

# Energy System Modelling

## Summer Semester 2018, Lecture 9

---

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

17th July 2018



# Table of Contents

1. Energy System Challenges
2. Variability of Wind, Solar & Demand
3. Optimising Electricity Only
4. Electricity, Heat and Transport
5. Open Energy Modelling
6. Conclusions

## Energy System Challenges

---

# What to do about variable renewables?

Backup energy costs money and may also cause CO<sub>2</sub> emissions.

Curtailling 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

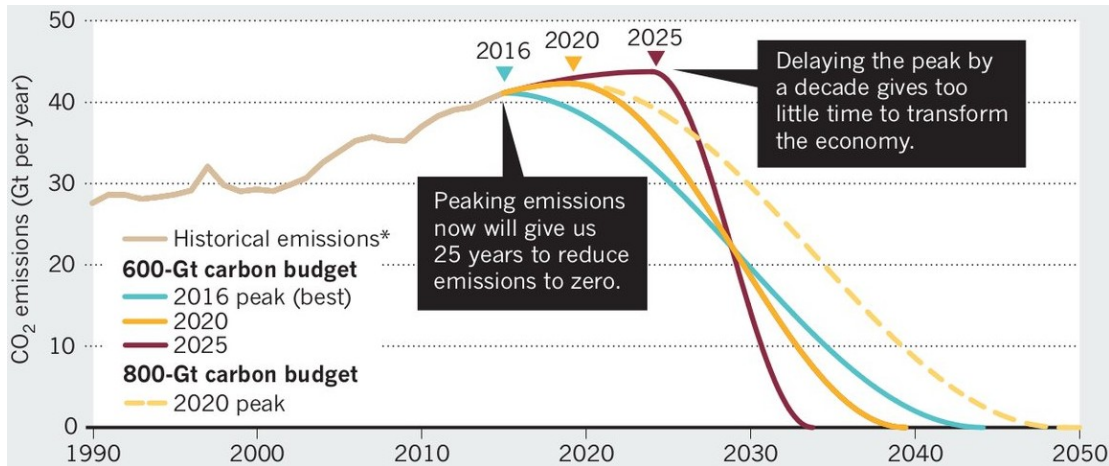
In this lecture we will consider **sector coupling**: the deeper coupling of electricity with other sectors, i.e. transport, heating and industry.

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).

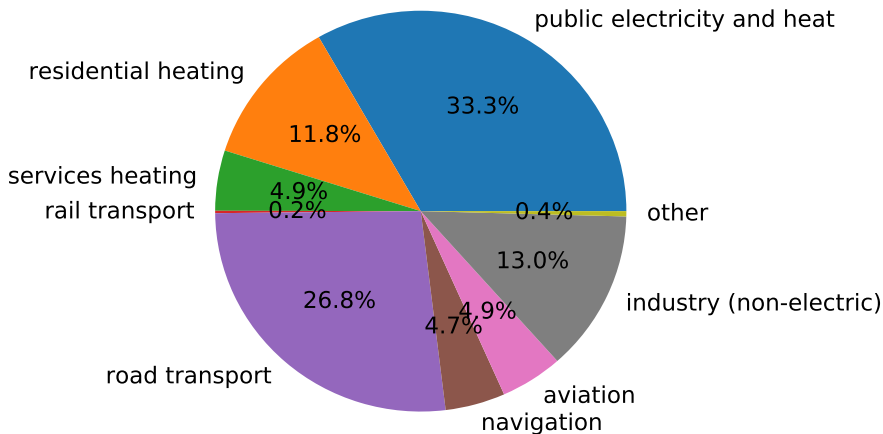
# The Global Carbon Dioxide Challenge: Budgets from 2016

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')



# It's not just about electricity demand...

EU28 CO<sub>2</sub> emissions in 2015 (total 3.2 Gt CO<sub>2</sub>, 8% of global):



...but electrification 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.

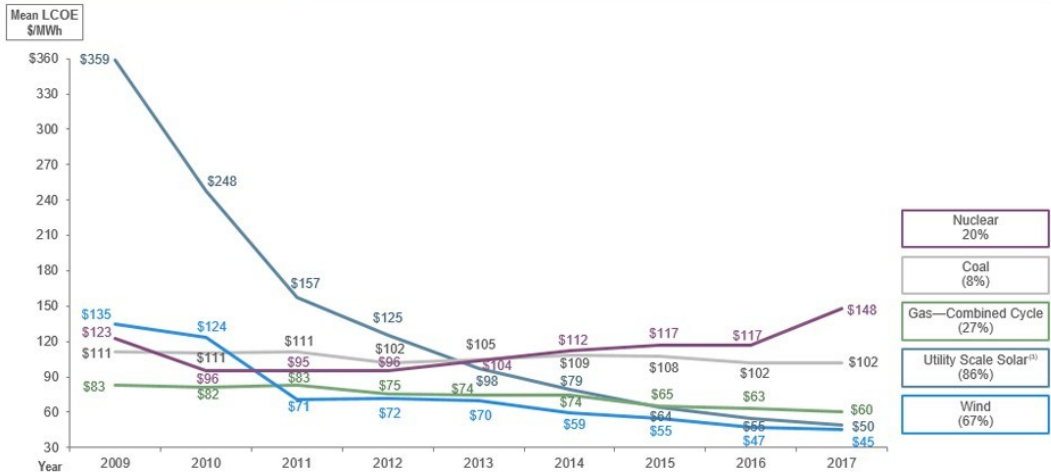


Fortunately, these sectors can also offer crucial **flexibility** back to the electricity system.



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

Selected Historical Mean LCOE Values<sup>(2)</sup>

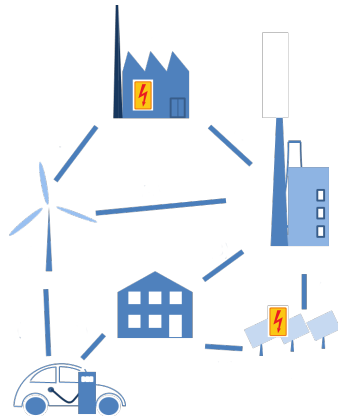


# Energy System Design: Research Questions

- What **infrastructure** does a highly renewable energy system require?
- **Where** should it go? And **when**?
- Given a desired CO<sub>2</sub> 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<sub>2</sub> 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

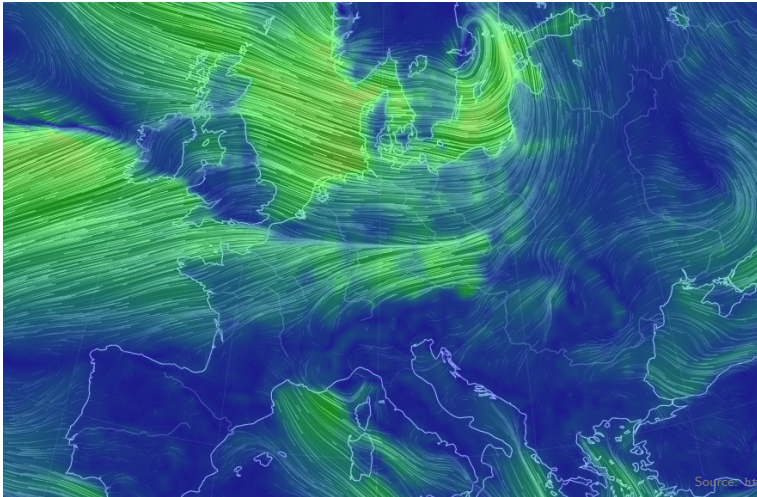
**Transparency is critical** for public acceptance.

## Variability of Wind, Solar & Demand

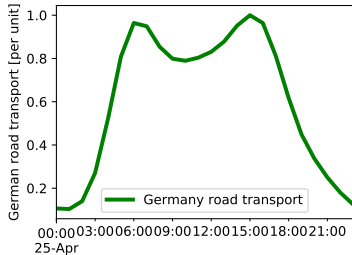
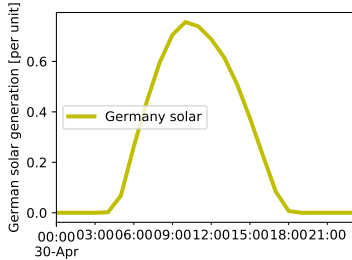
---

# 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.

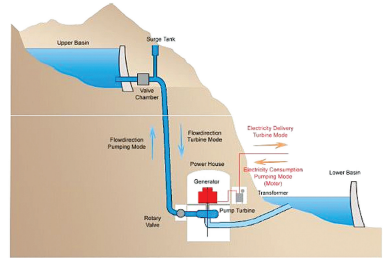


# Daily variations: challenges and solutions

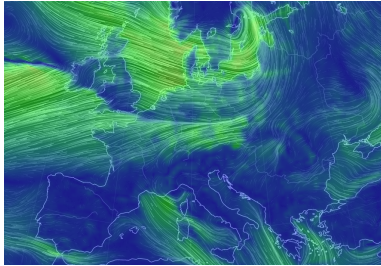


Daily variations in supply and demand can be balanced by

- **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**

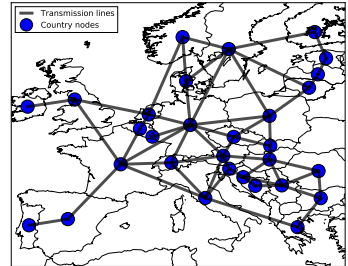
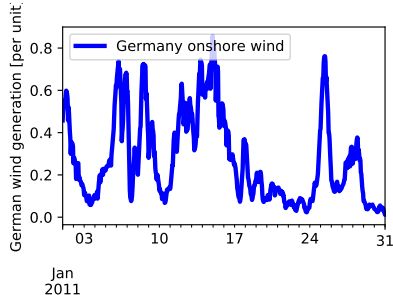


# Synoptic variations: challenges and solutions

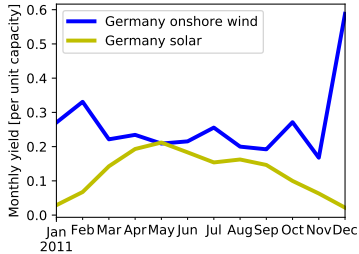


Synoptic variations in supply and demand can be balanced by

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

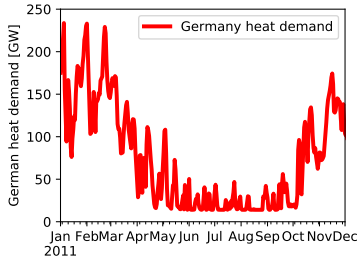


# Seasonal variations: challenges and solutions

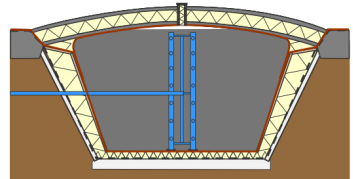


Seasonal variations in supply and demand can be balanced by

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



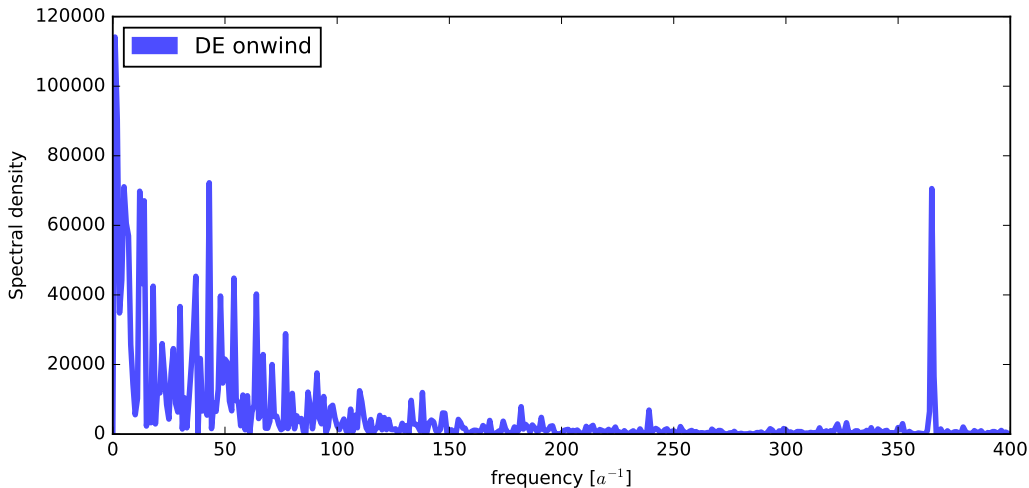
Pit thermal energy storage (PTES)  
(60 to 80 kWh/m<sup>3</sup>)





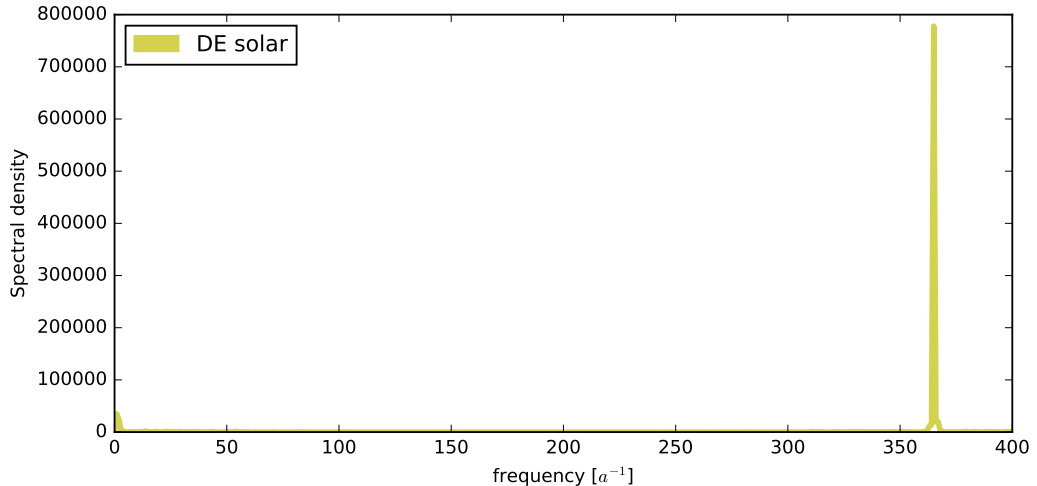
# German onshore wind spectrum

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<sub>2</sub> 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:

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

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<sub>2</sub> 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  $F_\ell$  of all the lines  $\ell$
- the flows  $f_{\ell,t}$  on each line  $\ell$  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  $t$

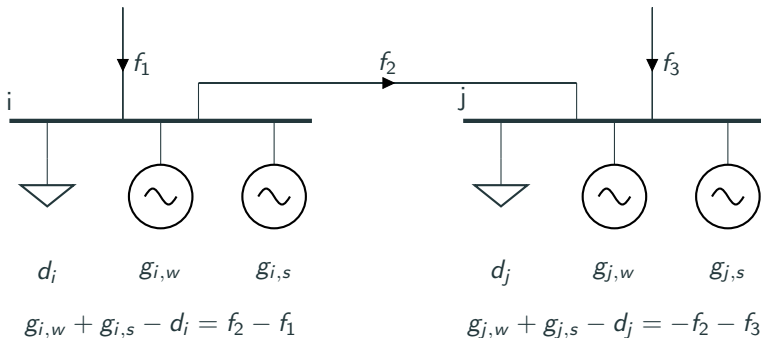
Representative time points are weighted  $w_t$  such that  $\sum_t w_t = 365 * 24$  and the capital costs  $c_*$  are annualised, so that the objective function represents the annual system cost.

## 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):

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

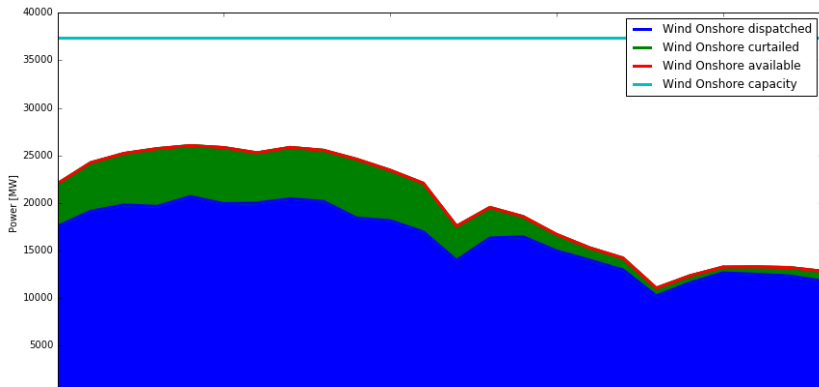
Nodes are shown as thick busbars connected by transmission lines (thin lines):



## 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  $\hat{G}_{i,s}$ .

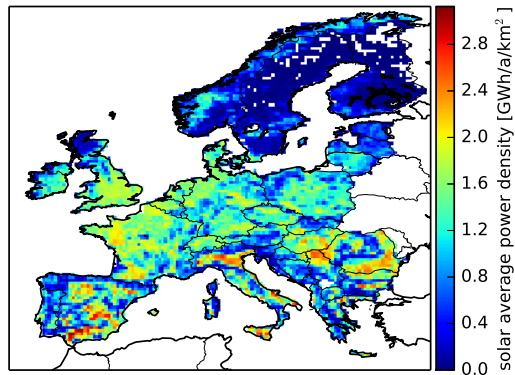
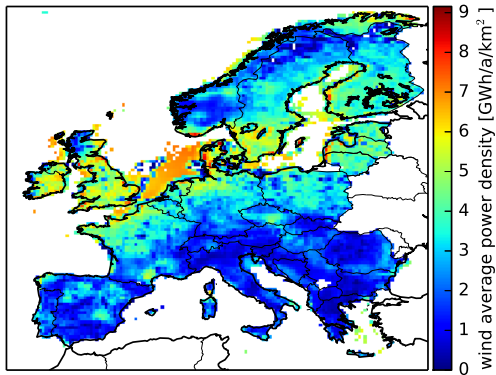
$$0 \leq g_{i,s,t} \leq G_{i,s,t} * G_{i,s} \leq G_{i,s} \leq \hat{G}_{i,s}$$





# 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  $e_{i,s,t}$ :

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

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  $\eta$ ; hydroelectric dams can also have a river inflow.

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

The linearised **power flows**  $f_\ell$  for each line  $\ell \in \{1, \dots, L\}$  in an AC network are determined by the **reactances**  $x_\ell$  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<sub>2</sub> and transmission volumes

CO<sub>2</sub> limits are respected, given emissions  $\varepsilon_{i,s}$  for each fuel source  $s$ :

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

We enforce a reduction of CO<sub>2</sub> emissions by 95% compared to 1990 levels, in line with German and EU targets for 2050.

Transmission volume limits are respected, given length  $d_\ell$  and capacity  $F_\ell$  of each line:

$$\sum_{\ell} d_\ell F_\ell \leq \text{CAP}_{\text{trans}} \quad \Leftrightarrow \quad \mu_{\text{trans}}$$

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

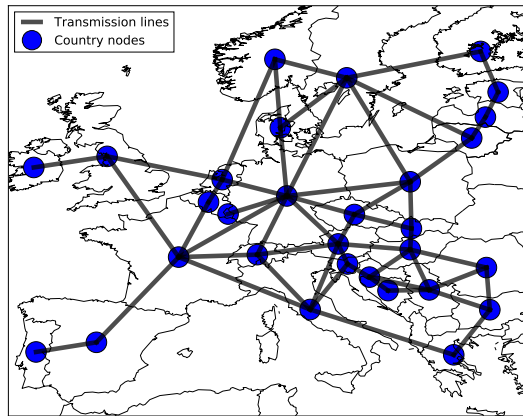
Inputs	Description
$d_{i,t}$	Demand (inelastic)
$G_{i,s,t}$	Per unit availability for wind and solar
$\hat{G}_{i,s}$	Generator installable potentials
various	Existing hydro data
various	Grid topology
$\eta_*$	Storage efficiencies
$c_{i,s}$	Generator capital costs
$o_{i,s,t}$	Generator marginal costs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

→

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

# Warm-up: Determine optimal electricity system

- Meet all electricity demand.
- Reduce CO<sub>2</sub> 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**).



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

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

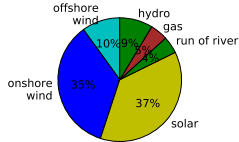
Interest rate of 7%, storage efficiency losses, only gas has CO<sub>2</sub> emissions, gas marginal costs.

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

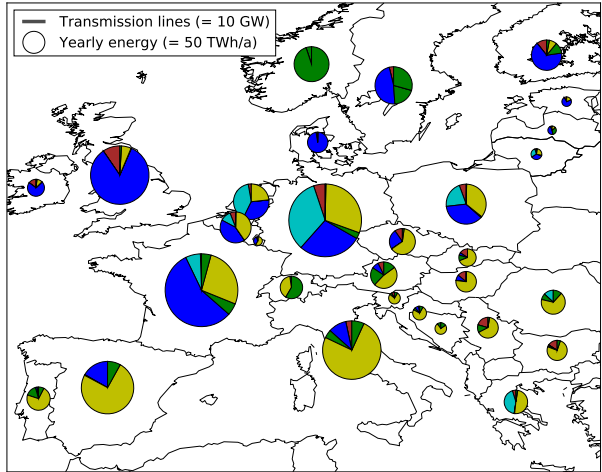
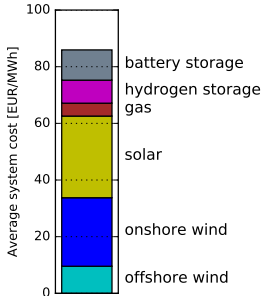


# Costs: No interconnecting transmission allowed

## Technology by energy:



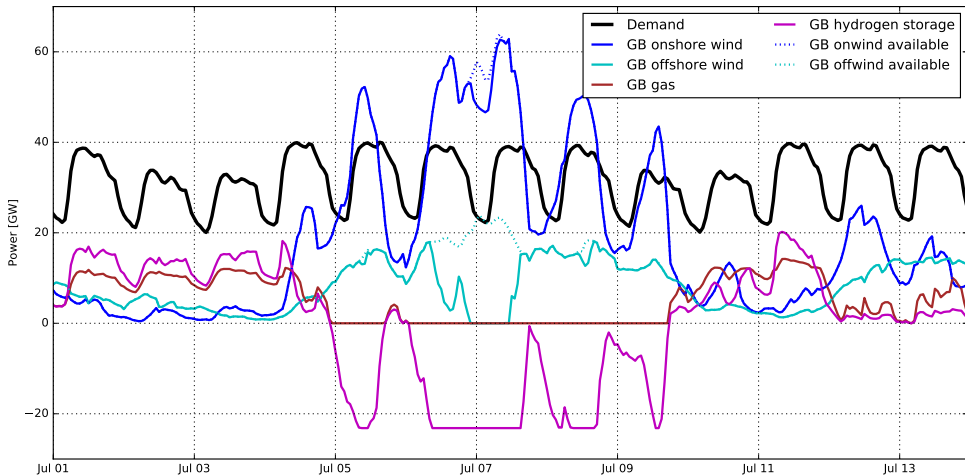
## Average cost €86/MWh:



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

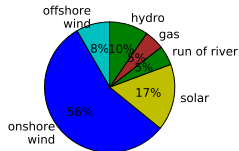
# Dispatch with no interconnecting transmission

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

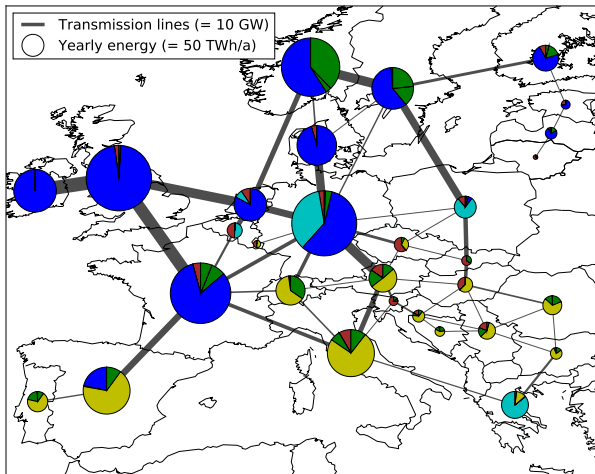
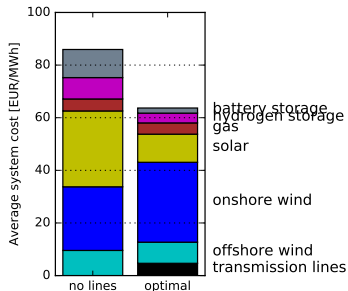


# Costs: Cost-optimal expansion of interconnecting transmission

## Technology by energy:



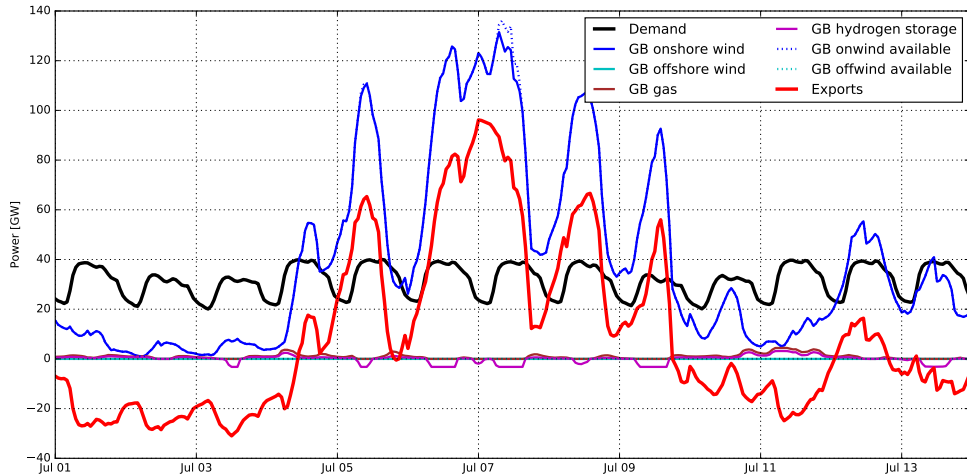
## Average cost €64/MWh:



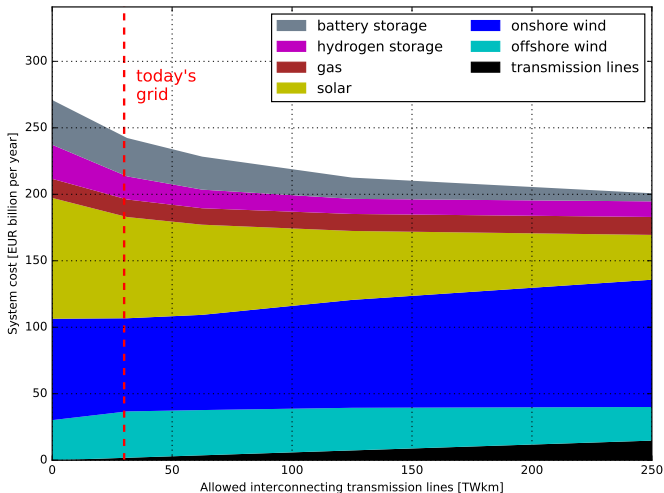
Large transmission expansion; onshore wind dominates. This optimal solution may run into public acceptance problems.

# Dispatch with cost-optimal interconnecting transmission

Almost all excess wind can be now be exported:

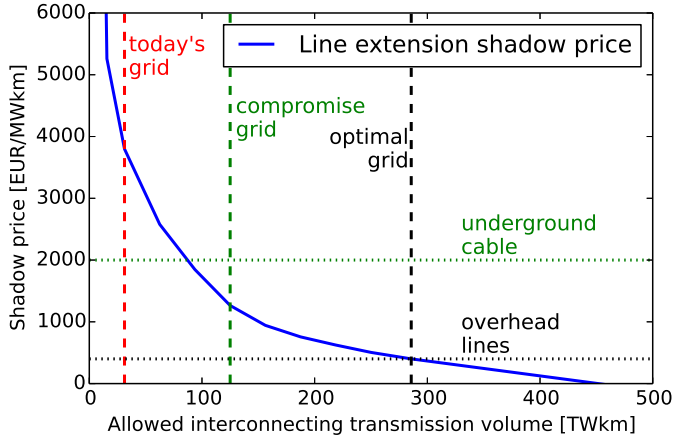


# Electricity Only Costs Comparison



- 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

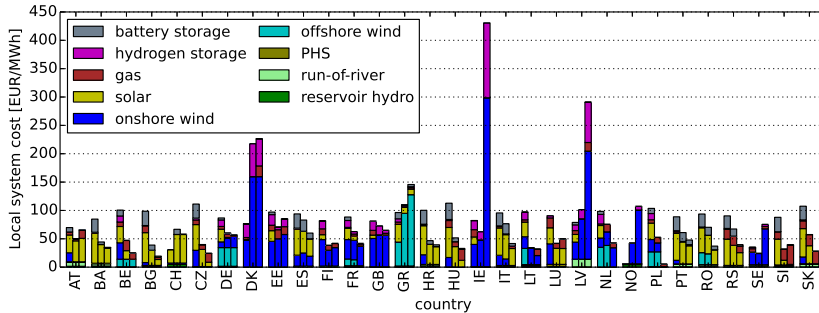
# Grid expansion CAP shadow price as CAP relaxed



- 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

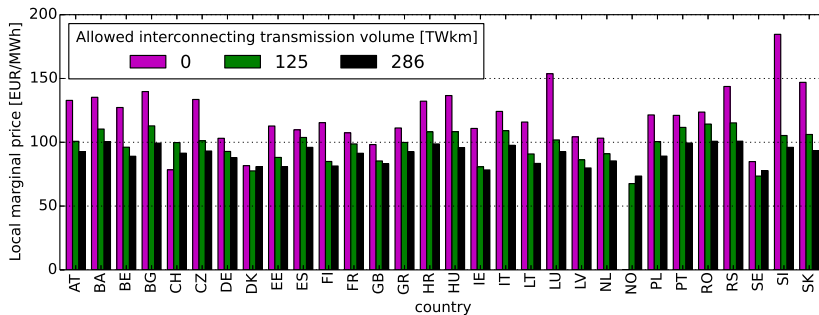
# Distribution of costs

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



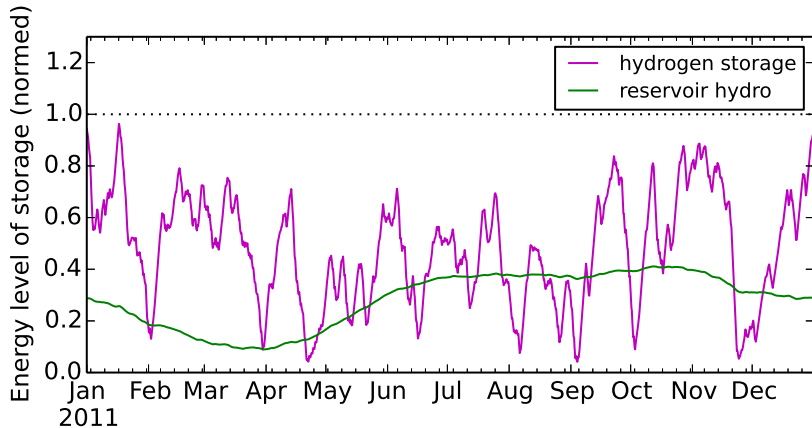
# Distribution of prices

...while market prices converge.



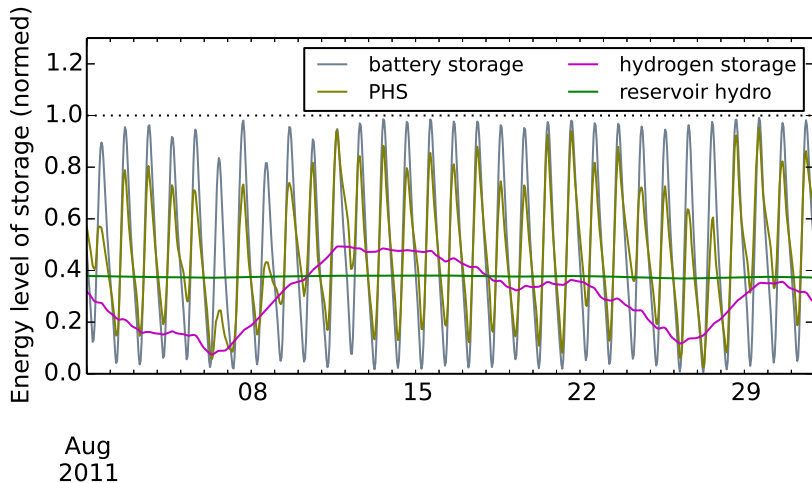


# Different flexibility options have difference temporal scales



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

# Different flexibility options have difference temporal scales



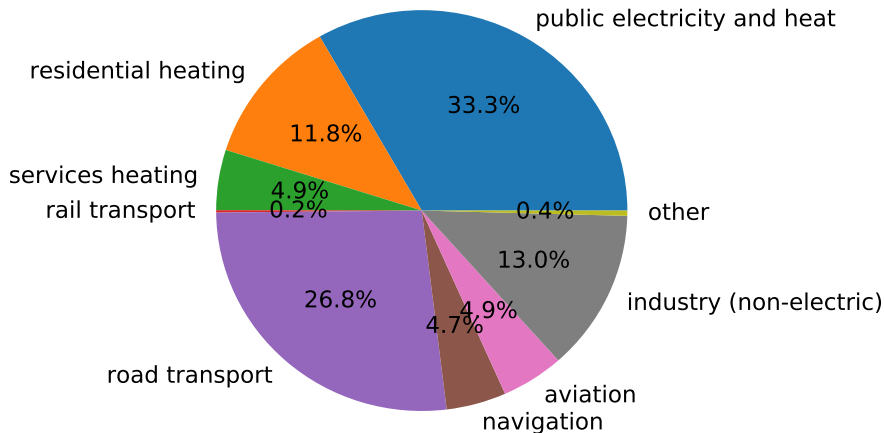
- Pumped hydro and battery storage are **daily**

# Electricity, Heat and Transport

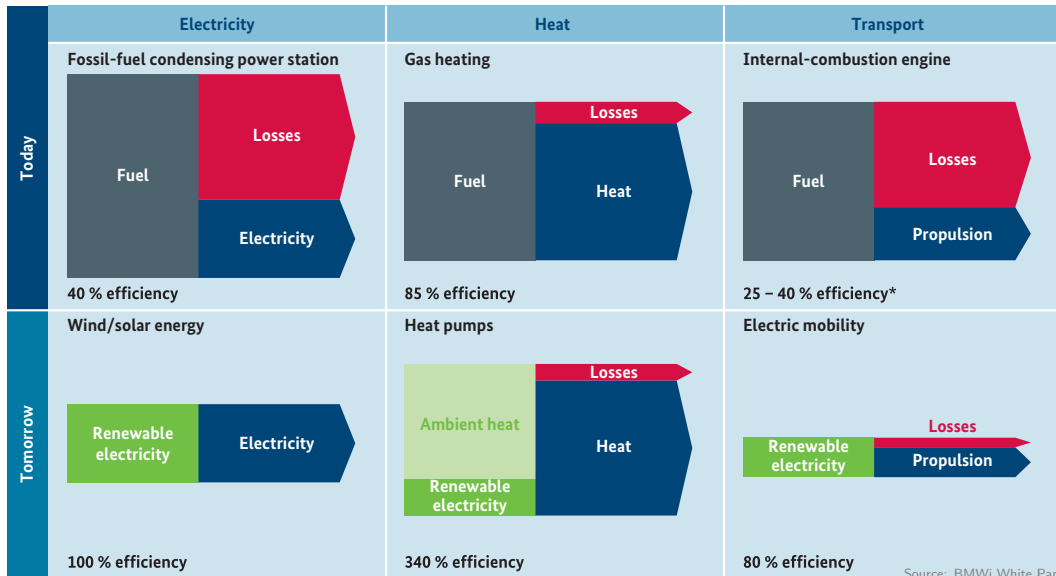
---

# Include other sectors: heating and land transport

Electricity, (low-temperature) heating and land transport cover 77% of 2015 CO<sub>2</sub> emissions:



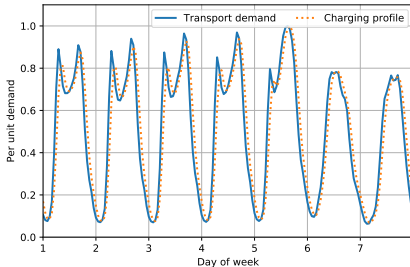
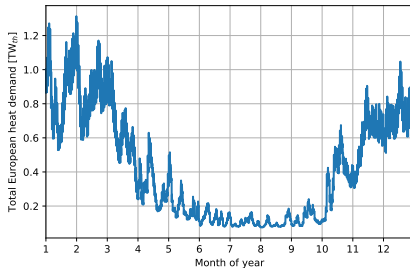
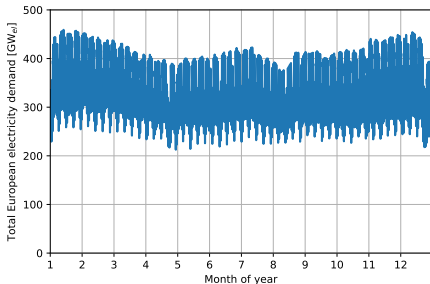
# Efficiency of renewables and sector coupling



# 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.

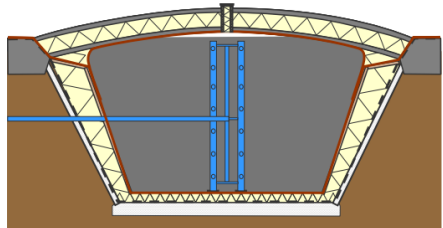
This enables decarbonisation of these sectors **and** offers more flexibility to the power system.

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



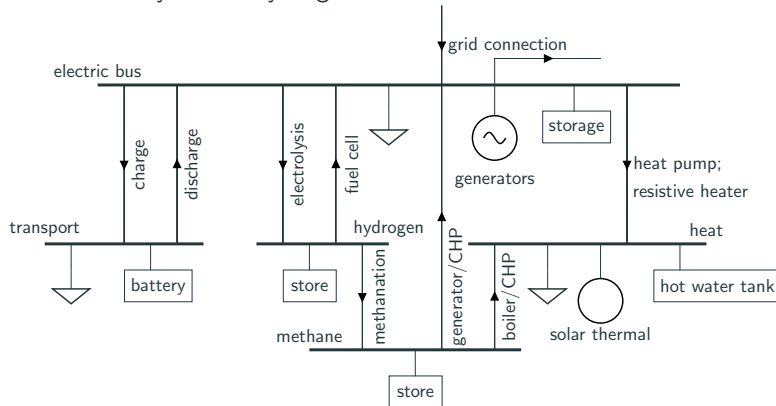
**Heat** and **synthetic fuels** are easier and cheaper to store than electricity, even over many months

**Pit thermal energy storage (PTES)**  
(60 to 80 kWh/m<sup>3</sup>)



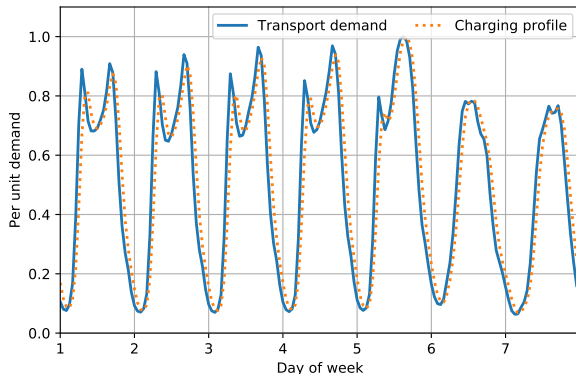
# Sector coupling: A new source of flexibility

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.





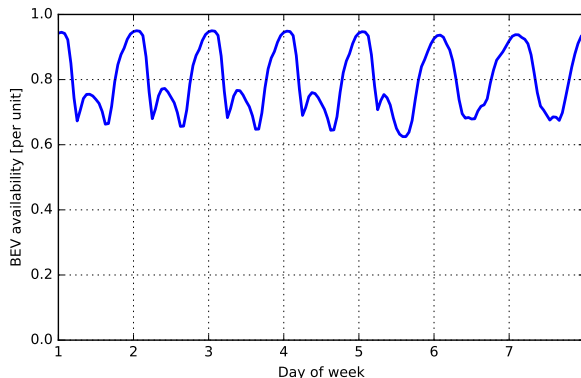
# Transport sector: Electrification of Transport



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  $1102 \text{ TWh}_{el}/a$  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.

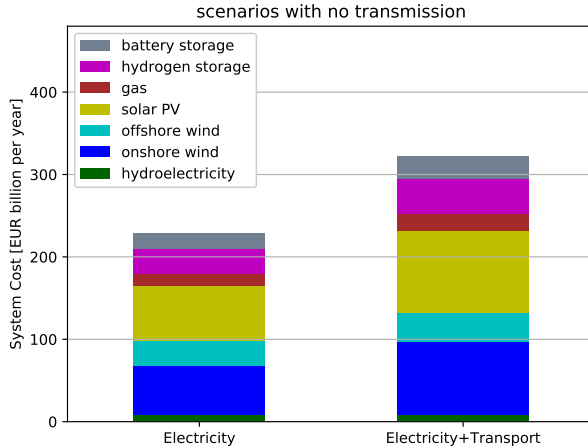
# Transport sector: Battery Electric Vehicles



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

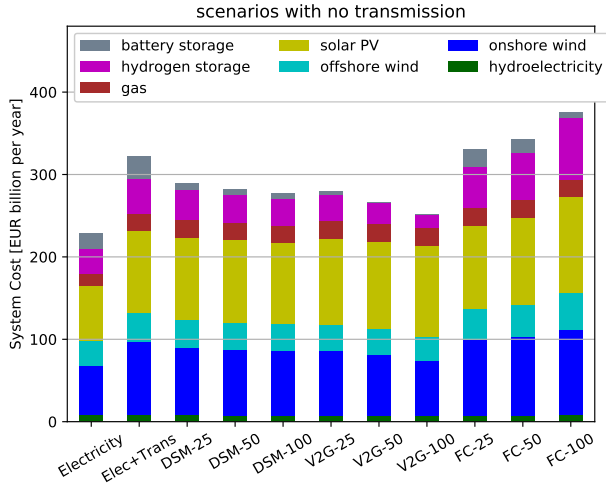
- Passenger cars to Battery Electric Vehicles (BEVs), 50 kWh battery available and 11 kW charging power
- Can participate in DSM and V2G, depending on scenario (state of charge returns to at least 75% every morning)
- All BEVs have time-dependent availability, averaging 80%, max 95% (at night)
- No changes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

# Coupling Transport to Electricity



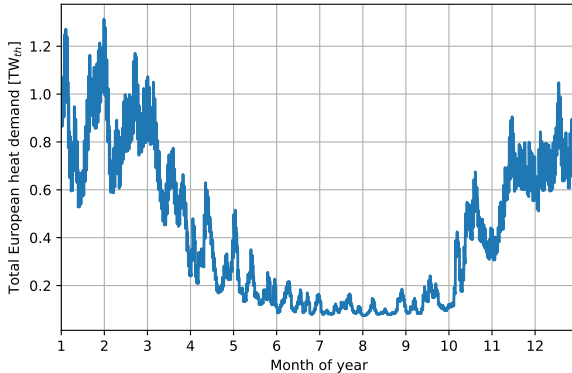
- If all road and rail transport is electrified, electrical demand increases 37%
- Costs increase 41% because charging profiles are very peaked (NB: distribution grid costs NOT included)
- Stronger preference for PV and storage in system mix because of daytime peak
- Can now use flexible charging

# 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<sub>th</sub>/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

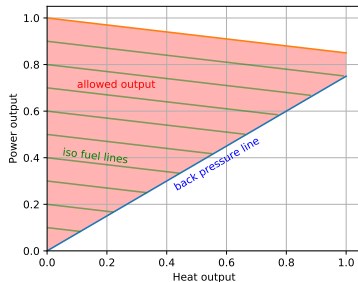
can be supplied by:

- 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:

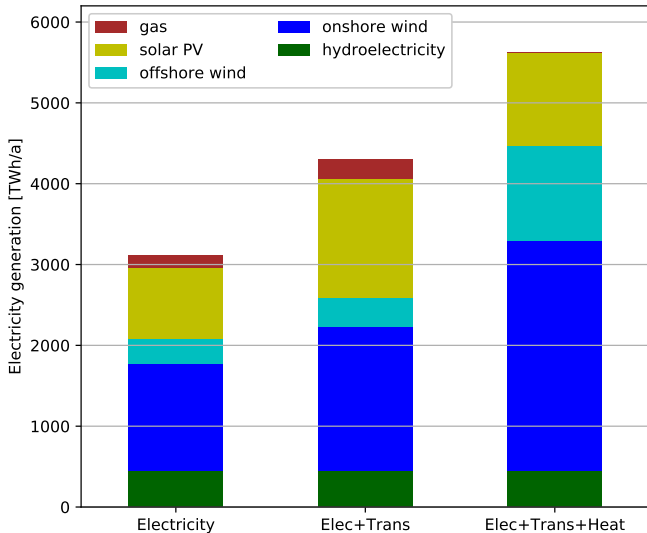


# Cost and other assumptions

Quantity	O'night cost [€]	Unit	FOM [%/a]	Lifetime [a]	Efficiency
GS Heat pump decentral	1400	$\text{kW}_{th}$	3.5	20	
AS Heat pump decentral	1050	$\text{kW}_{th}$	3.5	20	
AS Heat pump central	700	$\text{kW}_{th}$	3.5	20	
Resistive heater	100	$\text{kW}_{th}$	2	20	0.9
Gas boiler decentral	175	$\text{kW}_{th}$	2	20	0.9
Gas boiler central	63	$\text{kW}_{th}$	1	22	0.9
CHP	650	$\text{kW}_{el}$	3	25	
Central water tanks	30	$\text{m}^3$	1	40	$\tau = 180\text{d}$
District heating	220	$\text{kW}_{th}$	1	40	
Methanation+DAC	1000	$\text{kW}_{H_2}$	3	25	0.6

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

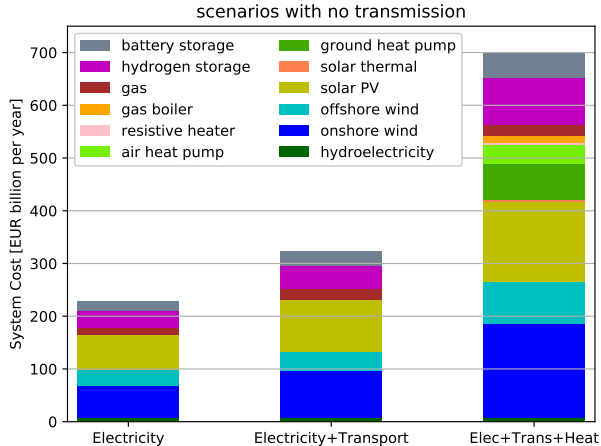
# Coupling Heating to Transport and Electricity: Electricity Demand



- To 4062 TWh<sub>el</sub>/a demand from electricity and transport, 3585 TWh<sub>th</sub>/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 ...

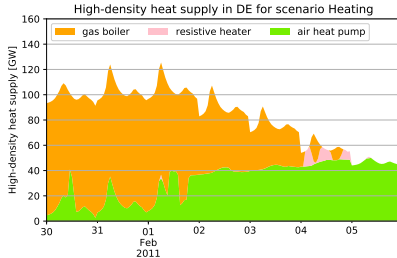
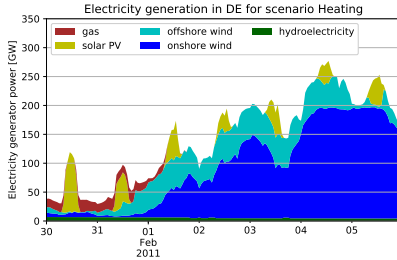


# Coupling Heating to Transport and Electricity: Costs



- Costs jump by 117% to cover new energy supply and heating infrastructure
- 95% CO<sub>2</sub> reduction means most heat is generated by heat pumps using renewable electricity
- Cold winter weeks with high demand, low wind, low solar and low heat pump COP mean backup gas boilers required

# Cold week in winter

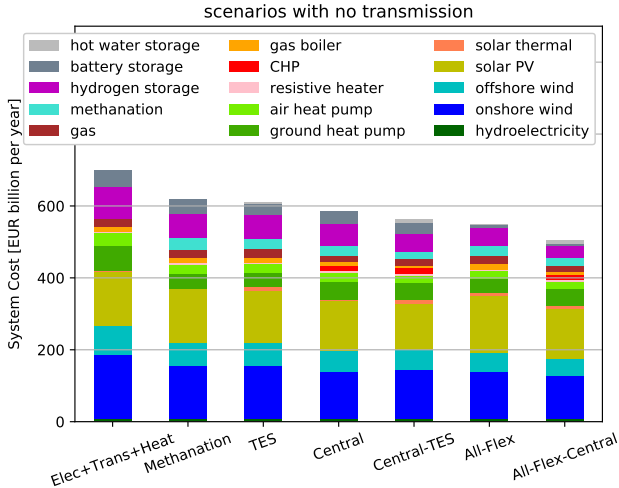


There are difficult periods in winter with:

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

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

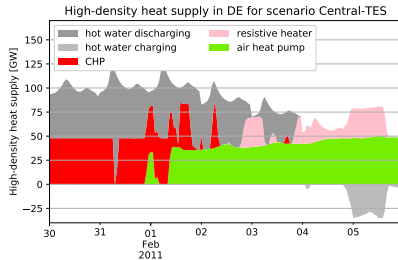
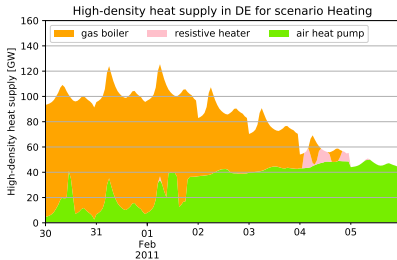
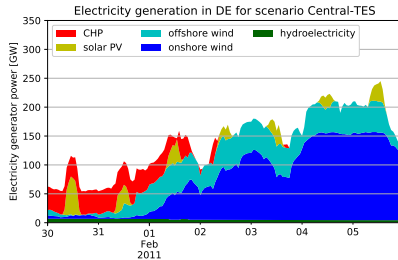
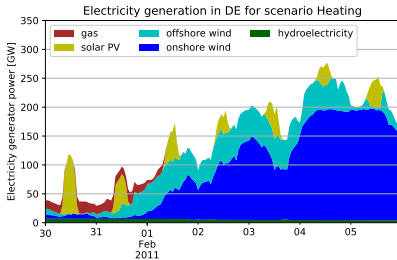
# Using heating flexibility



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

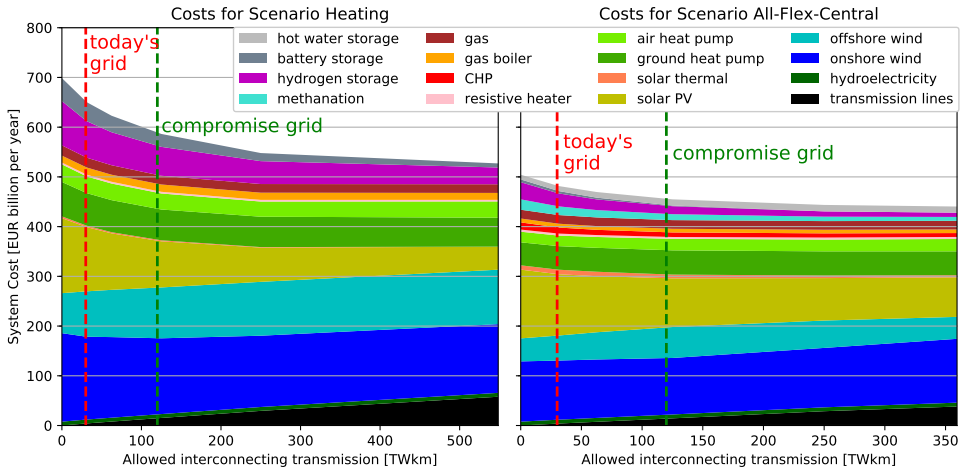
- production of **synthetic methane**
- centralised **district heating** in areas with dense heat demand
- long-term **thermal energy storage** (TES) in district heating networks
- **demand-side management** and vehicle-to-grid from battery electric vehicles (BEV)

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



# Sector Coupling with All Extra Flexibility (V2G and TES)

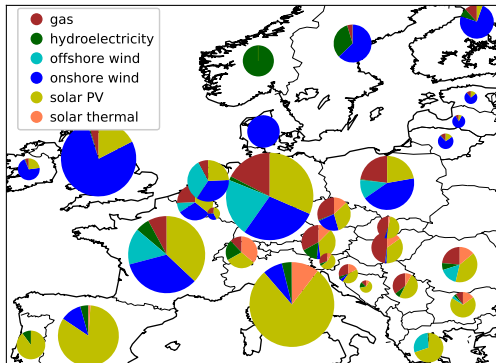
Benefit of cross-border transmission is weaker with full sector flexibility (right) than with inflexible sector coupling (left); comes close to today's costs of around € 377 billion per year



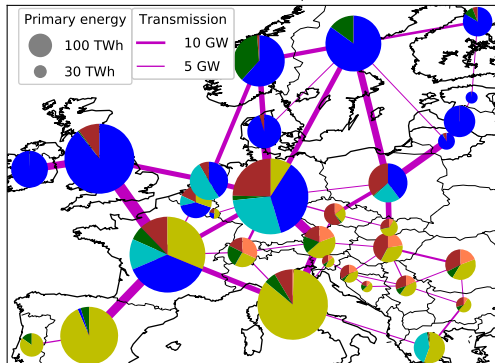
# Spatial distribution of primary energy for All-Flex-Central

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

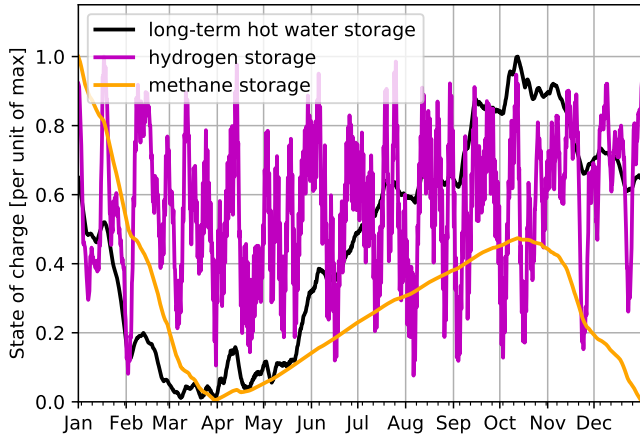
Scenario All-Flex-Central with no transmission



Scenario All-Flex-Central with optimal transmission

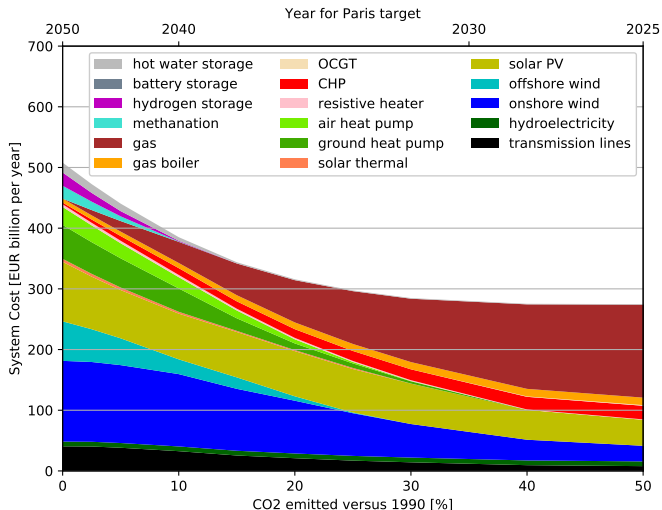


# Storage energy levels: different time scales



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

# Pathway down to zero emissions in electricity, heating and transport

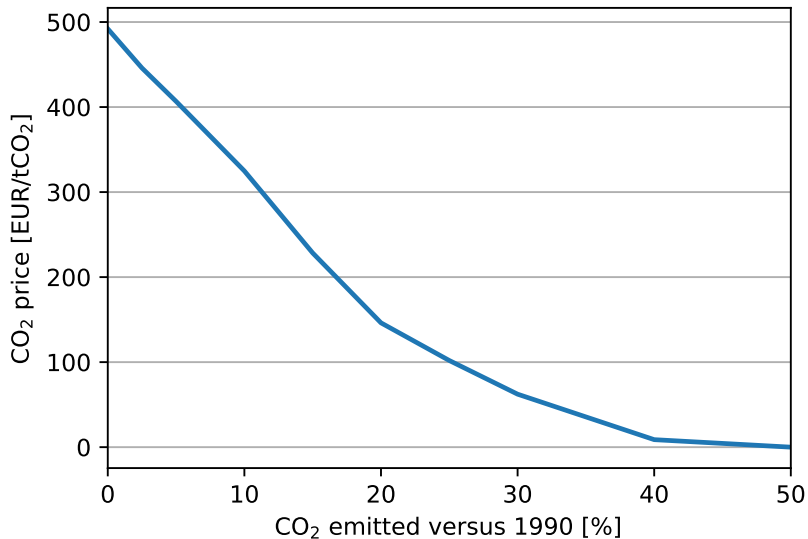


If we look at investments to eradicate CO<sub>2</sub> emissions in electricity, heating and transport we see:

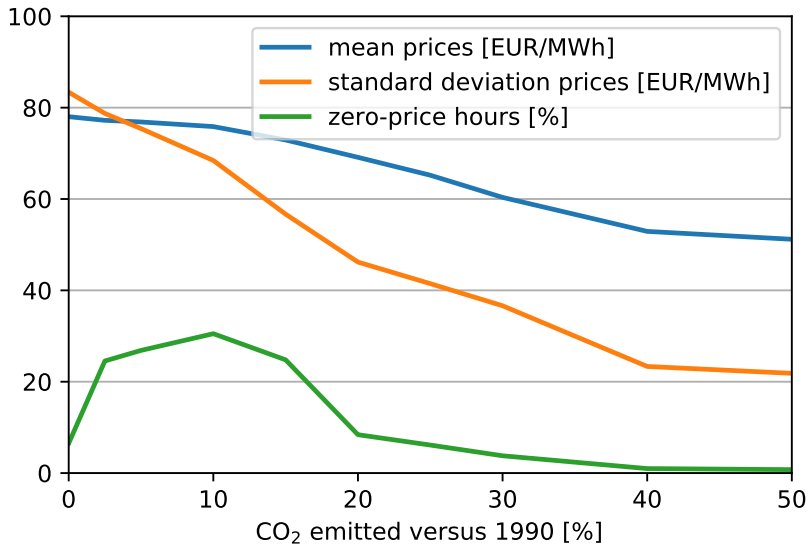
- Electricity and transport are decarbonised first
- Transmission increasingly important below 30%
- Heating comes next with expansion of heat pumps below 20%
- Below 10%, power-to-gas solutions replace natural gas



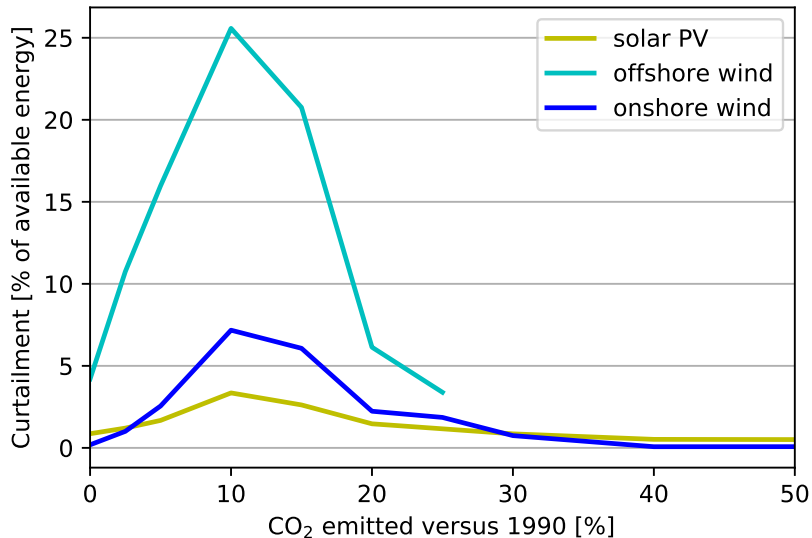
## CO<sub>2</sub> price rises to displace cheap natural gas



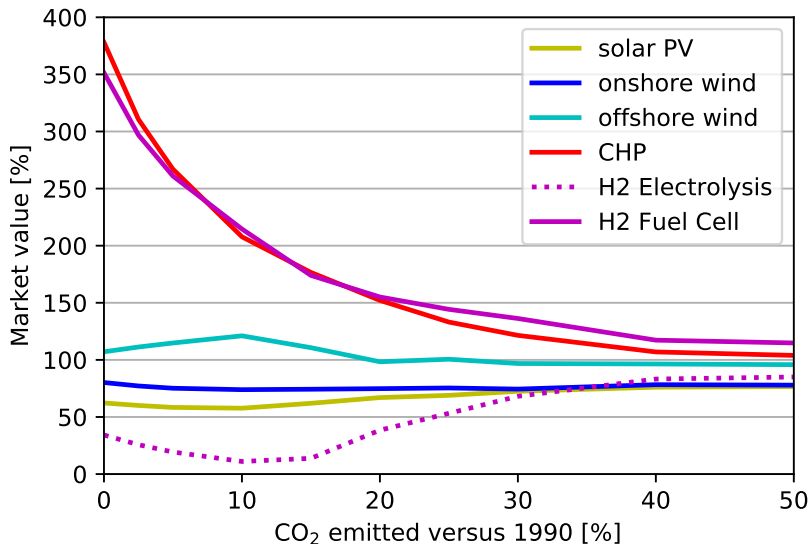
# Electricity price statistics: zero-price hours gone thanks to P2G



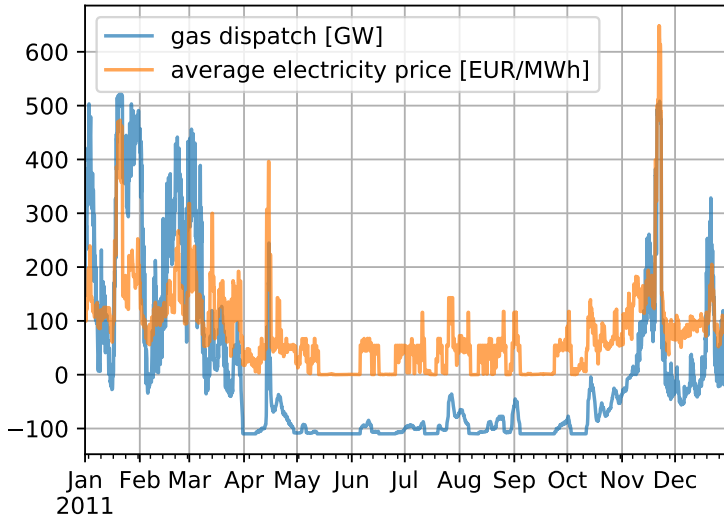
## Curtailment also much reduced



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



# Gas production/consumption tightly coupled to price



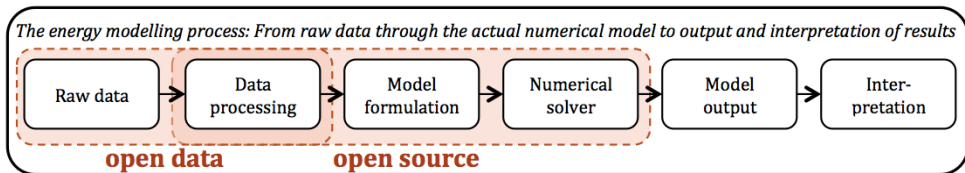
- Develop improvements on algorithmic side to enable larger problems (clustering, improved optimisation routines)
- Apply sector coupling to 200-node European model (instead of one-node-per-country) to see real transmission bottlenecks with scope, scale and sectors
- Explore pathway from here to 2050 (is P2X cost-effective sooner for local transmission bottlenecks? - these are not seen in the one-node-per-country sector model)
- Improve technology palette: bioenergy, waste heat, CCS, DAC, more synthetic electrofuels
- Complete sectoral coverage: aviation, shipping, process heat in industry
- Explore more grid optimisation options: HTC, DLR, PST, SPS with storage/DSM

# Open Energy Modelling

---

# Idea of Open Energy Modelling

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



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

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

**openmod** open energy  
modelling initiative

[openmod-initiative.org](https://openmod-initiative.org)

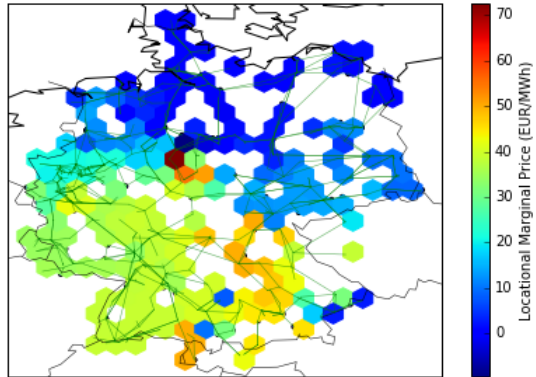


# Python for Power System Analysis (PyPSA)

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 CO<sub>2</sub> reduction easier = cheaper
- **Cross-sectoral** approaches are important to reduce CO<sub>2</sub> emissions **and** for flexibility
- **Policy prerequisites**: high, increasing and transparent **price for CO<sub>2</sub> pollution**; to manage grid congestion better: **smaller bidding zones**
- The energy system is complex and contains some uncertainty (e.g. cost developments, scalability of power-to-gas, consumer behaviour), so **openness is critical**

Unless otherwise stated, the graphics and text are Copyright ©Tom Brown, 2018.

The graphics and text for which no other attribution are given are licensed under a Creative Commons Attribution 4.0 International Licence.

