Karlsruhe Institute of Technology

Energy System Modelling
Summer Semester 2020, Lecture 12

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Sector Coupling: Invitation

What to do about variable renewables?

Backup energy costs money and may also cause CO_2 emissions.

Curtailing renewable energy is also a waste.

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

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

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

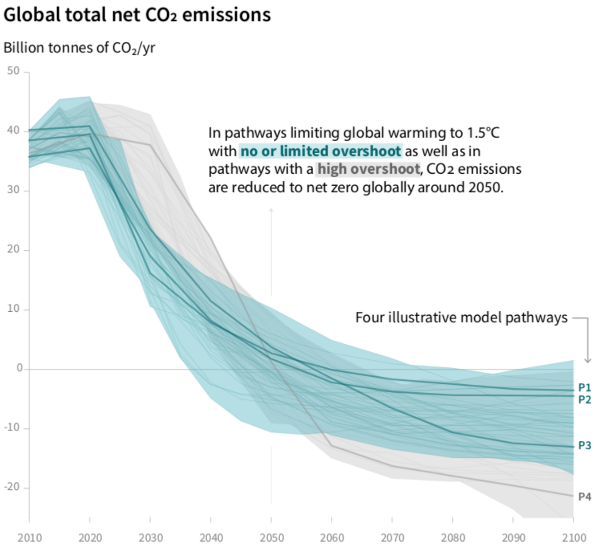
Sector coupling

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

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

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

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

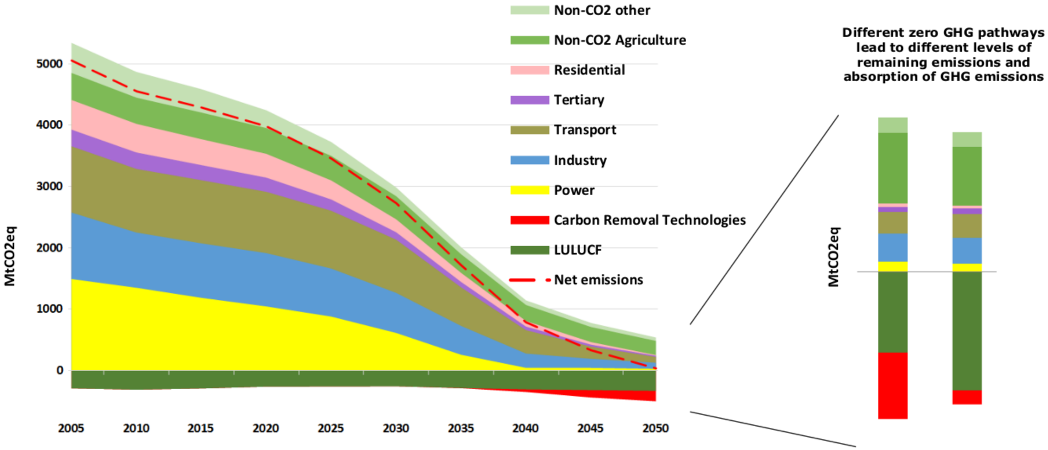


- Scenarios for global CO_2 emissions that limit warming to 1.5°C about industrial levels (**Paris agreement**)
- Today emissions **still rising**
- Level of use of negative emission technologies (NET) depends on rate of progress
- 2°C target without NET also needs rapid fall by 2050
- Common theme: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

Source: IPCC SR15 on 1.5C, 2018

The Greenhouse Gas Challenge: Net-Zero Emissions by 2050

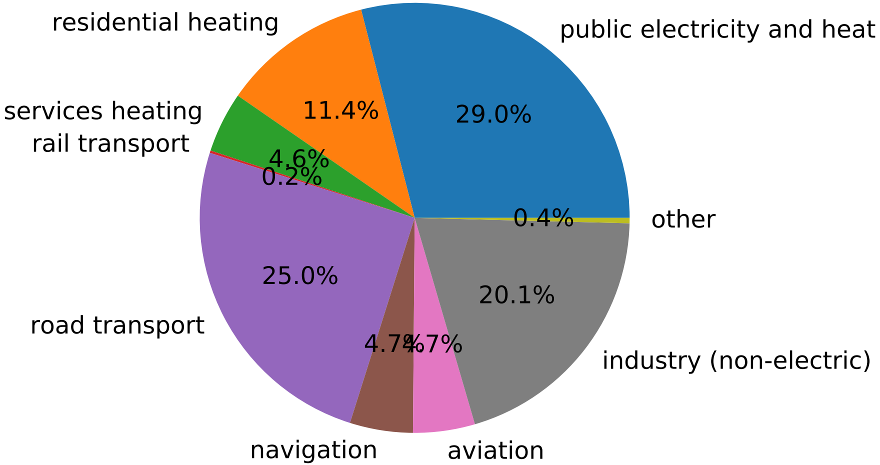
Paris-compliant 1.5° C scenarios from European Commission - **net-zero GHG in EU by 2050**



Source: European Commission 'Clean Planet for All', 2018

It's not just about electricity demand...

EU28 CO_2 emissions in 2016 (total 3.5 Gt CO_2, 9.7% of global):



Source: Brown, data from EEA

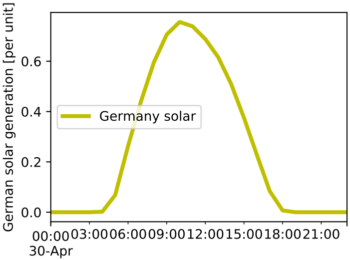
...but electification of other sectors is critical for decarbonisation

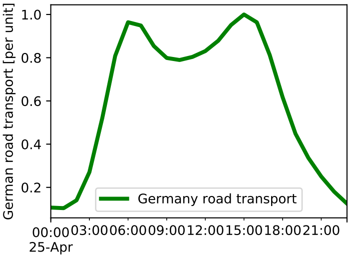
Wind and solar dominate the expandable potentials for low-carbon energy provision, so **electrification is essential** to decarbonise sectors such as transport and heating.

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

Source: Tesla; heat pump: Kristoferb at English Wikipedia

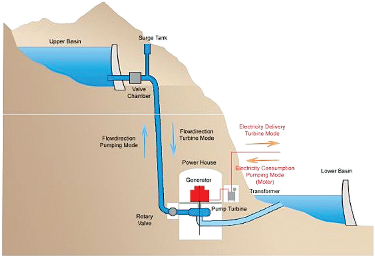
Daily variations: challenges and solutions



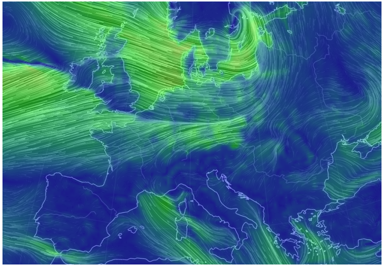


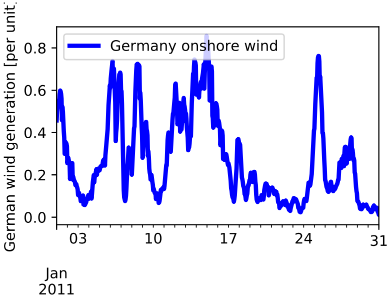
Daily variations in supply and demand can be balanced by

- **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**



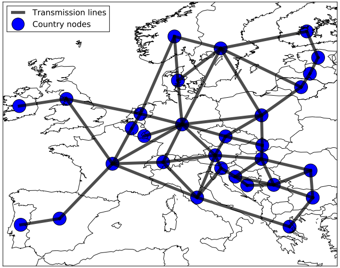
Synoptic variations: challenges and solutions



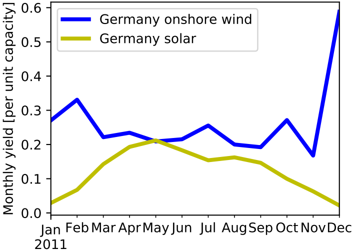


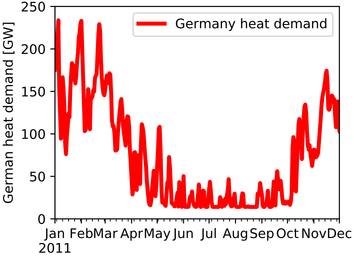
Synoptic variations in supply and demand can be balanced by

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



Seasonal variations: challenges and solutions

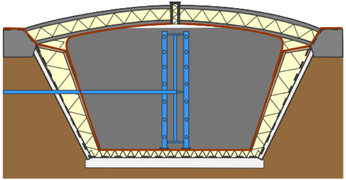




Seasonal variations in supply and demand can be balanced by

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

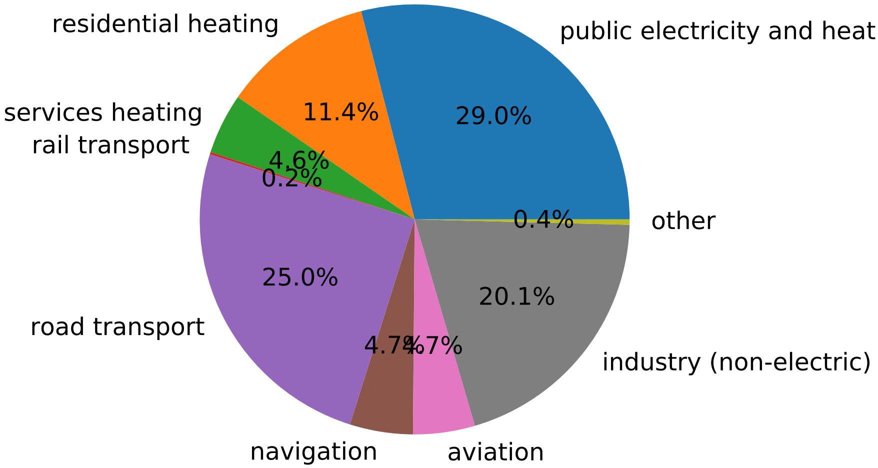
Pit thermal energy storage (PTES)
(60 to 80 kWh/m³)



Electricity, Heat in Buildings and Land Transport

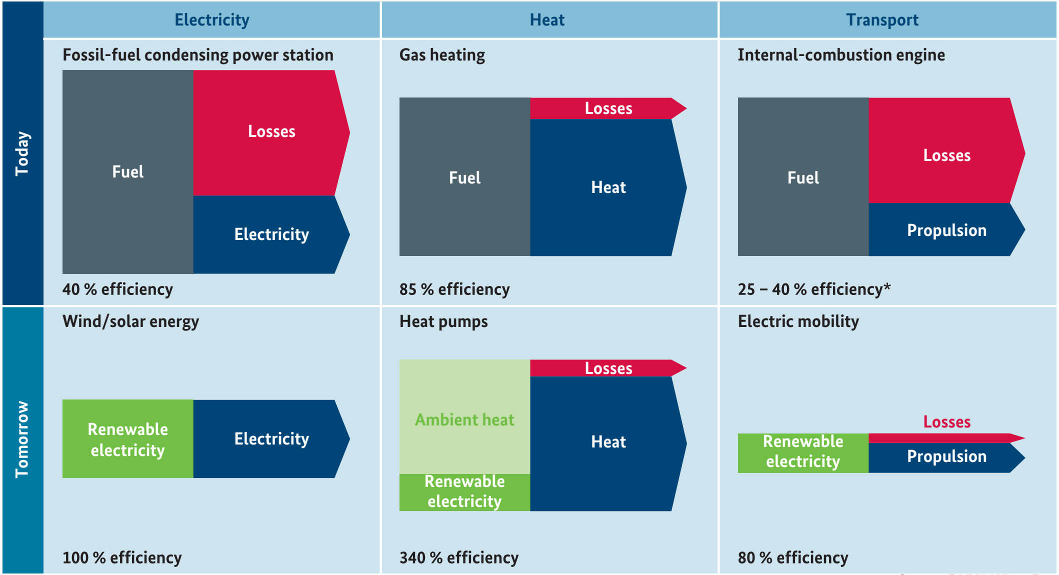
Include other sectors: building heating and land transport

Electricity, heating in buildings and land transport cover 77% of 2015 CO_2 emissions:



Source: Brown, data from EEA

Efficiency of renewables and sector coupling

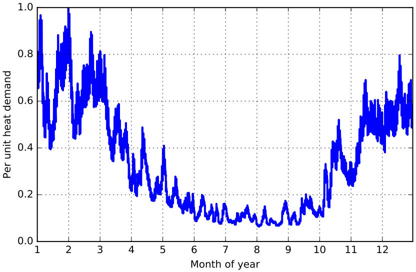


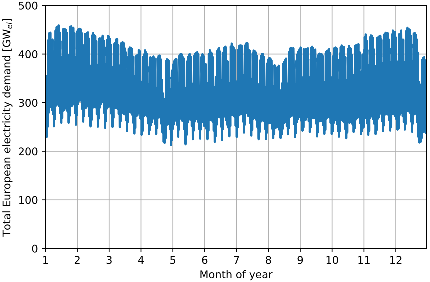
Source: BMWi White Paper 2015

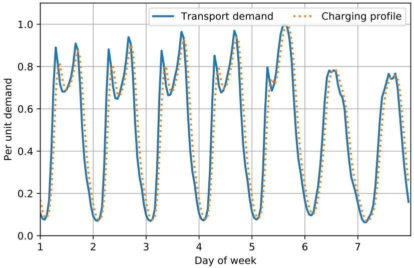
Challenge: Heating and transport demand highly peaked

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

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







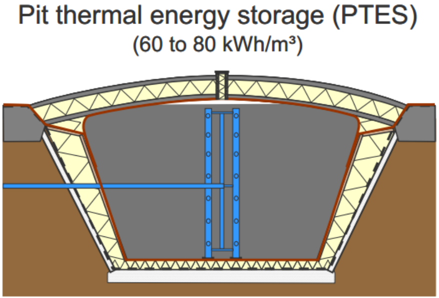
Sector Coupling

Idea: Couple the electricity sector to heating and mobility.

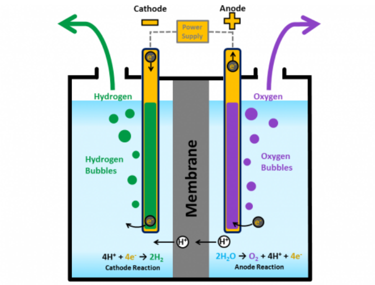
This enables decarbonisation of these sectors **and** offers more flexibility to the power system.

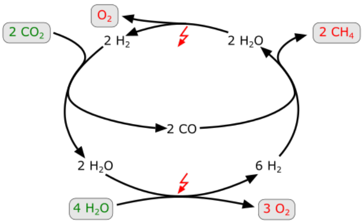
Battery electric vehicles can change their charging pattern to benefit the system and even feed back into the grid if necessary

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



Power-to-Gas (P2G)

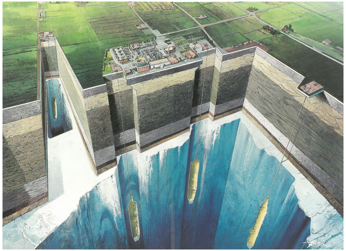




Power-to-Gas/Liquid (P2G/L) describes concepts to use electricity to electrolyse water to **hydrogen** H_2 (and oxygen O_2). We can combine hydrogen with carbon oxides to get **hydrocarbons** such as methane CH_4 (main component of natural gas) or liquid fuels C_nH_m. Used for **hard-to-defossilise sectors**:

- **dense fuels** for transport (planes, ships)
- **steel-making** & **chemicals industry**
- **high-temperature heat** or **heat for buildings**
- **backup energy** for cold low-wind winter periods, i.e. as storage

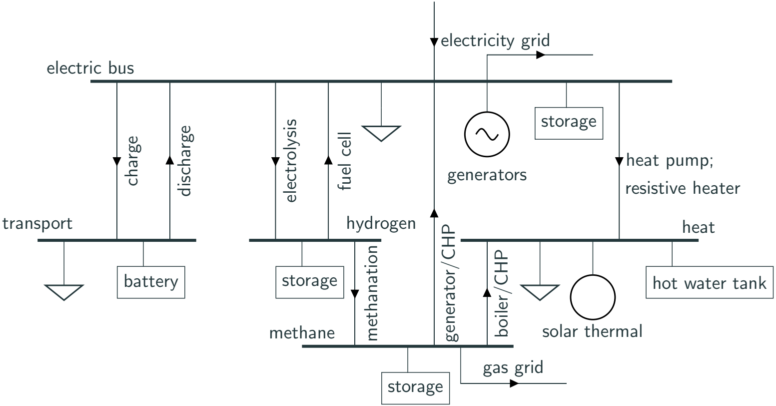
Gas storage and networks



- Gases and liquids are easy to **store** and **transport** than electricity.
- Storage capacity of the German natural gas network in terms of energy: ca 230 TWh. Europe wide it is 1100 TWh (see **online table**). In addition, losses in the gas network are small.
- (NB: Volumetric energy density of hydrogen, i.e. MWh/m^3, is around three times lower than natural gas.)
- Pipelines can carry many GW underground, out of sight.

Sector coupling: A new source of flexibility

Couple the electricity sector (electric demand, generators, electricity storage, grid) to electrified transport and low-T heating demand in buildings (model covers 75% of final energy consumption in 2014). Also allow production of synthetic hydrogen and methane.



Modelling: extend network graph for energy conversion processes

Extend the network graph with nodes i for each energy carrier (hydrogen, methane, low-temperature heat, etc.). The nodes represent sites of energy conservation.

Edges ℓ now represent energy conversion between energy carriers (such as heat pumps, electrolysers, fuel cells or gas boilers).

They are represented like lines but with an efficiency $\eta_{\ell,t}$ that modifies the incidence matrix:

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

Now $\alpha_{i\ell t} = 1$ if ℓ starts at i, $\alpha_{i\ell t} = -\eta_{\ell,t}$ if ℓ ends at i and zero otherwise.

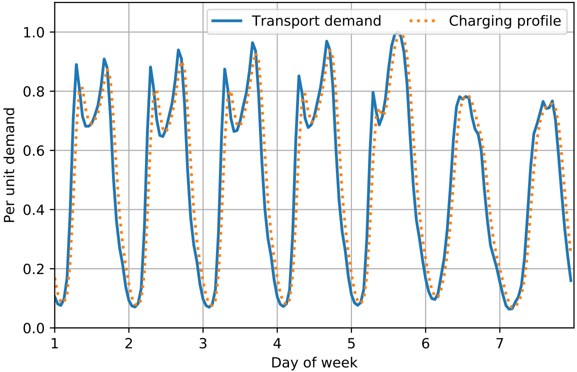
Note that $\eta_{\ell,t}$ can be time-dependent for processes that change their efficiency over time, like heat pumps which change with the outside temperature.

They are usually defined to be uni-directional:

$$0 \leq f_{\ell,t} \leq F_\ell$$

[In PyPSA energy conversion is represented with Link objects.]

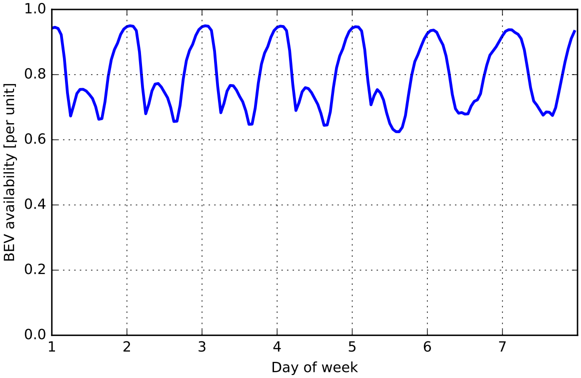
Transport sector: Electrification of Transport



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.

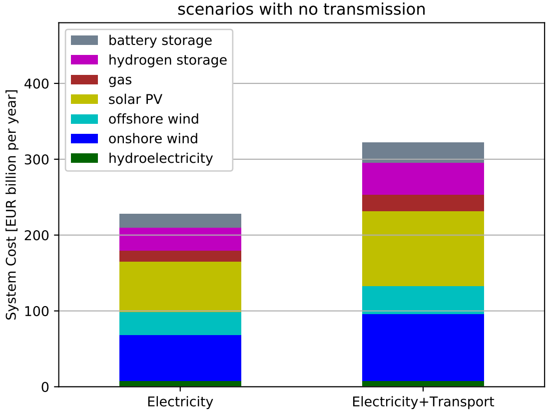
Transport sector: Battery Electric Vehicles



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

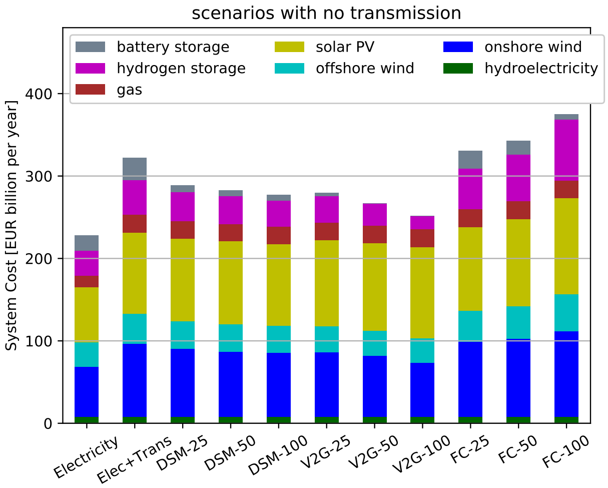
- Passenger cars to Battery Electric Vehicles (BEVs), 50 kWh battery available and 11 kW charging power
- Can participate in DSM and V2G, depending on scenario (state of charge returns to at least 75% every morning)
- All BEVs have time-dependent availability, averaging 80%, max 95% (at night)
- No changes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

Coupling Transport to Electricity in European Model with 95% Less CO_2



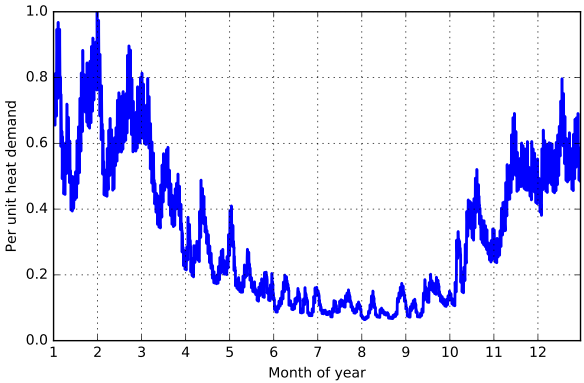
- Include transport demand in 30-node PyPSA electricity model for Europe
- Apply 95% CO_2 reduction vs 1990 to both electricity and transport
- If all road and rail transport is electrified, electrical demand increases 37%
- Costs increase 41% because charging profiles are very peaked (NB: distribution 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 for Buildings

We model both fully decentralised heating and cases where up to 45% of heat demand is met with district heating in northern countries. Heating technology options for buildings:

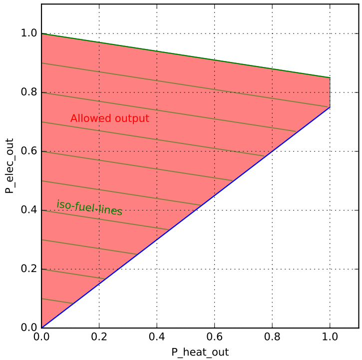
Decentral individual heating can be supplied by:

- 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:



Building renovations can be co-optimised to reduce space heating demand.

Heat pumps

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

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

Air-source heat pumps (ASHP):

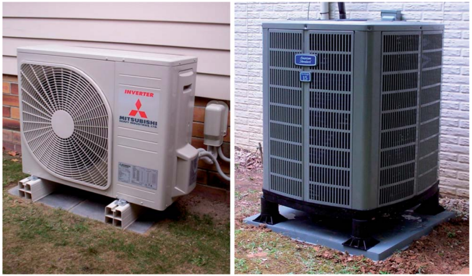


Fig. 5 Examples of air source heat pumps from Mitsubishi (left) and American Standard (right).

Ground-source heat pumps (GSHP):

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

Source: Staffell et al, 2012

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

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

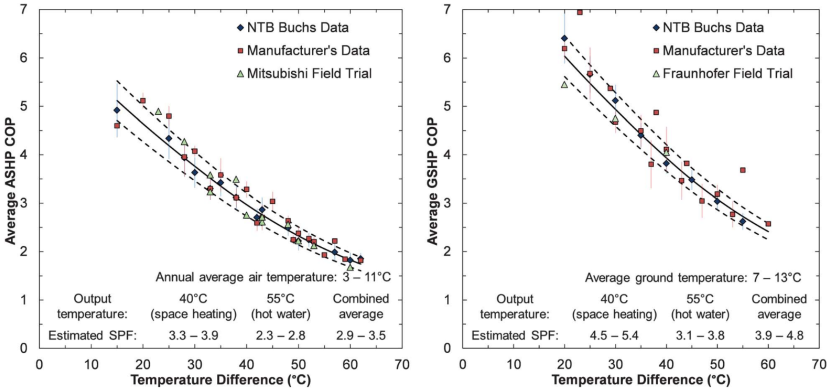
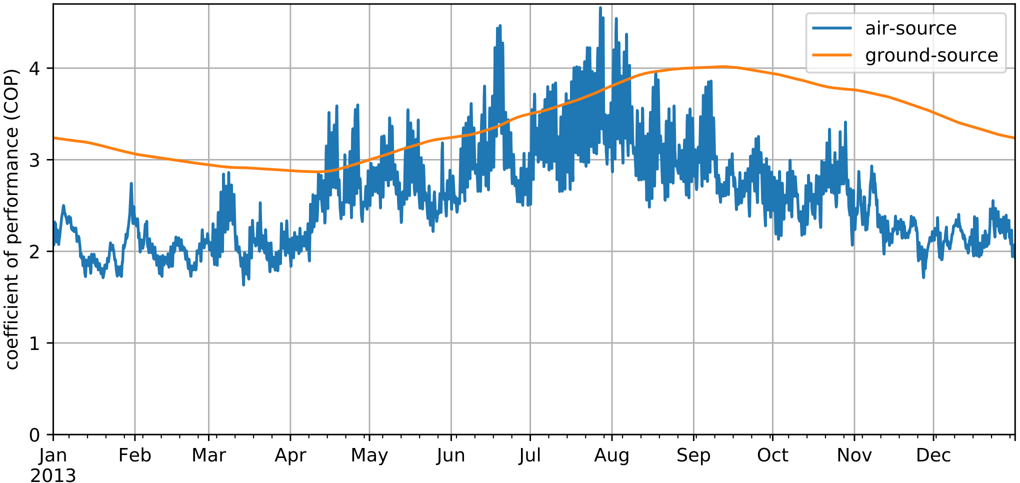


Fig. 9 Average heating coefficient of performance for air and ground source heat pumps (left and right, respectively) based on data taken from industrial surveys and field trials.[31,80–82] The inset tables show the expected performance for UK conditions.

Source: Staffell et al, 2012

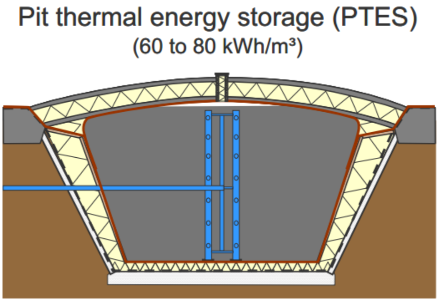
Heat pumps

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



Long-duration thermal energy storage

In Vojens, Denmark, an enormous pit storage of 203,000 m^3 is charged in summer with hot water at 80-95 C using 70,000 m^2 of solar thermal collectors, to provide heat to the district heating network in winter.



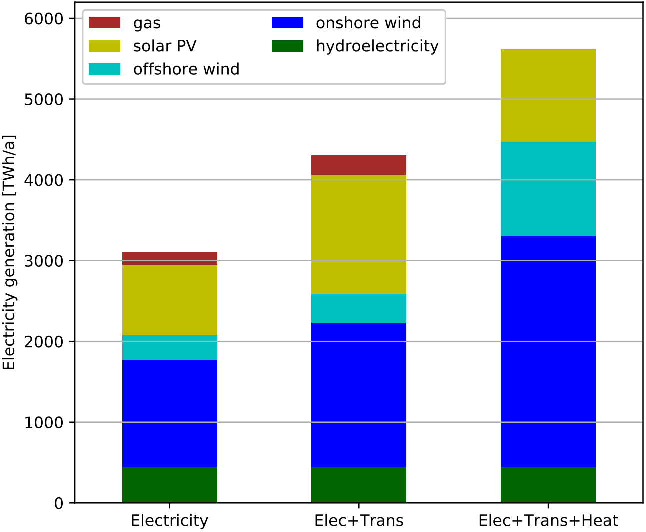
Source: Solar Thermal World

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	$\tau = 180d$
District heating	220	kW_{th}	1	40	
Methanation+DAC	1000	kW_{H_2}	3	25	0.6

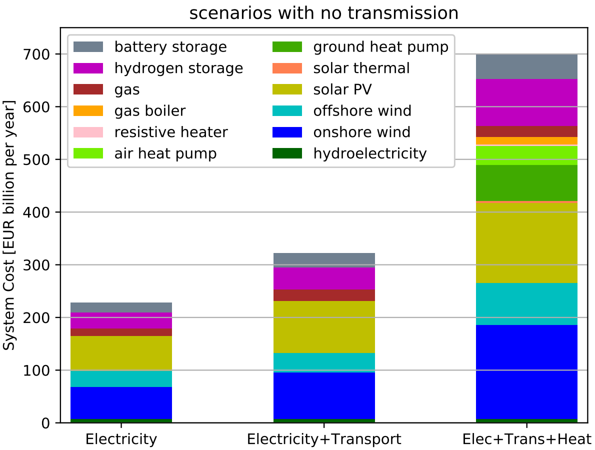
Costs oriented towards Henning & Palzer (2014, Fraunhofer ISE) and Danish Energy Database

Coupling Heating to Transport and Electricity: Electricity Demand



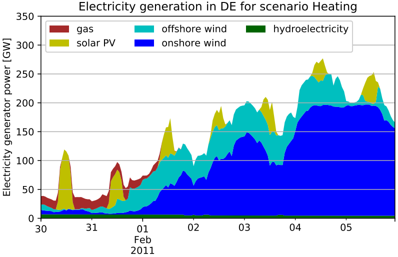
- To 4062 TWh_{el}/a demand from electricity and transport, add 3585 TWh_{th}/a heating demand
- With 95% CO_2 reduction, much of the heating demand is met via electricity, but with high efficiency from heat pumps
- Electricity demand 80% higher than current electricity demand
- Energy savings from building retrofitting can reduce this total

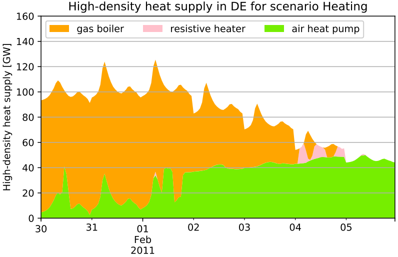
Coupling Heating to Transport and Electricity: Costs



- Costs jump by 117% to cover new energy supply and heating infrastructure
- 95% CO_2 reduction means most heat is generated by heat pumps using renewable electricity
- Cold winter weeks with high demand, low wind, low solar and low heat pump COP mean backup gas boilers required

Cold week in winter



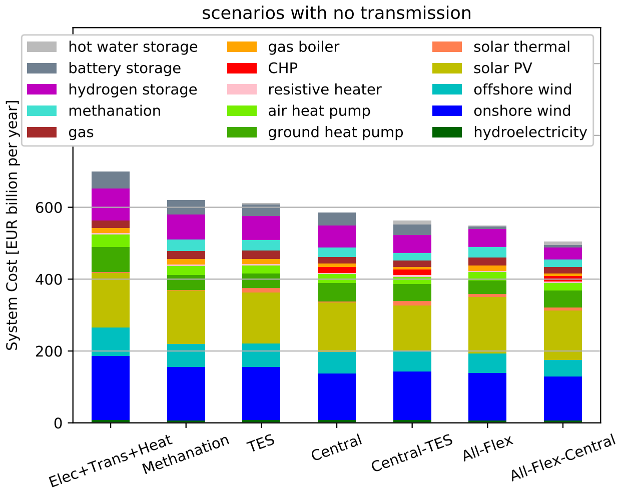


There are difficult periods in winter with:

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

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

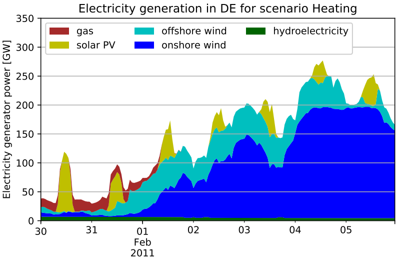
Using heating flexibility

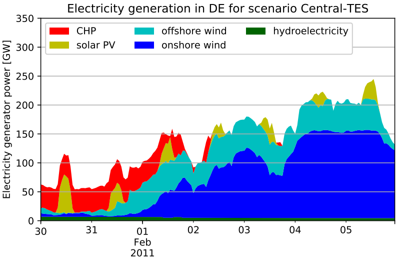


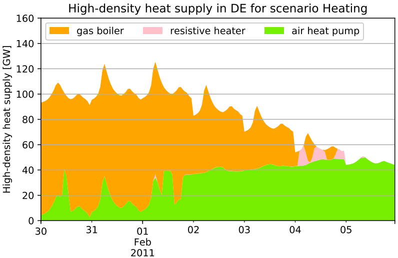
Successively activating couplings and flexibility **reduces costs** by 28%. These options include:

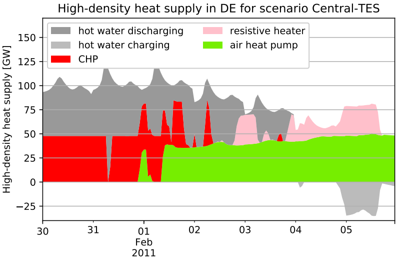
- production of **synthetic methane**
- centralised **district heating** in areas with dense heat demand
- long-term **thermal energy storage** (TES) in district heating networks
- **demand-side management** and vehicle-to-grid from battery electric vehicles (BEV)

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



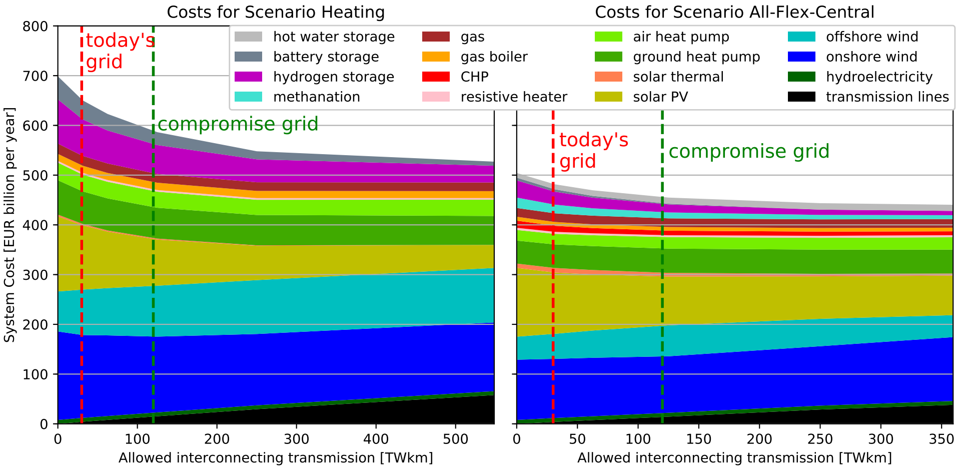






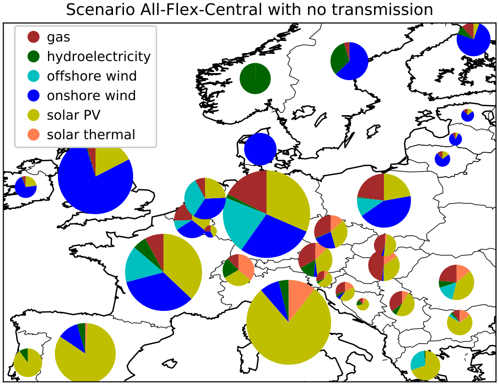
Sector Coupling with All Extra Flexibility (V2G and TES)

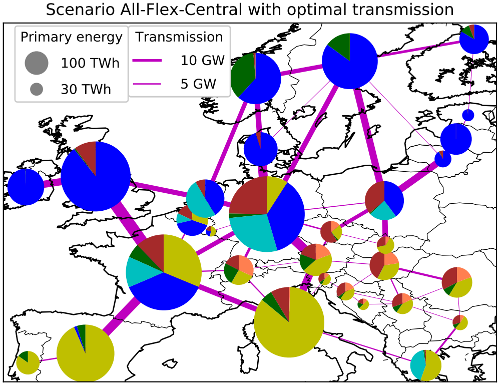
Benefit of cross-border transmission is weaker with full sector flexibility (right) than with inflexible sector coupling (left); comes close to today's costs of around € 377 billion per year



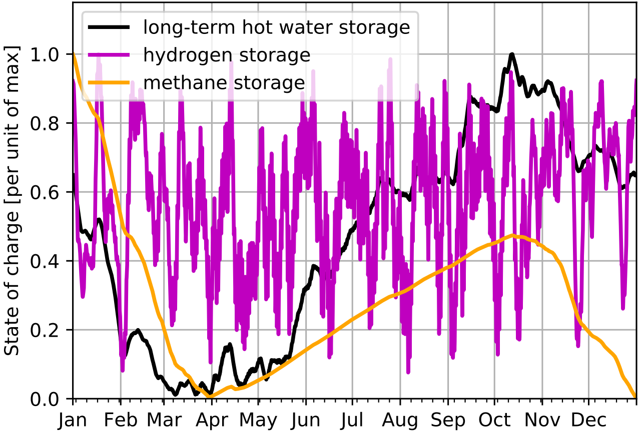
Spatial distribution of primary energy for All-Flex-Central

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



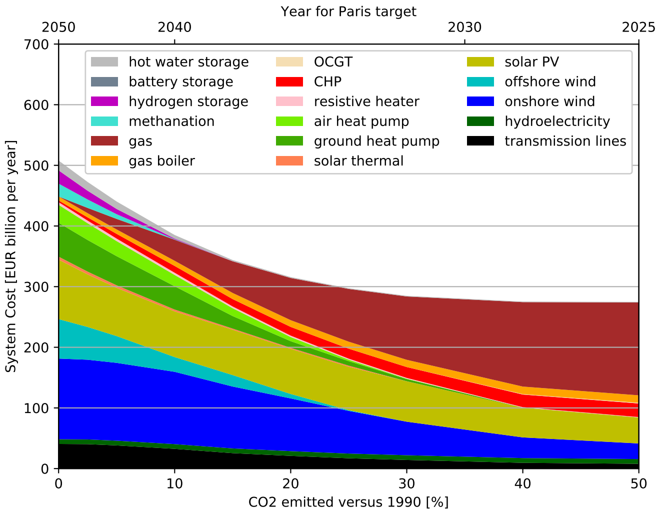


Storage energy levels: different time scales



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

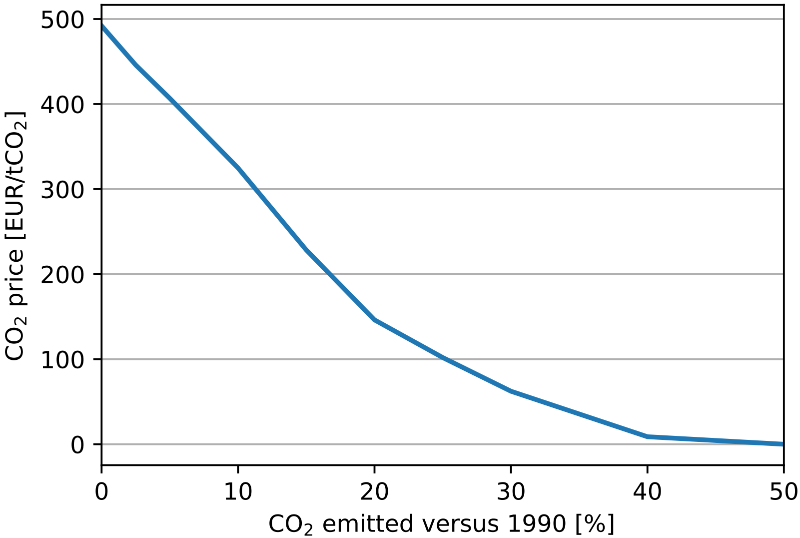
Pathway down to zero emissions in electricity, heating and transport



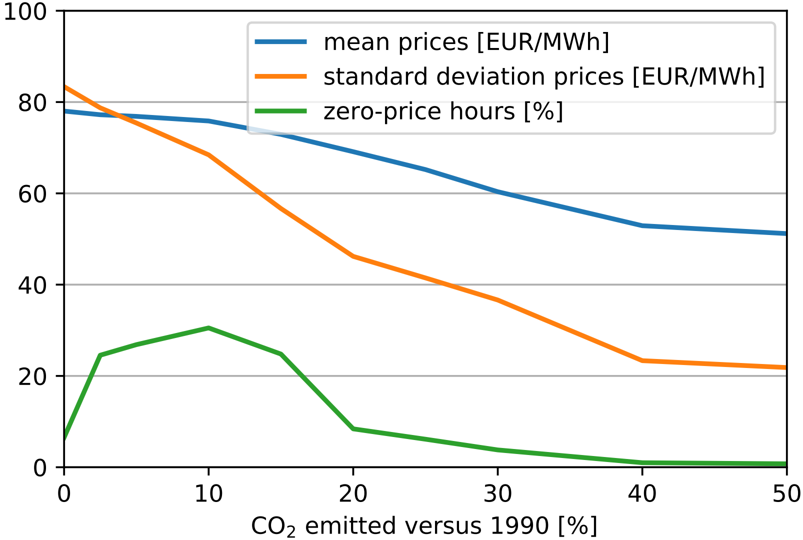
If we look at investments to eradicate CO_2 emissions in electricity, heating and transport we see:

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

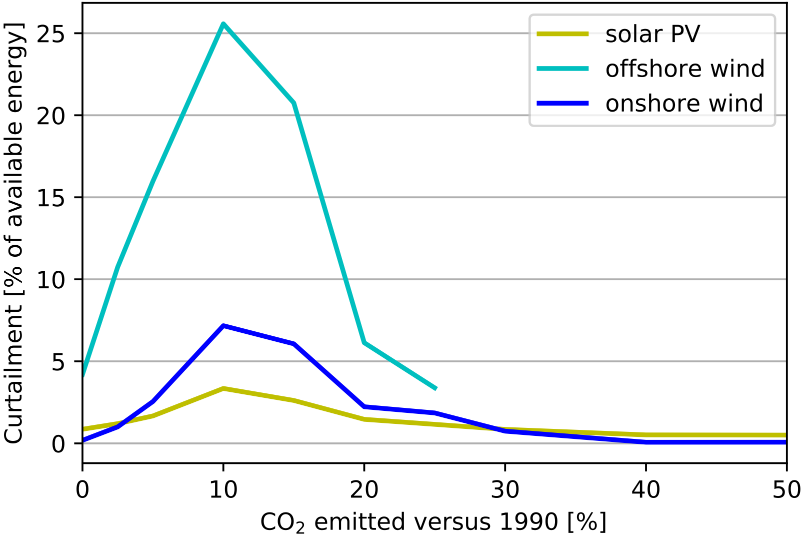
CO_2 price rises to displace cheap natural gas



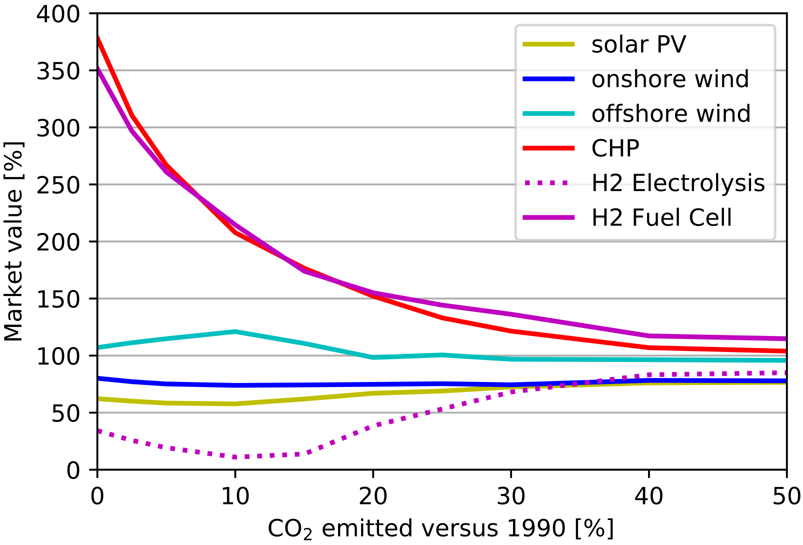
Electricity price statistics: zero-price hours gone thanks to P2G



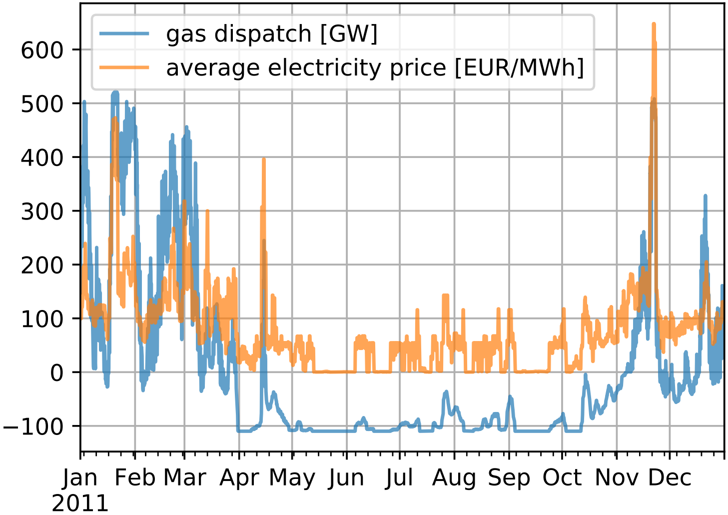
Curtailment also much reduced



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



Gas production/consumption tightly coupled to price



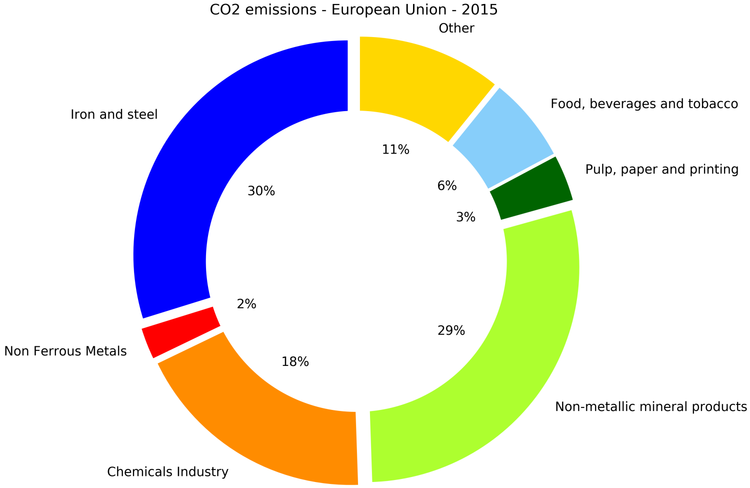
More Details in Papers

For more details, see the following papers:

- Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system, **link** (2018).
- Sectoral Interactions as Carbon Dioxide Emissions Approach Zero in a Highly-Renewable European Energy System, **link** (2019).

Industry, Shipping and Aviation

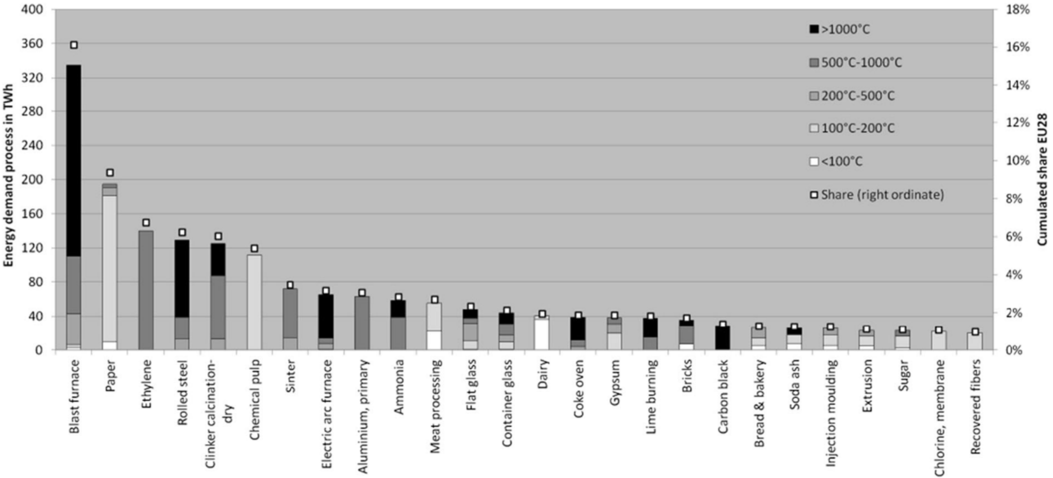
CO_2 direct emissions from industry by sector in Europe



- Non-ferrous metals: mainly aluminium, but also copper, lead etc.
- Non-metallic minerals: mainly cement, ceramics and glass
- Emissions come from combustion of fossil fuels for heat, as well as **process emissions** from chemical reactions

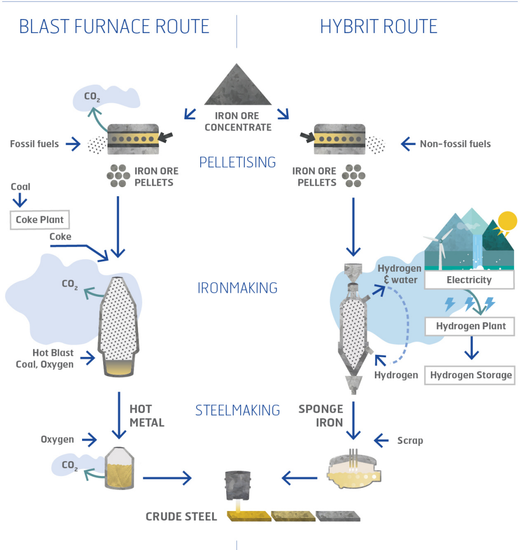
Process heat demand in Europe by sector and temperature

Temperatures >100 C not accessible via regular heat pumps. Need direct electrification, biomass, synthetic fuels (hydrogen, methane), nuclear or carbon capture.



Source: Rehfeldt et al, 2017

Iron and steel: direct reduce with hydrogen instead of coke



- Normally coke is used as a reducing agent in blast furnaces for smelting iron ore

$$2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2$$

- Instead: use hydrogen as the reducing agent

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$$

- Should scale up in late 2020s and 2030s.
- See **Vogl et al, 2018**.

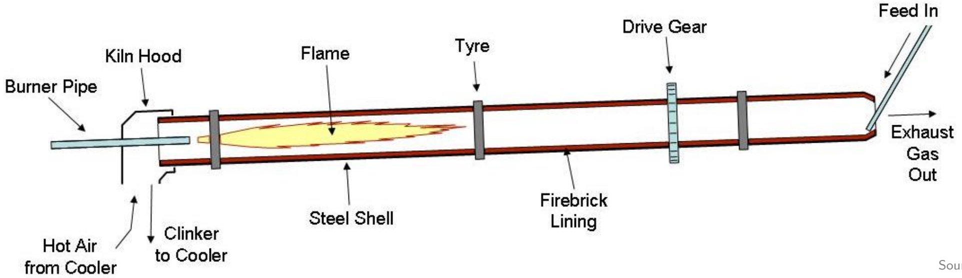
Source: HYBRIT project

Cement

Cement is used in construction to make concrete. CO_2 is emitted from fossil fuels to provide process heat and from the calcination reaction for fossil limestone

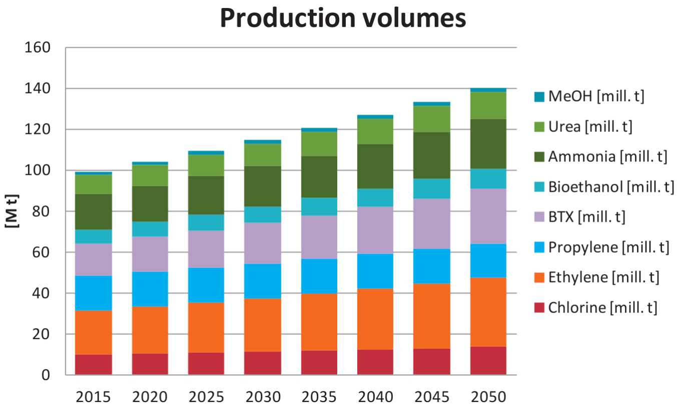
$$\mathrm{CaCO_3} \rightarrow \mathrm{CaO} + \mathrm{CO_2}$$

This is the biggest source of **process emissions** in industry in Europe. While we can replace process heat with low-carbon sources, process emissions are harder. Unless alternatives can be found for cement, this CO_2 can be captured and either sequestered underground (CCS) or used (CCU) to make chemicals like methane, liquid hydrocarbons or methanol.



Source: Wikipedia

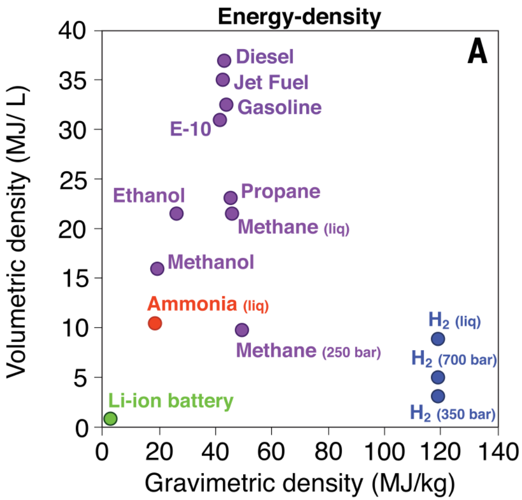
Chemicals



- Fossil fuels are used for process heat in the chemicals industry, but also as a **feedstock** for chemicals like ammonia (NH_3), ethylene (C_2H_4) and methanol (CH_3OH or MeOH)
- Ammonia, used for fertiliser, can be made from hydrogen and nitrogen using the Haber-Bosch process
- Ethylene, used for plastics, can be made by steam cracking from naphtha or ethane

Source: DECHEMA

Power to Transport Fuels



- Hydrogen has a very good gravimetric density (MJ/kg) but poor volumetric density (MJ/L).
- Liquid hydrocarbons provide much better volumetric density for e.g. aviation.
- WARNING: This graphic shows the thermal content of the fuel, but the **conversion efficiency** of e.g. an electric motor for battery electric or fuel cell vehicle is much better than an internal combustion engine.

Source: Davis et al, 2018

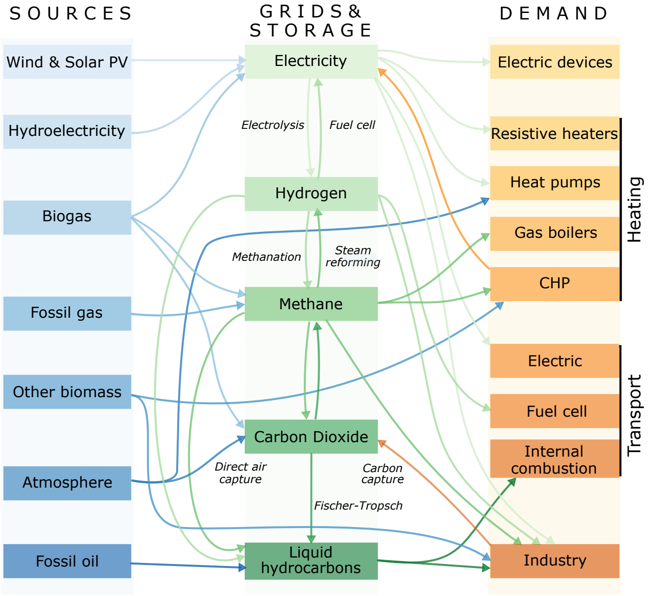
Defossilising non-electric industry processes, aviation, shipping

We assume higher recycling levels as well as process- and fuel-switching (under review):

Iron & Steel	70% from scrap, rest from direct reduction with 1.7 $MWhH_2$/tSteel + electric arc (process emissions 0.03 tCO_2/tSteel)
Aluminium	80% recycling, for rest: methane for high-enthalpy heat (bauxite to alumina) followed by electrolysis (process emissions 1.5 tCO_2/tAl)
Cement	Waste and solid biomass for heat; capture process emissions
Ceramics & other NMM	Electrification
Chemicals	Synthetic methane, synthetic naphtha and hydrogen
Other industry	Electrification; process heat from biomass
Shipping	Liquid hydrogen (could be replaced by other liquid fuels)
Aviation	Kerosene from Fischer-Tropsch

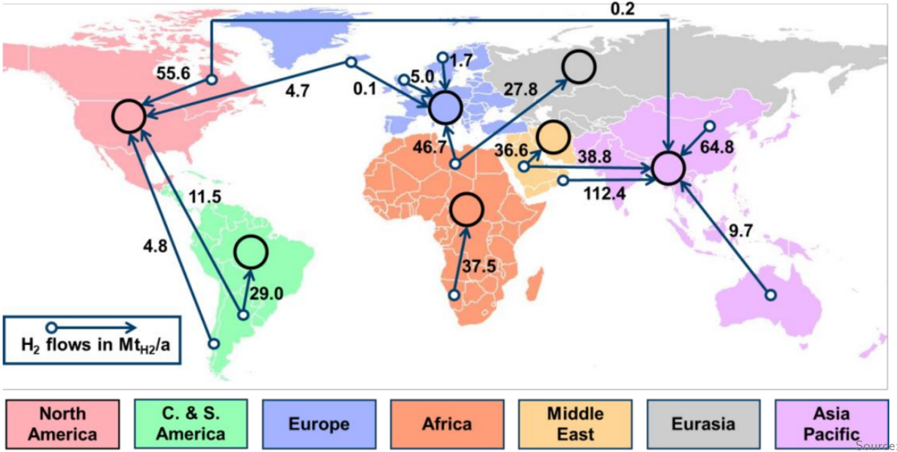
Carbon is tracked through system: 90% of industrial emissions are captured; direct air capture (DAC); synthetic methane and liquid hydrocarbons; transport and sequestration 20 €/tCO_2

Including all sectors needs careful management of carbon



Worldwide trade in synthetic fuels

Today fossil fuels are traded across the globe. Electrolytic-hydrogen-based synthetic fuels (e.g. hydrogen, ammonia, methane, liquid hydrocarbons and methanol) could also be piped/shipped worldwide. Possible future scenario for hydrogen trade from Helmholtz colleagues at FZJ IEK-3:



Source: Heuser et al, 2020

Open Energy Modelling

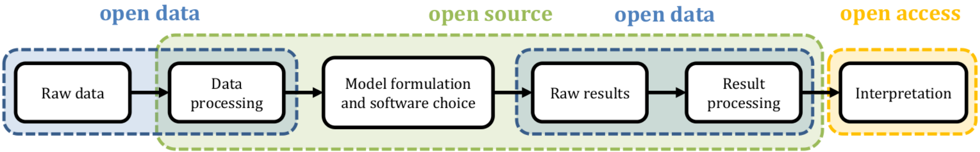
What is open modelling?

Open energy modelling means modelling with open software, open data and open publishing.

Open means that anybody is free to download the software/data/publications, inspect it, machine process it, share it with others, modify it, and redistribute the changes.

This is typically done by uploading the model to an online platform with an **open licence** telling users what their reuse rights are.

The **whole pipeline** should be open:



Why open modelling?

Openness . . .

- increases **transparency**, **reproducibility** and **credibility**, which lead to better research and policy advice (no more 'black boxes' determining hundreds of billions of energy spending)
- reduces **duplication of effort** and frees time/money to develop **new ideas**
- *can* improve research **quality** through feedback and correction
- allows easier **collaboration** (no need for contracts, NDAs, etc.)
- is a **moral imperative** given that much of the work is publicly funded
- puts pressure on **official data holders** to open up
- is essential given the increasing **complexity** of the energy system - we all need data from different domains (grids, buildings, transport, industry) and cannot collect it alone
- can increase **public acceptance** of difficult infrastructure trade-offs

See also S. Pfenninger et al, 'The importance of open data and software: Is energy research lagging behind?,' Energy Policy, V101, p211, 2017 and S. Pfenninger, 'Energy scientists

openmod: overview

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

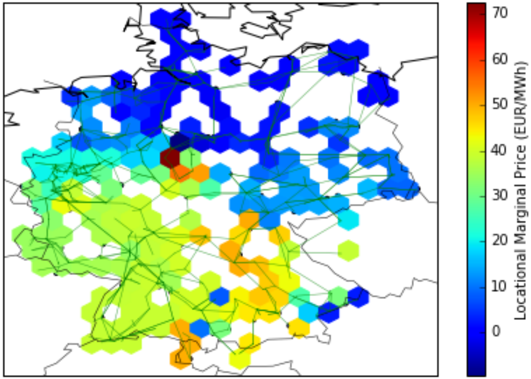
- **grass roots community** of open energy modellers from universities, research institutions and the interested public
- 700+ participants from all continents except Antarctica
- first meeting Berlin 18–19 September 2014
- promoting **open code**, **open data** and **open science** in energy modelling

Source: openmod initiative

Python for Power System Analysis (PyPSA)

Our free software PyPSA is available online at `https://pypsa.org/` and on github. It can do:

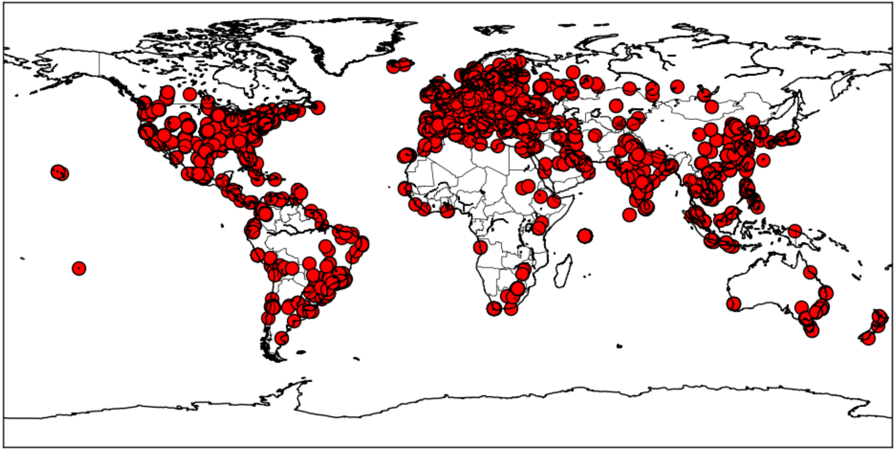
- Static **power flow**
- **Linear optimal power flow** (LOPF) (multiple periods, unit commitment, storage, coupling to other sectors)
- **Security-constrained LOPF**
- Total energy system **capacity expansion optimisation**



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

Python for Power System Analysis: Worldwide Usage

PyPSA is used worldwide by **dozens of research institutes and companies** (TU Delft, Shell, Fraunhofer ISE, DLR Oldenburg, FZJ, TU Berlin, RLI, TransnetBW, TERI, Flensburg Uni, Saudi Aramco, Edison Energy, spire and many others). Visitors to the website:



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, transport and industry is important (direct or indirect with synthetic fuels), to take advantage of low-carbon electricity
- **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**; financial and regulatory support for **new technologies** (heat pumps, hydrogen for steel)
- The energy system is complex and contains some uncertainty (e.g. cost developments, scaleability of power-to-gas, consumer behaviour), so **openness is critical**