Modelling the electricity grid for deep carbon dioxide reductions in all sectors

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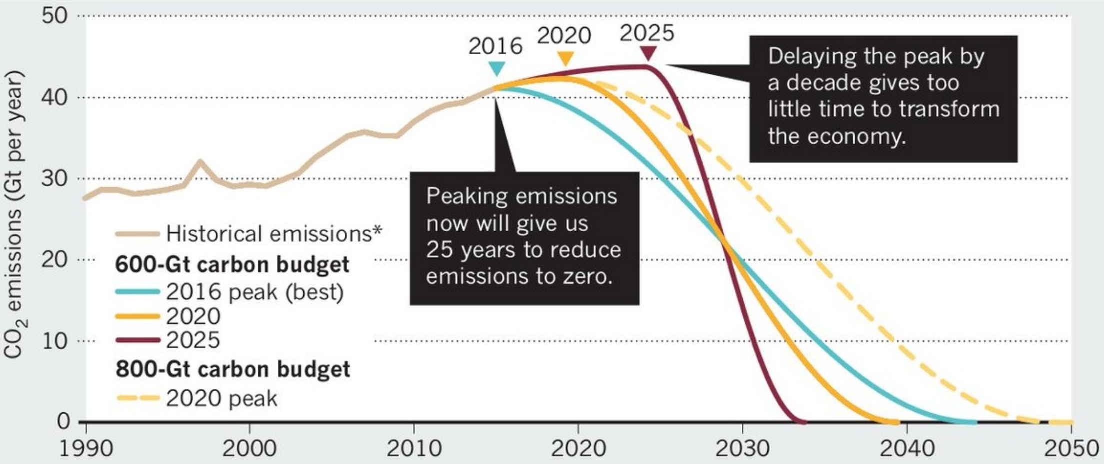
The Challenge

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')

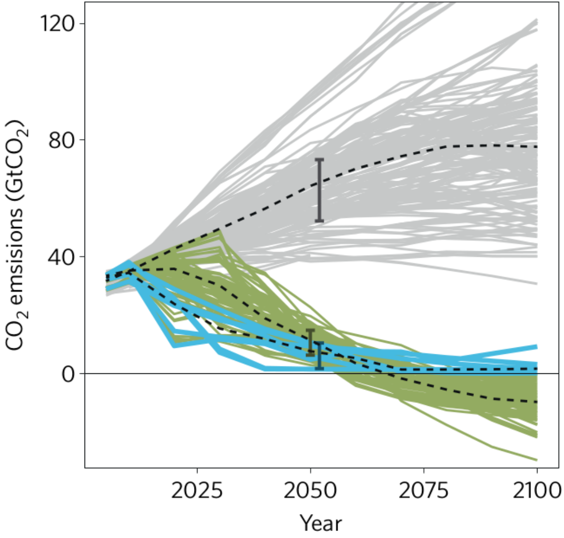


Source: 'Three years to safeguard our climate,' Nature, 2017

The Global Carbon Dioxide Challenge: 2C Looking to 2100

The budget to 2050 depends also on whether we allow net negative emissions, for which negative emission technologies (NET) are required to suck CO_2 out of the atmosphere, such as bioenergy with CCS (BECCS), direct air capture (DAC), enhanced weathering, afforestation, reforestation and ocean fertilisation.

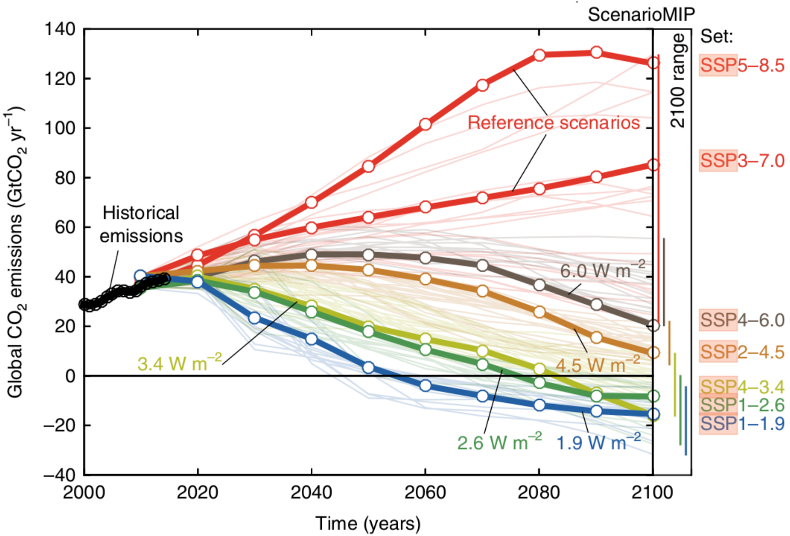
- Blue: 2C compliant without NET
- Green: 2C compliant with NET
- Grey: other non-compliant scenarios



Source: van Vuuren et al, Nature Energy, 2017

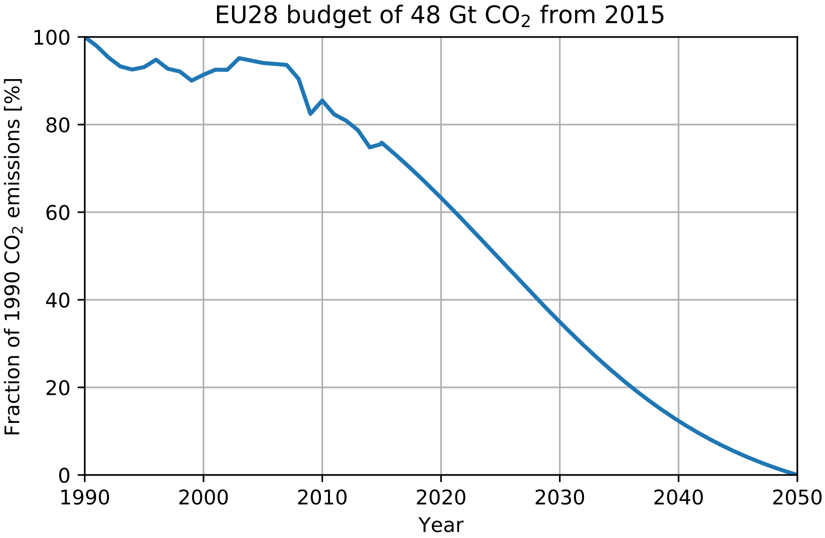
The Global Carbon Dioxide Challenge: 1.5C Looking to 2100

- Radiative forcing of 1.9 W/m^2 corresponds to 66% change of achieving 1.5C limit
- Scenarios that are 1.5C compliant require net zero CO_2 emissions by 2050 followed by net negative emissions until 2100



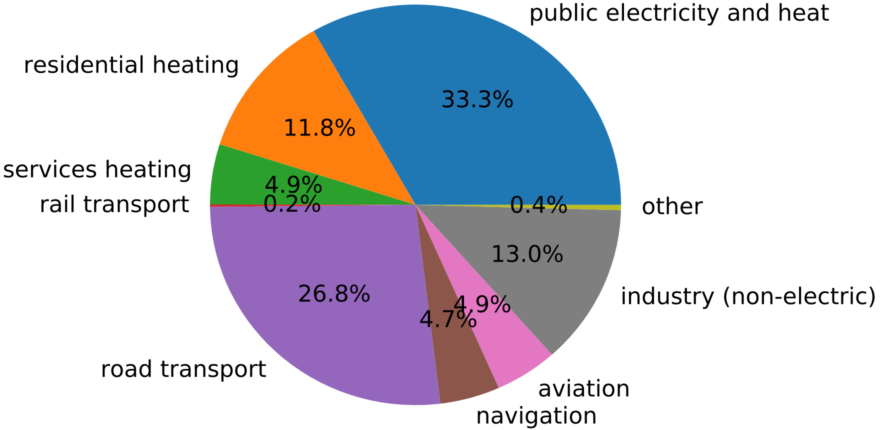
Source: Rogelj et al, Nature Climate Change, 2018

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

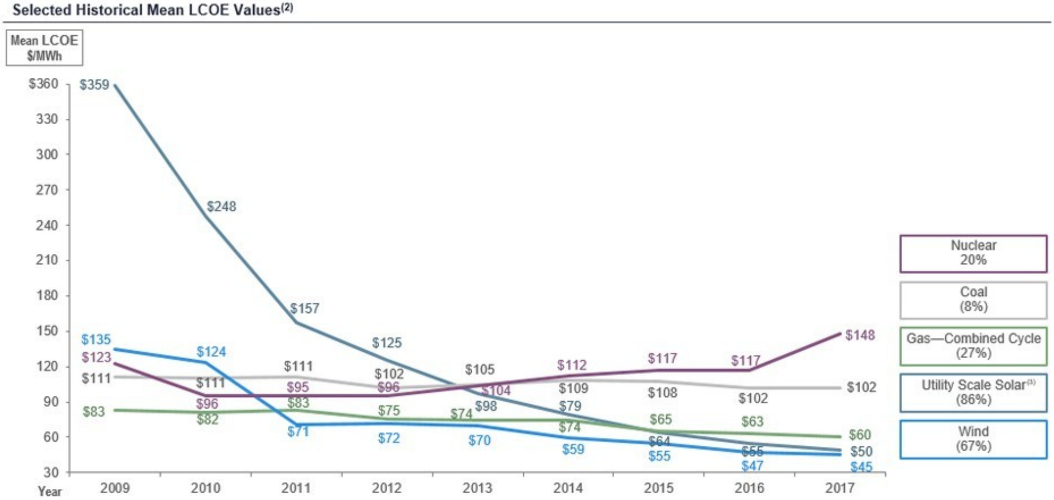
...but electification of other sectors is critical for decarbonisation

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

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



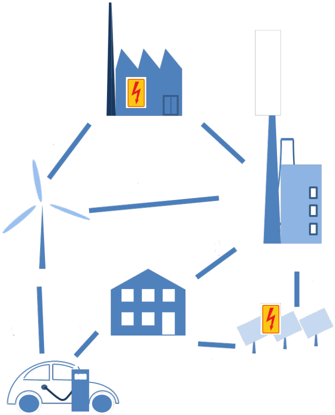
Source: Lazard's LCOE Analysis V11

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

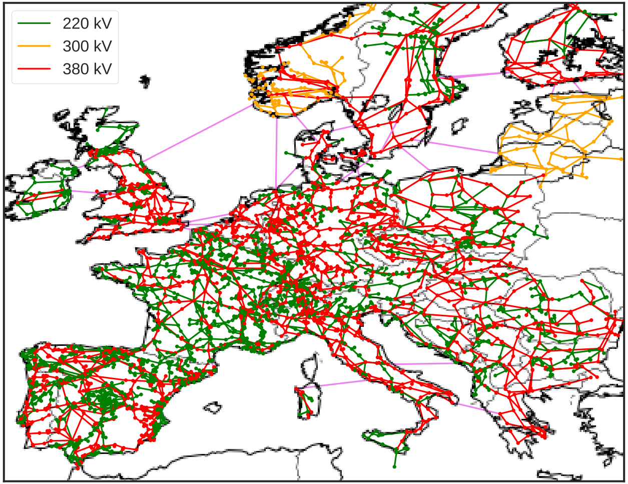
The Energy Transition is not just a case of “cost optimisation under CO_2 constraints”. There are also **social and political constraints**.
We need to assess:

- 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.

Problem 1: Spatial resolution

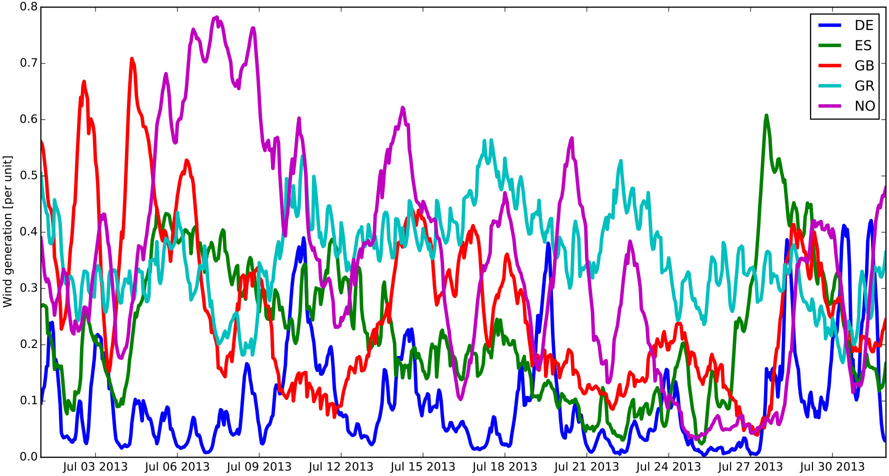
Need high **spatial resolution** to represent VRE variations and transmission constraints.



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

Problem 2: Temporal resolution

Need high **temporal resolution** to represent load and VRE resource variability, correlations and extreme events. Wind generation in Europe in July 2013:

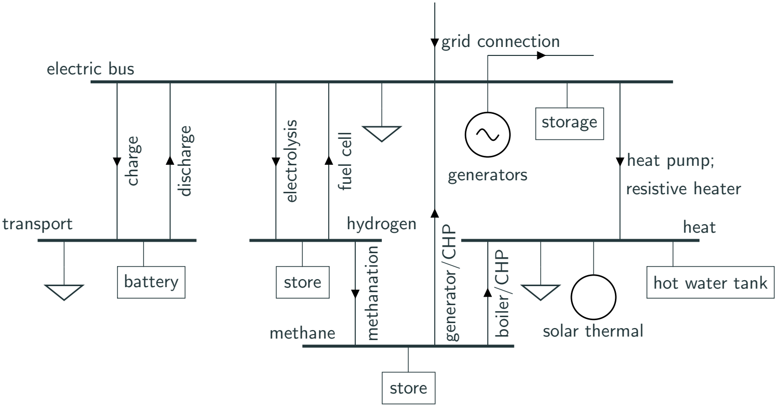


Problem 3: Model complexity

Large number of interacting **interdependencies** between places, times and sectors.

What can we **simplify** while retaining accuracy?

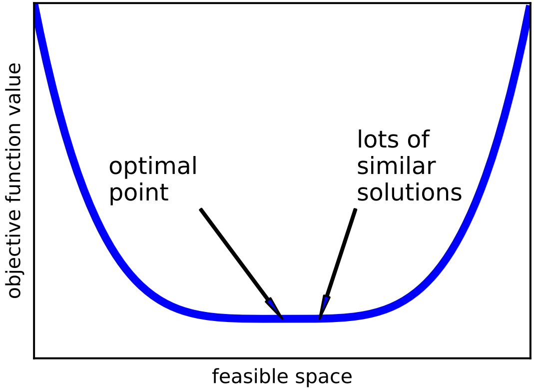
What should we **co-optimise** and what can be treated separately?



Problem 4: Understand Solution Space

How **sensitive** is our solution to changes in the inputs?

Researchers have focused in the past on **local** linear sensitivity, but it's also important to look at the **global behaviour** of the objective function on the feasible space, to understand where the costs increase the fastest.



Overarching goal

Find the **sweet spot** where:

- Computation time is finite (i.e. a week)
- Temporal resolution is "good enough"
- Spatial resolution is "good enough"
- Model detail is "good enough"

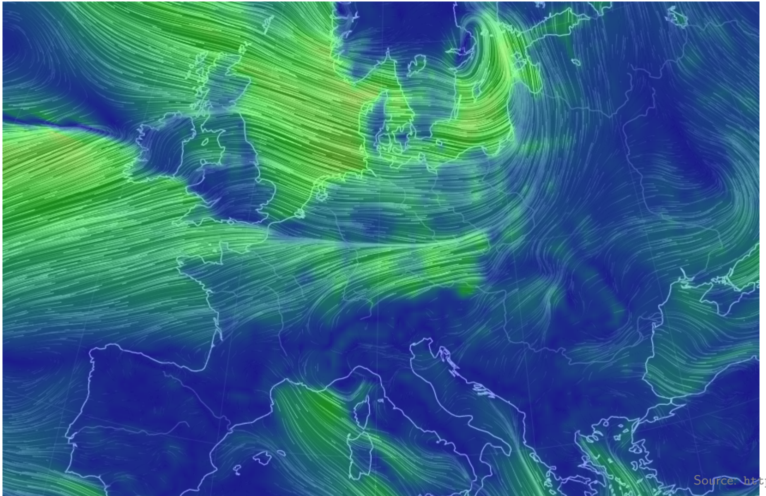
AND quantify the error we make by only being "good enough" (e.g. are important metrics $\pm 10\%$ or $\pm 50\%$ correct?)

AND be sure we're got a handle on all sectoral interdependencies that might affect the results.

Variability of Wind, Solar & Demand

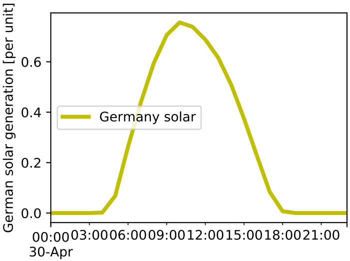
Variability: Different wind conditions over Europe

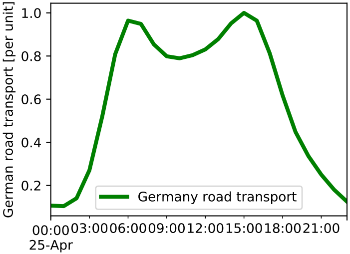
Wind, solar and demand vary at different time scales, e.g. wind is particularly affected by large weather systems at the **continental scale** that pass in 1-2 weeks. See videos of wind and solar.



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

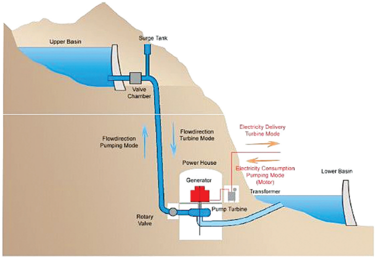
Daily variations: challenges and solutions



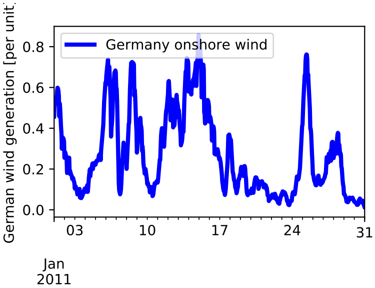


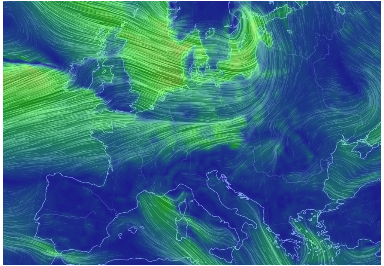
Daily variations in supply and demand can be balanced by

- **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**



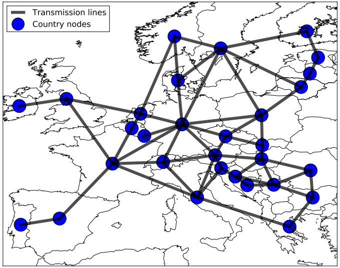
Synoptic variations: challenges and solutions



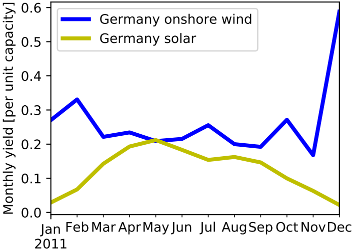


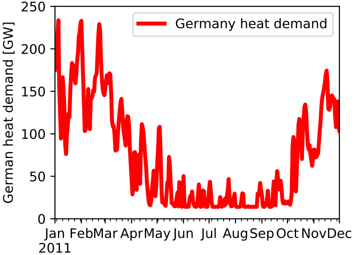
Synoptic variations in supply and demand can be balanced by

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



Seasonal variations: challenges and solutions

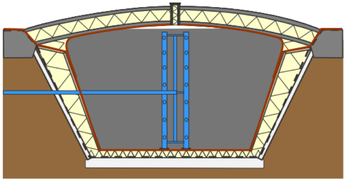




Seasonal variations in supply and demand can be balanced by

- **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)



Warm-Up: 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 (i.e. constraints for public acceptance)

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:

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

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
- (installed capacity) $\leq$ (**geographical potentials** for renewables)
- **CO_2 constraint** (95% reduction compared to 1990)
- **Flexibility** from gas plants, battery storage, hydrogen storage, networks

Optimisation problem

Optimisation problems take the following form:

We have an **objective function** $f : \mathbb{R}^k \to \mathbb{R}$ which is to be either maximised or minimised:

$$\max_x f(x)$$

$[x = (x_1, \ldots x_k)]$ subject to some **constraints** within $\mathbb{R}^k$:

$$\begin{array}{cccc} g_i(x) = c_i & \leftrightarrow & \lambda_i & i = 1, \ldots n \\ h_j(x) \leq d_j & \leftrightarrow & \mu_j & j = 1, \ldots m \end{array}$$

We introduce KKT 'Lagrange' multipliers λ_i and μ_j for each constraint equation.

The constraints define a **feasible space** within $\mathbb{R}^k$.

Lagrangian

We now study the **Lagrangian function**

$$\mathcal{L}(x, \lambda, \mu) = f(x) + \sum_i \lambda_i \left[c_i - g_i(x)\right] + \sum_j \mu_j \left[d_j - h_j(x)\right]$$

which is similar to the Lagrangian from Lagrangian mechanics, except that there are no time dynamics and we've included not just equality constraints, but also **inequality** constraints.

The stationary points of $\mathcal{L}(x, \lambda, \mu)$ tell us about the optima of $f(x)$ given the constraints.

The KKT variables can be intepreted as the change in the objective function, i.e. the cost/gain, as we relax the constraints

$$\lambda_i = \frac{\partial \mathcal{L}}{\partial c_i} \qquad \mu_j = \frac{\partial \mathcal{L}}{\partial d_j}$$

The KKT variables have an economic interpretation as the **shadow prices** of the constraints, i.e. the change in the value of the objective function $f(x^*)$ as we relax/tighten the constraints.

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.):

$$\min f(\bar{P}_\ell, \bar{g}_{n,s}, g_{n,s,t}) = \sum_\ell c_l \bar{P}_\ell + \sum_{n,s} c_{n,s}\bar{g}_{n,s} + \sum_{n,s,t} w_t o_{n,s} g_{n,s,t}$$

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

- the transmission capacity $\bar{P}_\ell$ of all the lines ℓ
- the generation and storage capacities $\bar{g}_{n,s}$ of all technologies (wind/solar/gas etc.) s at each node n
- the dispatch $g_{n,s,t}$ 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.

Model Inputs and Outputs

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

$\rightarrow$

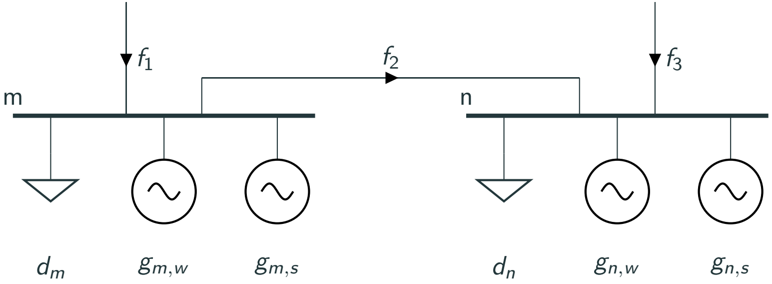
Outputs	Description
$\bar{g}_{n,s}$	Generator capacities
$g_{n,s,t}$	Generator dispatch
$\bar{P}_\ell$	Line capacities
$f_{\ell,t}$	Line flows
λ_*, μ_*	Lagrange/KKT multipliers of all constraints
f	Total system costs

Constraints 1/5: Nodal energy balance

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

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

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



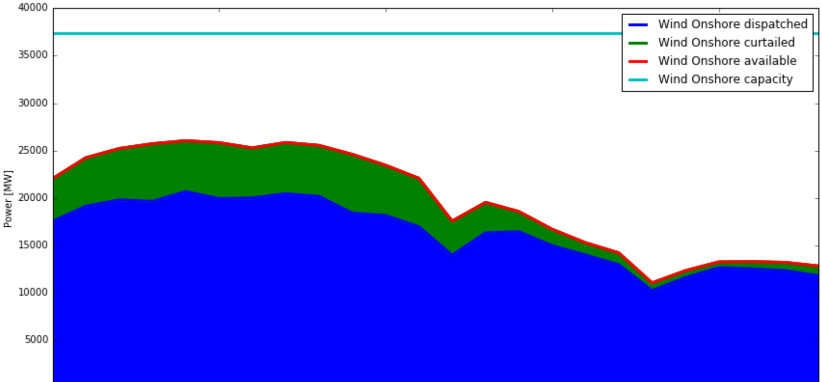
$d_m = g_{m,w} + g_{m,s} + f_1 - f_2$

$d_n = g_{n,w} + g_{n,s} + f_2 + f_3$

Constraints 2/5: Generation availability

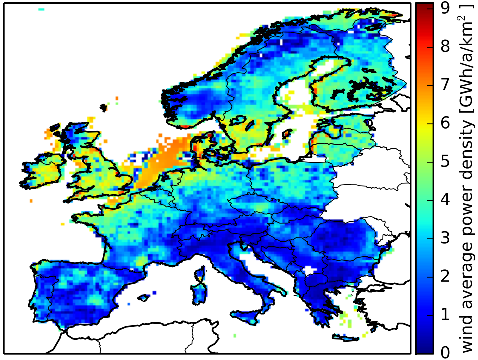
Generator/storage dispatch $g_{n,s,t}$ cannot exceed availability $\bar{g}_{n,s,t} * \bar{g}_{n,s}$, made up of per unit availability $0 \leq \bar{g}_{n,s,t} \leq 1$ multiplied by the capacity $\bar{g}_{n,s}$. The capacity is bounded by the installable potential $\hat{g}_{n,s}$.

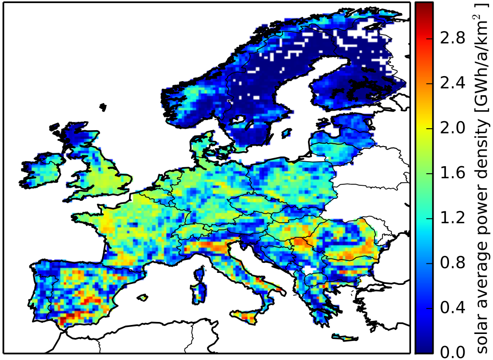
$$0 \leq g_{n,s,t} \leq \bar{g}_{n,s,t} * \bar{g}_{n,s} \leq \bar{g}_{n,s} \leq \hat{g}_{n,s}$$



Expansion potentials for wind and solar

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





Constraints 3/5: Storage consistency

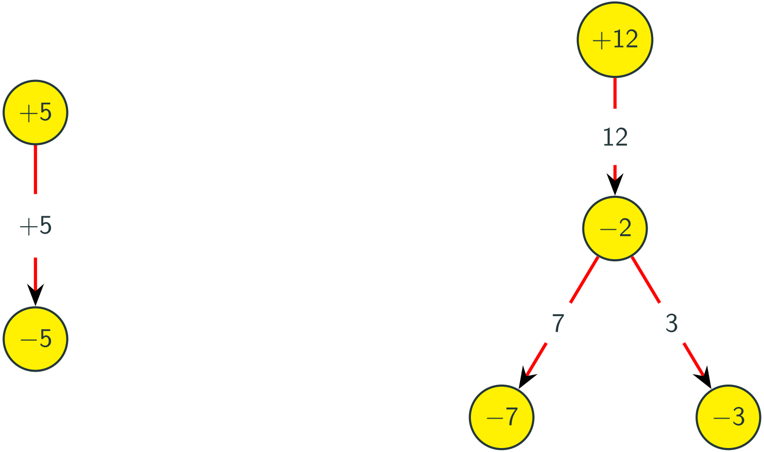
Storage units such as batteries or hydrogen storage can work in both storage and dispatch mode. They have a limited energy capacity (state of charge).

$$soc_{n,t} = \eta_0 soc_{n,t-1} + \eta_1 g_{n,t,\mathrm{store}} - \eta_2^{-1} g_{n,t,\mathrm{dispatch}}$$

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

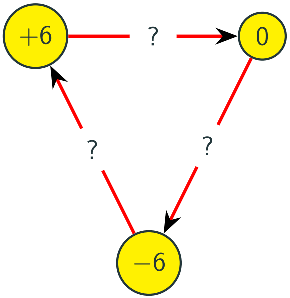
Kirchhoff's Current Law (KCL)

KCL (constraint 1/5) enforces energy conservation at each vertex (the power imbalance equals what goes out minus what comes in).

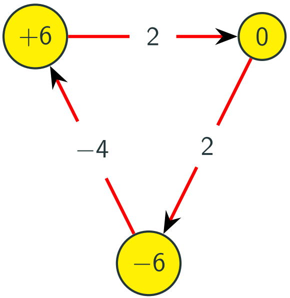


Kirchhoff's Voltage Law (KVL)

However, KCL isn't enough to determine the flow as soon as there are **closed cycles** (i.e. multiple paths between pairs of nodes) in the network. In addition, we need **Ohm's law** in combination with KVL: voltage differences around each cycle add up to zero.



For equal reactances for each edge:

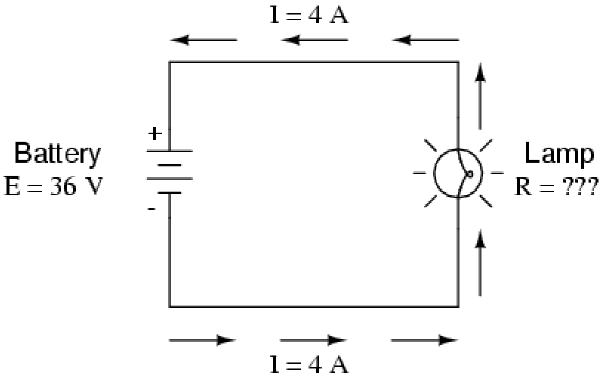


NB: For directed graph, sign determines direction of flow.

Ohm's Law

Ohm's Law: The potential difference (voltage) $V_1 - V_2$ across an ideal conductor is proportional to the current through it I. The constant of proportionality is called the **resistance**, R. Ohm's Law is thus:

$$V_1 - V_2 = I\,R$$



Analogy DC circuits to linear power flow

The equations for DC circuits and linear power flow in AC circuits are analogous:

$$I = \frac{V_i - V_j}{R} \qquad \leftrightarrow \qquad f_\ell = \frac{\theta_i - \theta_j}{x_\ell}$$

if we make the following identification:

Current flow I	$\leftrightarrow$	Active power flow f_ℓ
Potential/voltage V_i	$\leftrightarrow$	Voltage angle θ_i
Resistance R	$\leftrightarrow$	Reactance X

Constraints 4/5: Transmission Flows

The linearised **power flows** f_ℓ for each line $\ell \in \{1, \ldots L\}$ in an AC network are determined by the **reactances** x_ℓ of the transmission lines and the **net power injection** at each node p_n for $n \in \{1, \ldots N\}$, via the voltage angles θ_i at the nodes (like auxilliary variables):

$$f_\ell = \frac{\theta_i - \theta_j}{x_\ell}$$

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

$$|f_{\ell,t}| \leq \bar{P}_\ell$$

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.

Constraints 5/5: 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 95% compared to 1990 levels, in line with German and EU targets for 2050.

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

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

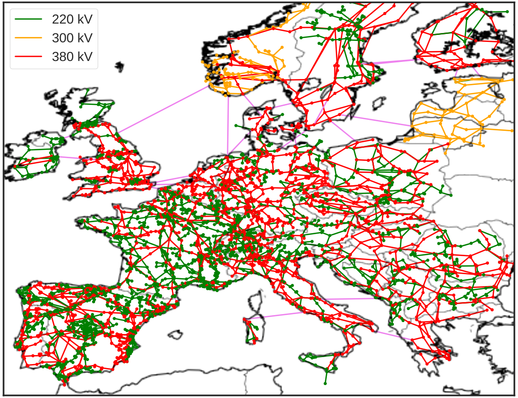
But we can also limit total new transmission volume in MWkm (d_ℓ is line length in km):

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

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

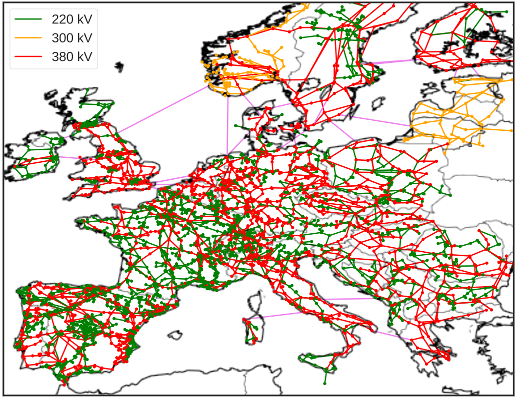
Warm-up: Determine optimal electricity system

- 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

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`

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.

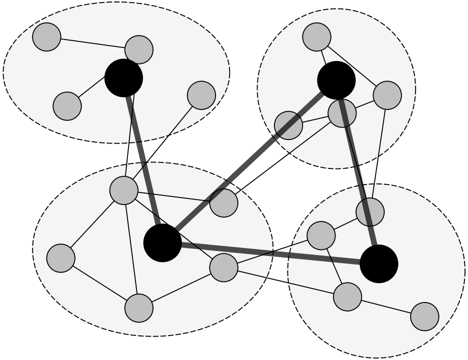
Batteries can store for 6 hours at maximal rating (efficiency 0.9×0.9), hydrogen storage for 168 hours (efficiency 0.75×0.58).

Reduce spatial resolution with clustering

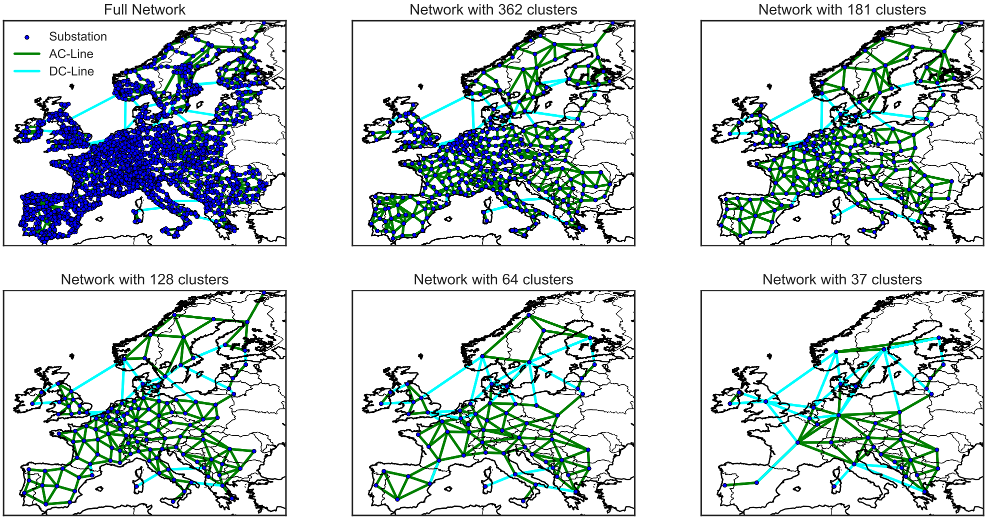
We need spatial resolution to:

- 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**

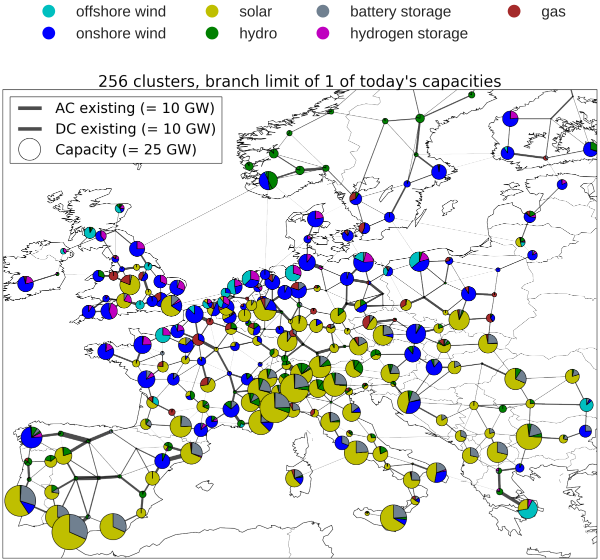
BUT we do not want to have to model all 5,000 network nodes of the European system.



Solution: k-means clustering



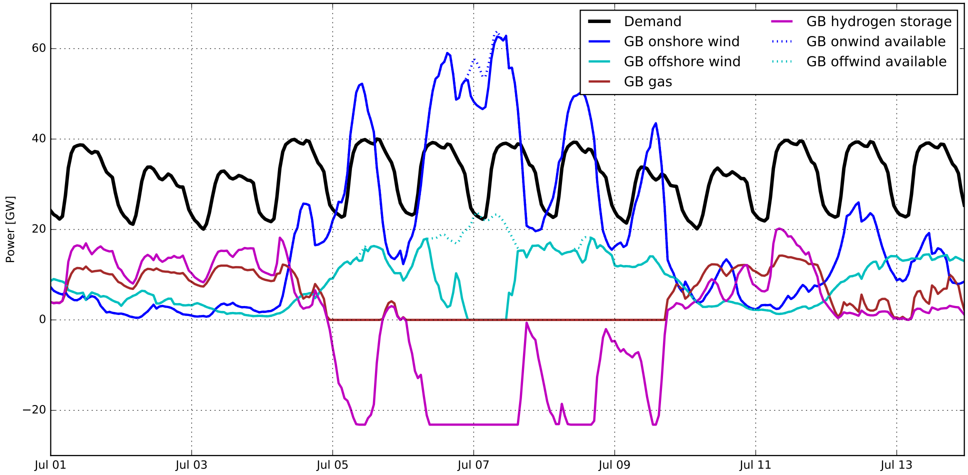
Electricity system with no grid expansion



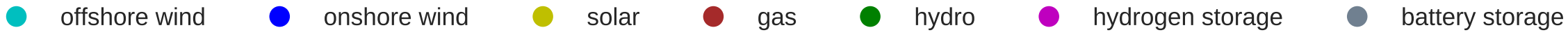
- Wind in North where grid capacity allows, solar in South
- With **no grid expansion**, lots of storage required to balance variability, **costs are high**
- Batteries pair with solar in South
- Hydrogen storages pairs with longer-term variations of wind in North

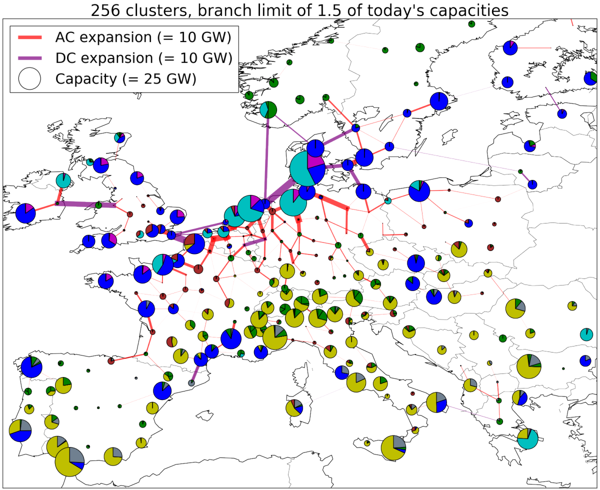
Dispatch with no grid expansion

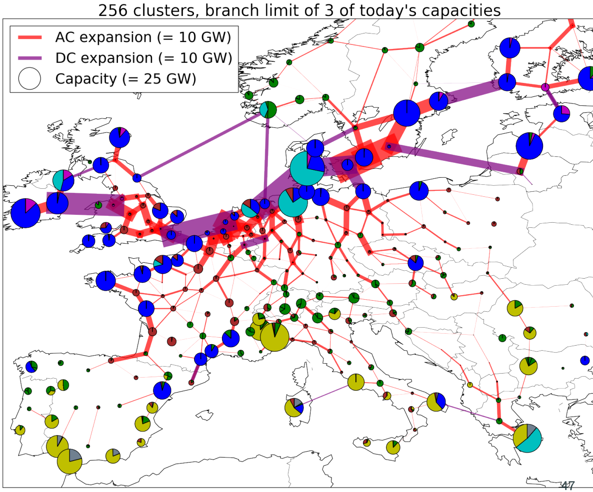
For Great Britain with limited interconnecting transmission, excess wind is either stored as hydrogen or curtailed:



When grid expansion allowed: avoid costly storage

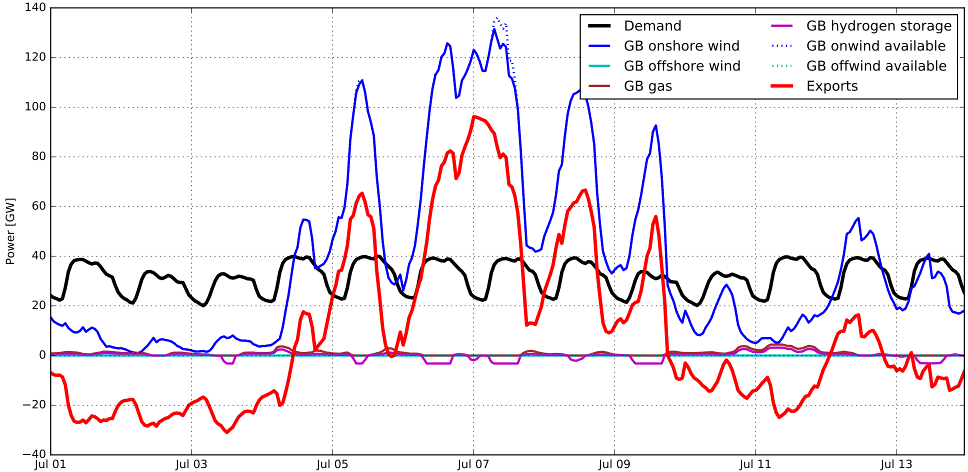




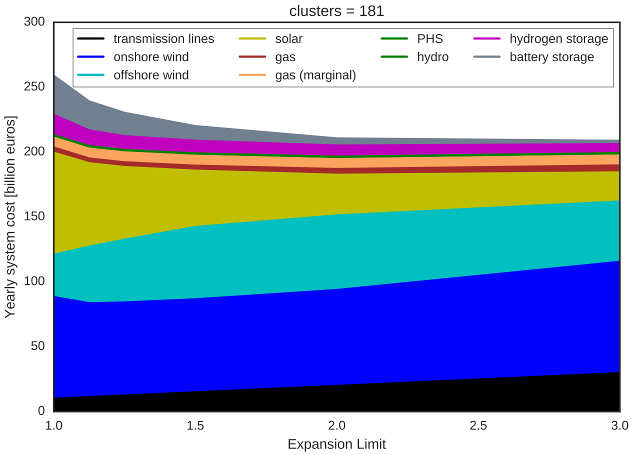


Dispatch with cost-optimal interconnecting transmission

Almost all excess wind can be now be exported:



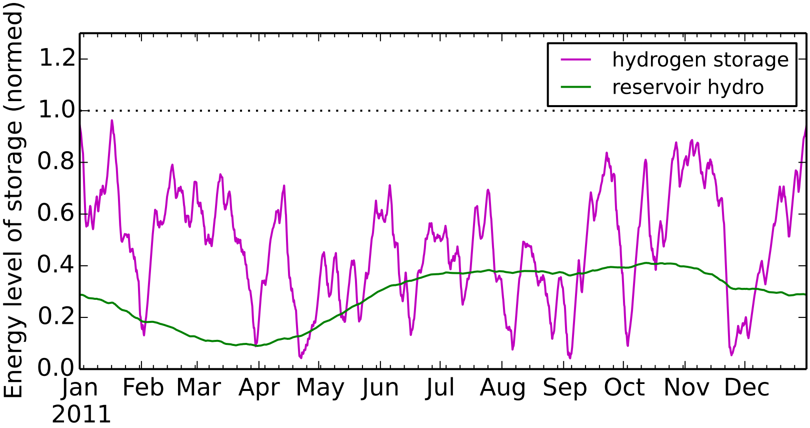
Cost behaviour as transmission expansion is allowed



- 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

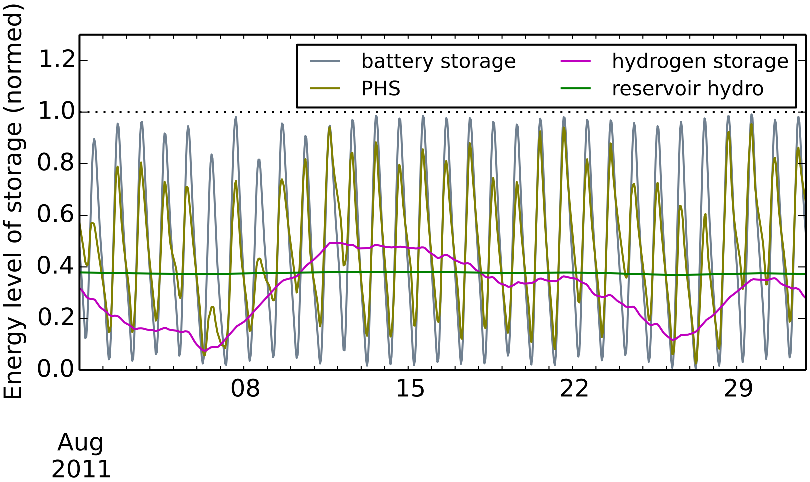
Source: Schlachtberger et al, 2017, Hörsch et al, 2017

Different flexibility options have difference temporal scales



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

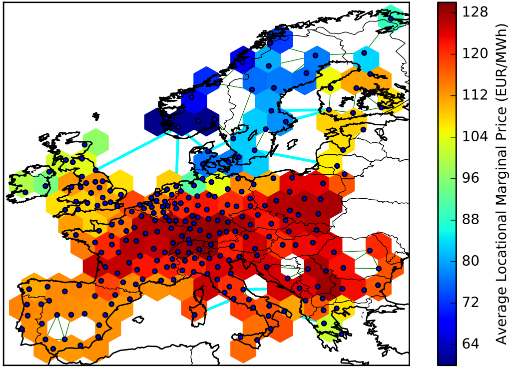
Different flexibility options have difference temporal scales



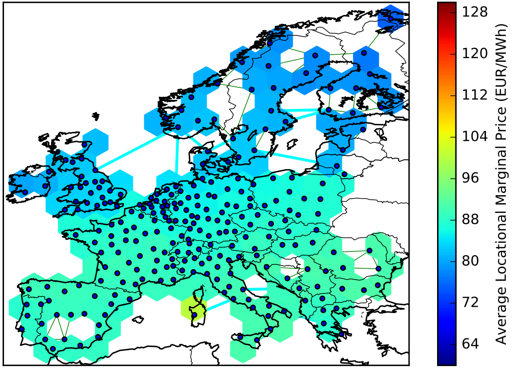
- Pumped hydro and battery storage are **daily**

Locational Marginal Prices CAP=1 versus CAP=3

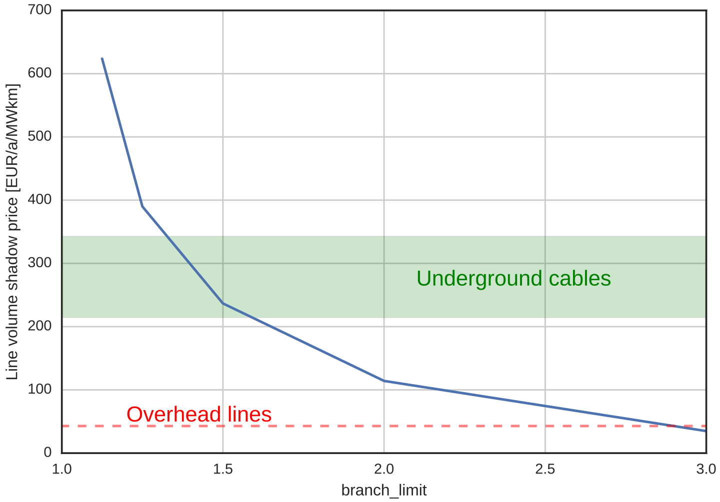
With today's capacities:



With three times today's grid:



Grid expansion cap shadow price as cap is relaxed

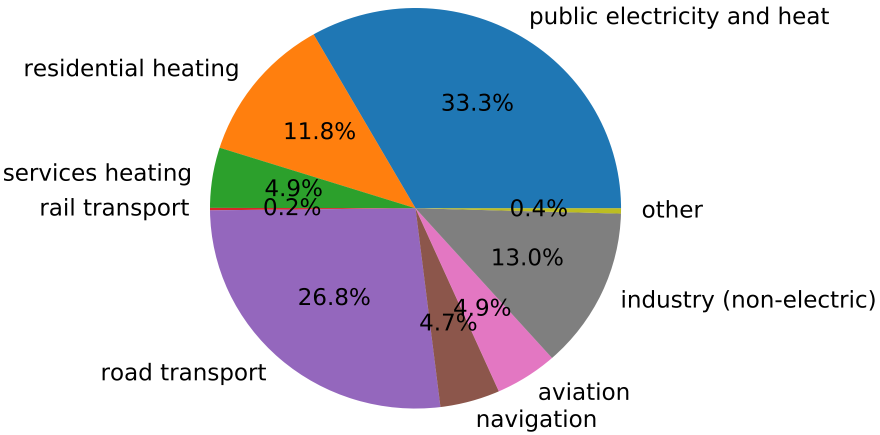


- With overhead lines the optimal system has around 3 times today's transmission volume
- With underground cables (5-8 times more expensive) the optimal system has around 1.3 to 1.6 times today's transmission volume

Electricity, Heat and Transport

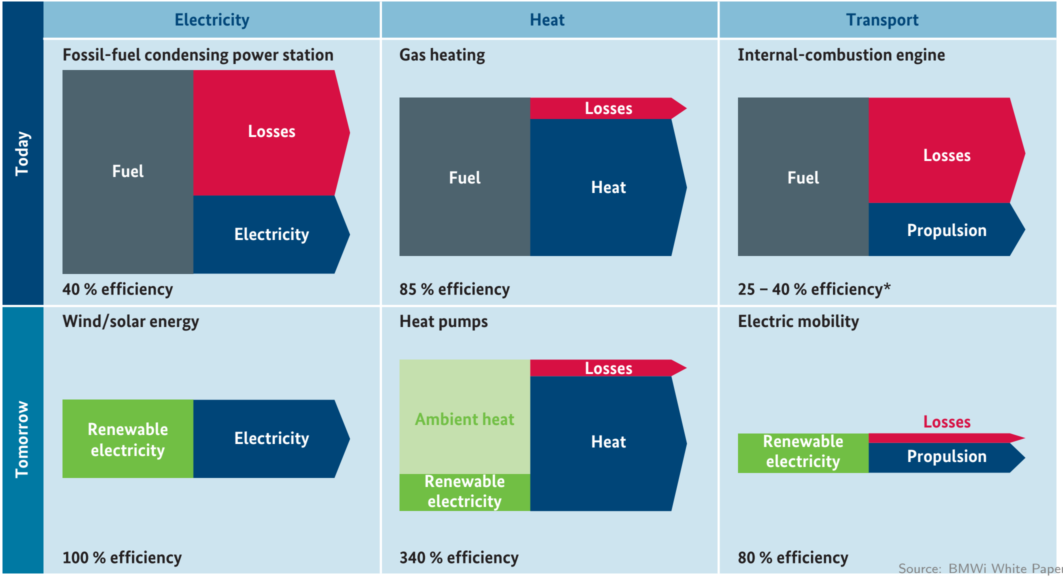
Include other sectors: heating and land transport

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

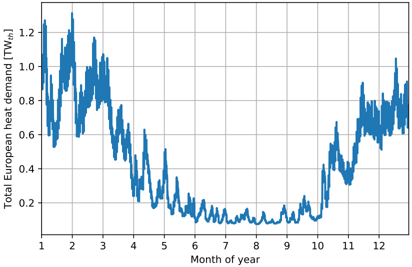


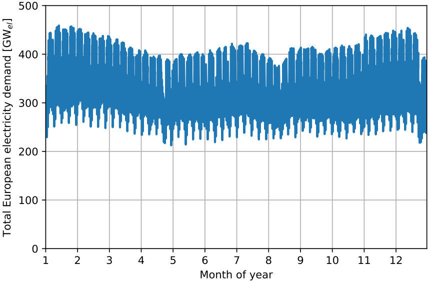
Source: BMWi White Paper 2015

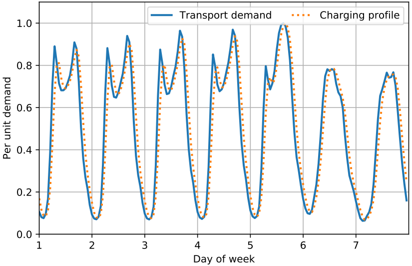
Challenge: Heating and transport demand strongly peaked

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

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







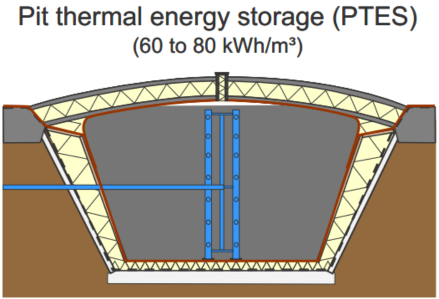
Sector Coupling

Idea: Couple the electricity sector to heating and mobility.

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

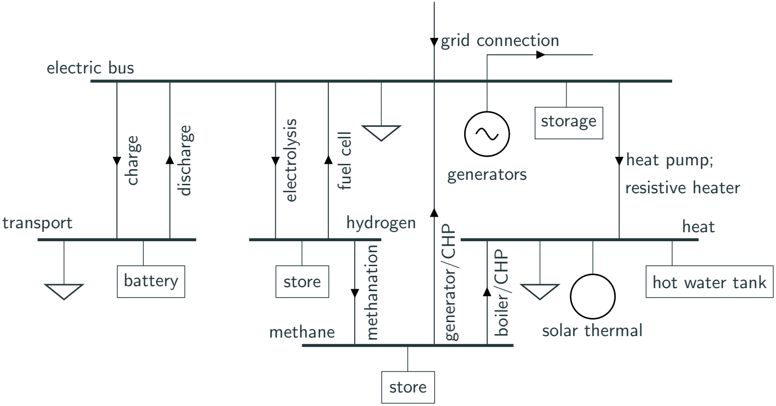
Battery electric vehicles can change their charging pattern to benefit the system and even feed back into the grid if necessary

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

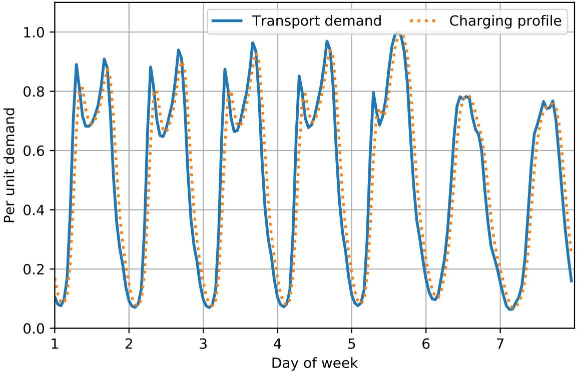


Sector coupling: A new source of flexibility

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.



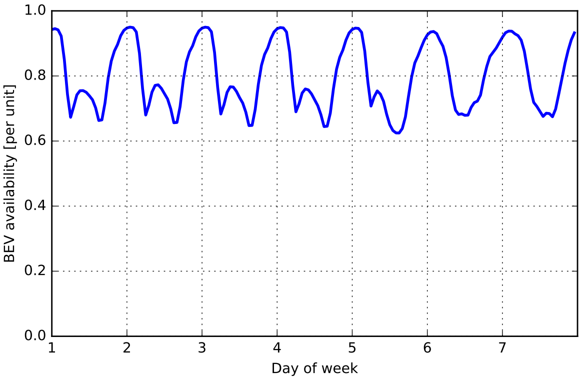
Transport sector: Electrification of Transport



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.

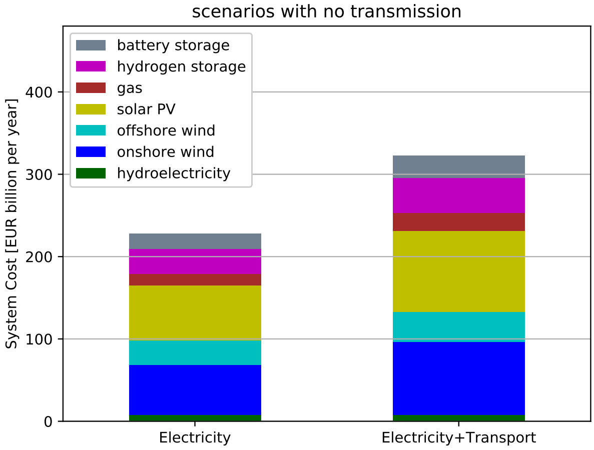
Transport sector: Battery Electric Vehicles



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

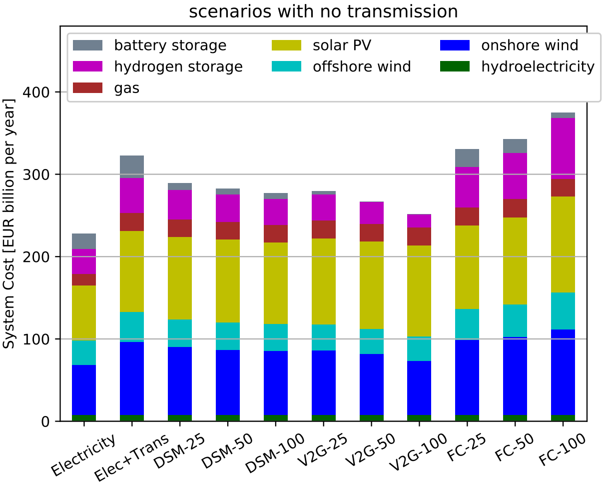
- Passenger cars to Battery Electric Vehicles (BEVs), 50 kWh battery available and 11 kW charging power
- Can participate in DSM and V2G, depending on scenario (state of charge returns to at least 75% every morning)
- All BEVs have time-dependent availability, averaging 80%, max 95% (at night)
- No changes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

Coupling Transport to Electricity



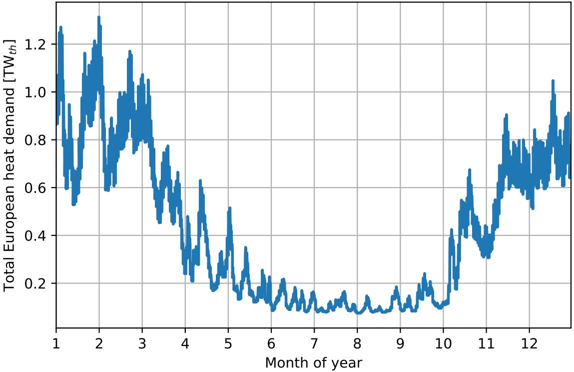
- If all road and rail transport is electrified, electrical demand increases 37%
- Costs increase 41% because charging profiles are very peaked (NB: distribution grid costs NOT included)
- Stronger preference for PV and storage in system mix because of daytime peak
- Can now use flexible charging

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.

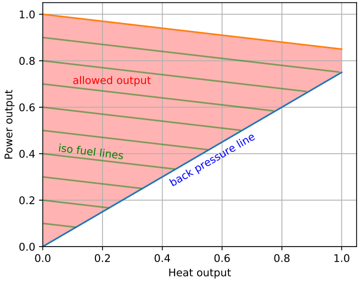
Decentral individual heating can be supplied by:

- 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:

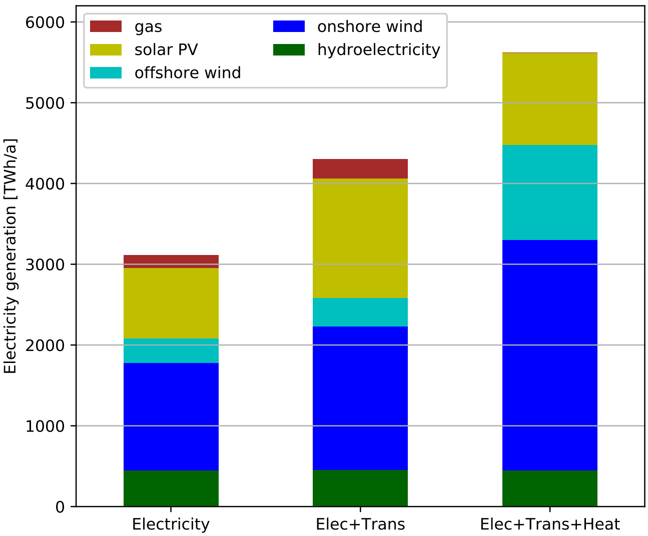


Cost and other assumptions

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

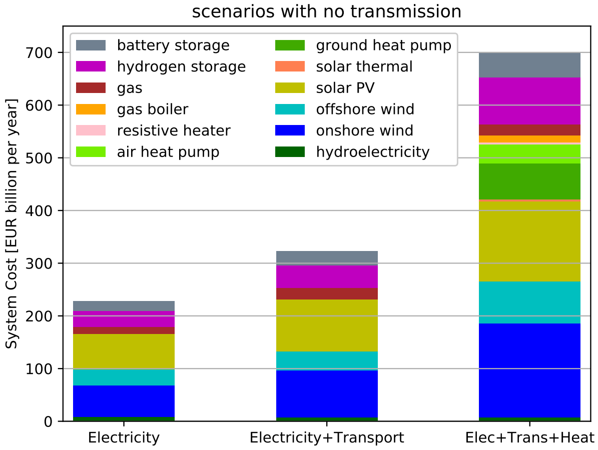
Costs oriented towards Henning & Palzer (2014, Fraunhofer ISE) and Danish Energy Database

Coupling Heating to Transport and Electricity: Electricity Demand



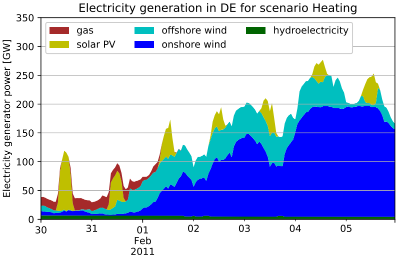
- To 4062 TWh_{el}/a demand from electricity and transport, 3585 TWh_{th}/a heating demand is added
- Much of the heating demand is met via electricity, but with high efficiency from heat pumps
- Electricity demand 80% higher than current electricity demand
- Efficiency savings can reduce this . . .

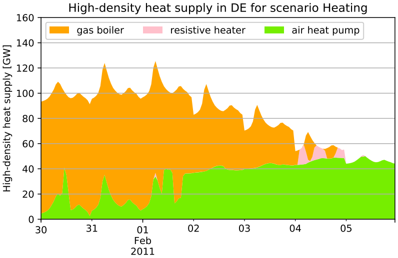
Coupling Heating to Transport and Electricity: Costs



- 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



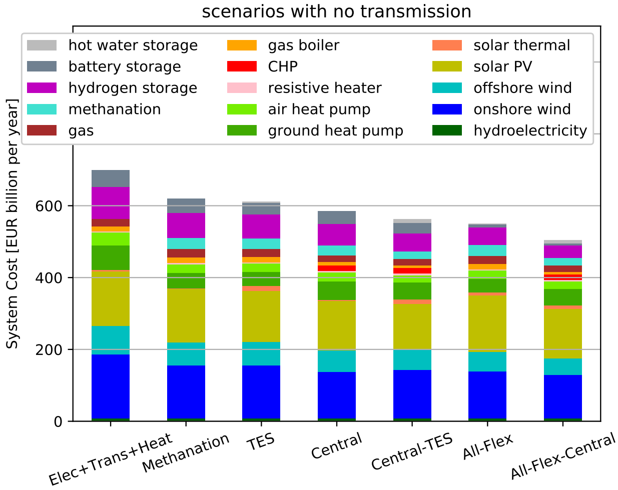


There are difficult periods in winter with:

- **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.

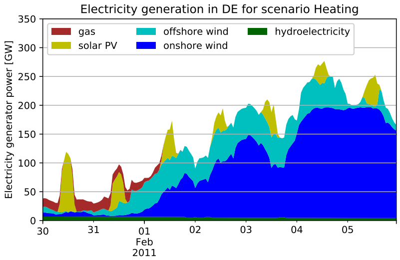
Using heating flexibility

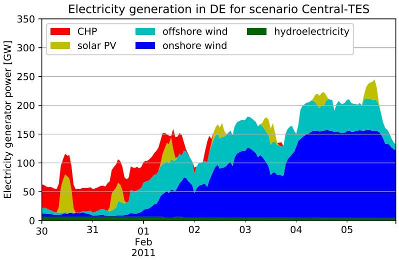


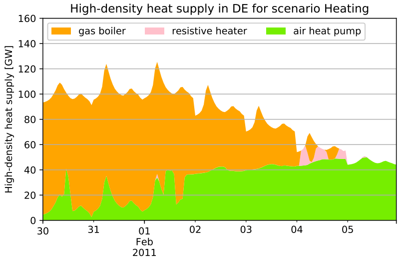
Successively activating couplings and flexibility **reduces costs** by 28%. These options include:

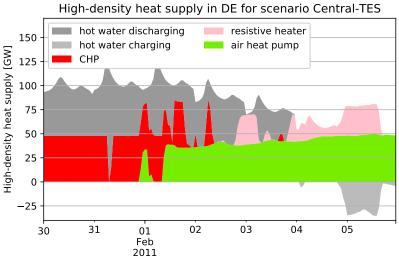
- production of **synthetic methane**
- centralised **district heating** in areas with dense heat demand
- long-term **thermal energy storage** (TES) in district heating networks
- **demand-side management** and vehicle-to-grid from battery electric vehicles (BEV)

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

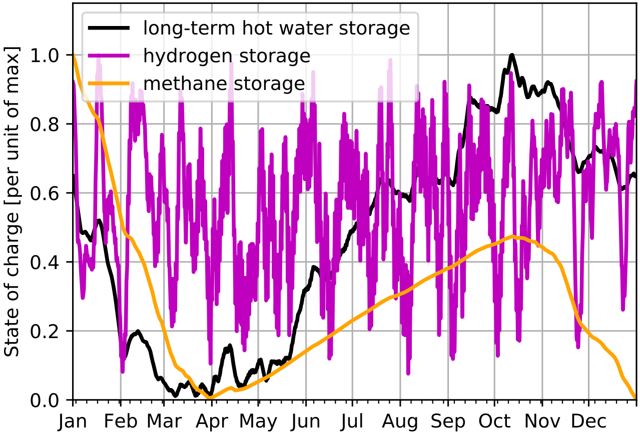








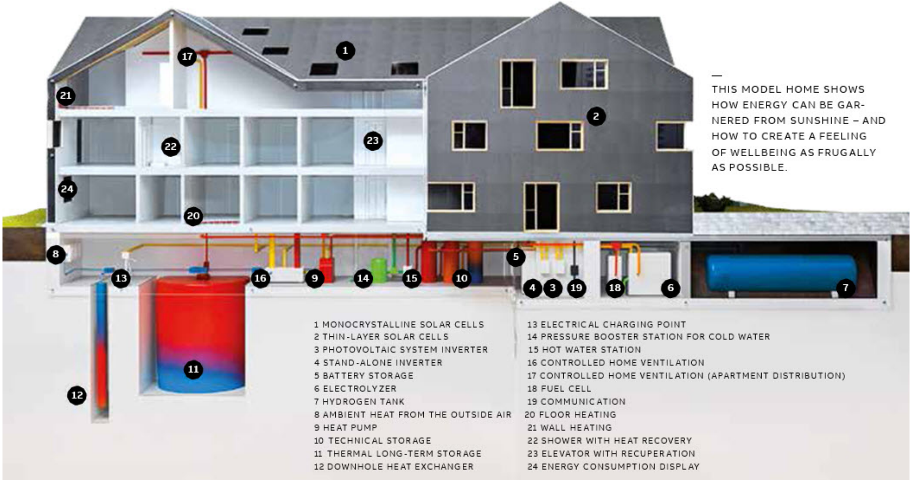
Storage energy levels: different time scales



- 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

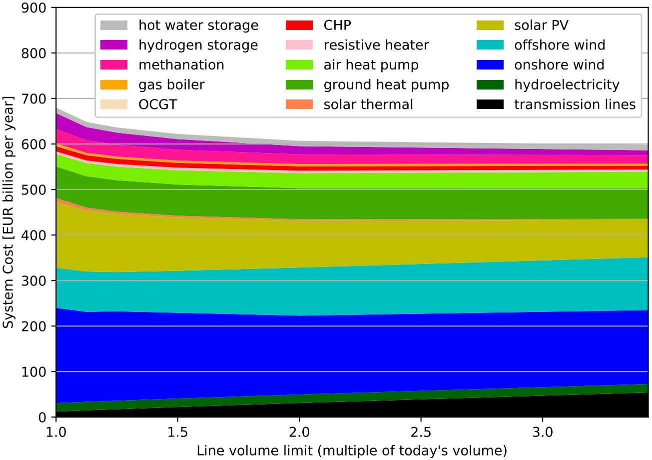
LTES and P2G in autarkic (self-sufficient) apartment block

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).



Benefit of grid expansion for sector-coupled system

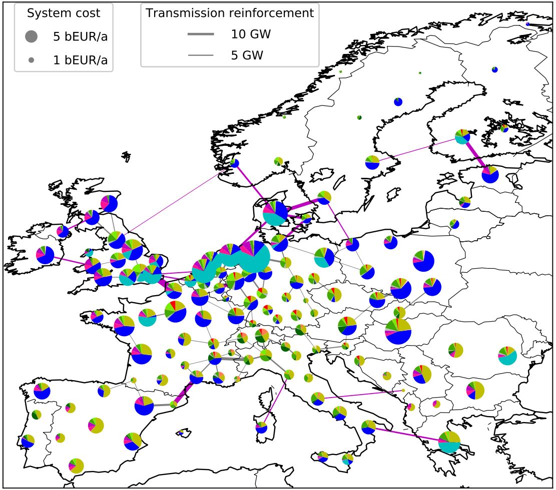
The previous sector coupling results come from a model with one node power country described in Brown et al 2018, for the case with no interconnecting transmission.



We recently applied the smart flexibility model to a 128-node model of Europe.

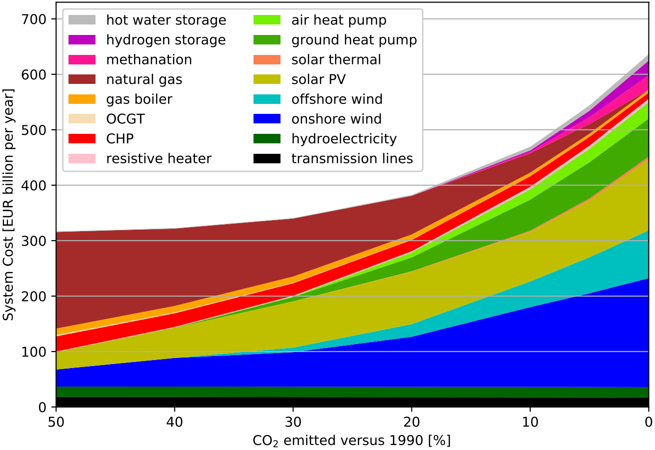
- The optimal volume of transmission is similar to electricity-only (around factor 3 bigger than today)
- Like electricity, over half of benefit available at 25% expansion (comparable to TYNDP)
- Total cost benefit of grid is higher: $\sim$ 80 billion €/a

Distribution of technologies



- Wind now also in South because of seasonal alignment with heat demand
- Solar now also in North because of match with transport demand
- 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

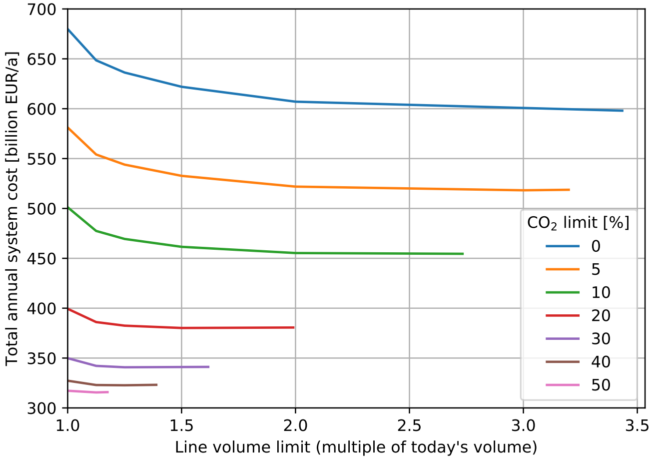
Pathway down to zero emissions in electricity, heating and transport



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 node 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)

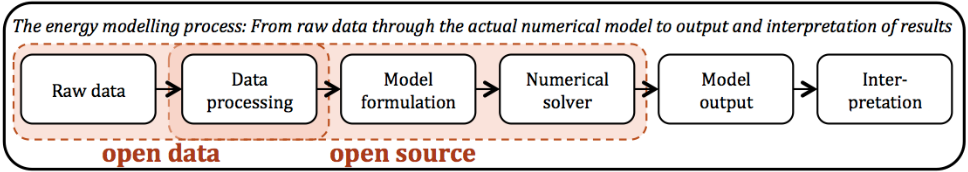
Outlook

- 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 ⇒ Transparency + Reproducibility

There's an initiative for that! Sign up for the mailing list / come to the next workshop:

openmod open energy modelling initiative

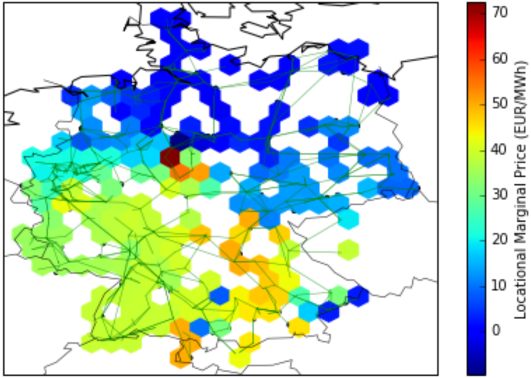
openmod-initiative.org

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** 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**

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