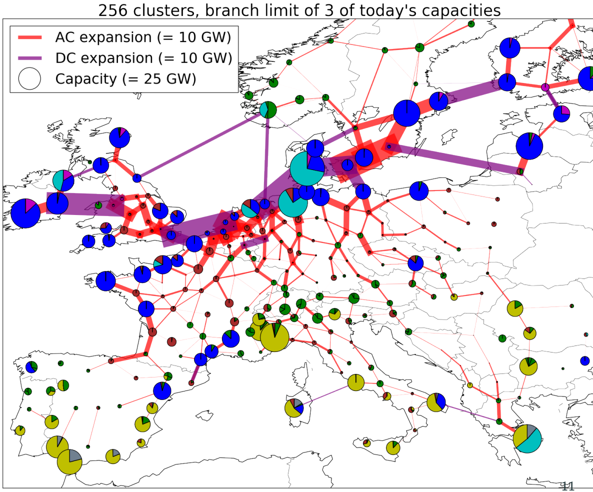


- Wind in North where grid capacity allows, solar in South
- With **no grid expansion**, lots of storage required to balance variability, **costs are high**
- Batteries pair with solar in South
- Hydrogen storages pairs with longer-term variations of wind in North

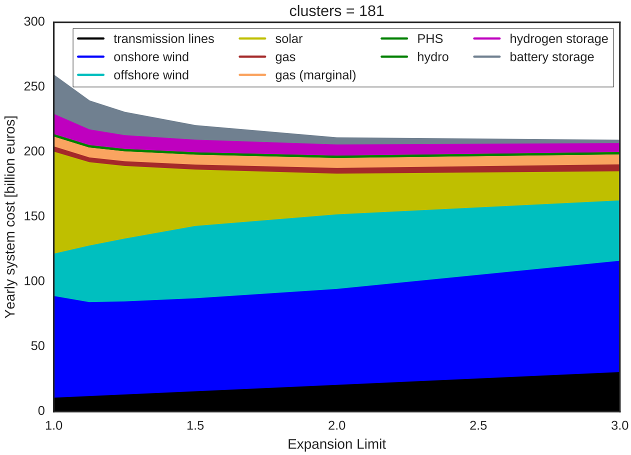
When grid expansion allowed: avoid costly storage

offshore wind   onshore wind   solar   gas   hydro   hydrogen storage   battery storage





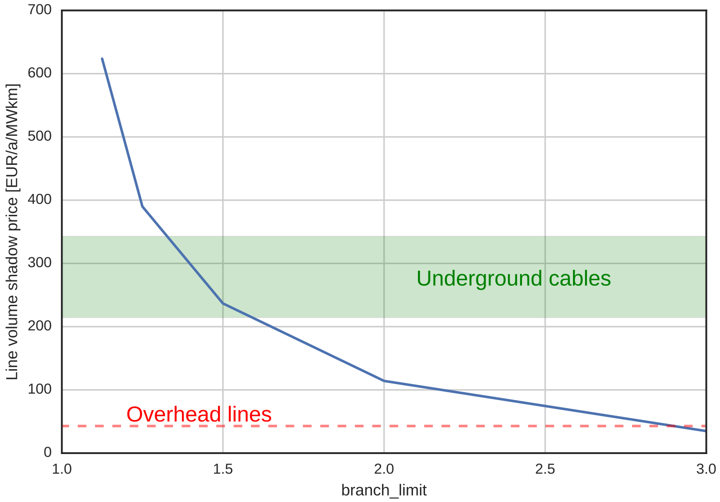
Cost behaviour as transmission expansion is allowed



- 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

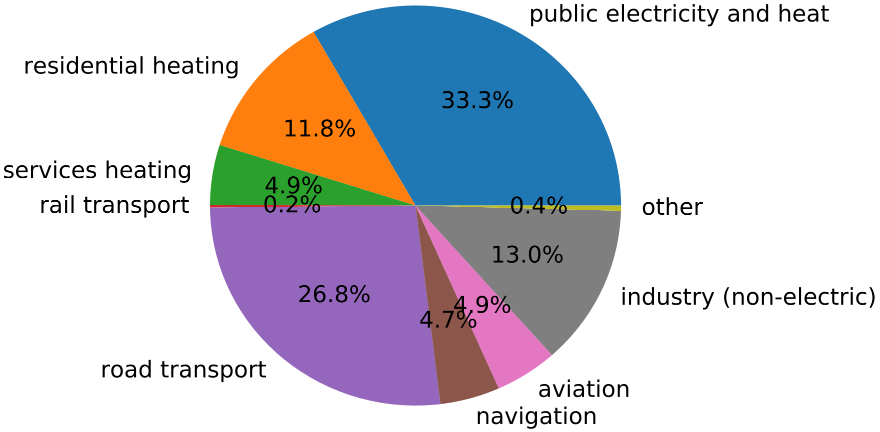
Grid expansion cap shadow price as cap is relaxed



- 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

Include other sectors: heating and land transport

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



Source: Brown, data from EEA

Sector Coupling

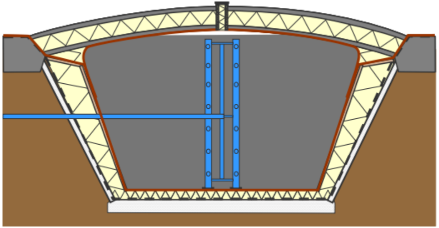
Idea: Couple the electricity sector to heating and mobility.

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

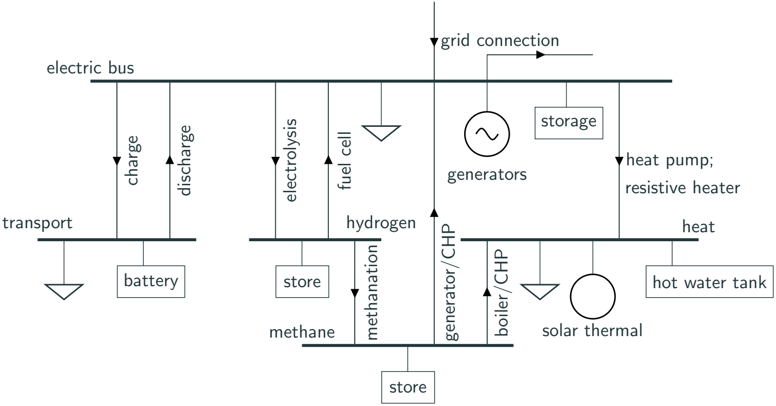
Pit thermal energy storage (PTES)
(60 to 80 kWh/m^3)



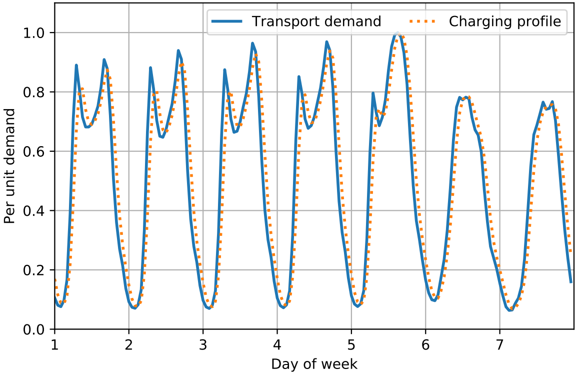
[NB: Computational restrictions mean going back to one-node-per-country for Europe.]

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.



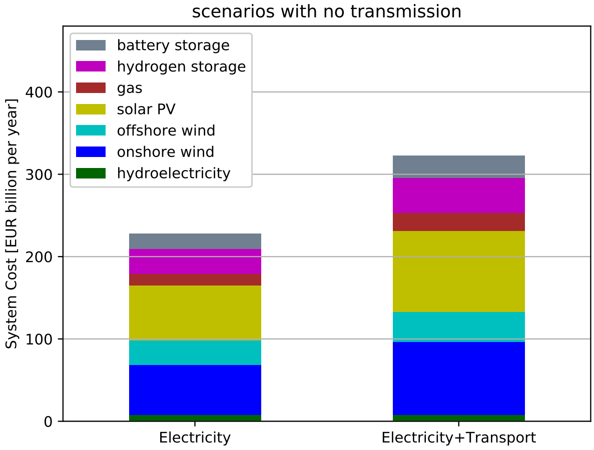
Transport sector: Electrification of Transport



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

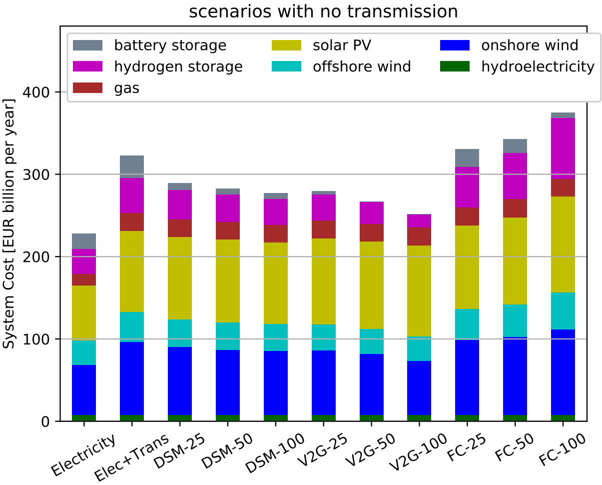
- All road and rail transport in each country is electrified, where it is not already electrified
- Because of higher efficiency of electric motors, final energy consumption 3.5 times lower than today at 1102 TWh_{el}/a for the 30 countries
- In model can replace Electric Vehicles (EVs) with Fuel Cell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

Coupling Transport to Electricity



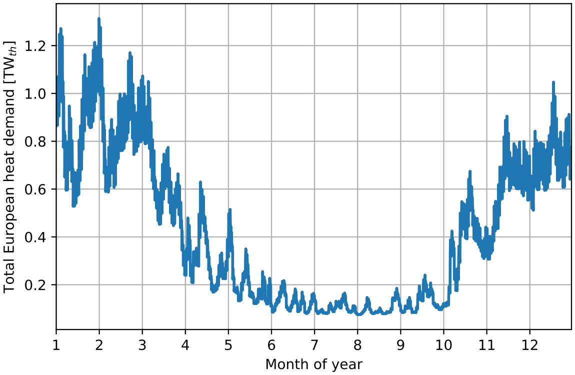
- If all road and rail transport is electrified, electrical demand increases 37%
- Costs increase 41% because charging profiles are very peaked (NB: distribution grid costs NOT included)
- Stronger preference for PV and storage in system mix because of daytime peak
- Can now use flexible charging

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.

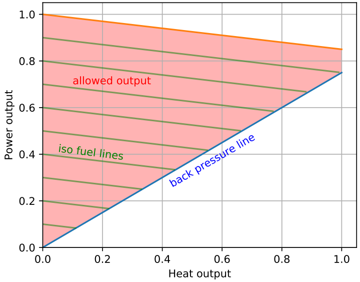
Decentral individual heating can be supplied by:

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

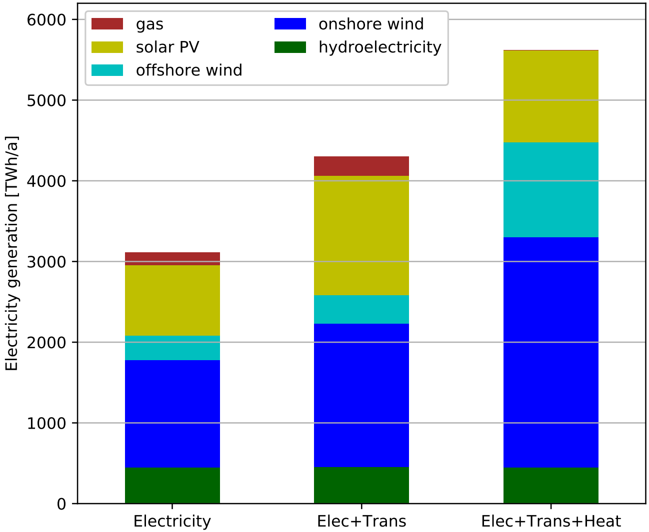
Central heating can be supplied via district heating networks by:

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

CHP feasible dispatch:

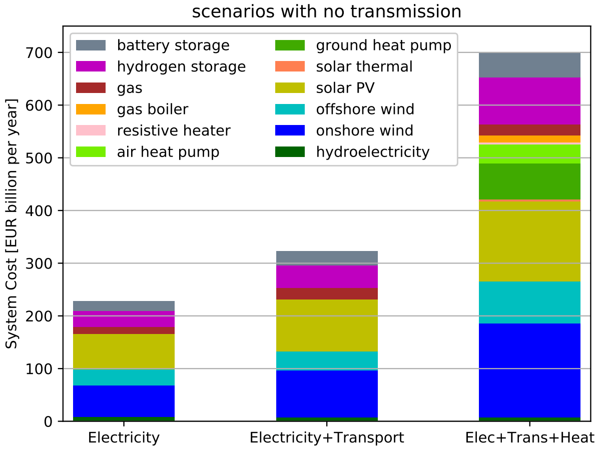


Coupling Heating to Transport and Electricity: Electricity Demand



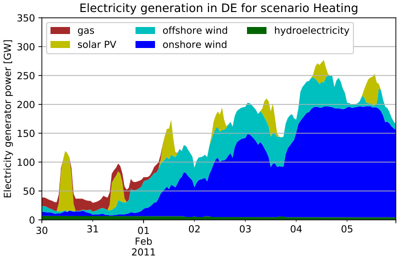
- To 4062 TWh_{el}/a demand from electricity and transport, 3585 TWh_{th}/a heating demand is added
- Much of the heating demand is met via electricity, but with high efficiency from heat pumps
- Electricity demand 80% higher than current electricity demand
- Efficiency savings can reduce this . . .

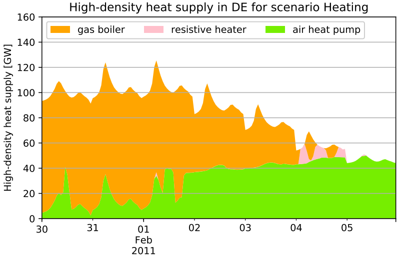
Coupling Heating to Transport and Electricity: Costs



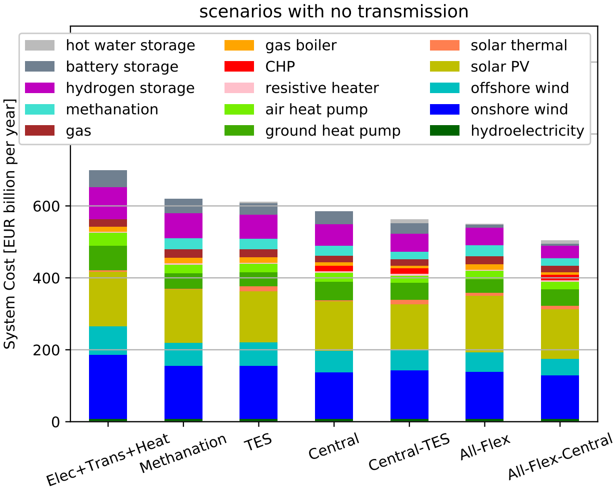
- Costs jump by 117% to cover new energy supply and heating infrastructure
- 95% CO_2 reduction means most heat is generated by heat pumps using renewable electricity
- Cold winter weeks with high demand, low wind, low solar and low heat pump COP mean backup gas boilers required

Cold week in winter



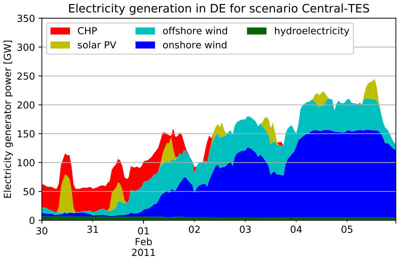


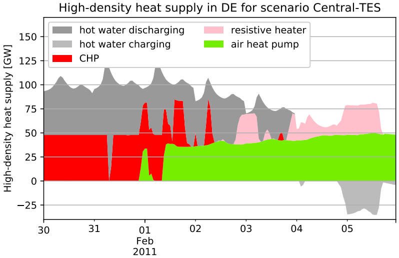
Using heating flexibility



- Successively activating couplings and flexibility reduces costs by 28%
- These options include: production of synthetic methane; centralised district heating in high-density areas; thermal energy storage (TES); and finally all BEV-V2G and heating flexibility.

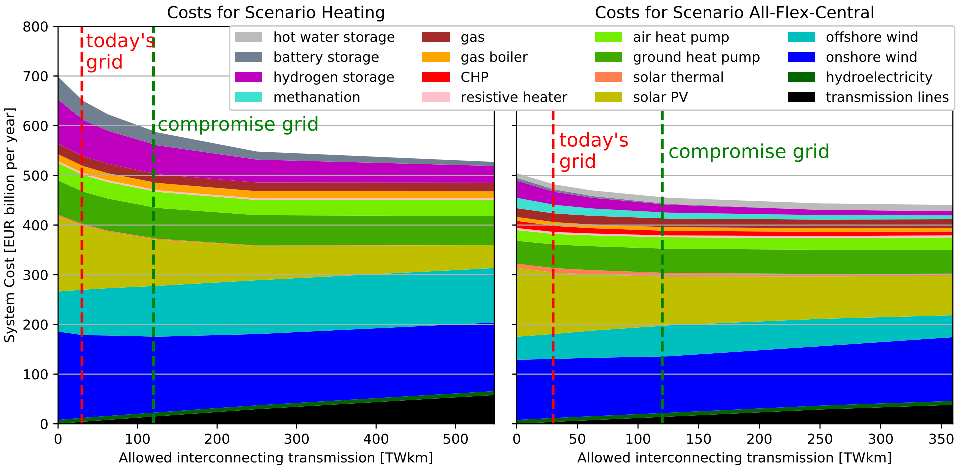
Cold week in winter with district heating, CHP and TES



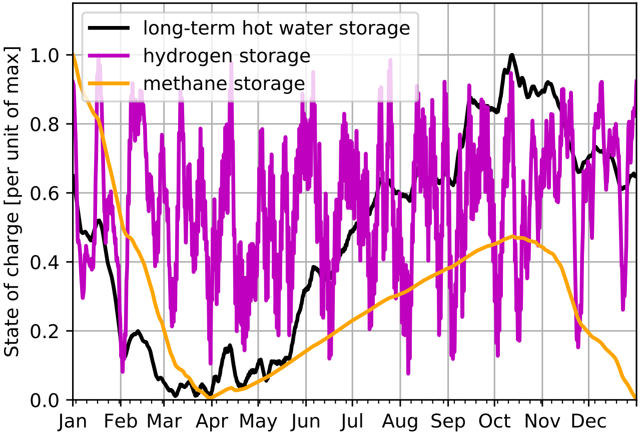


Sector Coupling with All Extra Flexibility (V2G and TES)

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

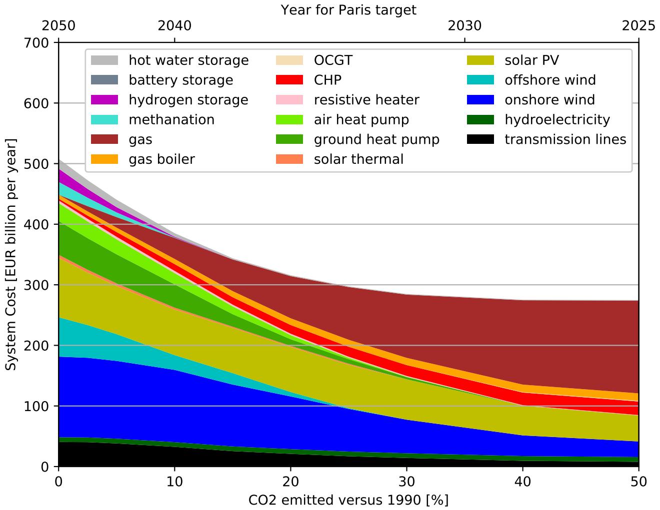


Storage energy levels: different time scales



- 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

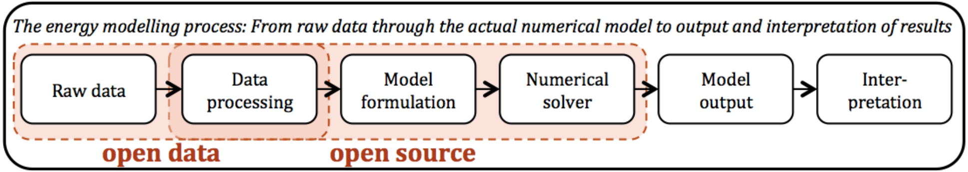


If we look at investments to eradicate CO_2 emissions in electricity, heating and transport we see:

- 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

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:
ETH Zürich, 6-8 June 2018.

openmod open energy modelling initiative

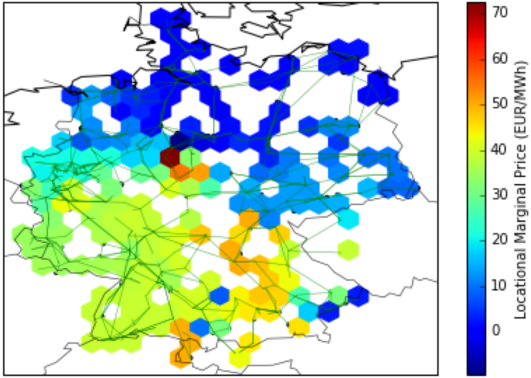
openmod-initiative.org

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

- 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
- **Solution for Europe**: grid+wind in North, decentral solar+storage in South
- **Grid helps** to make CO2 reduction easier = cheaper - we're **far** from over-building grid
- **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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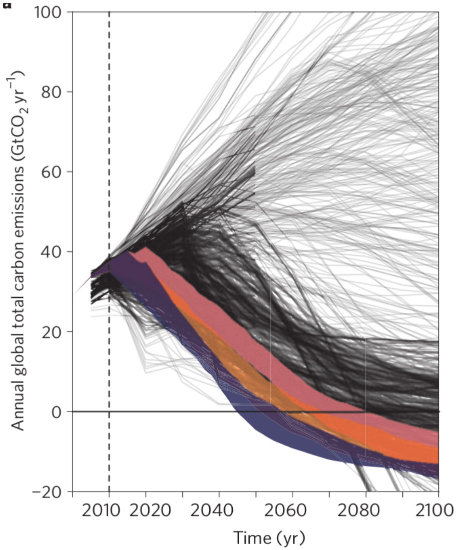
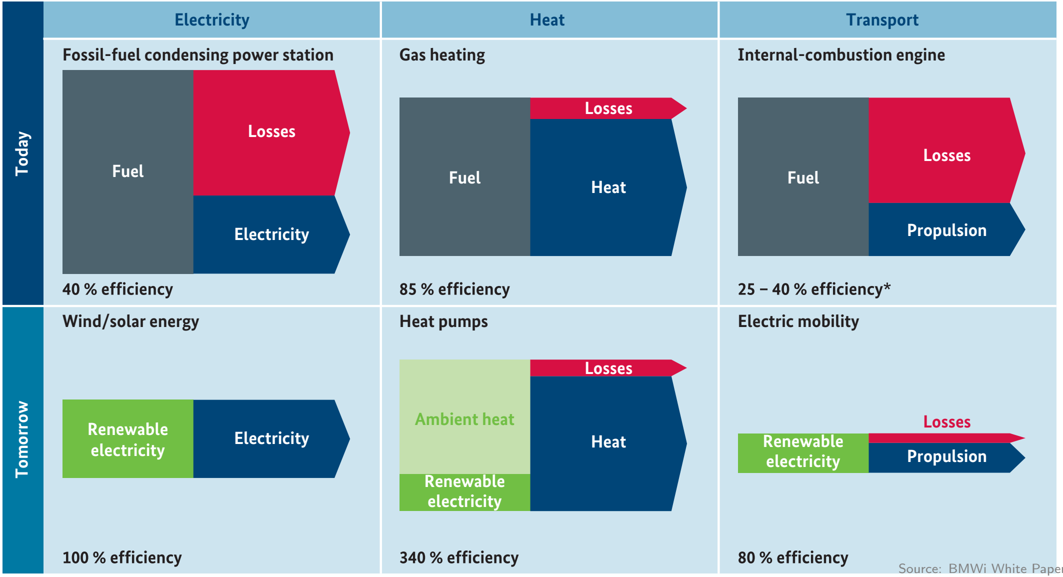
Reaching 1.5C with a good chance: net negative emissions



- To reach 1.5C with more than 50% chance (blue area) need to limit emissions to 200-400 GtCO2 from 2016
- This would require net emissions of zero mid-century followed by **net negative emssions** later in the century

Source: Rogelj et al 2015

Efficiency of renewables and sector coupling



Source: BMWi White Paper 2015