

# Transmission Networks versus Sector Coupling in a Highly Renewable Energy Scenario for Europe

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T. Brown<sup>1</sup>, M. Greiner<sup>2</sup>, A. Kies<sup>1</sup>, D. Schlachtberger<sup>1</sup>, S. Schramm<sup>1</sup>

<sup>1</sup>Frankfurt Institute for Advanced Studies (FIAS), University of Frankfurt; <sup>2</sup>Aarhus University

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**FIAS** Frankfurt Institute  
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# Research questions

1. What **infrastructure** (wind, solar, hydro generators, heating units, storage and networks) does a highly renewable energy system require and **where** should it go?
2. Given a desired CO<sub>2</sub> reduction (e.g. 95% compared to 1990), what is the **cost-optimal** combination of infrastructure (including all capital and marginal costs)?
3. What is the **trade-off** between international transmission, storage and **sector-coupling**?

# Need to capture spatial and temporal scope

Wind and solar generation is variable in time and space at different scales:

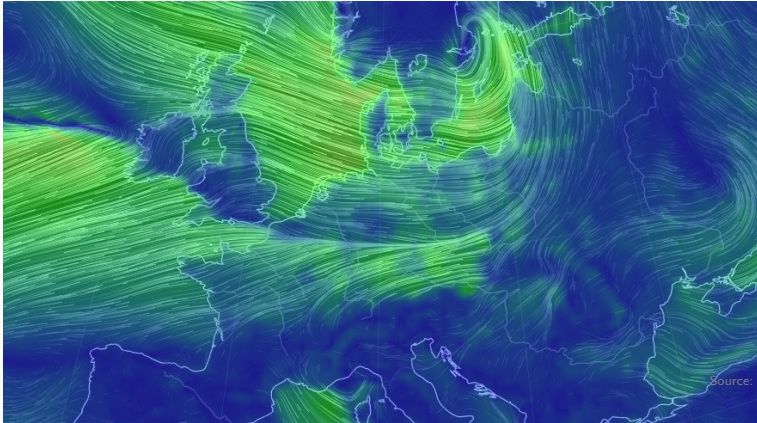
Variation	Time scale	Space scale	Solution
Diurnal	1 day	Earth circumference	Grid over multiple longitudes, Short-term storage, Demand-Side-Management (DSM)
Synoptic	3-10 days	~600 km	Continental-scale grids, Long-term storage
Seasonal	1 year	$\pm 23.4^\circ$ latitude	Grid over multiple latitudes, Long-term storage

Short-term storage includes batteries, pumped hydro and thermal energy storage (TES); long-term storage includes chemical storage, hydro reservoirs and long-term TES.

These solutions are not all feasible or cost-effective...

# Synoptic scales are key to cost-effectiveness in Europe

Given that wind is cheap and seasonally aligned with peak energy demand in Europe, cost-effective solutions tend to be dominated by wind. But wind has big synoptic-scale variations. These are caused by weather systems, which are bigger than countries and take days to pass, so you need either to integrate wind at the **continental scale** or use **long-term storage**.



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

# Linear optimisation of annual system costs

Given a desired CO<sub>2</sub> reduction, what is the most cost-effective energy system?

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

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

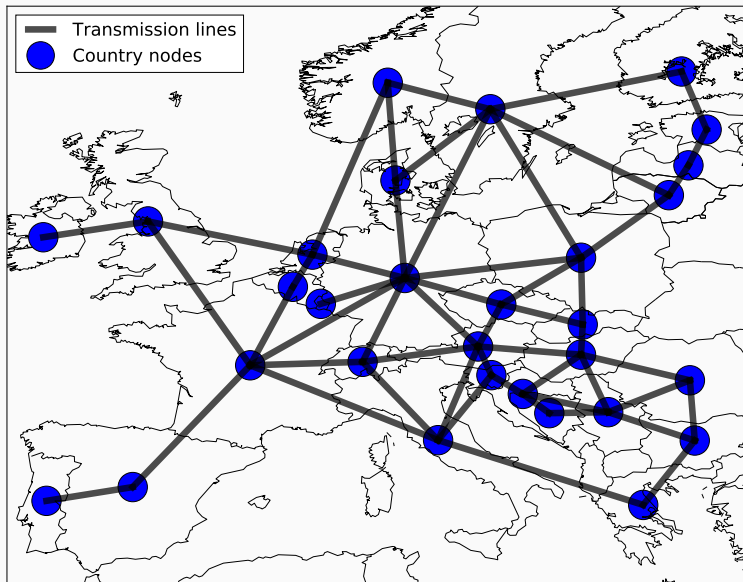
# Costs and assumptions for the electricity sector (projections for 2030)

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  $0.75 \times 0.58$ ).

## Europe: One node per country



# Global constraints on transmission volume

Transmission volume limits are respected, given length  $d_\ell$  and capacity  $\bar{P}_\ell$  of each line:

$$\sum_{\ell} d_{\ell} \bar{P}_{\ell} \leq \text{CAP}_{\text{trans}} \quad \leftrightarrow \quad \mu_{\text{trans}}$$

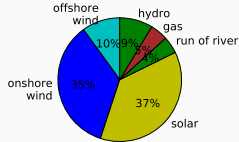
We successively change the transmission limit, to assess the costs of balancing power in time (i.e. storage) versus space (i.e. transmission networks).

First, consider ONLY the electricity sector.

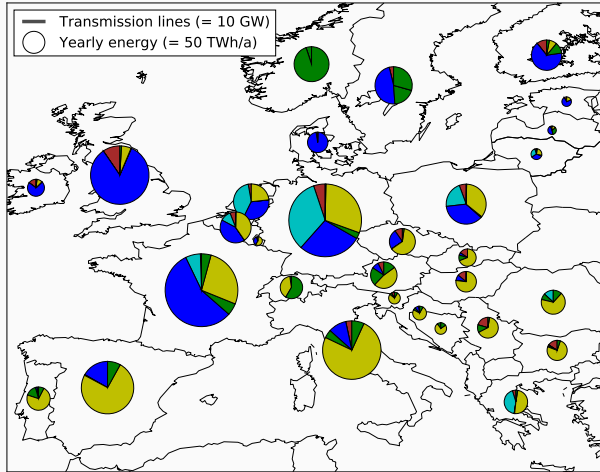
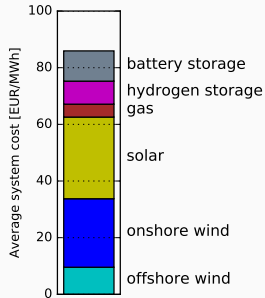


# Costs: No interconnecting transmission allowed

## Technology by energy:



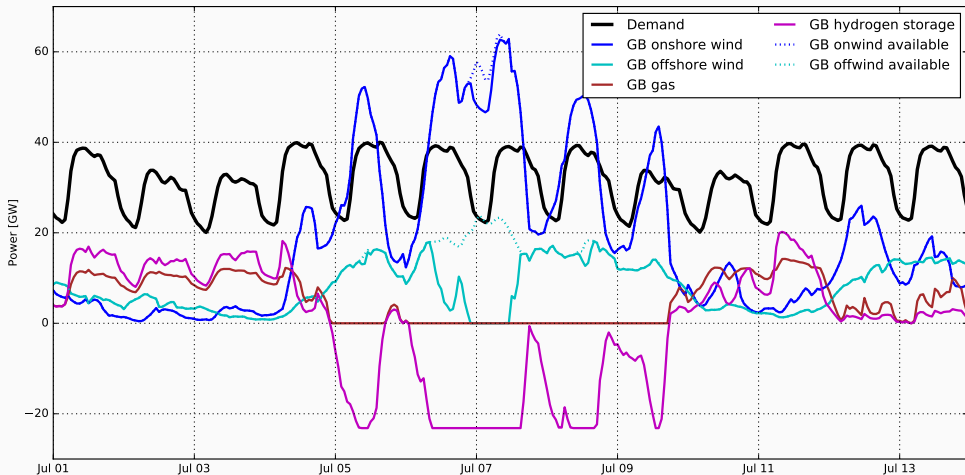
## Average cost €86/MWh:



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

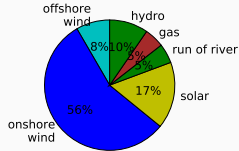
# Dispatch with no interconnecting transmission

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

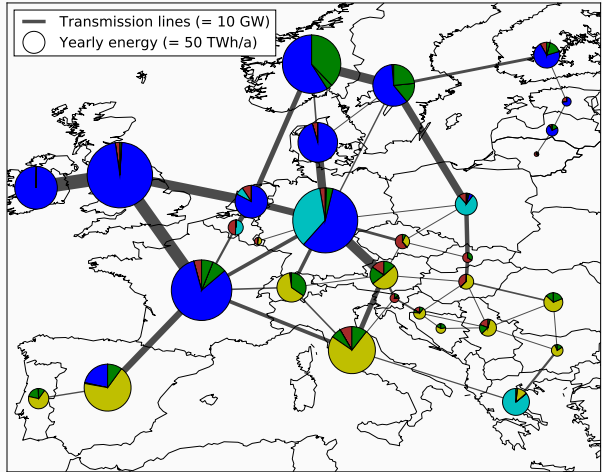
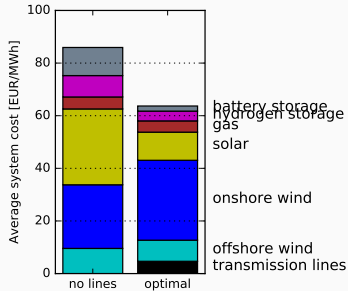


# Costs: Cost-optimal expansion of interconnecting transmission

## Technology by energy:



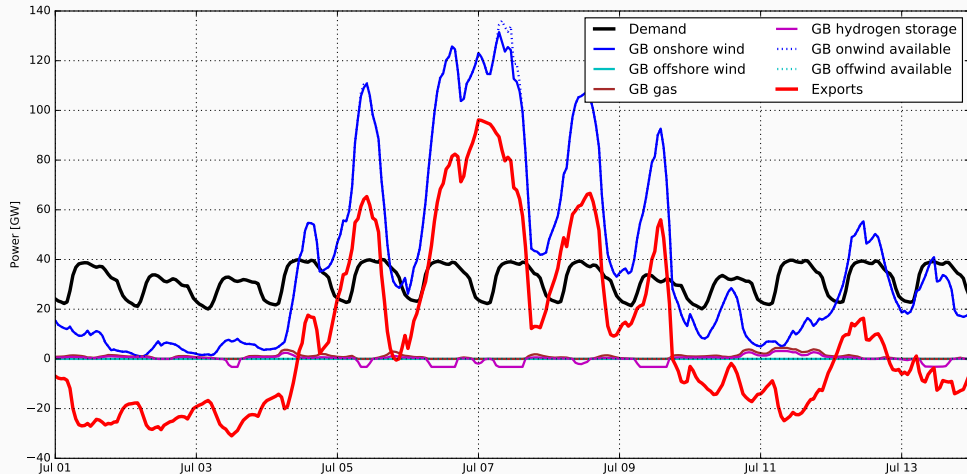
## Average cost €64/MWh:



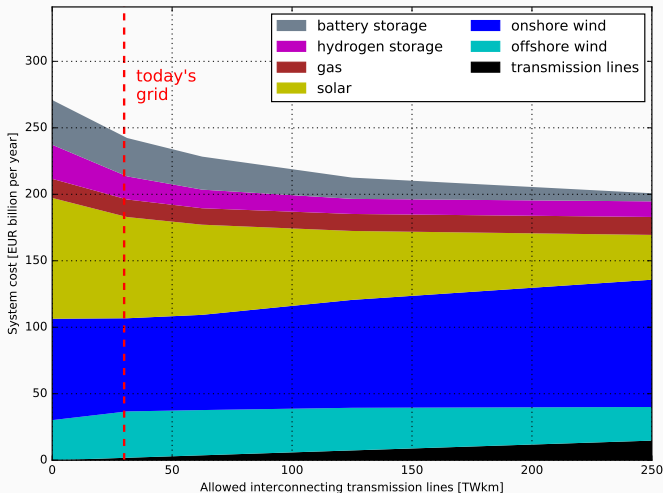
Large transmission expansion; onshore wind dominates. This optimal solution may run into public acceptance problems.

# Dispatch with cost-optimal interconnecting transmission

Almost all excess wind can be now be exported:

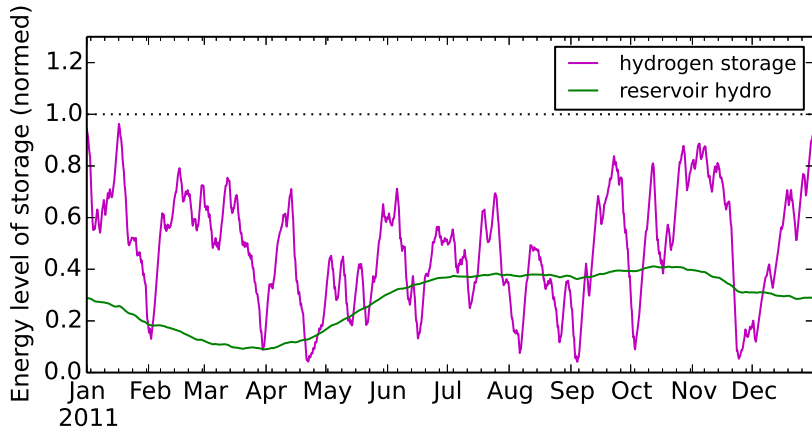


# Electricity Only Costs Comparison



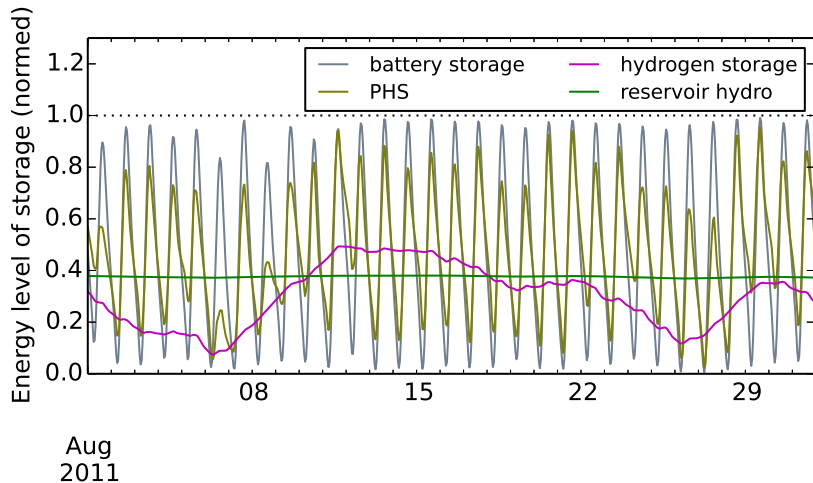
- Average total system costs can be as low as € 64/MWh
- Energy is dominated by wind (64% for the cost-optimal system), followed by hydro (15%) and solar (17%)
- Restricting transmission results in more storage to deal with variability, driving up the costs by up to 34%
- Many benefits already locked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

# 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

# Sector Coupling

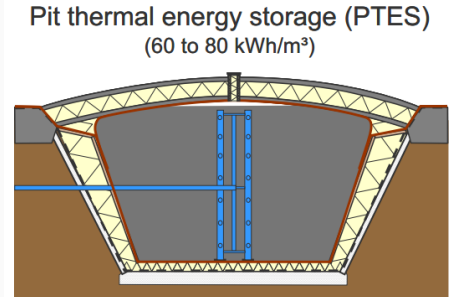
**Idea:** Couple the electricity sector to heating and mobility.

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

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



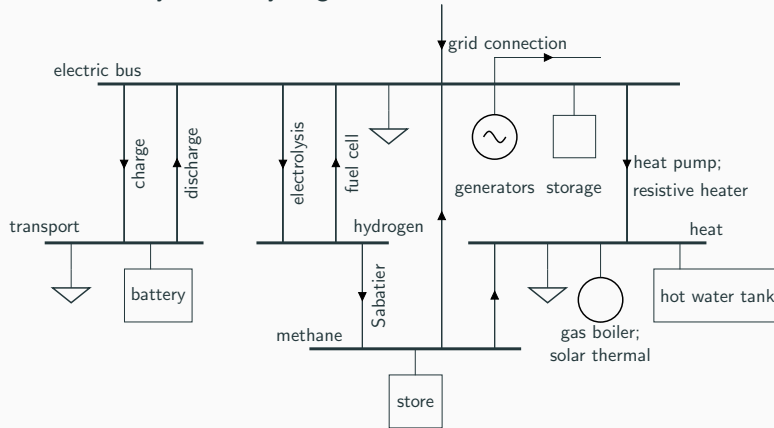
**Heat** is much easier and cheaper to store than electricity, even over many months



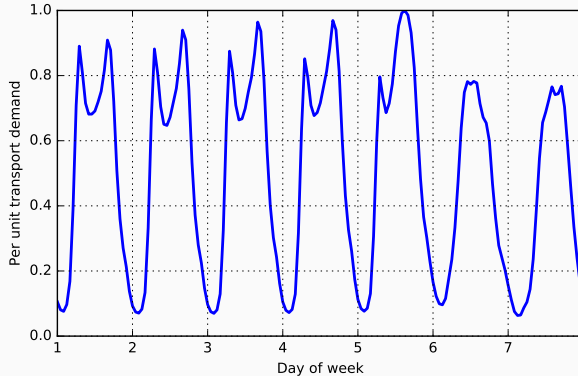


# Sector coupling: A new source of flexibility

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.



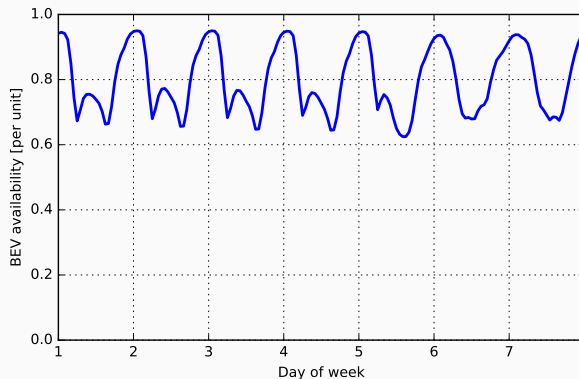
# Transport sector: Electrification of Transport



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 at 1014 TWh<sub>el</sub>/a for the 30 countries than today
- 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

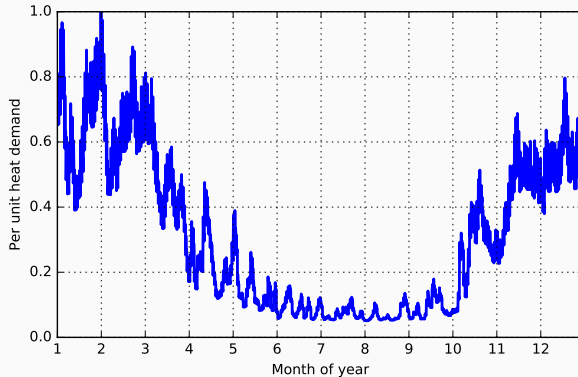


Availability (i.e. fraction of vehicles plugged in) of Battery Electric Vehicles (BEV).

BEV production costs 10-20% more expensive than Diesel in 2030, but lower fuel costs.

- Assumed that all passenger cars are Battery Electric Vehicles (BEVs), each with 50 kWh battery available (rest as buffer) and 11 kW charging power
- Assumed that all BEVs have time-dependent availability, averaging 80%, maximum 95% (at night)
- No changes in consumer behaviour assumed (e.g. car-sharing), but even with 50% reduction in BEVs, the results are barely effected (0.1%)
- BEVs are treated as exogenous (capital costs NOT included in calculation)

# 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  $3231 \text{ TWh}_{th}/a$ .
- Heating demand can be met by resistive heaters, gas boilers, solar thermal, Combined-Heat-and-Power (CHP) units and heat pumps, which have an average Coefficient of Performance of just under 3. 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 60% of heat demand is met with district heating in northern countries.

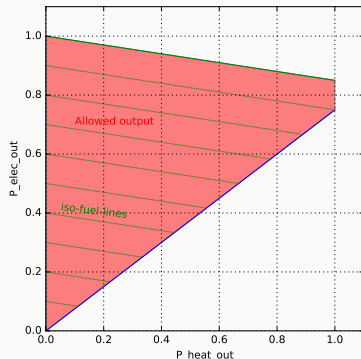
Decentral heating can be supplied by:

- Gas boilers
- Resistive heaters
- Small CHPs
- Small solar thermal
- Water tanks with short time constant  $\tau = 3$  days
- Heat pumps

Central heating can be supplied via district heating networks by:

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

CHP feasible dispatch:



## Cost and other assumptions

Quantity	Overnight Cost [€]	Unit	FOM [%/a]	Lifetime [a]
Sabatier	1100	$\text{kW}_{gas}$	2	20
Heat pump	1050	$\text{kW}_{th}$	1.5	20
Resistive heater	100	$\text{kW}_{th}$	2	20
Gas boiler	300	$\text{kW}_{th}$	1	20
Decentral solar thermal	270	$\text{kW}_{th}$	1.3	20
Central solar thermal	140	$\text{kW}_{th}$	1.4	20
Decentral CHP	1400	$\text{kW}_{el}$	3	25
Central CHP	650	$\text{kW}_{el}$	3	25
Central water tanks	20	$\text{m}^3$	1	40
District heating	400	$\text{kW}_{th}$	1	50

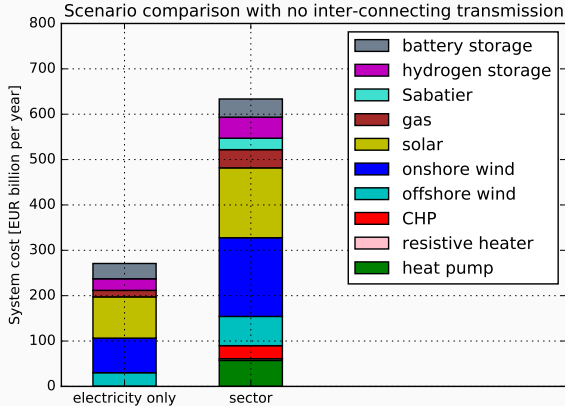
Costs oriented towards Henning & Palzer (2014, Fraunhofer ISE)

# Scenarios: Add flexibility one feature at a time

We now consider 10 scenarios where flexibility is added in stages:

1. **electricity only**: no sector coupling
2. **sector**: sector coupling to heating and transport with no use of sector flexibility
3. **sector BEV**: sector coupling; Battery Electric Vehicles (BEV) can shift their charging time
4. **sector BEV V2G**: sector coupling; BEV can in addition feed back into the grid (V2G)
5. **sector FC50**: sector coupling; 50% of BEV replaced by FCV
6. **sector FC100**: sector coupling; 100% of BEV replaced by FCV
7. **sector TES**: sector coupling with short-term Thermal Energy Storage (TES)  $\tau = 3$  days
8. **sector central**: sector coupling with 60% district heating in North and long-term TES
9. **sector all flex**: sector coupling with all flexibility options
10. **sector all flex central**: sector coupling with all flexibility options and 60% district heating

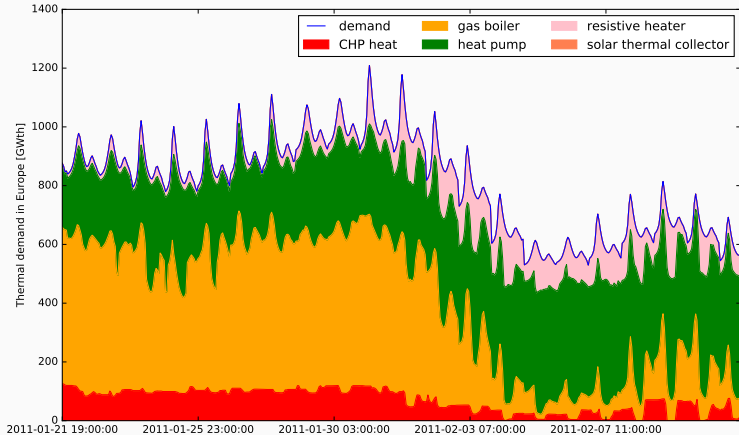
# From electricity to sector coupling



- With sector coupling costs are over twice as much because of higher energy demand, heating units and strong seasonality of heating demand.
- Decentralised heating demand peak (1262  $\text{GW}_{th}$ ) met by heat pumps (41%), gas boilers (26%), resistive heaters (17%) and CHP (15%).
- No additional flexibility activated.
- 800  $\text{TWh}_{th}/a$  of natural gas used (limited by  $\text{CO}_2$  cap); 725  $\text{TWh}_{th}/a$  of hydrogen produced; 530  $\text{TWh}_{th}/a$  of syngas produced, i.e. 40% of methane used is synthetic

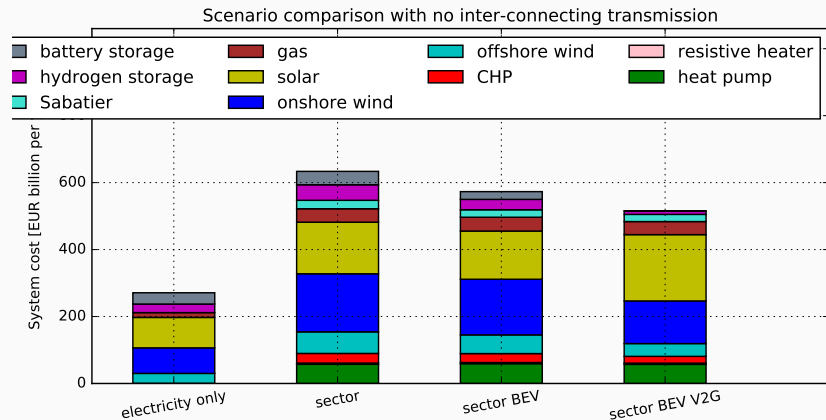


# Heat coverage for decentralised heating



- Over the year heat pumps (green) provide most of the heat energy, as in the second week shown here
- However when demand is high, heat pump COP is low and there is no wind or sun, gas boilers must step in (orange), as in first week shown here, to cover most of the heat demand

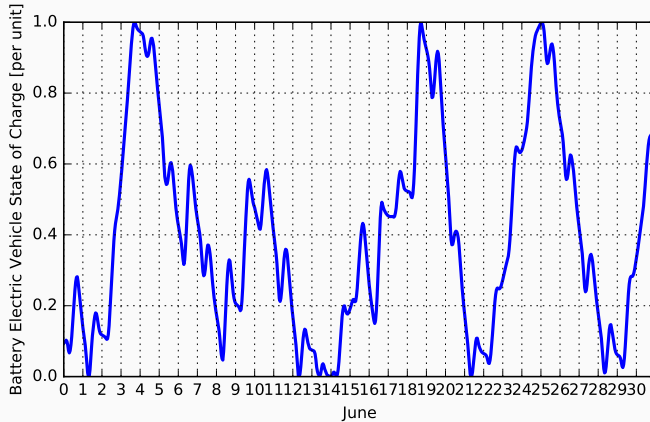
# Using Electric Vehicle flexibility



- Shifting the charging time to benefit the system reduces system costs by 10%.
- This Demand-Side Management reduced the need for stationary storage by half.
- Allowing BEVs to feed back into the grid (V2G) reduces costs by a further 10%.
- This eliminates the need for batteries and allows much more solar to be integrated.

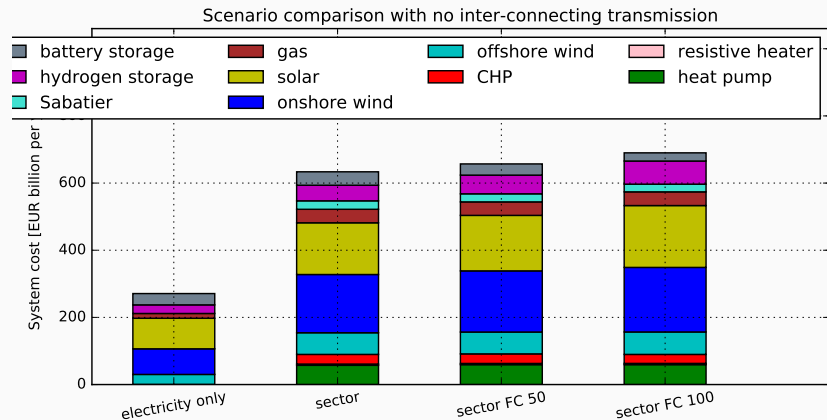
With V2G total solar capacity jumps from 1,764 GW to 2,426 GW.

# Battery Electric Vehicle state of charge



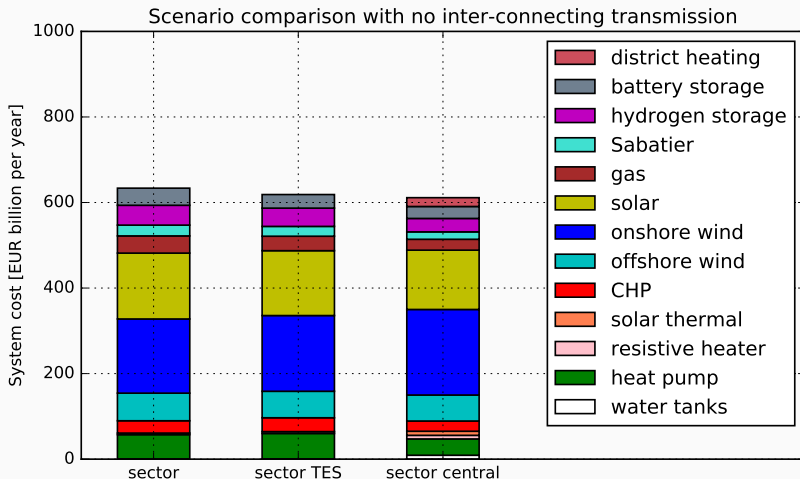
- Aggregated Battery Electric Vehicle state of charge in Germany shows very little day-to-day cycling which would degrade the battery, even with V2G and lots of solar
- Bigger longer-term synoptic variations driven by wind
- NB: This shows only the SOC available to the V2G (50 kWh per vehicle); there is also a buffer that is not available to V2G
- Only 0.1% change in total costs if V2G capacity reduced by 50%

# Using Fuel Cells instead of Electric Vehicles



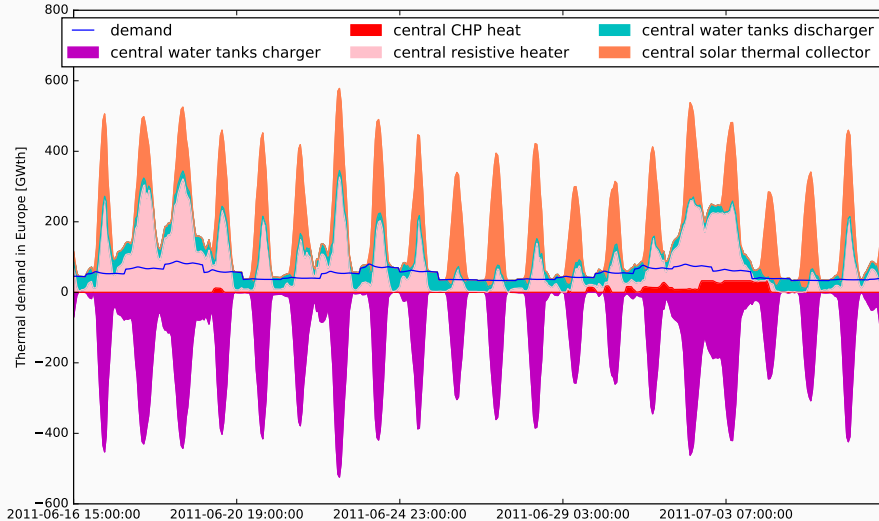
- The lower efficiency of fuel cells (60%) means more energy has to be generated, leading to higher overall costs.
- These higher costs are NOT compensated by the extra flexibility of cheap hydrogen storage.
- FCEVs are also more expensive than BEVs, then comes the hydrogen infrastructure costs...

# Using heating sector flexibility



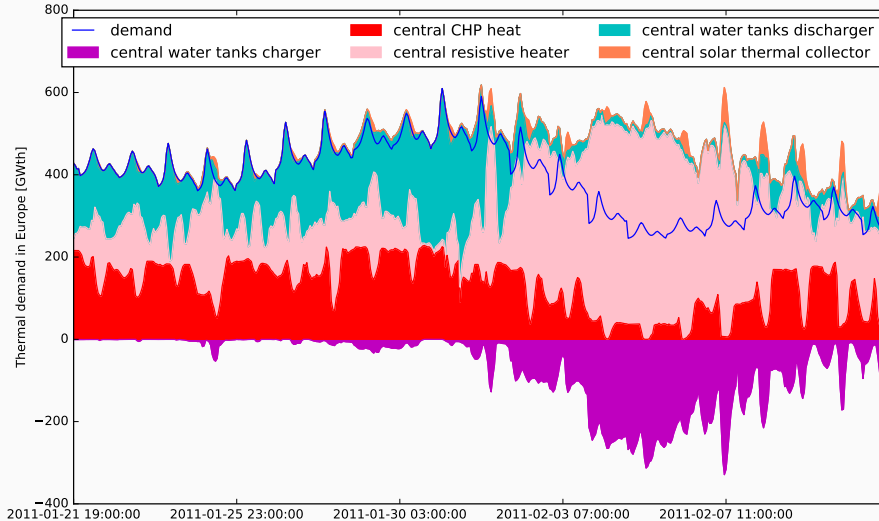
- Allowing short-term Thermal Energy Storage (TES) ( $\tau = 3$  days) has only a 2% effect on the costs.
- Using 60% centralised heating enables the use of long-term TES ( $\tau = 180$  days). In this case solar thermal is built to fill the TES in the summer. The cost decrease is mostly compensated by the cost of the district heating.

# Centralised heating: charging TES with solar thermal in summer



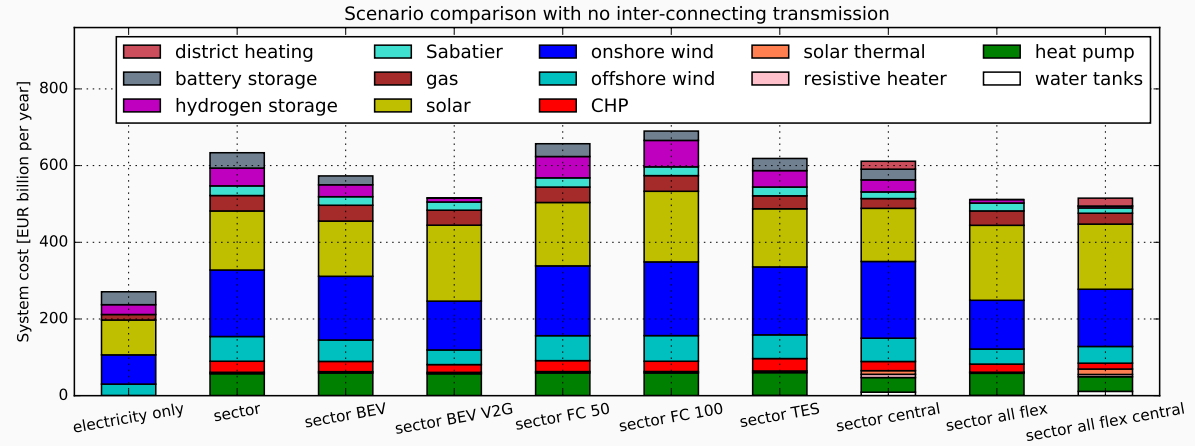
In summer solar thermal collectors (orange) and resistive heaters (pink) fill up the long-term centralised thermal energy storage (purple).

# Centralised heating: discharging TES in winter



In winter, demand is met by a combination of CHP (red), resistive heating (pink) and the discharge from the long-term centralised TES (cyan).

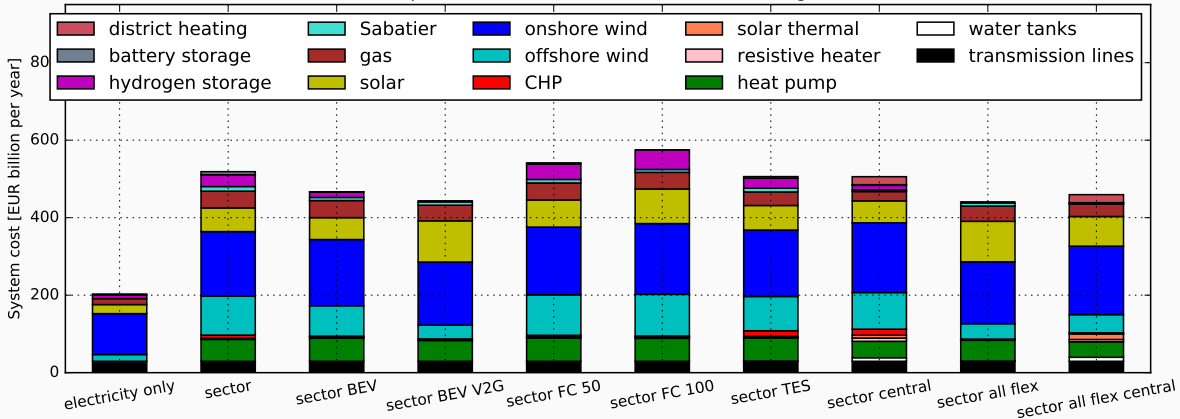
# Scenario comparison with no inter-connecting transmission



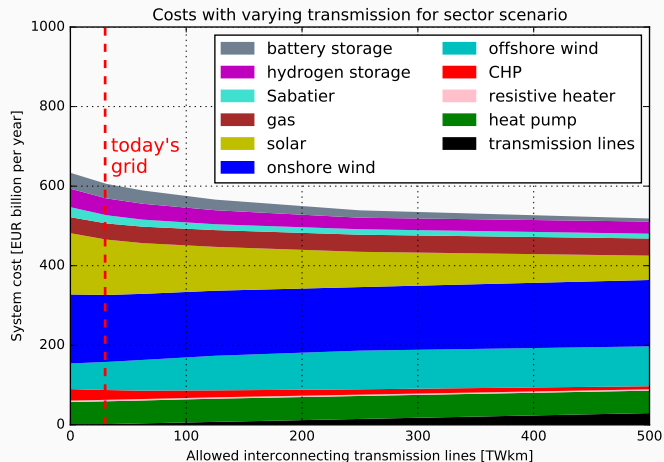


# Scenario comparison with optimal inter-connecting transmission

Scenario comparison with 500 TWkm of inter-connecting transmission

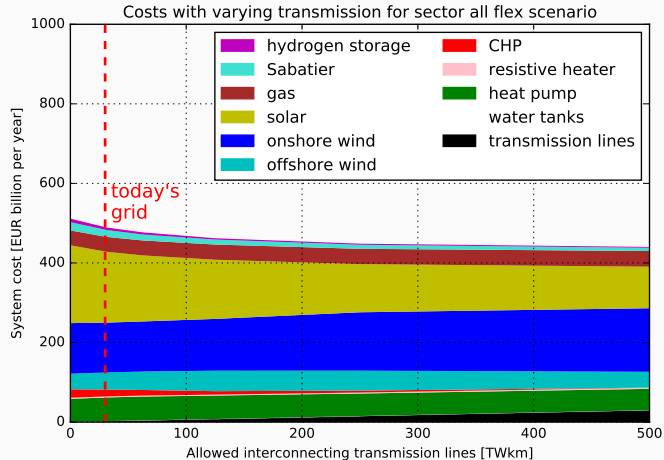


# Sector Coupling with No Extra Flexibility



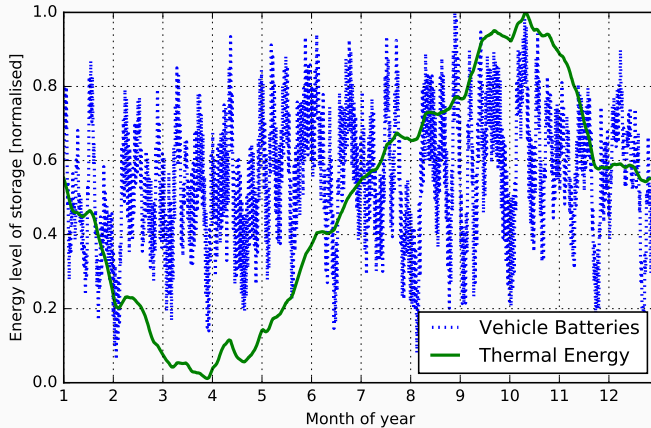
- Solution with no inter-connecting transmission costs 33% more than optimal transmission (comparable to electricity-only scenario)
- Gas boilers replace CHPs as transmission increases, since transmission reduces need for gas for balancing in electricity sector
- Need stationary batteries and hydrogen storage to balance RES variability
- Transmission allows cheaper wind to substitute for solar power

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



- The benefits of inter-connecting transmission are now much weaker: it reduces costs by only 16%
- Even with no transmission, the system is cheaper than all levels of transmission for sector-coupling with no sector flexibility
- System costs are comparable to today's (with same cost assumptions, today's system comes out around € 377 billion per year, excluding 'externalities')

# Storage energy levels: different time scales

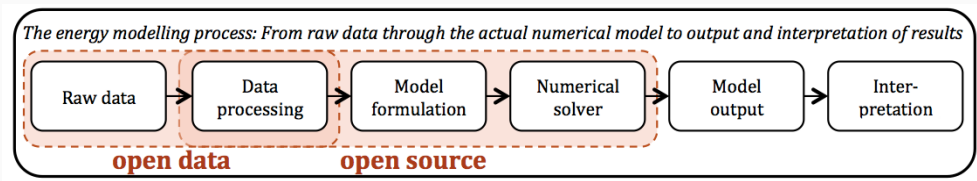


The different scales on which storage flexibility work can be seen clearly when examining the state of charge.

- Long-Term Thermal Energy Storage (TES) has a dominant seasonal pattern, charging in summer and discharging in winter. Additional synoptic-scale fluctuations are super-imposed.
- Battery Electric Vehicles (BEV) with Vehicle-To-Grid (V2G) show large fluctuations on daily and synoptic scales.

# 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! Next workshop in Frankfurt, 19-21 April 2017.

**openmod** open energy  
modelling initiative

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

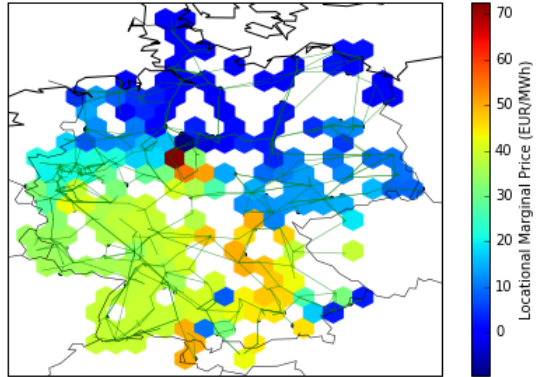
Source: openmod initiative

# Python for Power System Analysis (PyPSA)

The FIAS software PyPSA is online at <http://pypsa.org/> and on github. It can do:

- Static power flow
- Linear optimal power flow
- Security-constrained linear optimal power flow
- Unit commitment
- Total electricity system investment optimisation

It has models for storage, meshed AC grids, meshed DC grids, hydro plants, variable renewables and sector coupling.



# Conclusions

- This is **no single solution** for highly renewable systems, but a **family of solutions** with different costs and compromises
- Generation costs always dominate total costs, but the grid can cause higher generation costs if expansion is restricted
- Cost-optimal grid expansion favours wind over solar
- Much of the need for stationary storage can be eliminated by sector-coupling: in particular the use of flexible charging from (and discharging into) the grid by battery electric vehicles can reduce system costs by up to 20%, and enable more solar integration
- With sector coupling, grid expansion becomes less important
- Understanding the need for **flexibility at different temporal and spatial scales** is key to mastering the complex interactions in the energy system

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