Sector Coupling in a Simplified, Highly Renewable European Energy System

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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_2 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?

Chief question: How to deal with variability

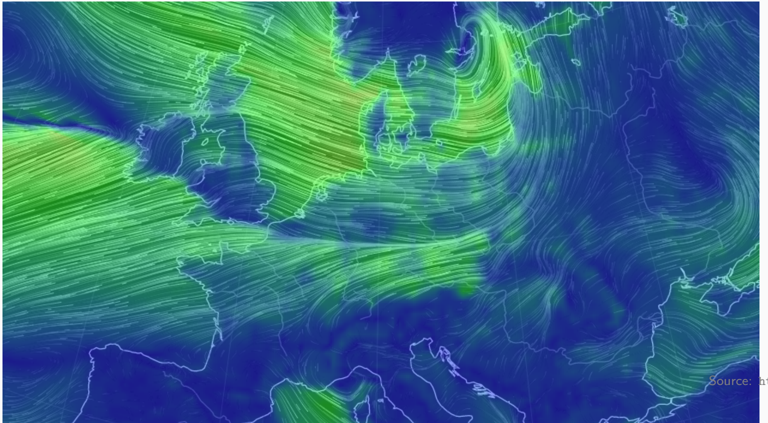
Wind and solar generation is variable in time and space. The variations on different scales require different solutions.

Variation	Time scale	Space scale
Diurnal	1 day	Earth circumference
Synoptic	3-10 days	$\sim$600-1000 km
Seasonal	1 year	Hadley cell

We can use hydro/chemical/thermal storage to balance temporal variations; for spatial balancing, large grids are required. 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

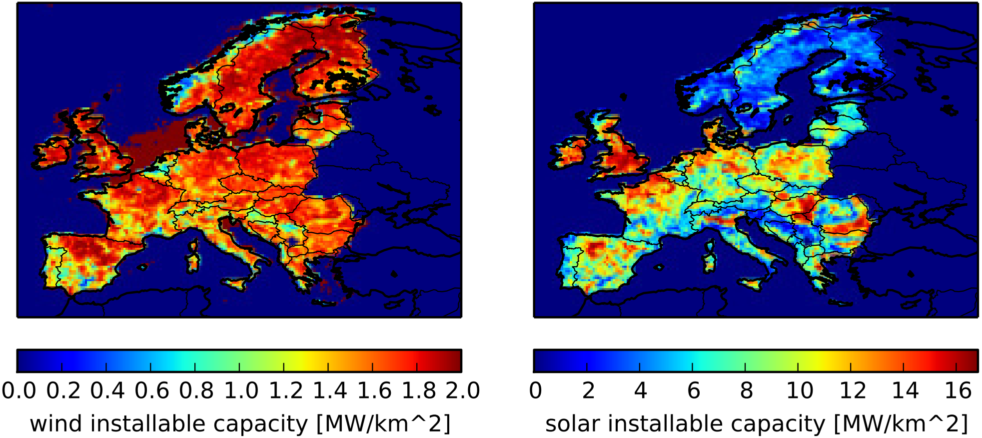
Given a desired CO_2 reduction, what is the most cost-effective energy system?

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

subject to

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

Geographical potentials for wind and solar

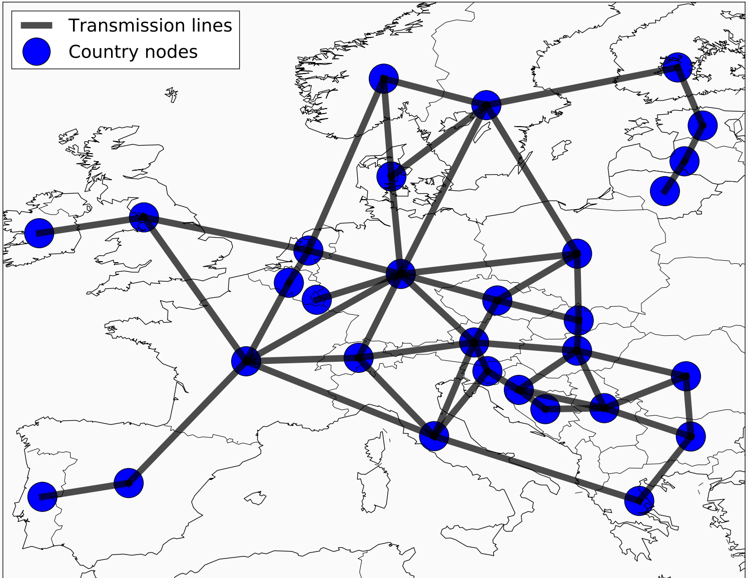


Cost and other assumptions

Quantity	Overnight Cost [€]	Unit	FOM [%/a]	Lifetime [a]
Wind onshore	1182	kW_{el}	3	20
Wind offshore	2506	kW_{el}	3	20
Solar PV	600	kW_{el}	4	20
Gas	400	kW_{el}	4	30
Battery storage	1275	kW_{el}	3	20
Hydrogen storage	2070	kW_{el}	1.7	20
Transmission line	400	MWkm	2	40
Heat pump	1050	kW_{th}	1.5	20
Resistive heater	100	kW_{th}	2	20
Gas boiler	300	kW_{th}	1	20
Large-scale water tanks	20	m^3	1	40

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

Europe: One node per country



International versus national solutions: Global constraints on transmission volumes

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

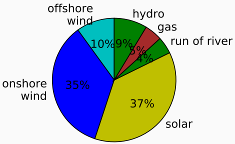
$$\sum_\ell d_\ell \bar{P}_\ell \quad \leq \quad \mathrm{CAP}_{\mathrm{trans}} \qquad\qquad \leftrightarrow \qquad \lambda_{\mathrm{trans}}$$

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

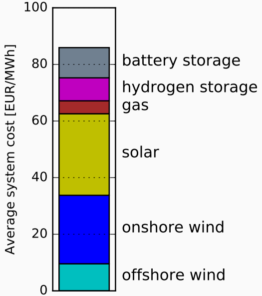
First, consider ONLY the electricity sector.

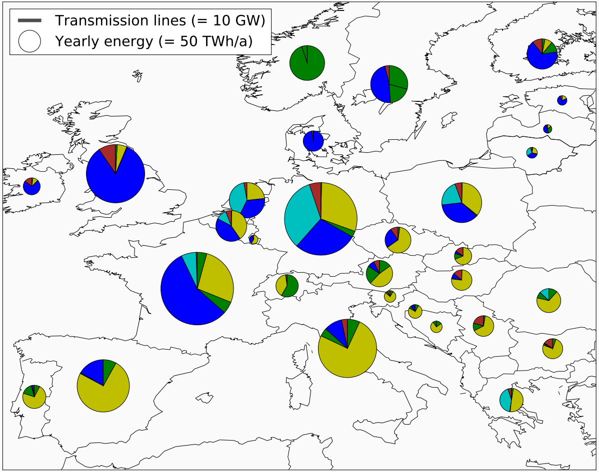
Costs: No interconnecting transmission allowed

Technology by energy:



Average cost €86/MWh:

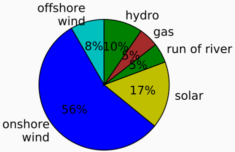




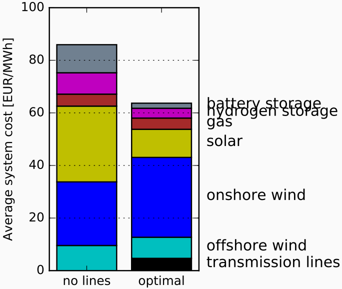
Countries must be self-sufficient at all times; lots of storage and some gas to deal with fluctuations of wind and solar.

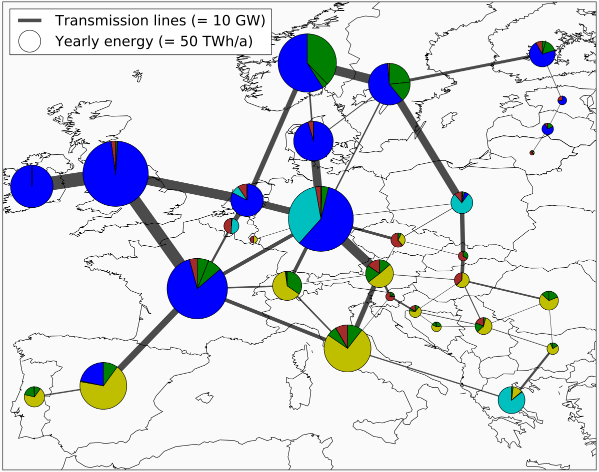
Costs: Cost-optimal expansion of interconnecting transmission

Technology by energy:



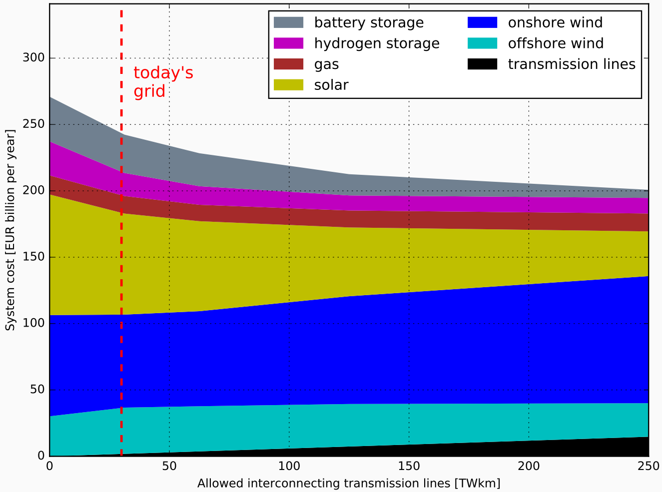
Average cost €64/MWh:





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

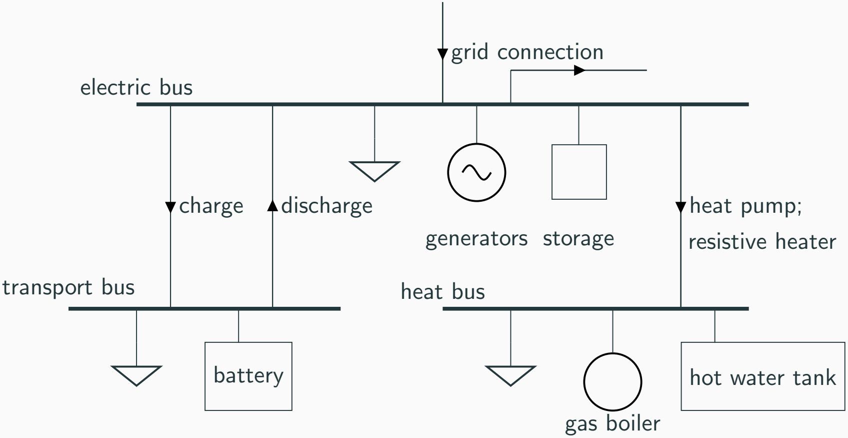
Electricity Only Costs Comparison



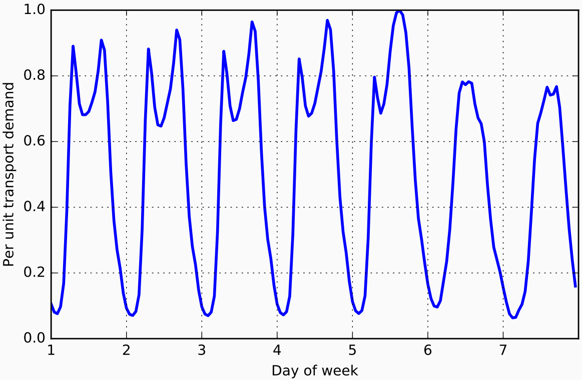
- Average total system costs can be as low as € 64/MWh
- Energy is dominated by wind (64% for the cost-optimal system), followed by hydro (15%) and solar (17%)
- Restricting transmission results in more storage to deal with variability, driving up the costs by up to 34%
- Many benefits already locked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

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).



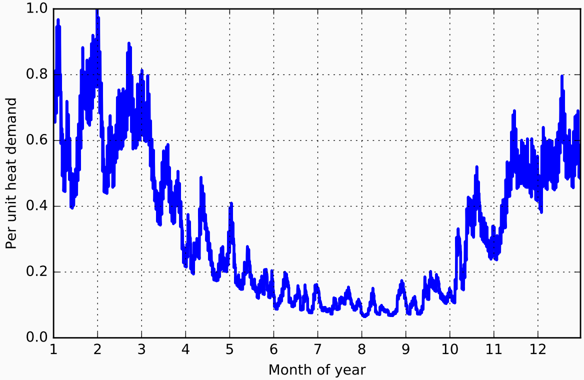
Transport sector: Battery Electric Vehicles



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; no changes in consumer behaviour assumed (e.g. car-sharing).
- Assumed that all passenger cars are Battery Electric Vehicles (BEVs), each with 50 kWh battery and 11 kW charging power, connected to grid 90% of time.
- BEVs are treated as exogenous (capital costs NOT included in calculation).
- Because of higher efficiency of electric motors, final energy consumption 3.5 times lower at 1014 TWh_{el}/a for the 30 countries.

Heating sector: Electric Heat Pumps with Thermal Energy Storage (TES)



Heat demand profile from 2011 in all 30 countries based on average daily temperatures in each country using degree-day approx. and population distribution (NUT3 level).

- All space and water heating in the residential and services sectors is considered, with no additional efficiency measures (conservative) - total heating demand is 3231 TWh_{th}/a.
- Heating demand can be met by resistive heaters, gas boilers and heat pumps, which have a uniform Coefficient of Performance of 3. No CHP, waste heat or solar heating.
- Thermal Energy Storage (TES) is available to the system in the form of cheap hot water tanks, with a long time constant for heat loss of $\tau = 180$ days.

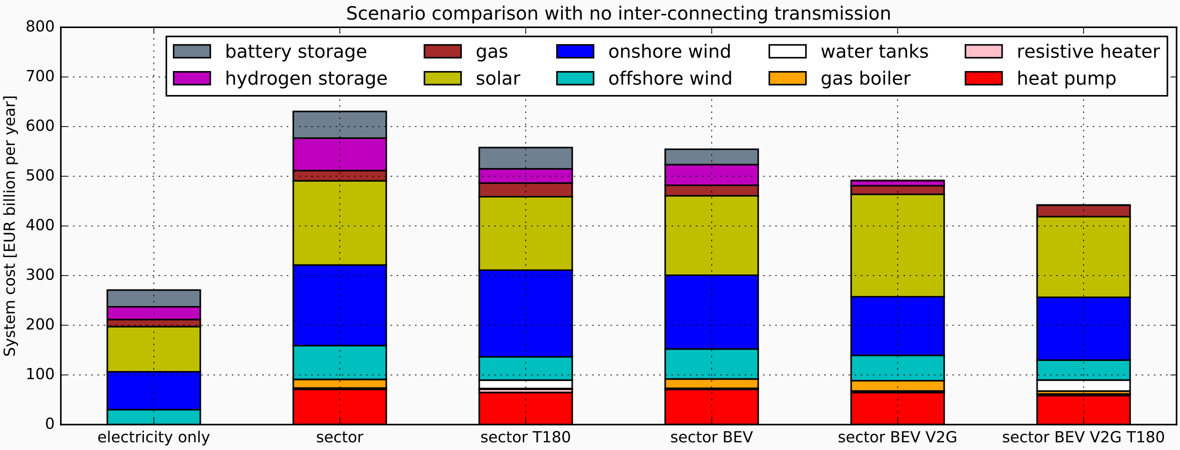
Scenarios: Add flexibility one feature at a time

We now consider 6 scenarios where flexibility is added in stages:

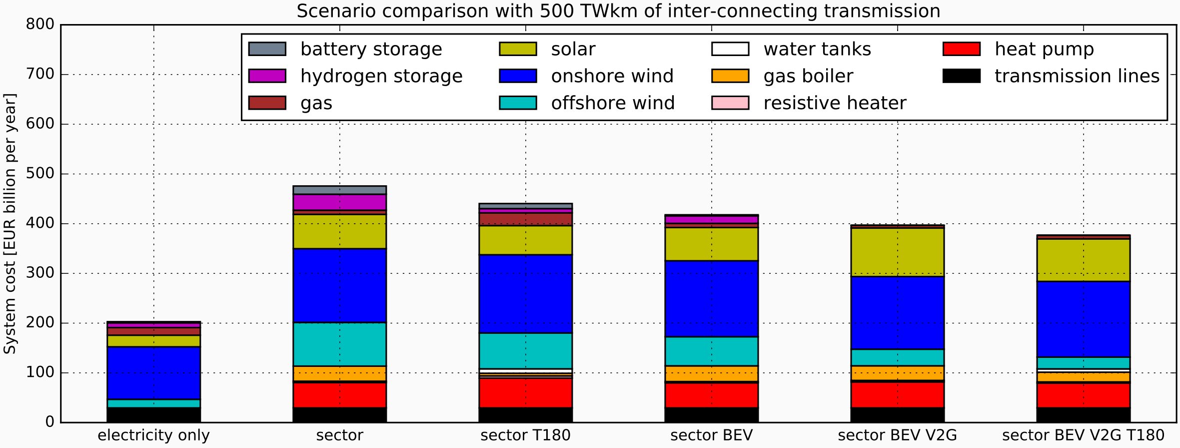
1. **electricity only**: no sector coupling
2. **sector**: sector coupling to heating and transport with no use of sector flexibility
3. **sector T180**: sector coupling with long-term Thermal Energy Storage (TES) $\tau = 180$ days
4. **sector BEV**: sector coupling; Battery Electric Vehicles (BEV) can shift their charging time
5. **sector BEV V2G**: sector coupling; BEV can in addition feed back into the grid (Vehicle-2-Grid)
6. **sector BEV V2G T180**: sector coupling with all flexibility options

We also consider each scenario at different levels of expansion of inter-connecting transmission.

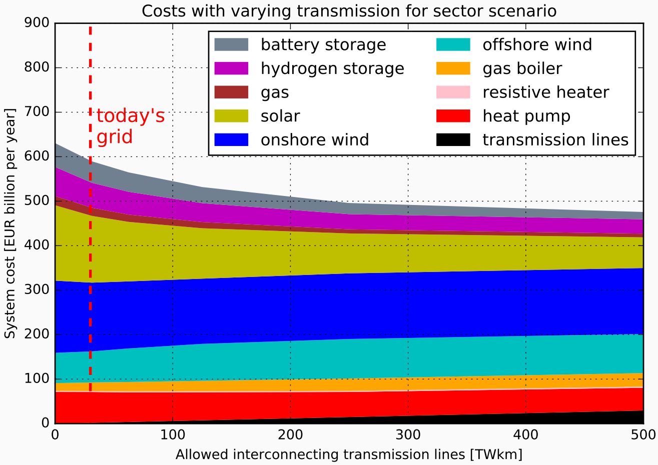
Scenario comparison with no inter-connecting transmission



Scenario comparison with optimal inter-connecting transmission

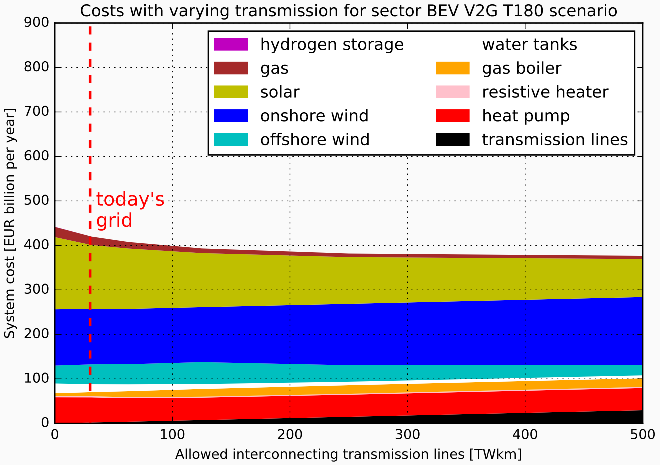


Sector Coupling with No BEV and No TES



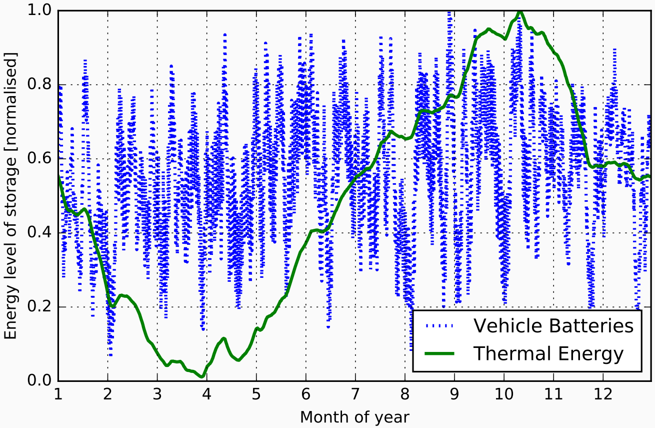
- Solution with no inter-connecting transmission costs 33% more than optimal transmission (comparable to electricity-only scenario)
- Heat pumps make a big contribution to cost, but are replaced by gas boilers when transmission reduces need for gas for balancing in electricity sector
- Need stationary batteries and hydrogen storage to balance RES variability
- Transmission allows cheaper wind to substitute for solar power

Sector Coupling with BEV and V2G and TES with $\tau = 180$ days



- The benefits of inter-connecting transmission are now much weaker: it reduces costs by only 15%
- 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')
- Water tank TES built 3 times more when inter-connection is restricted

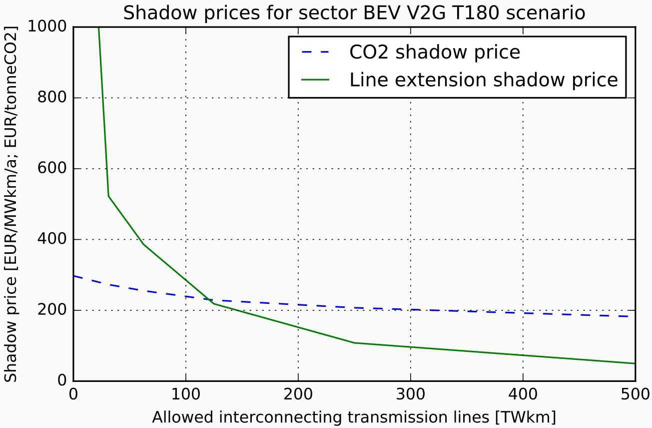
Storage energy levels: different time scales



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

- 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.

Line extension and CO_2 shadow prices

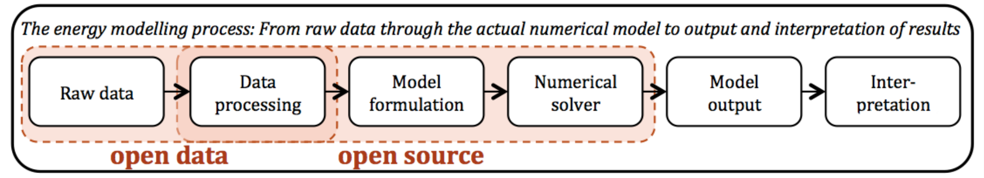


Additional information can be derived by examining the shadow prices of important constraints.

- The shadow price of line extension allows us to read off the optimal grid extension levels for different line extension costs: overhead lines gives around 500 TWkm, while underground cable gives around 150 TWkm.
- A CO_2 price of between 200 and 300 €/tonne is required to make these solutions viable in a free market.

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, with a wiki, a lively mailing list and regular workshops:

openmod open energy modelling initiative

openmod-initiative.org

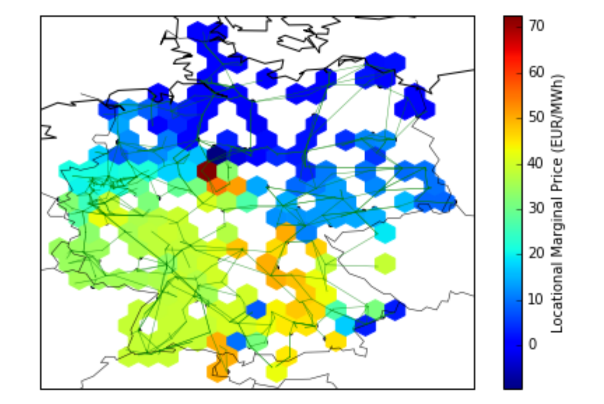
Source: openmod initiative

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
- Total electricity system investment optimisation

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



Conclusions

- The questions are no longer *whether a renewable system is possible* or *whether it can be affordable*; rather it is what compromises will we make and how much will they cost?
- System costs can be comparable to today's (excluding vehicle capital costs), if we allow lots of onshore wind, international grid expansion and sector-coupling flexibility.
- However, solutions with no or little transmission but more solar and storage are only between 17% and 33% more expensive, which gives policy-makers the flexibility to choose based on non-technical non-economic criteria (like public acceptance of grids).
- Long-term Thermal Energy Storage (TES) can replace some electric storage and reduce total system costs by up to 12%.
- The grid-integration and grid-friendly operation of Battery Electric-Vehicles eliminates the need for stationary batteries and can reduce total system costs by 20%.
- Major challenges for modelling: getting more grid detail, while retaining European scope; including other heating technologies (CHP, waste, solar heat); reducing model complexity.

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