Energy System Modelling
Summer Semester 2019, Lecture 9

Dr. Tom Brown, tom.brown@kit.edu, https://nworbmot.org/
Karlsruhe Institute of Technology (KIT), Institute for Automation and Applied Informatics (IAI)

14th June 2019

Karlsruhe Institute of Technology

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Energy System Challenges

What to do about variable renewables?

Backup energy costs money and may also cause CO_2 emissions.

Curtailing renewable energy is also a waste.

We consider **four options** to deal with variable renewables:

1. Smoothing stochastic variations of renewable feed-in over **larger areas using networks**, e.g. the whole of European continent.
2. Using **storage** to shift energy from times of surplus to deficit.
3. **Shifting demand** to different times, when renewables are abundant.
4. Consuming the electricity in **other sectors**, e.g. transport or heating.

Optimisation in energy networks is a tool to assess these options.

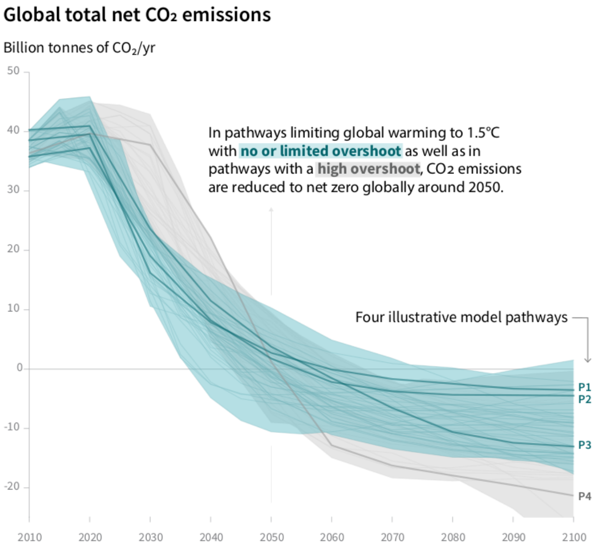
Sector coupling

In this lecture we will consider **sector coupling**: the deeper coupling of electricity with other sectors, i.e. transport, heating and industry.

In fact we will see that sector coupling is not just 'an option for dealing with variable renewables' but is **unavoidable** if we are going to reduce carbon dioxide emissions in the other sectors. It began decades ago with the coupling of power and heat in CHPs.

Furthermore sector coupling involves both **storage** (since in transport energy-dense fuels/batteries are required for vehicles; in heating some chemical storage may be unavoidable for cold snaps) and **demand-side management** (e.g. for shifting battery electric vehicle charging, or shifting heat pump operation).

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

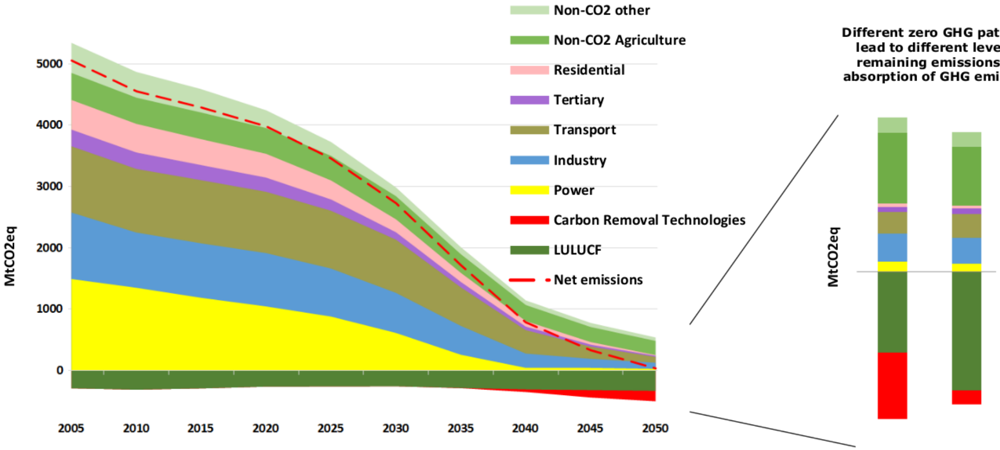


- Scenarios for global CO_2 emissions that limit warming to 1.5°C about industrial levels (**Paris agreement**)
- Today emissions **still rising**
- Level of use of negative emission technologies (NET) depends on rate of progress
- 2°C target without NET also needs rapid fall by 2050
- Common theme: **net-zero by 2050**

Source: IPCC SR15 on 1.5C, 2018

The Greenhouse Gas Challenge: Net-Zero Emissions by 2050

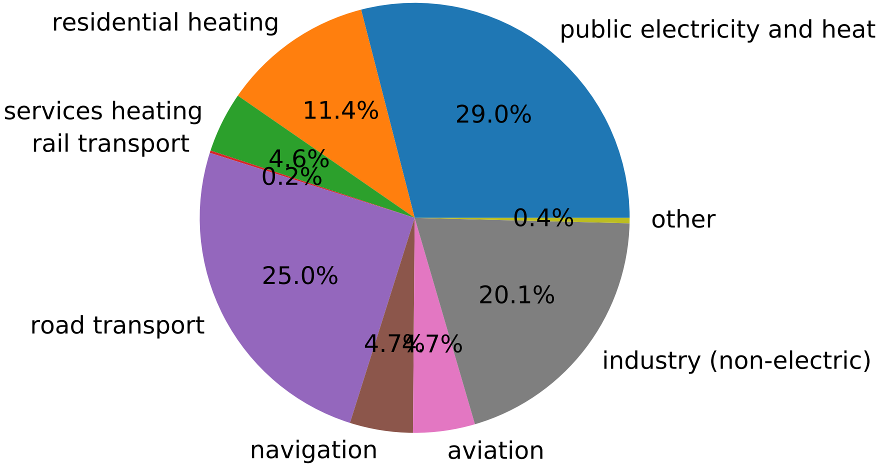
Paris-compliant 1.5° C scenarios from European Commission - **net-zero GHG in EU by 2050**



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

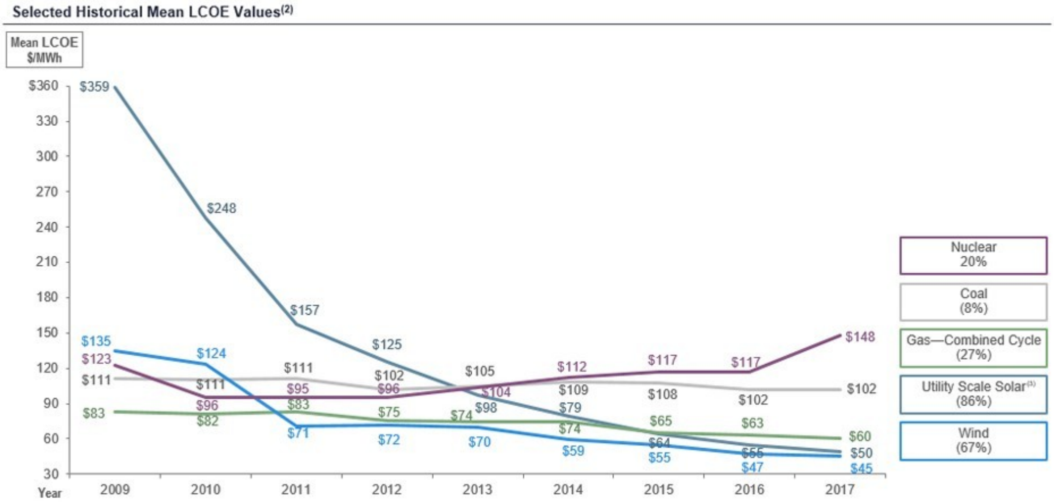
...but electification of other sectors is critical for decarbonisation

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

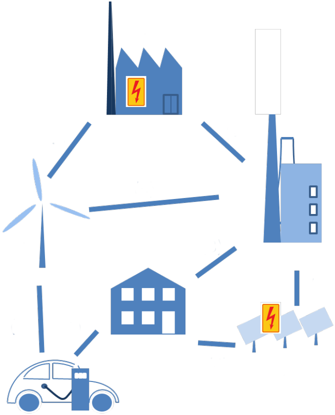
Low cost of renewable energy 2017 (NB: ignores variability)



Source: Lazard's LCOE Analysis V11

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:

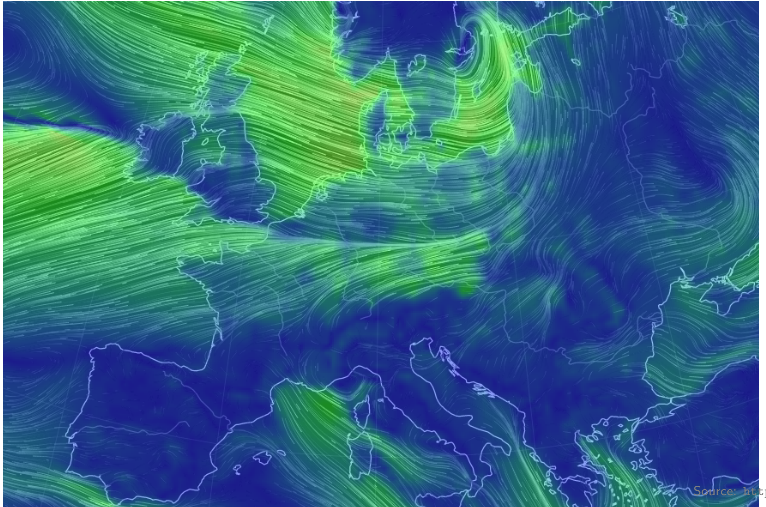
- Reducing need for transmission using **storage / sector coupling** (e.g. battery electric vehicles, thermal storage)
- **New technologies** that can minimise the landscape impact of transmission
- **Efficiency** and **sufficiency** to reduce demand

Transparency is critical for public acceptance.

Variability of Wind, Solar & Demand

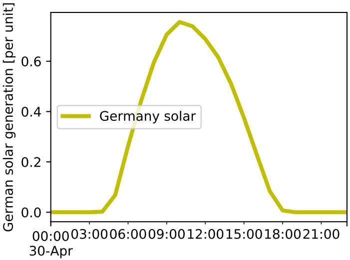
Variability: Different wind conditions over Europe

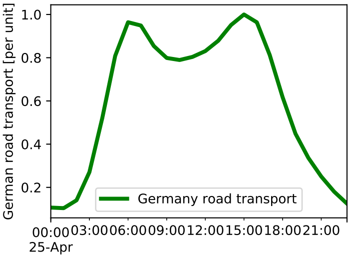
Wind, solar and demand vary at different time scales, e.g. wind is particularly affected by large weather systems at the **continental scale** that pass in 1-2 weeks. See videos of wind and solar.



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

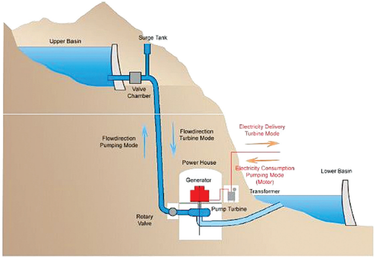
Daily variations: challenges and solutions



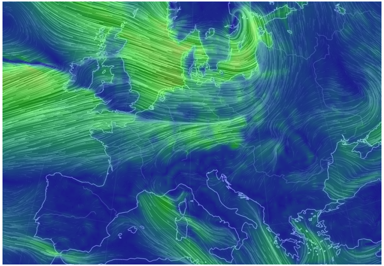


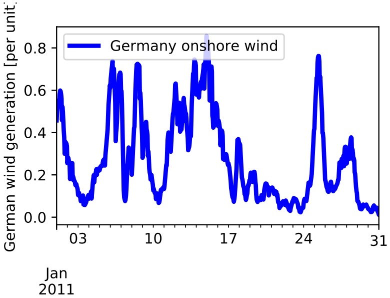
Daily variations in supply and demand can be balanced by

- **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**



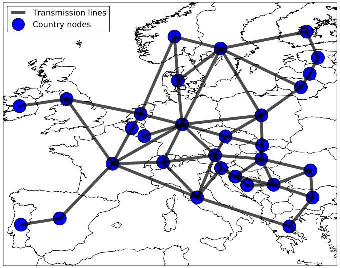
Synoptic variations: challenges and solutions



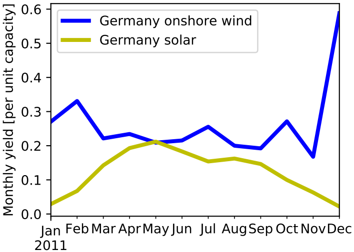


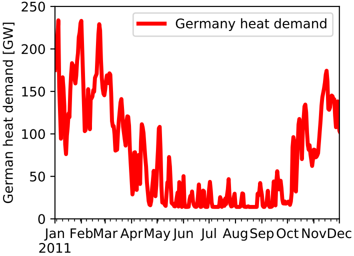
Synoptic variations in supply and demand can be balanced by

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



Seasonal variations: challenges and solutions

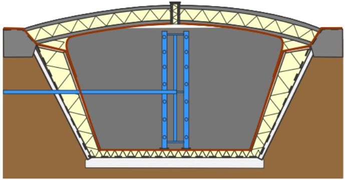




Seasonal variations in supply and demand can be balanced by

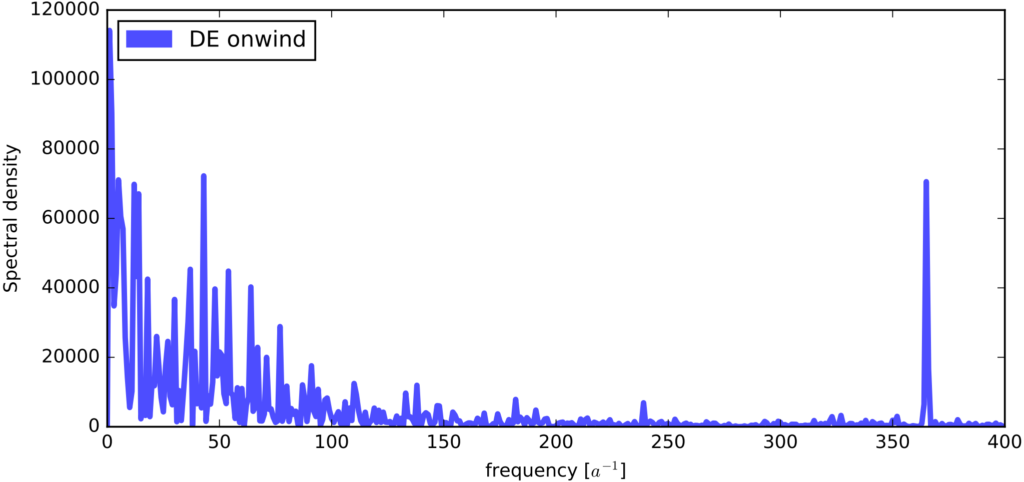
- **long-term storage** (e.g. chemically with hydrogen or methane storage, long-term thermal energy storage, hydro reservoirs)
- **north-south grids over multiple latitudes**

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



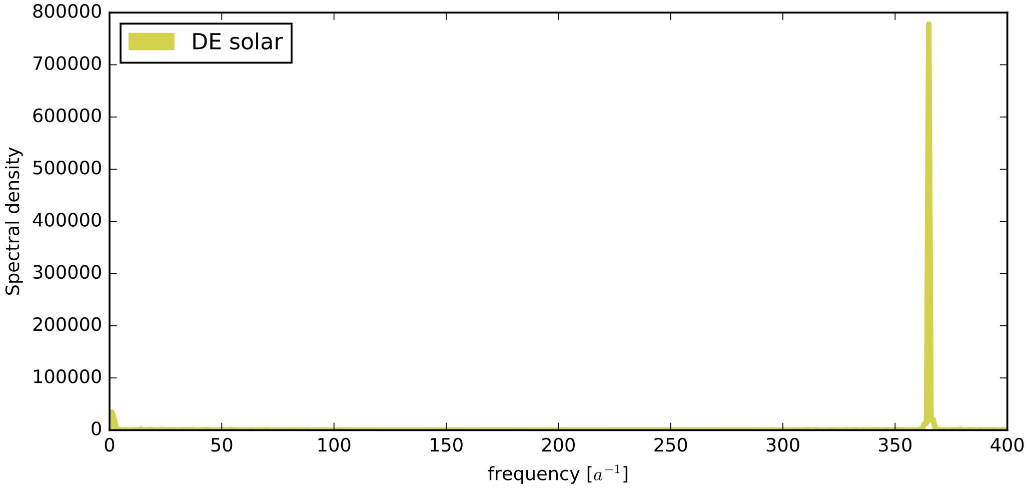
German onshore wind spectrum

If we Fourier transform, seasonal, synoptic and daily patterns become visible.



German solar spectrum

For solar, the daily pattern is dominant, also some seasonal modes.



Optimising Electricity Only

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 (investment **and** operation).

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

Linear optimisation of annual system costs

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

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

subject to

- meeting energy demand at each node n (e.g. countries) and time t (e.g. hours of year)
- wind, solar, hydro (variable renewables) availability $\forall\, n, t$
- electricity transmission constraints between nodes
- (installed capacity) $\leq$ (geographical potential for renewables)
- CO_2 constraint (95% reduction compared to 1990)
- Flexibility from gas plants, battery storage, hydrogen storage, networks

Linear optimisation problem

Objective is the minimisation of **total annual system costs**, composed of **capital costs** c_* (investment costs) and **operating costs** o_* (fuel ,etc.):

$$\min f(F_\ell, f_{\ell,t}, G_{i,s}, g_{i,s,t}) = \sum_\ell c_l F_\ell + \sum_{i,s} c_{i,s} G_{i,s} + \sum_{i,s,t} w_t o_{i,s} g_{i,s,t}$$

We optimise for i nodes, representative times t and transmission lines l:

- the transmission capacity F_ℓ of all the lines ℓ
- the flows $f_{\ell,t}$ on each line ℓ at each time t
- the generation and storage capacities $G_{i,s}$ of all technologies (wind/solar/gas etc.) s at each node i
- the dispatch $g_{i,s,t}$ of each generator and storage unit at each point in time t

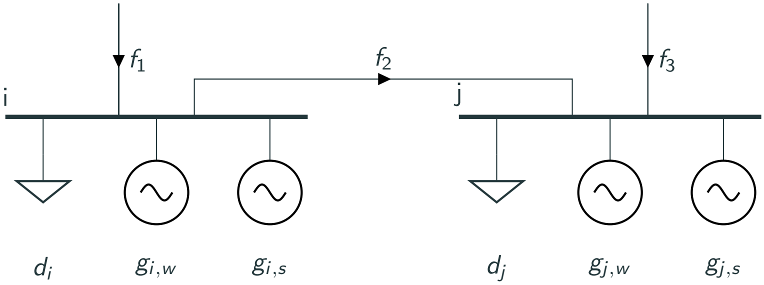
Representative time points are weighted w_t such that $\sum_t w_t = 365 * 24$ and the capital costs c_* are annualised, so that the objective function represents the annual system cost.

Constraints 1/6: Nodal energy balance

Demand $d_{i,t}$ at each node i and time t is always met by generation/storage units $g_{i,s,t}$ at the node or from transmission flows $f_{\ell,t}$ on lines attached at the node (Kirchhoff's Current Law):

$$\sum_s g_{i,s,t} - d_{i,t} = \sum_\ell K_{i\ell} f_{\ell,t} \qquad \leftrightarrow \qquad \lambda_{i,t}$$

Nodes are shown as thick busbars connected by transmission lines (thin lines):

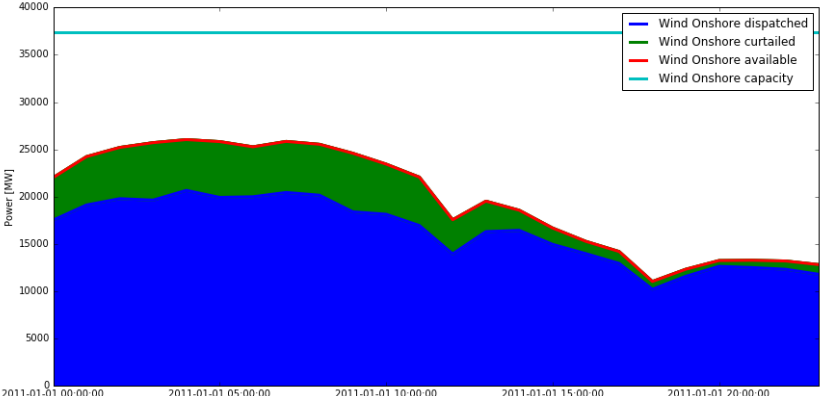


$g_{i,w} + g_{i,s} - d_i = f_2 - f_1$ $\qquad$ $g_{j,w} + g_{j,s} - d_j = -f_2 - f_3$

Constraints 2/6: Generation availability

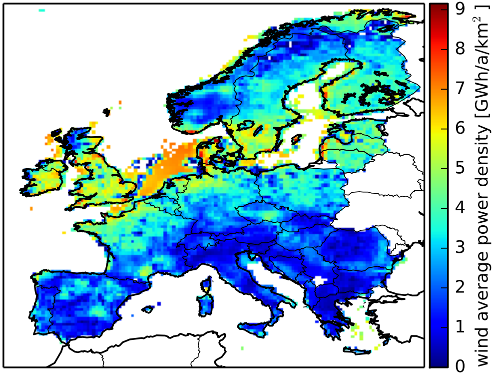
Generator/storage dispatch $g_{i,s,t}$ cannot exceed availability $G_{i,s,t} * G_{i,s}$, made up of per unit availability $0 \leq G_{i,s,t} \leq 1$ multiplied by the capacity $G_{i,s}$. The capacity is bounded by the installable potential $\hat{G}_{i,s}$.

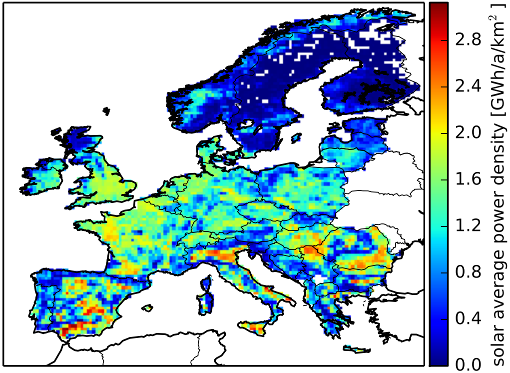
$$0 \leq g_{i,s,t} \leq G_{i,s,t} * G_{i,s} \leq G_{i,s} \leq \hat{G}_{i,s}$$



Installation potentials limited by geography

Expansion potentials are limited by **land usage** and **conservation areas**; potential yearly energy yield at each site limited by **weather conditions**:





Constraints 3/6: Storage consistency

Storage units such as batteries or hydrogen storage can work in both storage and dispatch mode. This has to be consistent with the state of charge $e_{i,s,t}$:

$$e_{i,s,t} = \eta_0 e_{i,s,t-1} + \eta_1 g_{i,s,t,\mathrm{store}} - \eta_2^{-1} g_{i,s,t,\mathrm{dispatch}}$$

The state of charge is limited by the energy capacity $E_{i,s}$:

$$0 \leq e_{i,s,t} \leq E_{i,s} \quad \forall i, s, t$$

There are efficiency losses η; hydroelectric dams can also have a river inflow.

Constraints 4/6: Kirchoff's Laws for Physical Flow

The linearised **power flows** f_ℓ for each line $\ell \in \{1, \dots L\}$ in an AC network are determined by the **reactances** x_ℓ of the transmission lines and the **net power injection** at each node p_i for $i \in \{1, \dots N\}$.

We have to satisfy Kirchoff's Laws, which can be compactly expressed using the **incidence matrix** $K \in \mathbb{R}^{N \times L}$ (boundary operator in homology theory) of the graph and the **cycle basis** $C \in \mathbb{R}^{L \times (L-N+1)}$ (kernel of K)

- Kirchoff's Current Law: $p_i = \sum_\ell K_{i\ell} f_\ell$
- Kirchoff's Voltage Law: $\sum_\ell C_{\ell c} x_\ell f_\ell = 0$

Constraints 5/6: Transmission Line Thermal Limits

Transmission flows cannot exceed the thermal capacities of the transmission lines (otherwise they sag and hit buildings/trees):

$$|f_{\ell,t}| \leq F_\ell$$

Constraints 6/6: Global constraints on CO_2 and transmission volumes

CO_2 limits are respected, given emissions $\varepsilon_{i,s}$ for each fuel source s:

$$\sum_{i,s,t} g_{i,s,t} \frac{\varepsilon_{i,s}}{\eta_s} \leq \text{CAP}_{\text{CO}_2} \qquad \leftrightarrow \qquad \mu_{\text{CO}_2}$$

We enforce a reduction of CO_2 emissions by 95% compared to 1990 levels, in line with German and EU targets for 2050.

Transmission volume limits are respected, given length d_ℓ and capacity F_ℓ of each line:

$$\sum_{\ell} d_\ell F_\ell \leq \text{CAP}_{\text{trans}} \qquad \leftrightarrow \qquad \mu_{\text{trans}}$$

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

Model Inputs and Outputs

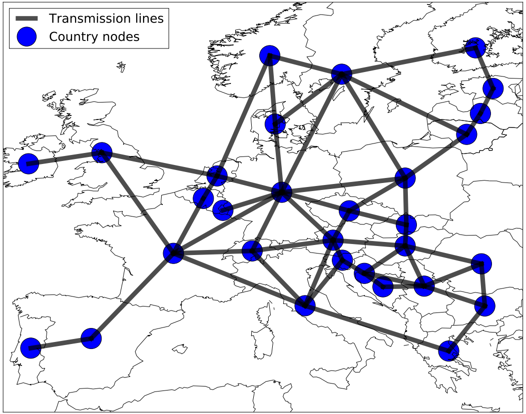
Inputs	Description
$d_{i,t}$	Demand (inelastic)
$G_{i,s,t}$	Per unit availability for wind and solar
$\hat{G}_{i,s}$	Generator installable potentials
various	Existing hydro data
various	Grid topology
η_*	Storage efficiencies
$c_{i,s}$	Generator capital costs
$o_{i,s,t}$	Generator marginal costs
c_ℓ	Line costs

$\rightarrow$

Outputs	Description
$G_{i,s}$	Generator capacities
$g_{i,s,t}$	Generator dispatch
F_ℓ	Line capacities
$f_{\ell,t}$	Line flows
λ_*, μ_*	Lagrange/KKT multipliers of all constraints
f	Total system costs

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

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

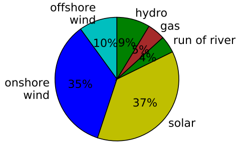
Quantity	Overnight Cost [€]	Unit	FOM [%/a]	Lifetime [a]
Wind onshore	1182	kW_{el}	3	20
Wind offshore	2506	kW_{el}	3	20
Solar PV	600	kW_{el}	4	20
Gas	400	kW_{el}	4	30
Battery storage	1275	kW_{el}	3	20
Hydrogen storage	2070	kW_{el}	1.7	20
Transmission line	400	MWkm	2	40

Interest rate of 7%, storage efficiency losses, only gas has CO_2 emissions, gas marginal costs.

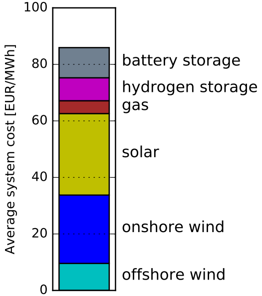
Batteries can store for 6 hours at maximal rating (efficiency 0.9×0.9), hydrogen storage for 168 hours (efficiency 0.75×0.58).

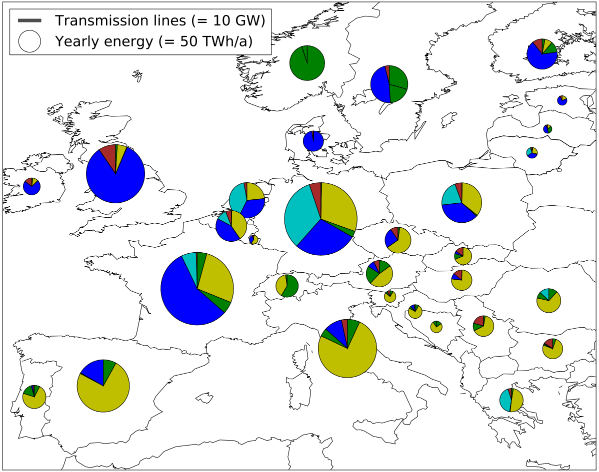
Costs: No interconnecting transmission allowed

Technology by energy:



Average cost **€86/MWh**:

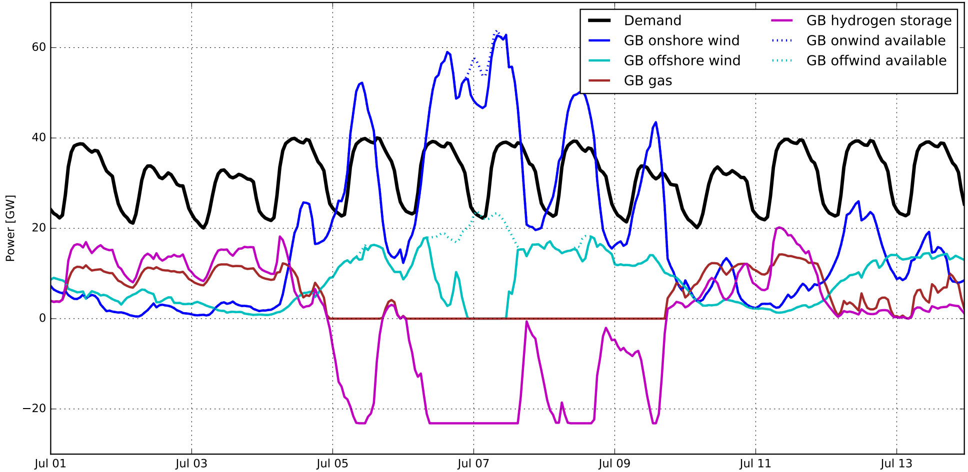




Countries must be self-sufficient at all times; lots of storage and some gas to deal with fluctuations of wind and solar.

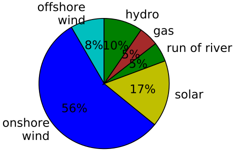
Dispatch with no interconnecting transmission

For Great Britain with no interconnecting transmission, excess wind is either stored as hydrogen or curtailed:

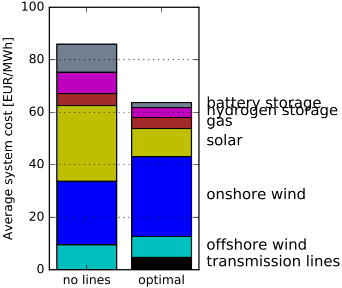


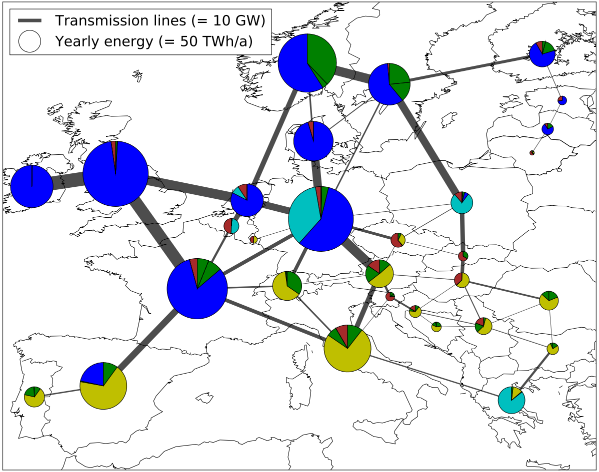
Costs: Cost-optimal expansion of interconnecting transmission

Technology by energy:



Average cost **€64/MWh**:

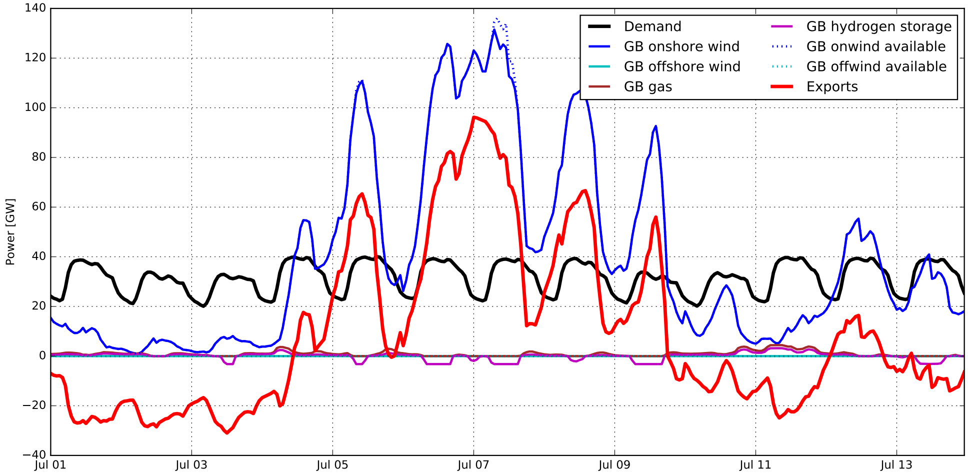




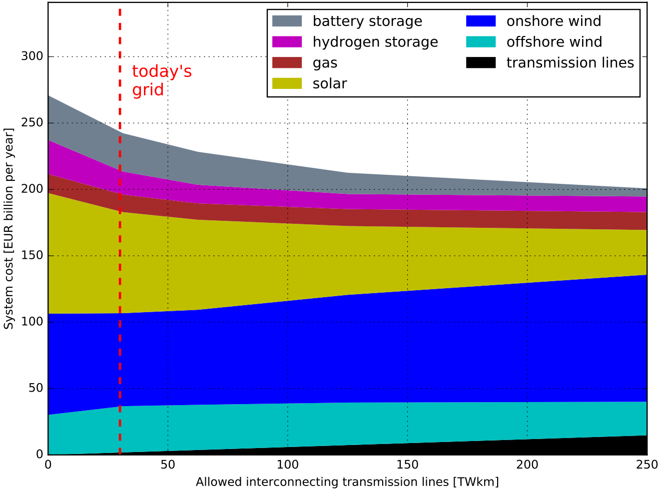
Large transmission expansion; onshore wind dominates. This optimal solution may run into public acceptance problems.

Dispatch with cost-optimal interconnecting transmission

Almost all excess wind can be now be exported:

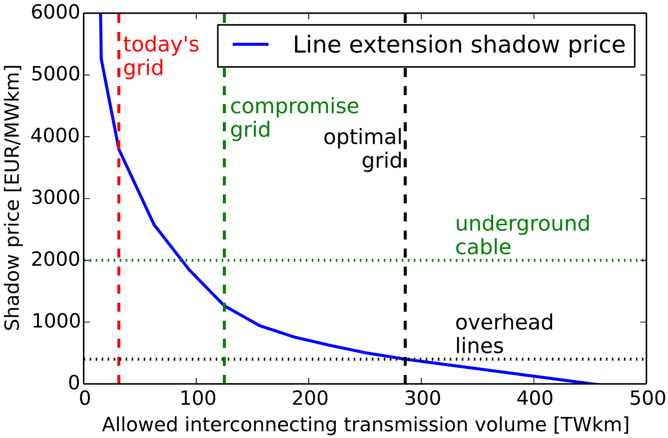


Electricity Only Costs Comparison



- Average total system costs can be as low as € 64/MWh
- Energy is dominated by wind (64% for the cost-optimal system), followed by hydro (15%) and solar (17%)
- Restricting transmission results in more storage to deal with variability, driving up the costs by up to 34%
- Many benefits already locked in at a few multiples of today's grid

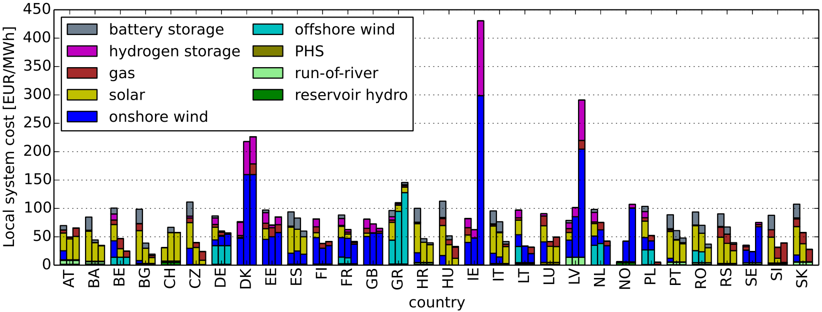
Grid expansion CAP shadow price as CAP relaxed



- With overhead lines the optimal system has around 7 times today's transmission volume
- With underground cables (5-8 times more expensive) the optimal system has around 3 times today's transmission volume

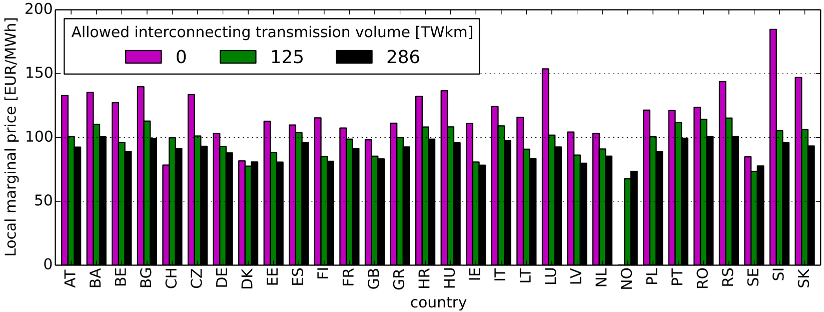
Distribution of costs

As transmission volumes increase, costs become more unequally distributed...

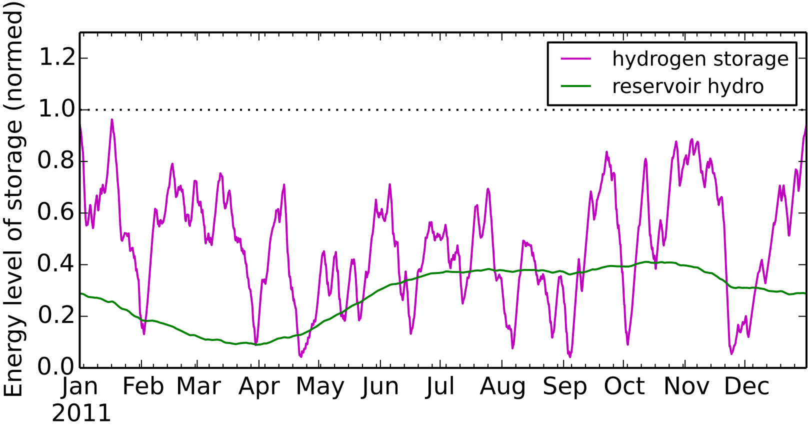


Distribution of prices

...while market prices converge.

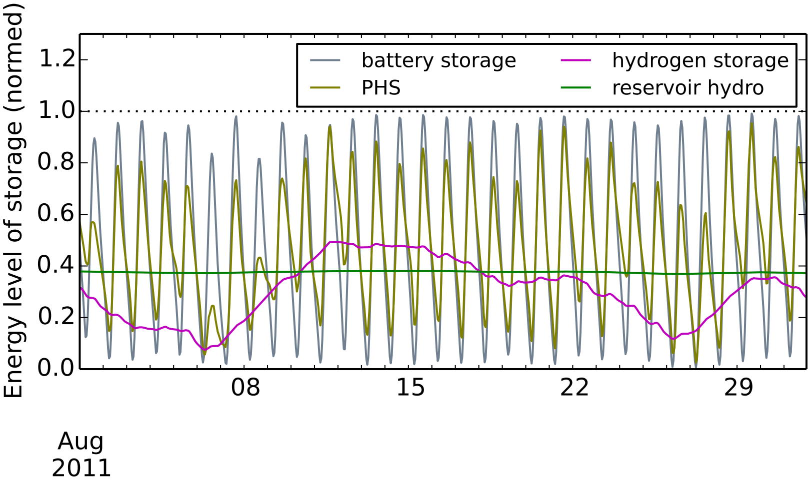


Different flexibility options have difference temporal scales



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

Different flexibility options have difference temporal scales

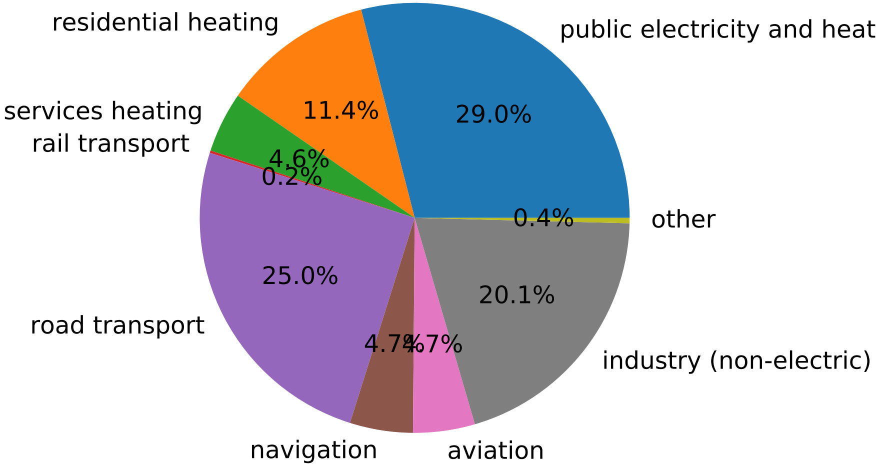


- Pumped hydro and battery storage are **daily**

Electricity, Heat and Transport

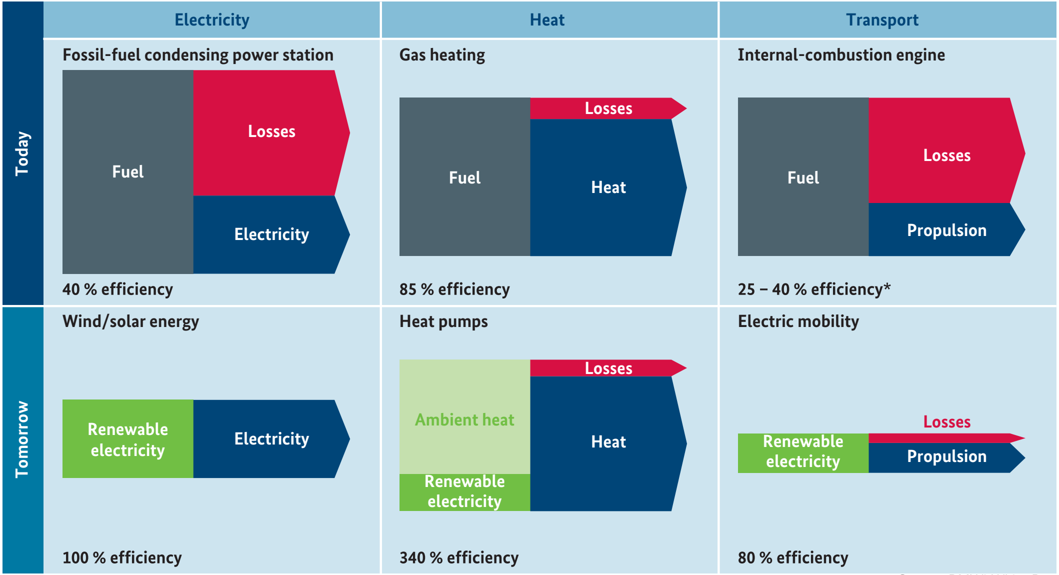
Include other sectors: heating and land transport

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

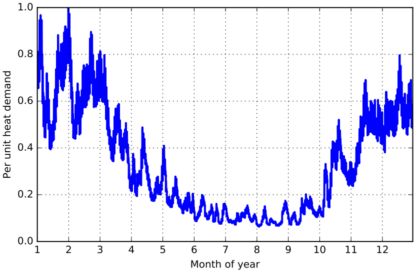


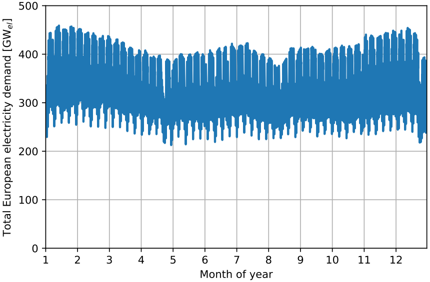
Source: BMWi White Paper 2015

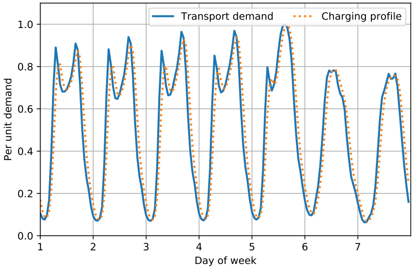
Challenge: Heating and transport demand highly peaked

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

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







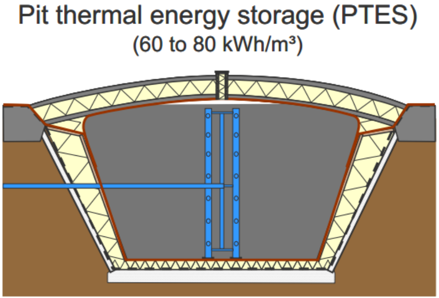
Sector Coupling

Idea: Couple the electricity sector to heating and mobility.

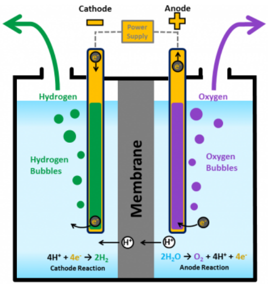
This enables decarbonisation of these sectors **and** offers more flexibility to the power system.

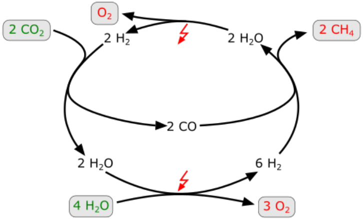
Battery electric vehicles can change their charging pattern to benefit the system and even feed back into the grid if necessary

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



Power-to-Gas (P2G)



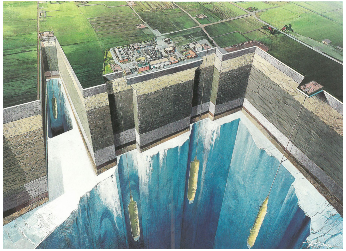


Power-to-Gas (P2G) describes concepts to use electricity to electrolyse water to **hydrogen** H_2 (and oxygen O_2). We can combine hydrogen with carbon oxides to get **hydrocarbons** such as methane CH_4 (main component of natural gas) or liquid fuels C_nH_m.

These can be used for **hard-to-defossilise sectors**:

- **dense fuels** for transport (planes, ships)
- **steel-making**
- **chemicals industry**
- **high-temperature heat**
- **heat for buildings**

Power-to-Gas (P2G)



Gases and liquids are easy to **store** and **transport** than electricity.

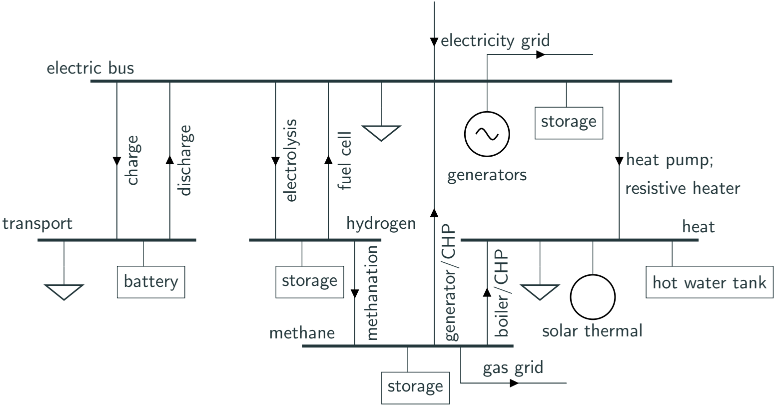
Storage capacity of the German natural gas network in terms of energy: ca 200 TWh. In addition, losses in the gas network are small.

(NB: Volumetric energy density of hydrogen, i.e. MWh/m^3, is around three times lower than natural gas.)

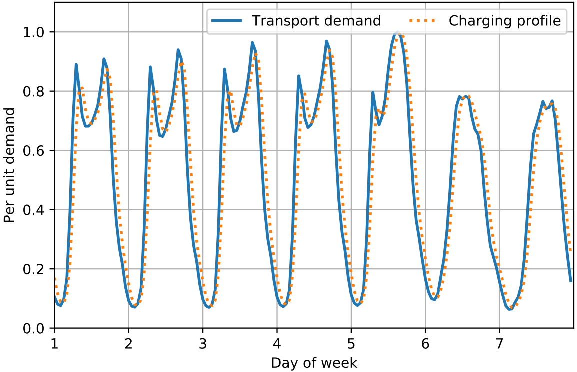
Pipelines can carry many GW underground, out of sight.

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.



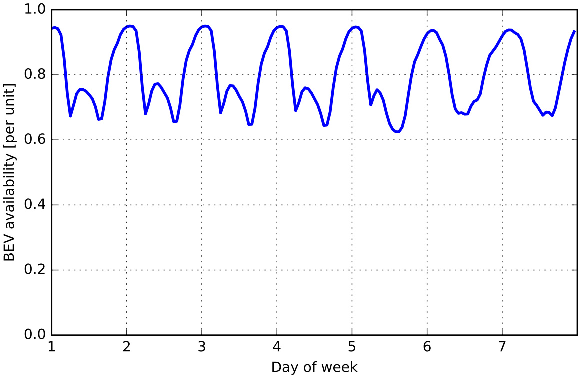
Transport sector: Electrification of Transport



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.

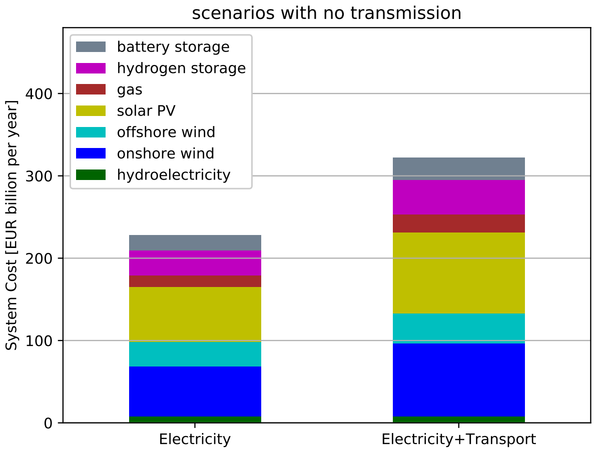
Transport sector: Battery Electric Vehicles



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

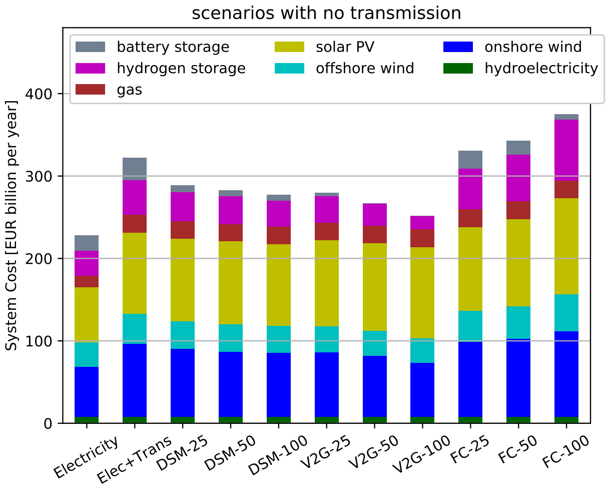
- Passenger cars to Battery Electric Vehicles (BEVs), 50 kWh battery available and 11 kW charging power
- Can participate in DSM and V2G, depending on scenario (state of charge returns to at least 75% every morning)
- All BEVs have time-dependent availability, averaging 80%, max 95% (at night)
- No changes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

Coupling Transport to Electricity



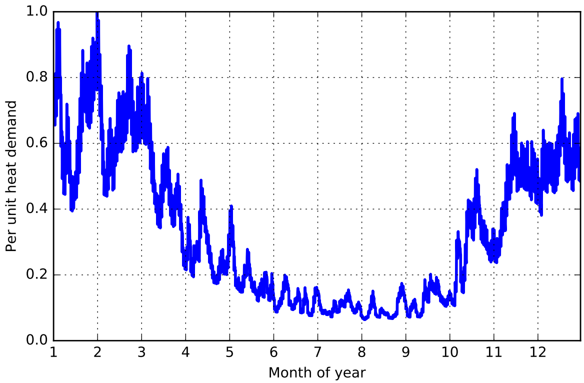
- If all road and rail transport is electrified, electrical demand increases 37%
- Costs increase 41% because charging profiles are very peaked (NB: distribution grid costs NOT included)
- Stronger preference for PV and storage in system mix because of daytime peak
- Can now use flexible charging

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.

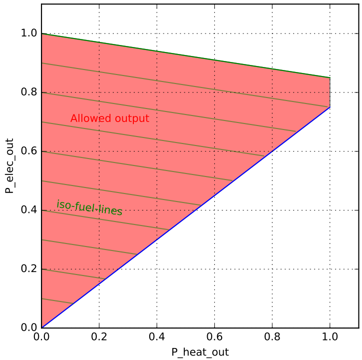
Decentral individual heating can be supplied by:

- 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:



Heat pumps use external work (usually electricity) to move thermal energy in the opposite direction of spontaneous heat transfer, e.g. by absorbing heat from a cold space (**source**) and release it into a warmer one (**sink**).

When the sink is a building, the source is usually the outside air or ground.

Air-source heat pumps (ASHP):

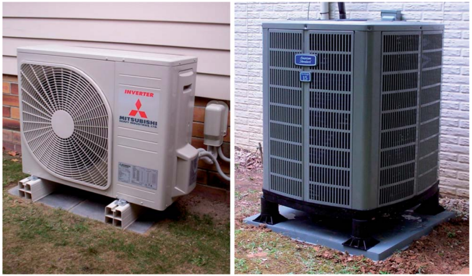


Fig. 5 Examples of air source heat pumps from Mitsubishi (left) and American Standard (right).

Ground-source heat pumps (GSHP):

Fig. 6 The installation of ground loops for GSHP systems using slinky horizontal pipes (left) and a vertical borehole (right)

Source: Staffell et al, 2012

The **coefficient of performance** (COP) is defined as the ratio:

$$COP = \frac{\text{thermal energy moved from source to sink}}{\text{input work (electricity)}} \propto \frac{1}{T_{\text{sink}} - T_{\text{source}}}$$

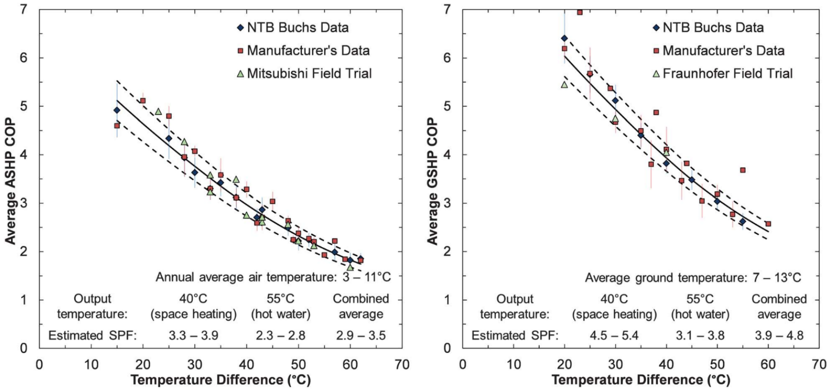
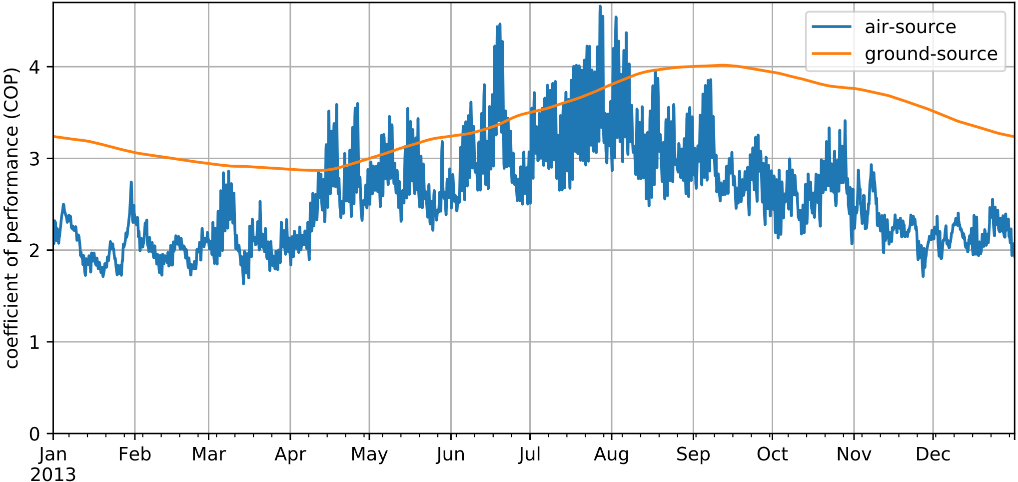


Fig. 9 Average heating coefficient of performance for air and ground source heat pumps (left and right, respectively) based on data taken from industrial surveys and field trials.[31,80–82] The inset tables show the expected performance for UK conditions.

Source: Staffell et al, 2012

Heat pumps

Example of time-dependent COP for air-source and ground-source heat pumps in a location in Germany. The ground temperature is more stable over the year, leading to a stable COP.

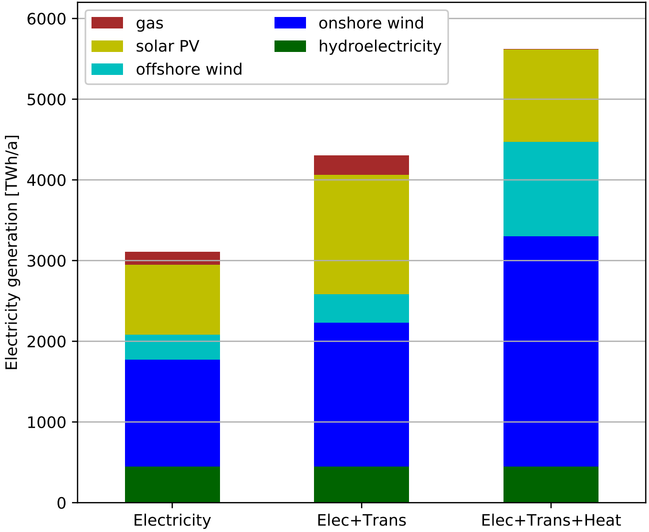


Cost and other assumptions

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

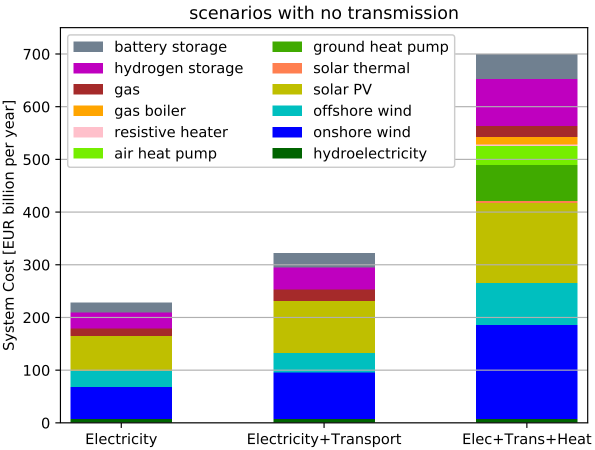
Costs oriented towards Henning & Palzer (2014, Fraunhofer ISE) and Danish Energy Database

Coupling Heating to Transport and Electricity: Electricity Demand



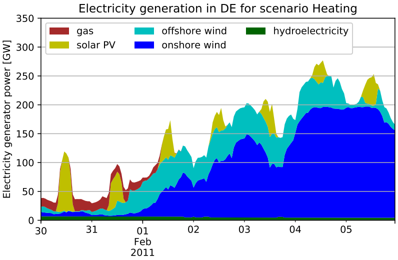
- To 4062 TWh_{el}/a demand from electricity and transport, 3585 TWh_{th}/a heating demand is added
- Much of the heating demand is met via electricity, but with high efficiency from heat pumps
- Electricity demand 80% higher than current electricity demand
- Efficiency savings can reduce this . . .

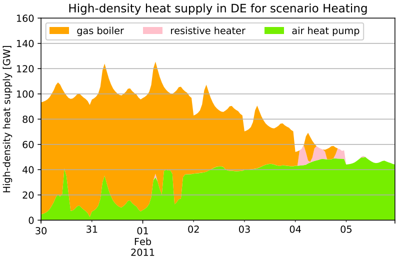
Coupling Heating to Transport and Electricity: Costs



- 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



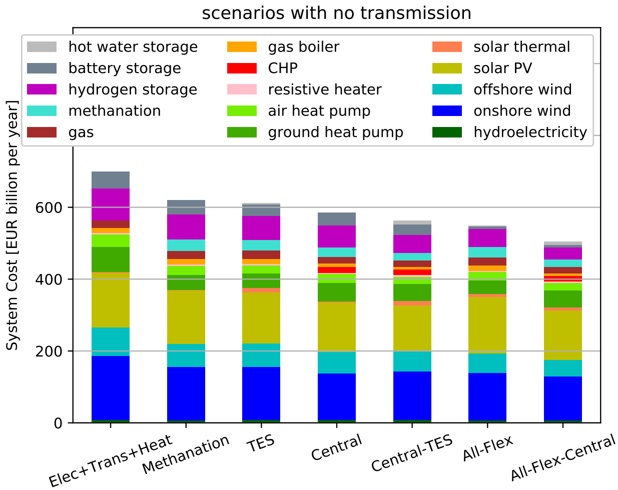


There are difficult periods in winter with:

- **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.

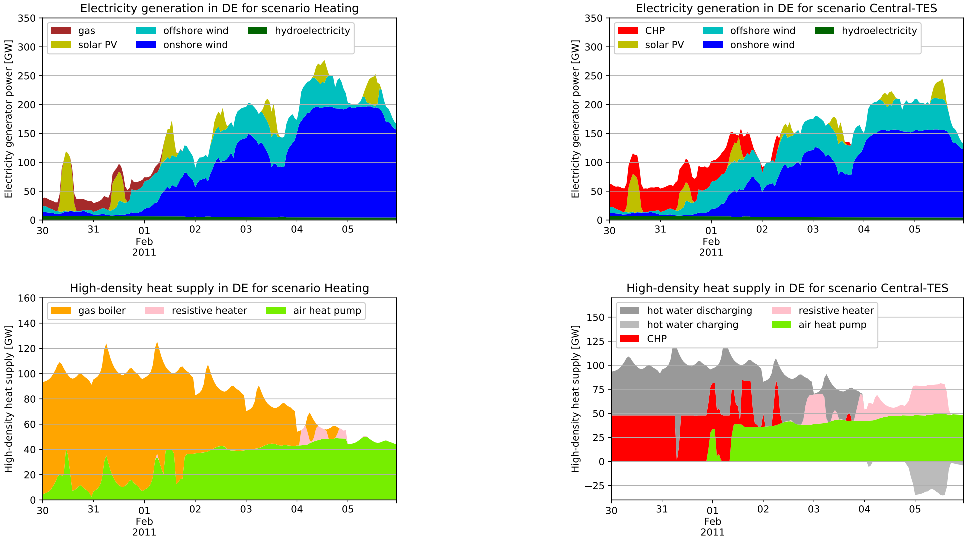
Using heating flexibility



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

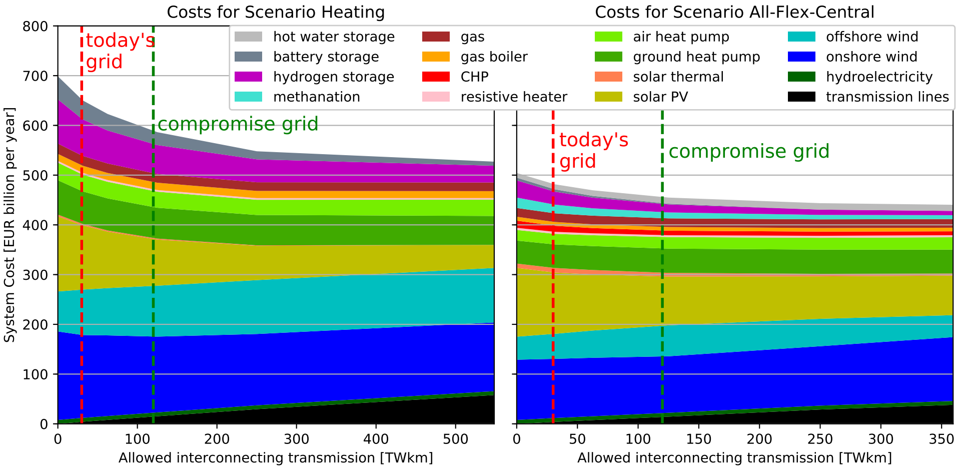
- production of **synthetic methane**
- centralised **district heating** in areas with dense heat demand
- long-term **thermal energy storage** (TES) in district heating networks
- **demand-side management** and vehicle-to-grid from battery electric vehicles (BEV)

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



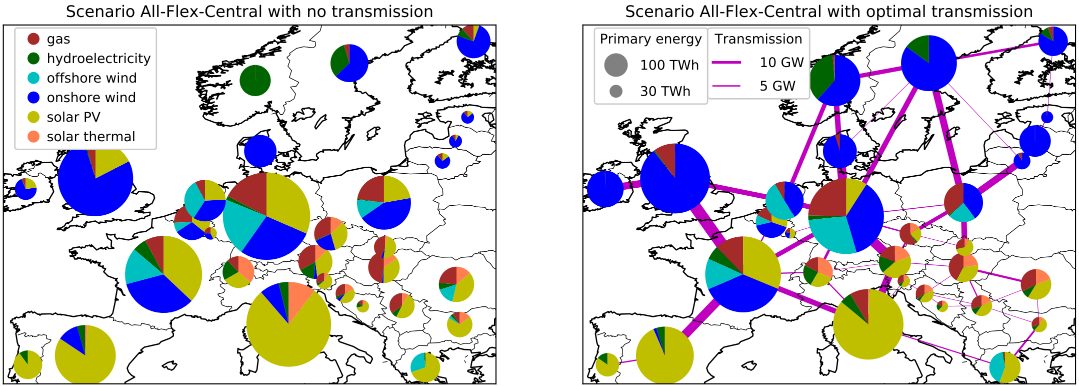
Sector Coupling with All Extra Flexibility (V2G and TES)

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

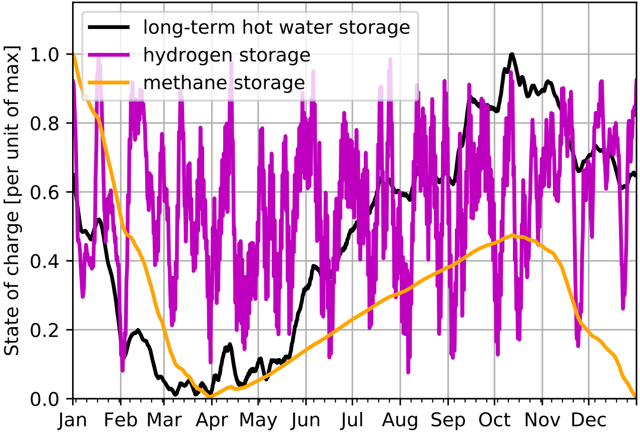


Spatial distribution of primary energy for All-Flex-Central

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

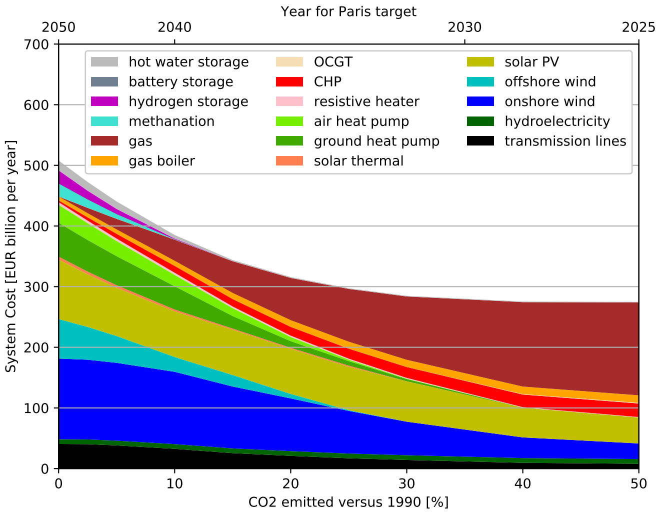


Storage energy levels: different time scales



- 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

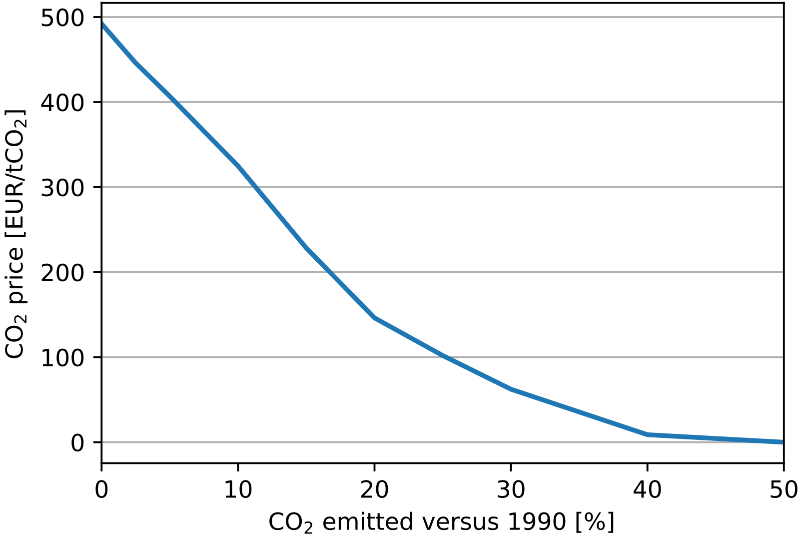
Pathway down to zero emissions in electricity, heating and transport



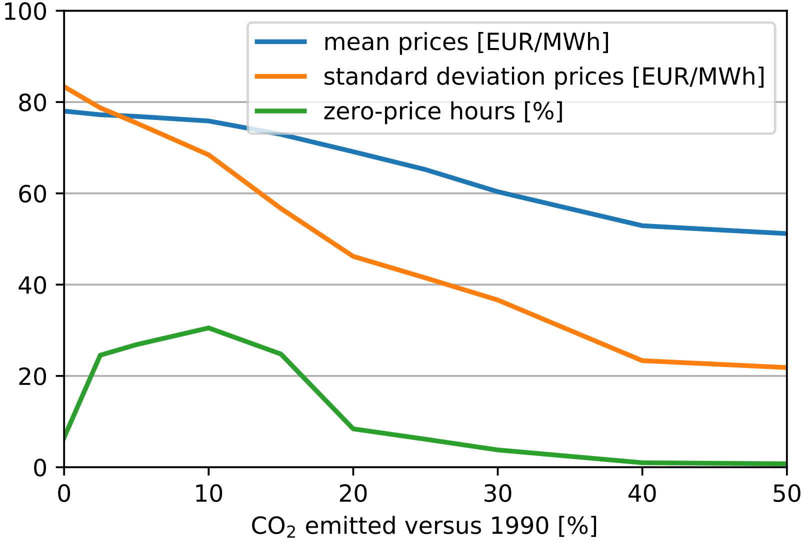
If we look at investments to eradicate CO_2 emissions in electricity, heating and transport we see:

- 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

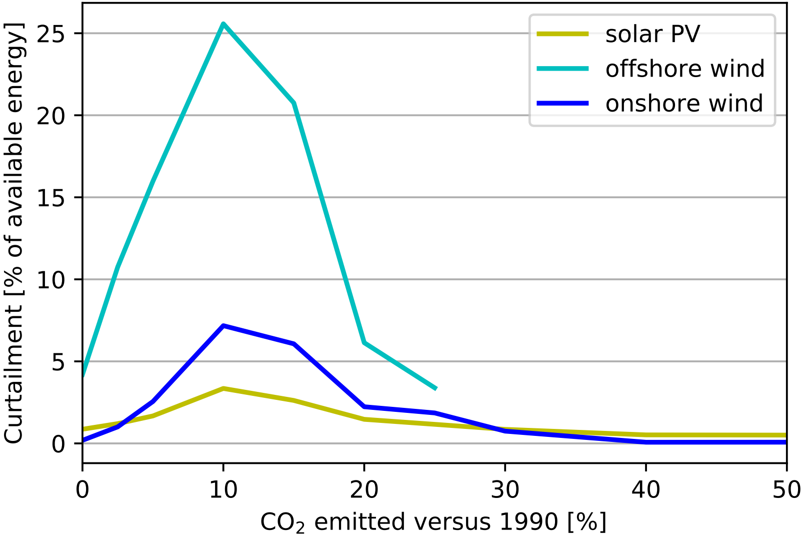
CO_2 price rises to displace cheap natural gas



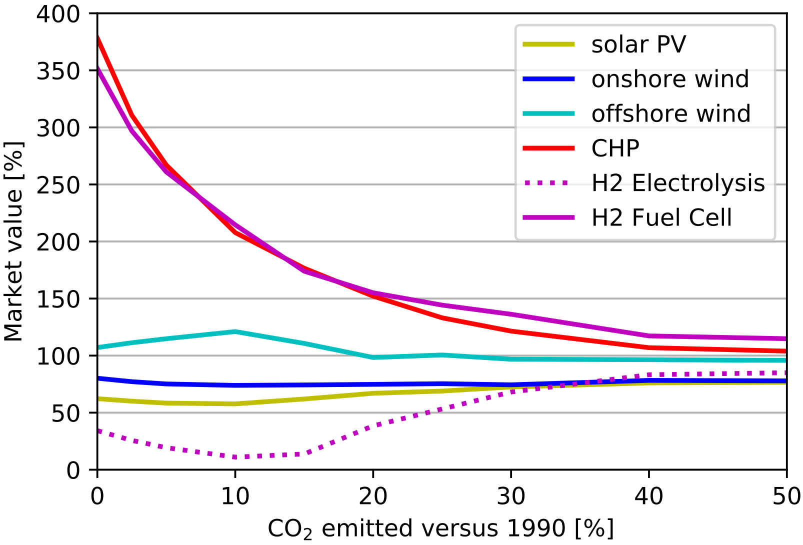
Electricity price statistics: zero-price hours gone thanks to P2G



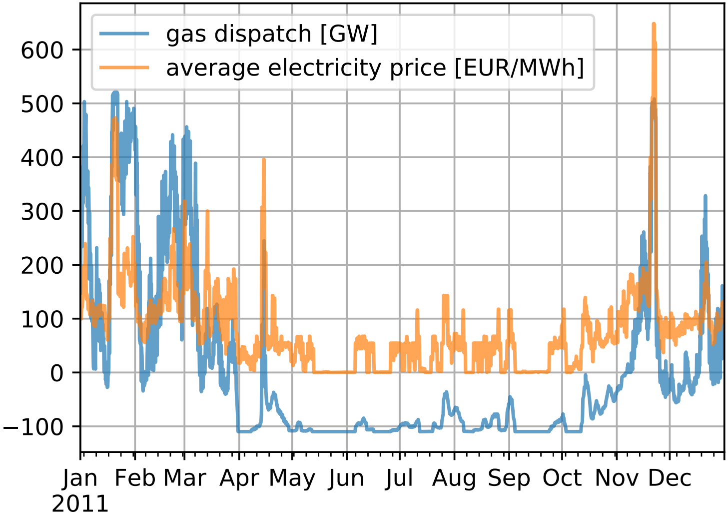
Curtailment also much reduced



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

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

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

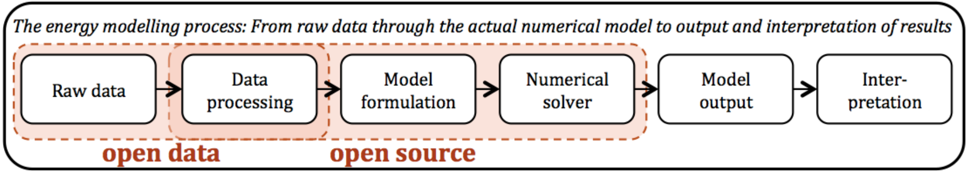
Iron & Steel	70% from scrap, rest from direct reduction with 1.7 $MWhH_2$/tSteel + electric arc (process emissions 0.03 tCO_2/tSteel)
Aluminium	80% recycling, for rest: methane for high-enthalpy heat (bauxite to alumina) followed by electrolysis (process emissions 1.5 tCO_2/tAl)
Cement	Waste and solid 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 process emissions are captured; direct air capture (DAC); synthetic methane and liquid hydrocarbons; transport and sequestration costs 20 €/tCO_2

Open Energy Modelling

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:

openmod open energy modelling initiative

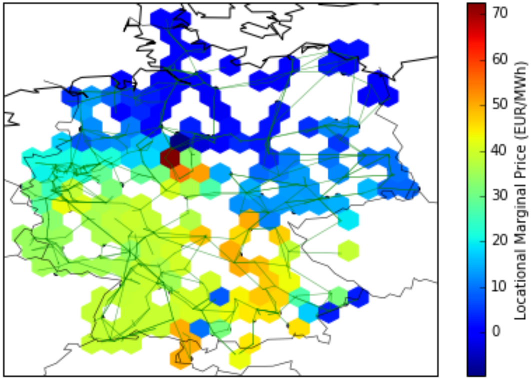
openmod-initiative.org

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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