Energy Systems, Summer Semester 2024
Lecture 13: Sector Coupling

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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.

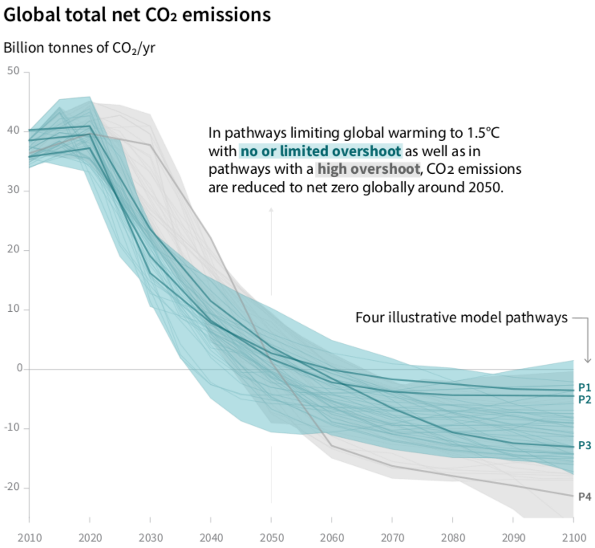
Sector coupling

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

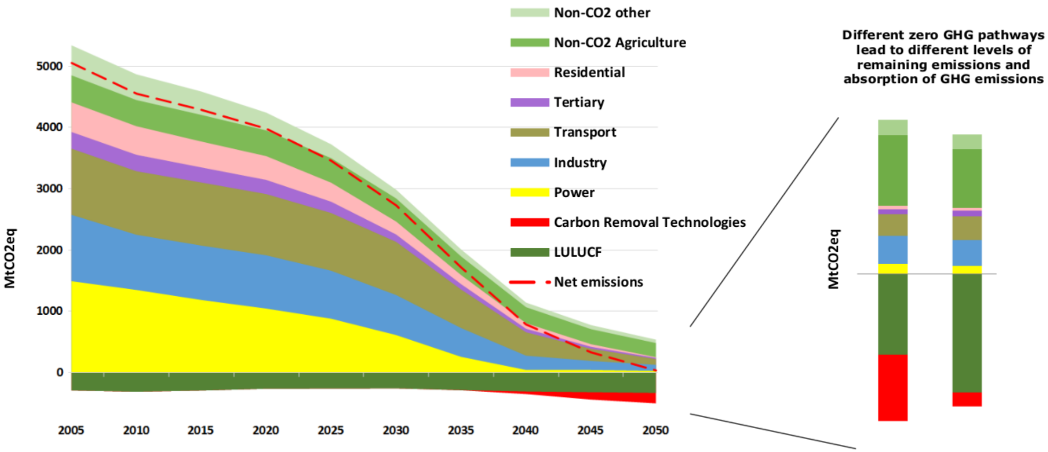


- Scenarios for global CO_2 emissions that limit warming to 1.5°C about industrial levels (**Paris agreement**)
- Today emissions **still rising**
- Level of use of negative emission technologies (NET) depends on rate of progress
- 2°C target without NET also needs rapid fall by 2050
- Common theme: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

Source: IPCC SR15 on 1.5C, 2018

The Greenhouse Gas Challenge: Net-Zero Emissions by 2050

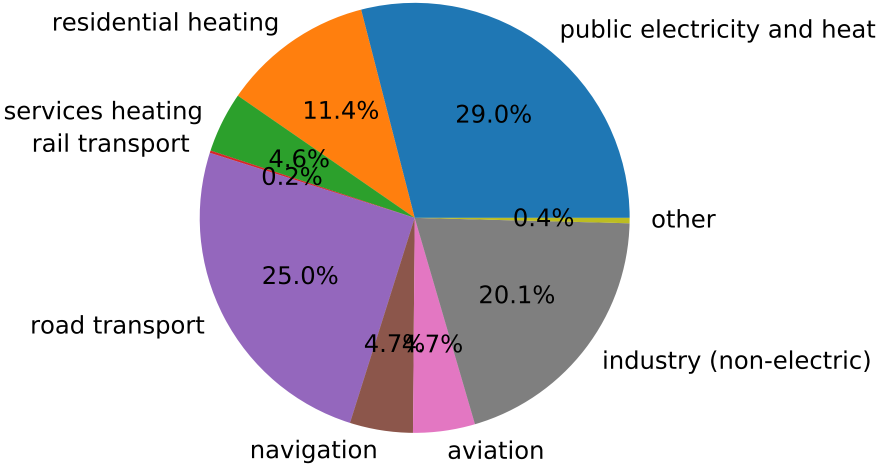
Paris-compliant 1.5° C scenarios from European Commission - **net-zero GHG in EU by 2050**



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

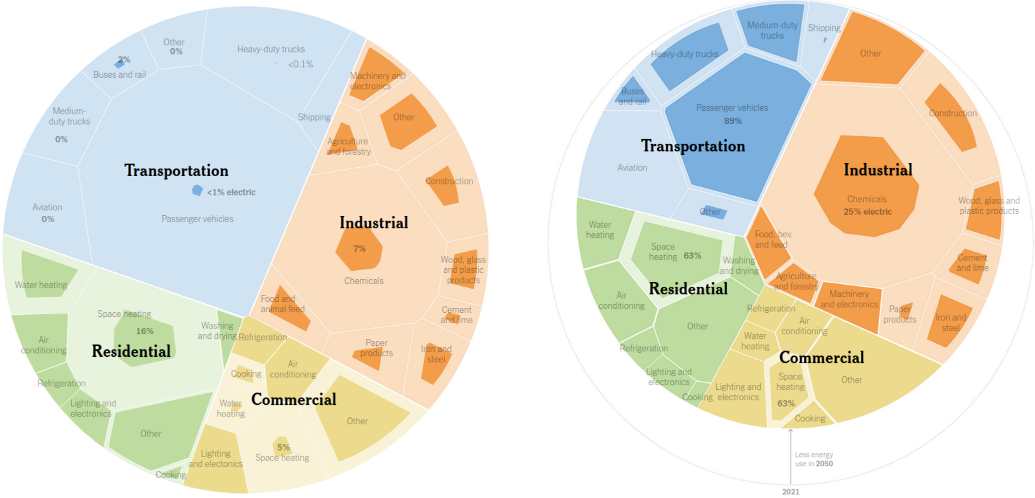
Wind and solar dominate the expandable potentials for low-carbon energy provision, so **electrification is essential** to decarbonise sectors such as transport and heating.

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

Source: Tesla; heat pump: Kristoferb at English Wikipedia

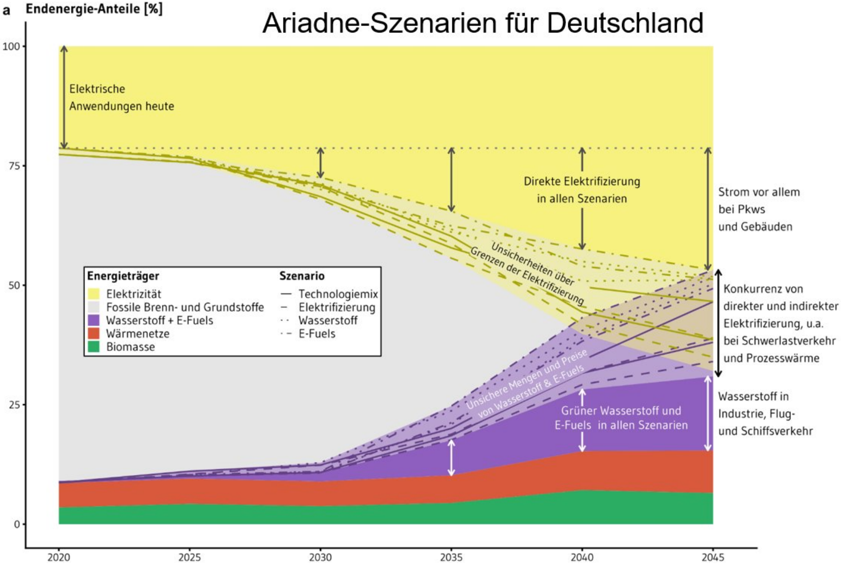
Many scenarios show an increase in electrification

Electricity as a fraction of final energy demand in 2019 versus 2050 in United States.



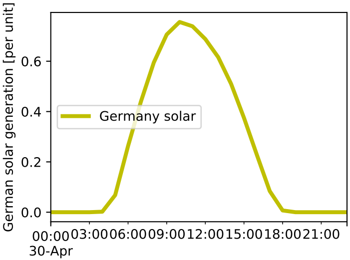
Source: New York Times, 2023

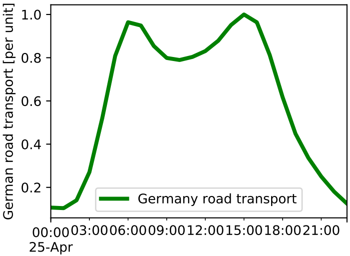
Many scenarios show increase in electrification



Source: ARIADNE Projekt, 2021

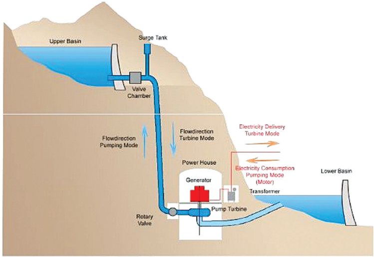
Daily variations: challenges and solutions



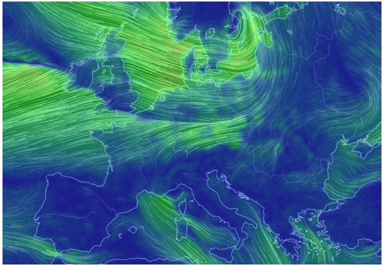


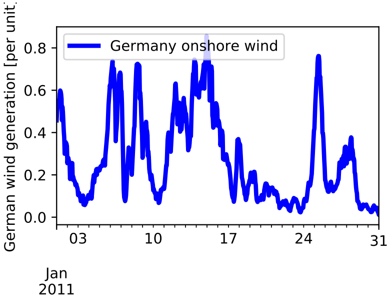
Daily variations in supply and demand can be balanced by

- **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**



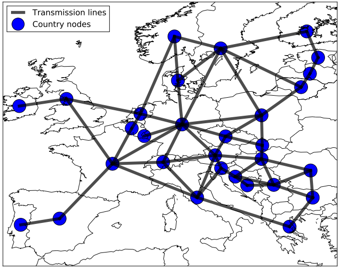
Weekly variations: challenges and solutions



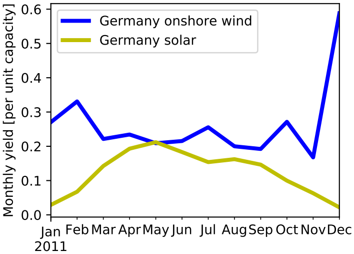


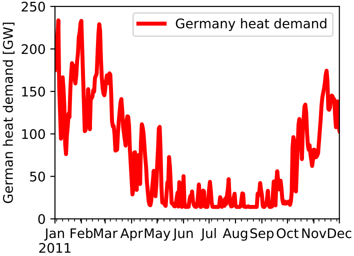
Weekly variations in supply and demand can be balanced by

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



Seasonal variations: challenges and solutions



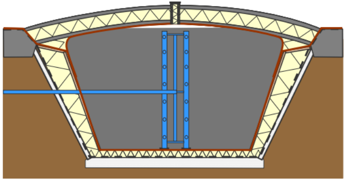


Seasonal variations in supply and demand can be balanced by

- **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)



1860s: Debate on green hydrogen

Debate in London 'Times' in 1863 referenced by Jevons' 'Coal Question' in 1865.

TO THE EDITOR OF THE TIMES.

Sir,—In his admirable address at Newcastle, Sir W. Armstrong mentions electricity as being supposed likely to furnish a substitute for coal, and shows that battery action is too costly, because involving double decomposition. He also remarks that motion is convertible into electricity. Let me add that we shall probably find here a solution of the problem.

By means of magnets and of motion the most powerful and steady currents of electricity can be generated to produce the light which nightly joins England to France, or for the deposition of metals, or the decomposition of water. This last most important application has by no means received due attention. Unsuccessful and imperfect attempts have been made to produce by this means oxygen and hydrogen gases in large quantities.

Steam as the motive power is inadmissible, because, as is now known, the gases evolved will produce no more heating force than is required to raise the steam.

But tide, wind, and water mills furnish always cheap motive power.

We have only to convert this into oxygen and hydrogen gases by means of magneto-electricity to supply ourselves with stores of fuel so boundless as to enable us to contemplate with composure the incessant destruction of our coal seams—hitherto the strong foundations of British power and renown.

Your obedient servant,

G. A. KEYWORTH.

Hastings, Aug. 28.

Hitherto we have considered mechanical force only, but it is obvious that if coal were used up we should want some source of heat as well as force. A favourite notion is to employ wind, water, or tidal mills to turn magneto-electric machines, and by the stream of electricity produced to decompose water, thus furnishing a continuous supply of artificial gaseous fuel. Such a plan was proposed in the *Times* during the discussion on the French Treaty. But an answer, attributed to Dr. Percy of the School of Mines, soon appeared, showing the amount of [162] fuel derivable to be inconsiderable. The waste of power must be vastly greater in such a process of transmutation than in the system of artificial water power which we have considered. Besides, if uniform experience is to be trusted, a steam-engine would be a much more economical means of turning the magneto-electric machines than either a wind, water, or tidal machine. We should therefore only use coal in a roundabout manner to generate a less valuable fuel. For the hydrogen gas generated, though in some instances valuable, would in general be immensely less convenient than coal. For equal weights, it gives about four times as much heat as coal, but hydrogen is so light that *for equal volumes it gives one five-thousandth part as much heat*. To compress it in a small space would require more force than the combustion of the fuel itself would furnish, and gas companies do not find it convenient to compress their gas. Hydrogen too has so much higher a diffusive power than coal-gas, that it could hardly be retained in gasometers or ordinary pipes. Even the loss of coal-gas by leakage is said to be nearly twenty-five per cent.

Source: Jevons (1865)

1923: J.B.S. Haldane: Wind & Hydrogen Vision for Britain

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Personally, I think that four hundred years hence the power question in England may be solved somewhat as follows: The country will be covered with rows of metallic windmills working electric motors which in their turn supply current at a very high voltage to great electric mains. At suitable distances, there will be great power stations where during windy weather the surplus power will be used for the electrolytic decomposition of water into oxygen and hydrogen. These gasses will be liquefied, and stored in vast vacuum jacketed reservoirs, probably sunk in the ground. If these reservoirs are sufficiently large, the loss of liquid due to leakage inwards of heat will not be great; thus the proportion evaporating daily from a reservoir 100 yards square by 60 feet deep would not be 1/1000 of that lost from a tank measuring two feet each way. In times of calm, the gasses will be recombined in explosion motors working dynamos which produce electrical energy once more, or more probably in oxidation cells. Liquid hydrogen is weight for weight the most efficient known method of storing energy, as it gives about three times as much heat per pound as petrol. On the other hand it is very light, and bulk for bulk has only one third of the efficiency of petrol. This will not, however, detract from its use in aeroplanes, where weight is more important than bulk. These huge reservoirs of liquified gasses will enable wind energy to be stored, so that it can be expended for industry, transportation, heating and lighting, as desired. The initial costs will be very considerable, but the running expenses less than those of our present system. Among its more obvious advantages will be the fact that energy will be as cheap in one part of the country as another, so that industry will be greatly decentralized; and that no smoke or ash will be produced.

Source: J.B.S. Haldane 'Daedalus' (1923)

1975: Bent Sørensen: 1st consistent 100% RE scenario

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In 1975 Bent Sørensen published a scenario for 100% renewable energy in Denmark. He dealt with the variability of wind (with hydrogen) & solar thermal (with TES).

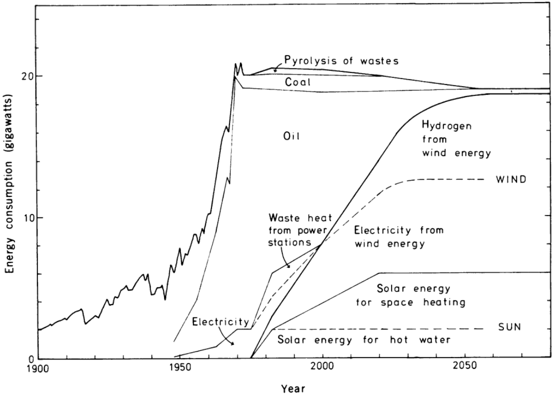


Fig. 4. Net energy consumption in Denmark, shown according to sources. Up to 1974, actual data are shown (*14*); data after 1974 indicate the proposed plan. The relative weighting between solar and wind energy shares might be altered, for example, if a major breakthrough occurred in the development of solar cells, making them competitive to wind-produced electricity under Danish conditions. The heavy, solid line indicates the proposed total share of solar and wind energy.

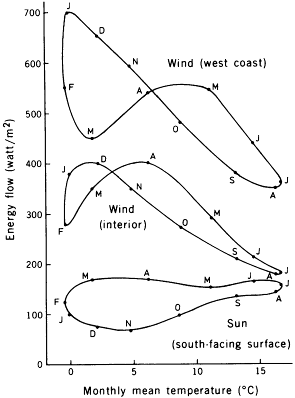


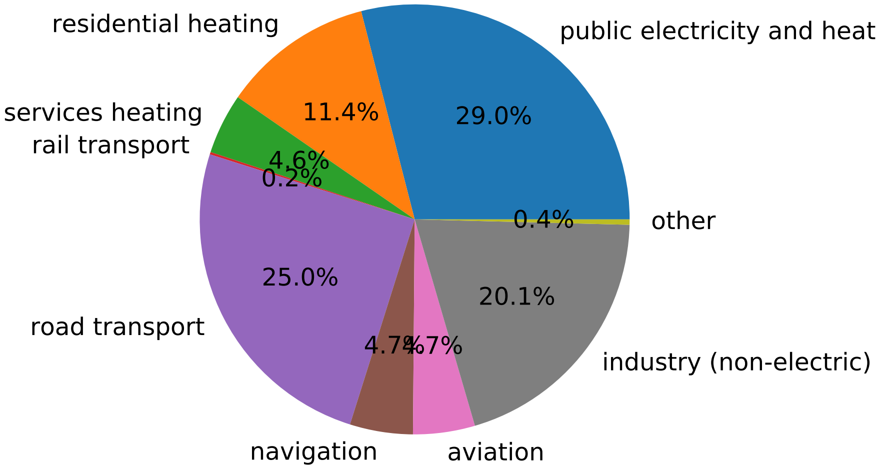
Fig. 2. Monthly average energy flow from continuous sources through a vertical square meter in Denmark, as function of the monthly mean temperature. The sun's height over the horizon at noon is 11° at winter's solstice. The wind data are taken 25 meters above smooth ground.

Source: Sørensen (1975) Science

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

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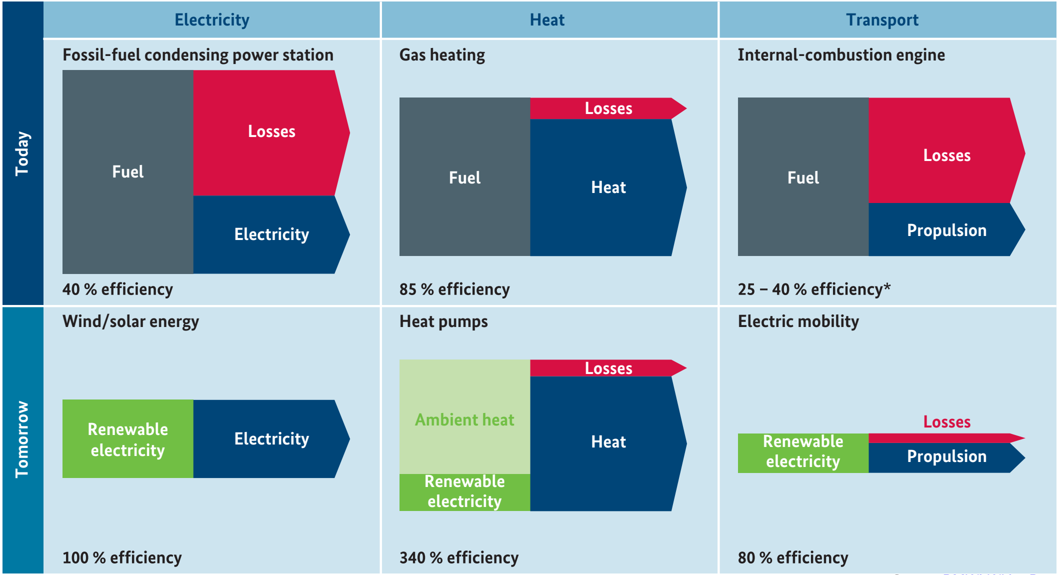
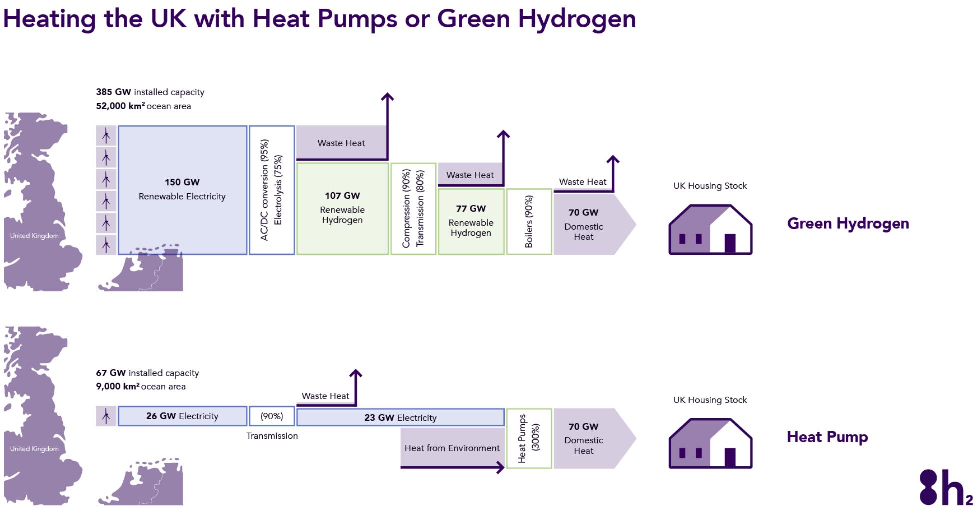


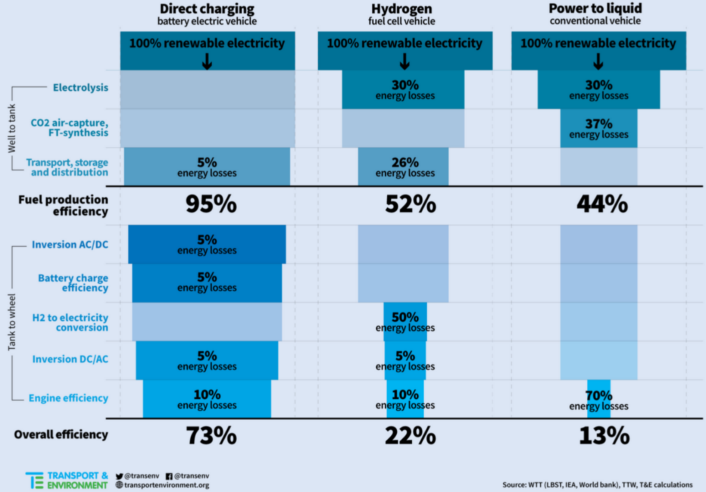
Source: BMWi White Paper 2015

Electrification via heat pumps versus hydrogen boilers



Source: Hydrogen Science Coalition

Electric vehicles versus efuels

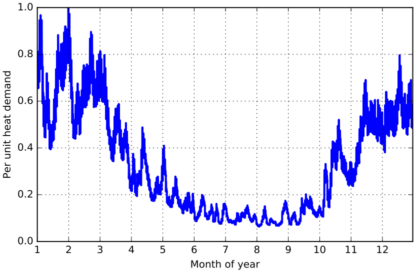


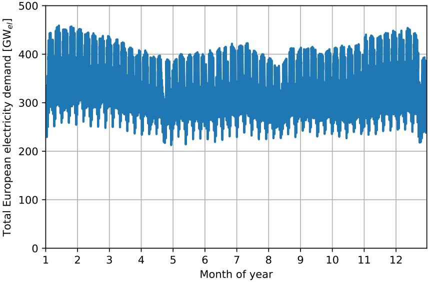
Important caveat: efficiency is not cost. There are regions in the world (e.g. Patagonia) with very inexpensive wind and solar resources for efuels, where low cost could outweigh losses.

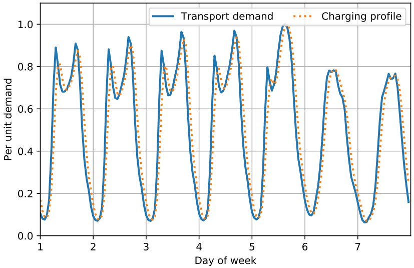
Challenge: Heating and transport demand highly peaked

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

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





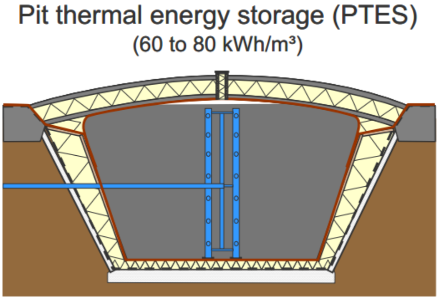


Idea: Couple the electricity sector to heating and mobility.

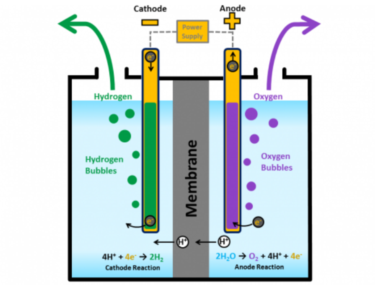
This enables decarbonisation of these sectors **and** offers more flexibility to the power system.

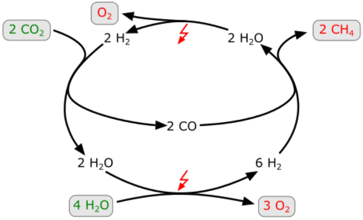
Battery electric vehicles can change their charging pattern to benefit the system and even feed back into the grid if necessary

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



Power-to-Gas (P2G)

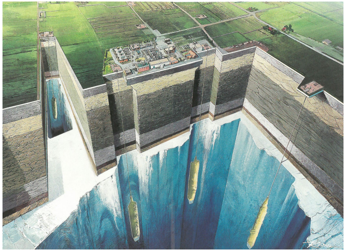




Power-to-Gas/Liquid (P2G/L) describes concepts to use electricity to electrolyse water to **hydrogen** H_2 (and oxygen O_2). We can combine hydrogen with carbon oxides to get **hydrocarbons** such as methane CH_4 (main component of natural gas) or liquid fuels C_nH_m. Used for **hard-to-defossilise sectors**:

- **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

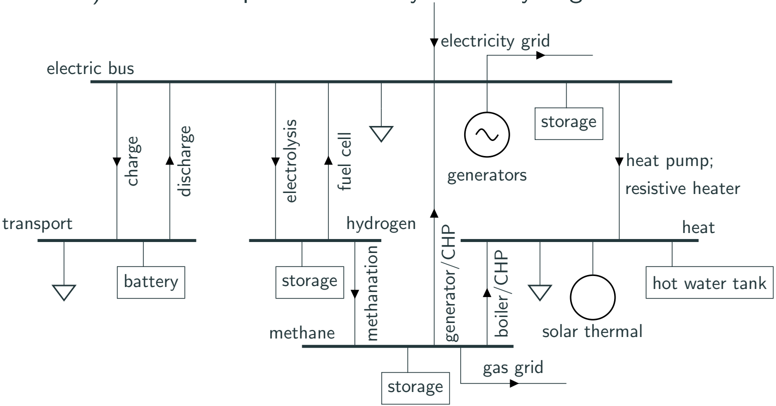
Gas storage and networks



- 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

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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.

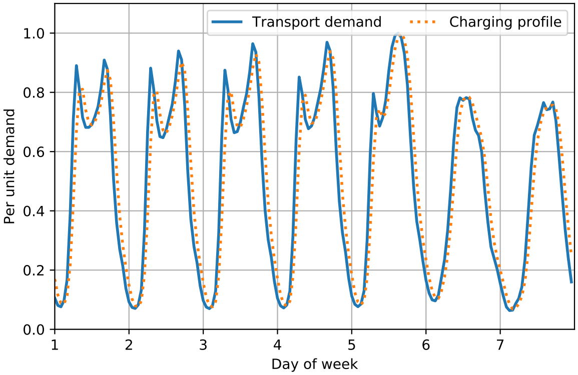
Note that $\eta_{\ell,t}$ can be time-dependent for processes that change their efficiency over time, like heat pumps which change with the outside temperature.

They are usually defined to be uni-directional:

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

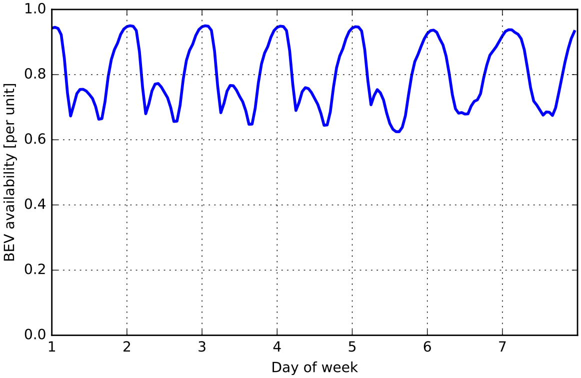
[In PyPSA energy conversion is represented with Link objects.]

Transport sector: Electrification of Transport



Weekly profile for the transport demand based on statistics gathered by the German Federal Highway Research Institute (BASt).

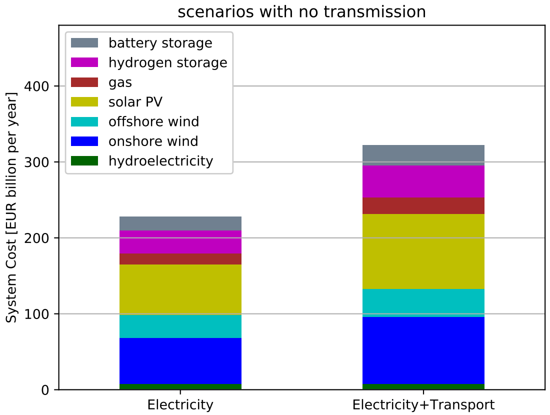
- All road and rail transport in each country is electrified, where it is not already electrified
- Because of higher efficiency of electric motors, final energy consumption 3.5 times lower than today at 1102 $\mathrm{TWh_{el}}/\mathrm{a}$ for the 30 countries
- In model can replace Electric Vehicles (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.



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

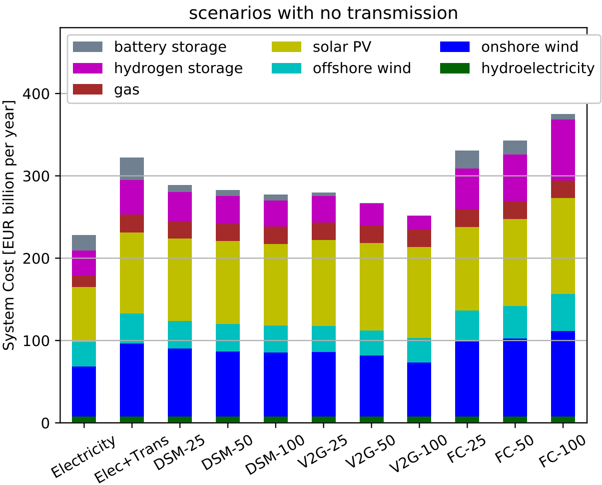
- Passenger cars to Battery Electric Vehicles (BEVs), 50 kWh battery available and 11 kW charging power
- Can participate in DSM and V2G, depending on scenario (state of charge returns to at least 75% every morning)
- All BEVs have time-dependent availability, averaging 80%, max 95% (at night)
- No changes 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



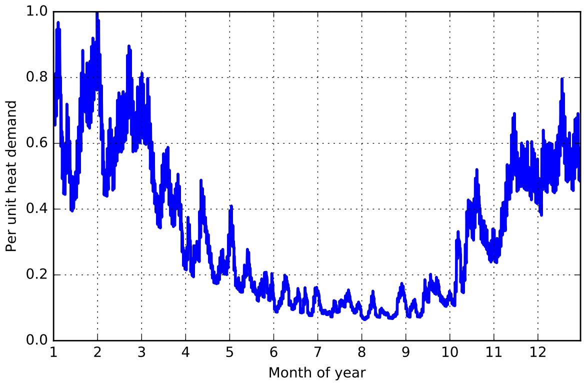
- Include transport demand in 30-node PyPSA electricity model for Europe
- Apply 95% CO_2 reduction vs 1990 to both electricity and transport
- If all road and rail transport is electrified, electrical demand increases 37%
- Costs increase 41% because charging profiles are very peaked (NB: distribution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

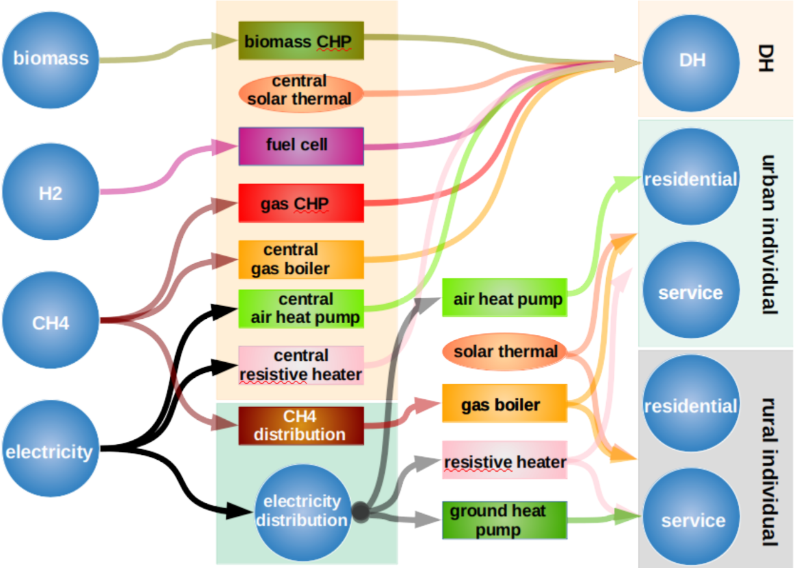
Heating sector: Many Options with Thermal Energy Storage (TES)



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 $\mathrm{TWh_{th}/a}$.
- 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.

Heating supply options



Source: Zeyen et al, 2021

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:

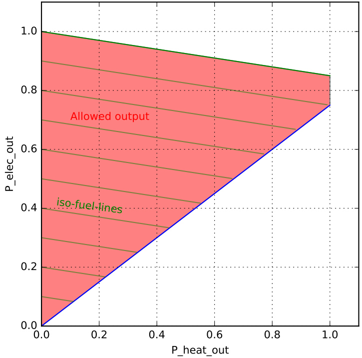
Decentral individual heating can be supplied by:

- 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 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):

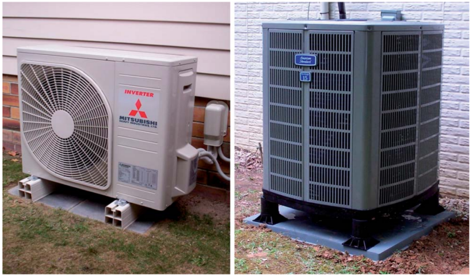


Fig. 5 Examples of air source heat pumps from Mitsubishi (left) and American Standard (right).

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

Heat pumps

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

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

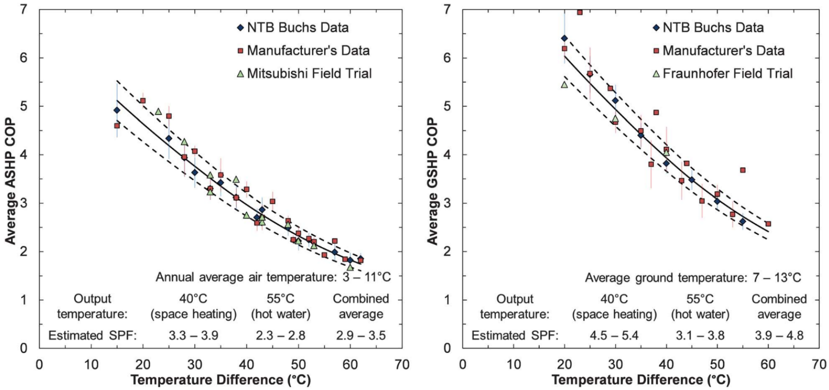
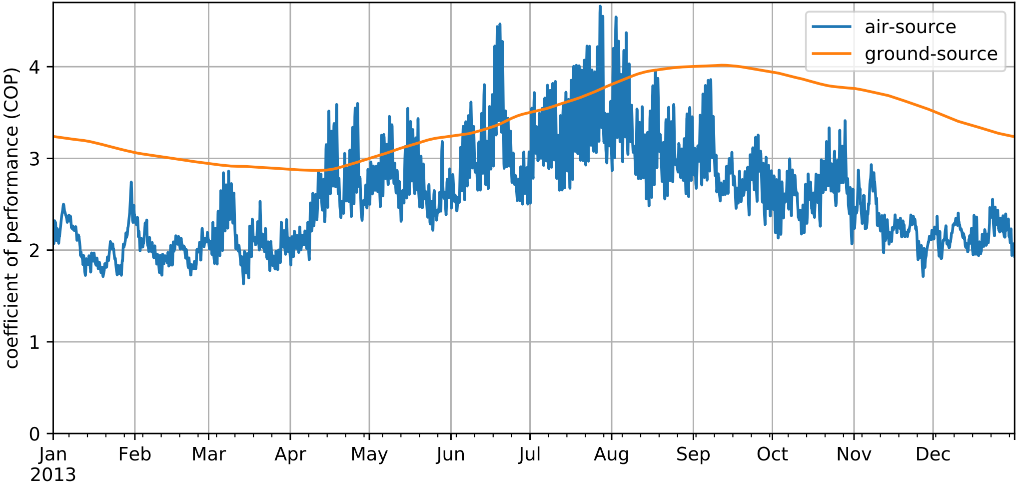


Fig. 9 Average heating coefficient of performance for air and ground source heat pumps (left and right, respectively) based on data taken from industrial surveys and field trials.[31,80–82] The inset tables show the expected performance for UK conditions.

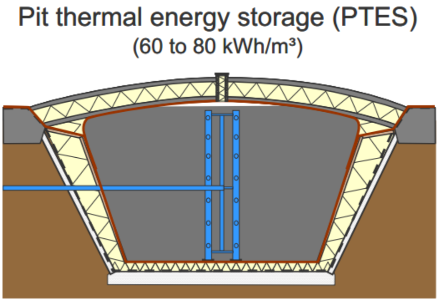
Source: Staffell et al, 2012

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.



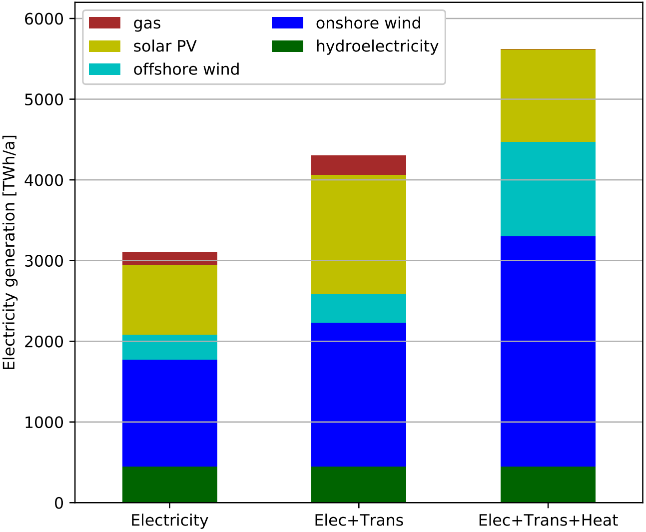
Source: Solar Thermal World

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

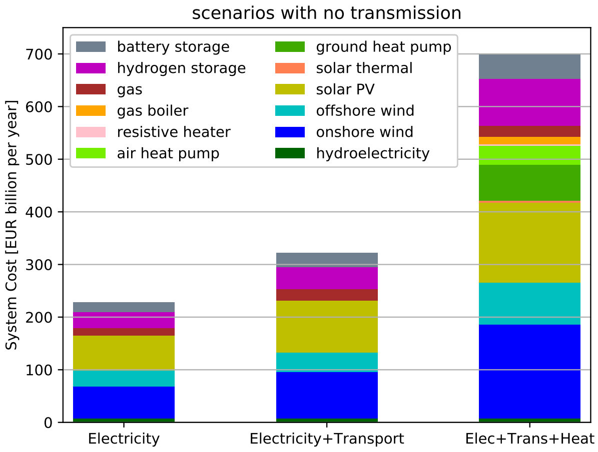
Costs oriented towards Henning & Palzer (2014, Fraunhofer ISE) and Danish Energy Database

Coupling Heating to Transport and Electricity: Electricity Demand



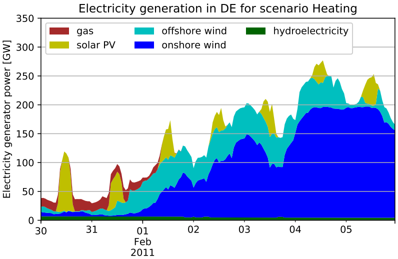
- To 4062 TWh_{el}/a demand from electricity and transport, add 3585 TWh_{th}/a heating demand
- With 95% CO_2 reduction, much of the heating demand is met via electricity, but with high efficiency from heat pumps
- Electricity demand 80% higher than current electricity demand
- Energy savings from building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

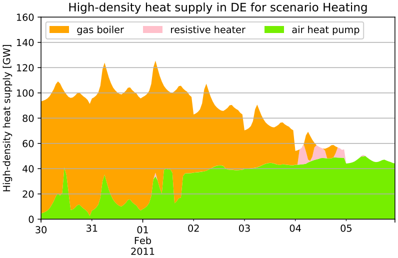
Coupling Heating to Transport and Electricity: Costs



- 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



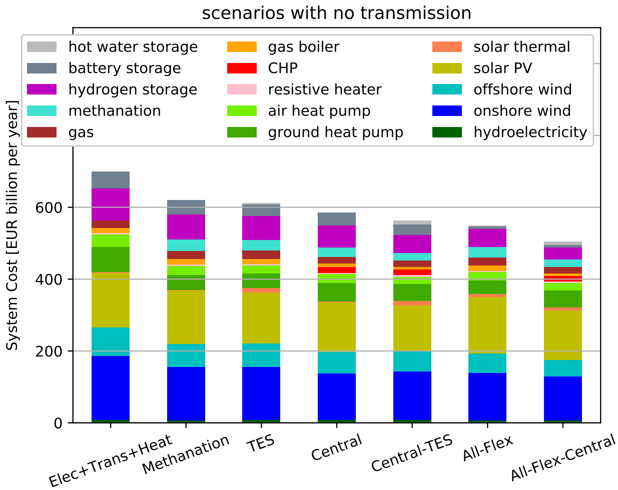


There are difficult periods in winter with:

- **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.

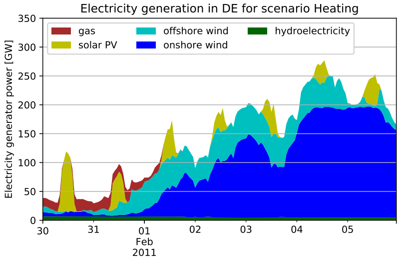
Using heating flexibility

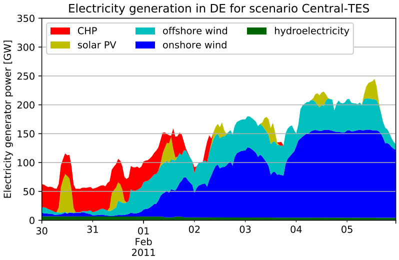


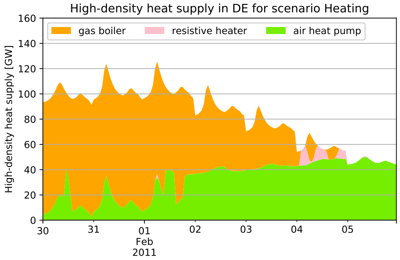
Successively activating couplings and flexibility **reduces costs** by 28%. These options include:

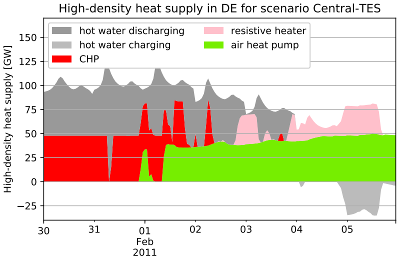
- production of **synthetic methane**
- centralised **district heating** in areas with dense heat demand
- long-term **thermal energy storage** (TES) in district heating networks
- **demand-side management** and vehicle-to-grid from battery electric vehicles (BEV)

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

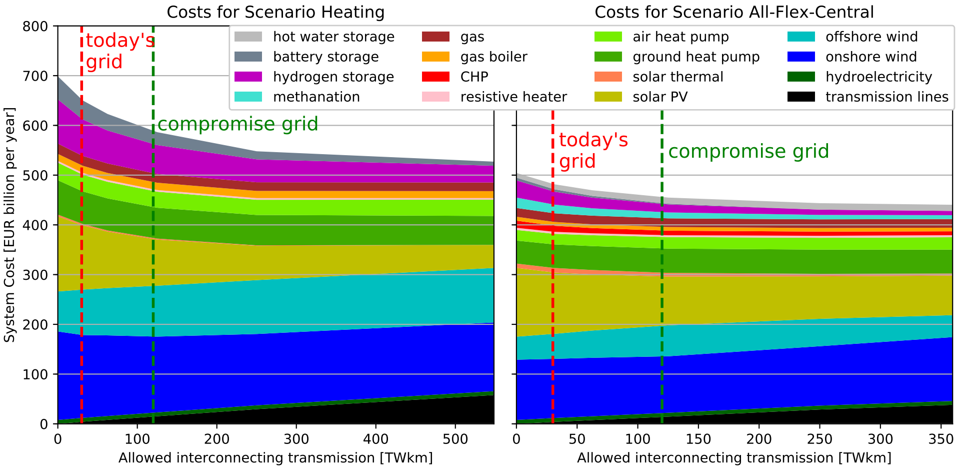






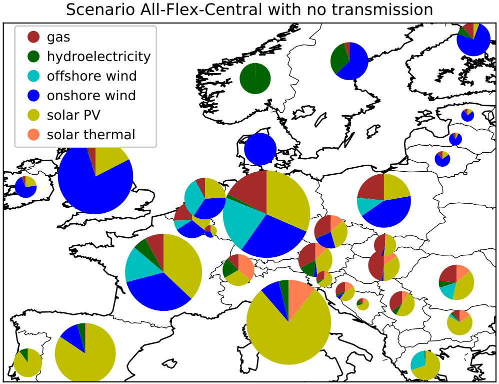


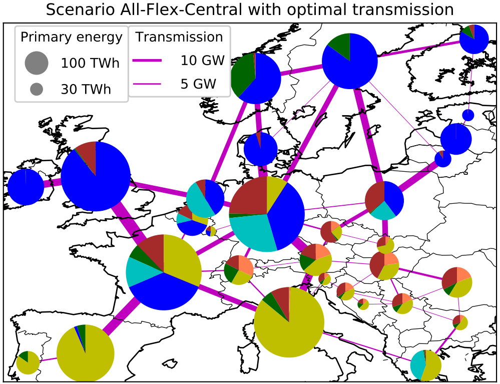
Benefit of cross-border transmission is weaker with full sector flexibility (right) than with inflexible sector coupling (left); comes close to today's costs of around € 377 billion per year



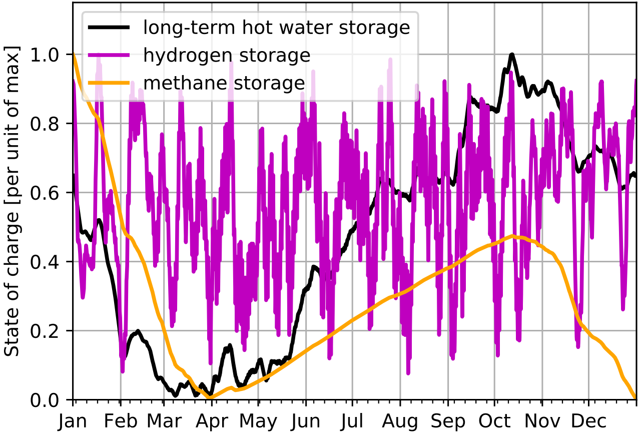
Spatial distribution of primary energy for All-Flex-Central

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 weekly-scale fluctuations are super-imposed
- Battery Electric Vehicles (BEV) and battery storage vary daily

Renovations for energy efficiency

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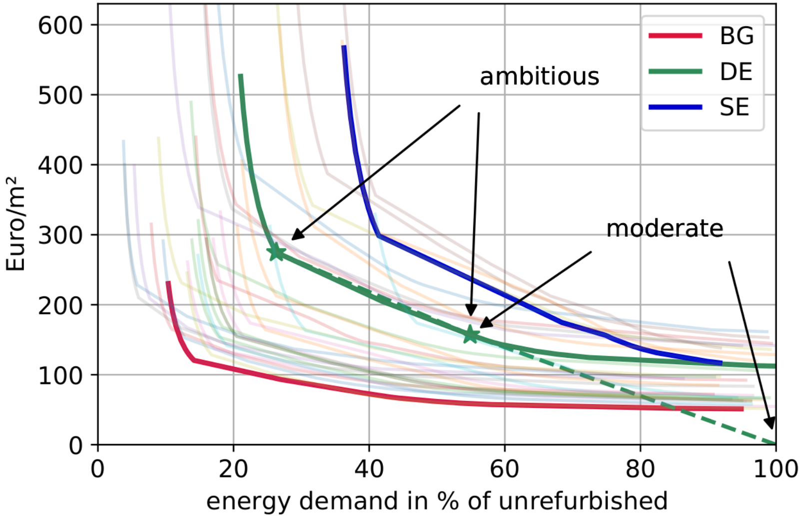
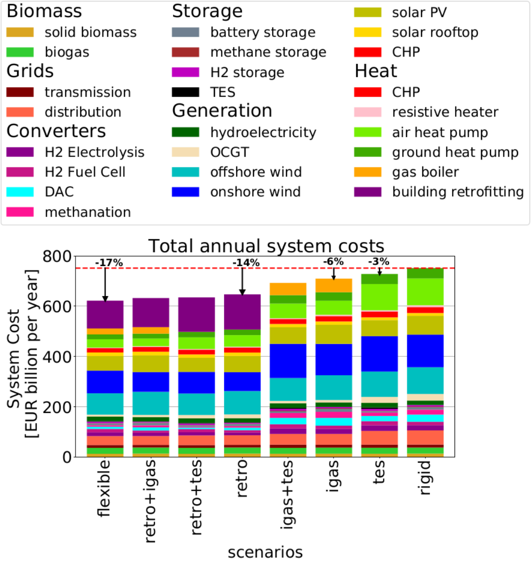
Building renovations can be co-optimised to reduce space heating demand.



Source: Zeyen et al, 2021

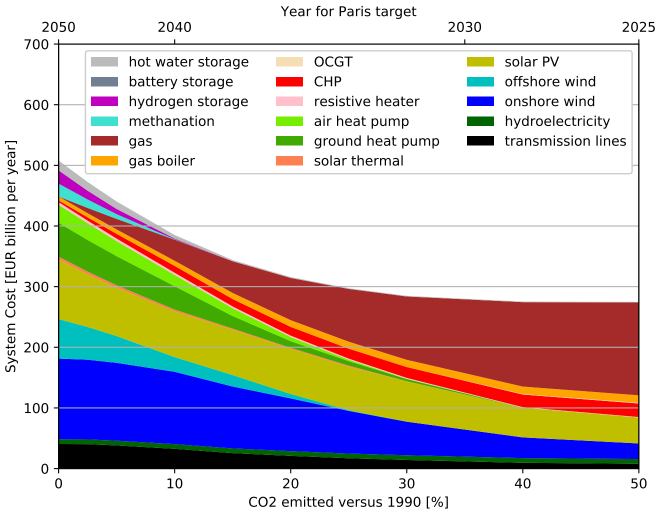
Results for co-optimisation of renovations and supply



- Scenarios for European heating show benefits of building retrofitting and flexibility
- Renovations save 17% of costs by reducing winter demand peaks
- Thermal energy storage (TES) saves around costs of 3% (25 bn€/a)
- With renovations and heat pumps, benefit of hybrid heat pumps (backup gas boilers) is small
- With renovations can remove gas distribution grid with little cost impact

Source: Zeyen et al, 2021

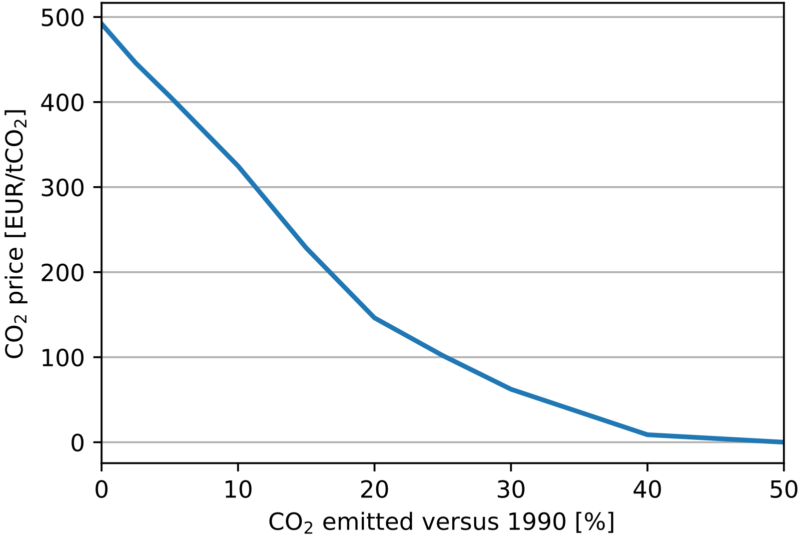
Pathway down to zero emissions in electricity, heating and transport



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

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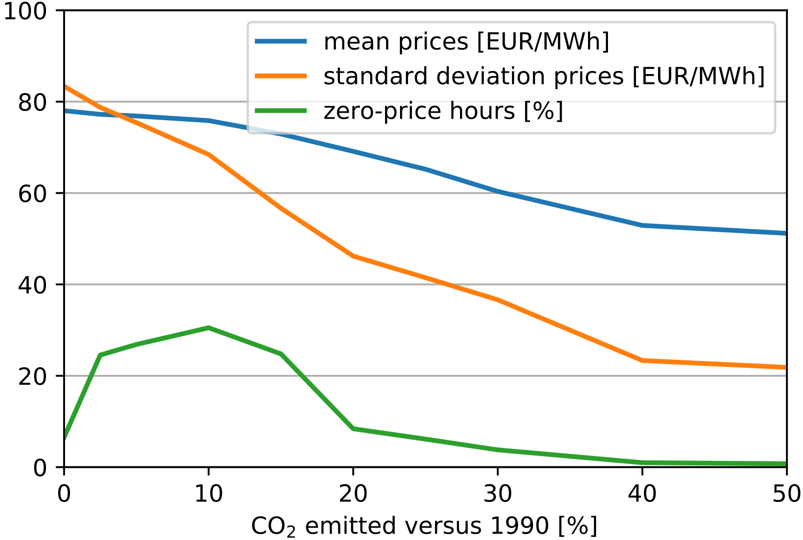
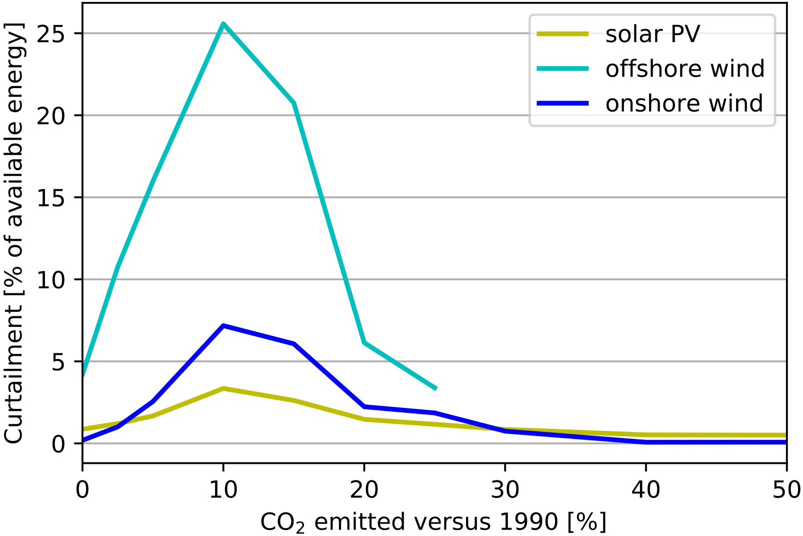


Curtailment also much reduced



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

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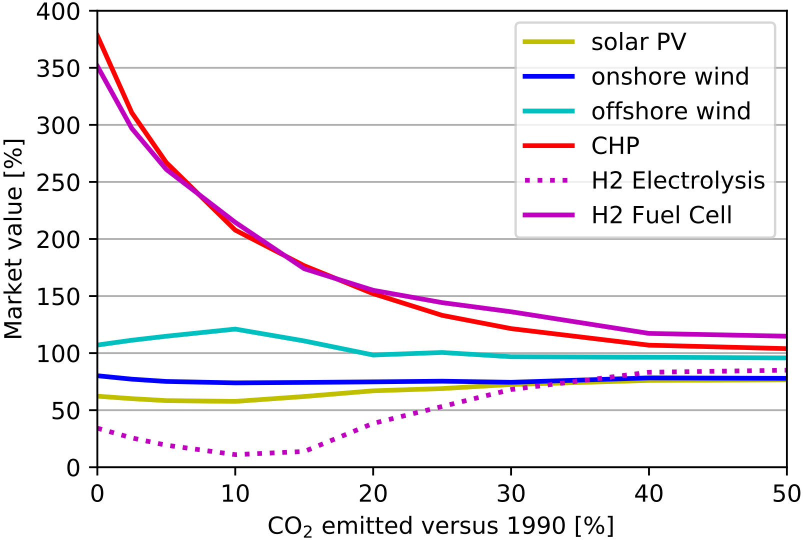
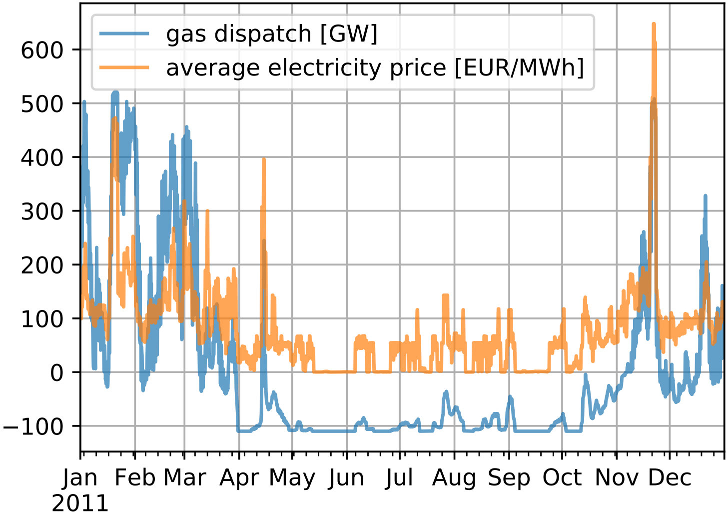


Gas production/consumption tightly coupled to price



Pathway for European energy system from now until 2050

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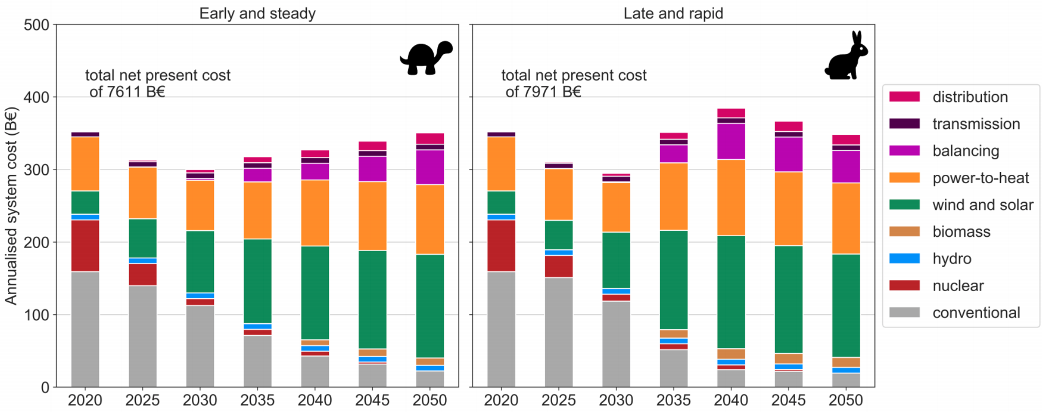
For a fixed CO_2 budget, it's more cost-effective to **cut emissions early** than wait.

NB: These results only include electricity, heating in buildings and land-based transport.



Source: M. Victoria et al (2020)

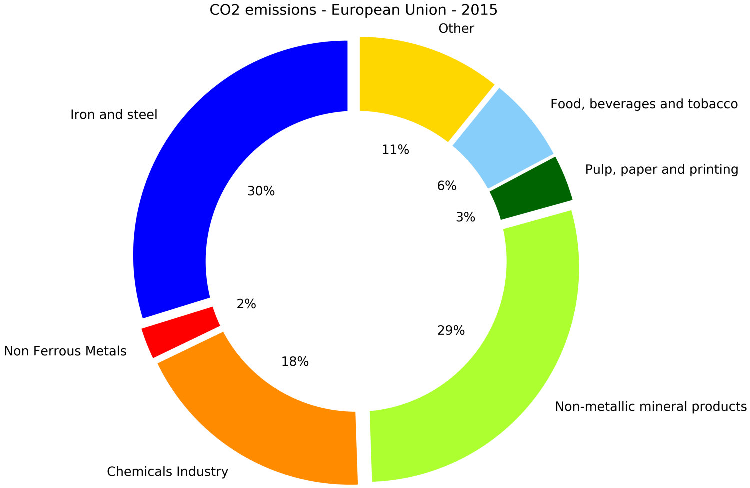
More Details in Papers

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).
- Early decarbonisation of the European energy system pays off, **arXiv link** (2020).

Industry, Shipping and Aviation

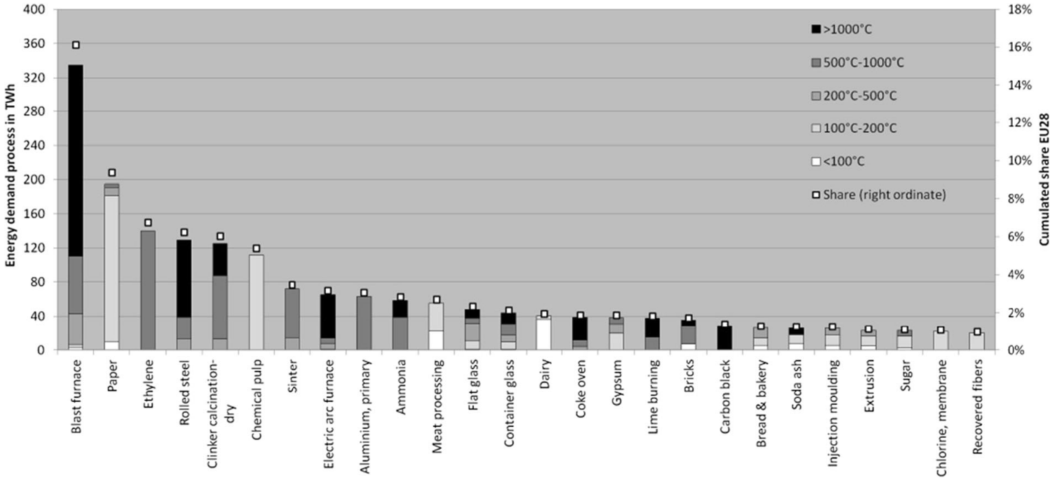
CO_2 direct emissions from industry by sector in Europe



- 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

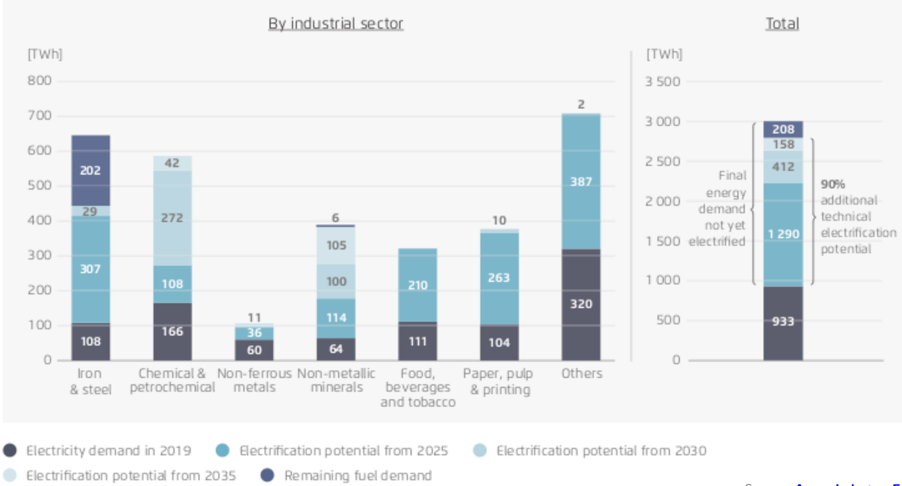
Temperatures >100 C not accessible via regular heat pumps. Need direct electrification, biomass, synthetic fuels (hydrogen, methane), nuclear or carbon capture.



Source: Rehfeldt et al, 2017

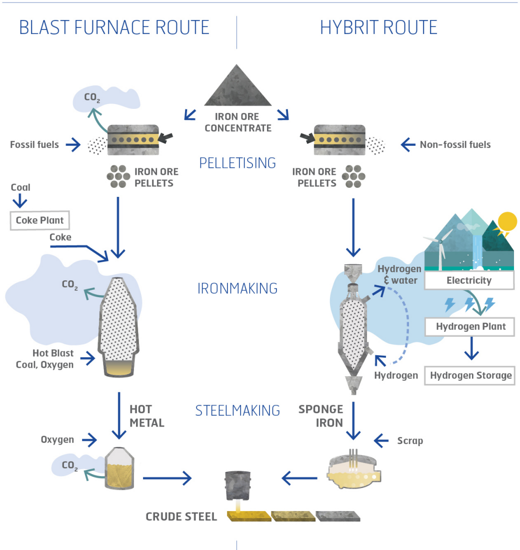
Technical potential for electrification in EU27 is high

Technical potential for electrifying 2019 industry demand is high but many barriers too: high investment, electricity cost, need for larger grid connection.



Source: Agora Industry, Fraunhofer ISI, 2024

Iron and steel: direct reduce with hydrogen instead of coke



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

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

- Alternative: 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**.
- Lower TRL alternative from 2030s: **molten oxide electrolysis**.

Source: **HYBRIT project**

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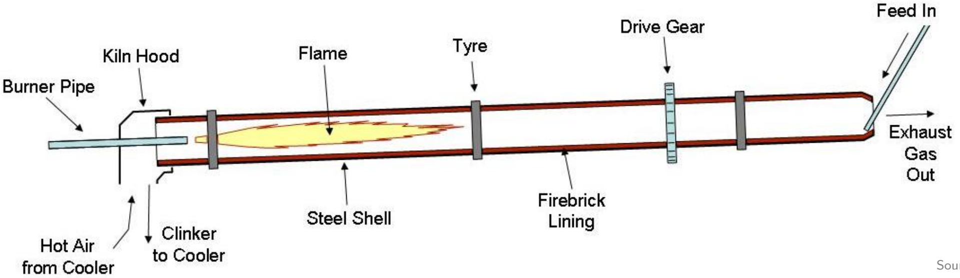
Cement is used in construction to make concrete. CO_2 is emitted from fossil fuels to provide process heat and from the calcination reaction for fossil limestone

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

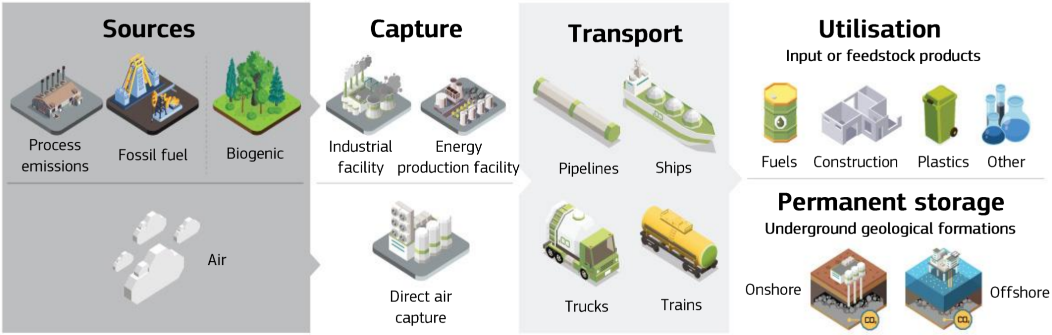
This is the biggest source of **process emissions** in industry in Europe. While we can replace process heat with low-carbon sources, process emissions are harder. Unless alternatives can be found for cement, this CO_2 can be captured and either sequestered underground (CCS) or used (CCU) to make chemicals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



Source: Wikipedia

Carbon dioxide management

Most scenarios show that in 2030-50 Europe will need carbon capture from point sources, following by CO_2 transport, usage in fuels and materials (carbon capture and usage, CCU) or long-term underground storage/sequestration (CCS). These options are collectively known as **carbon dioxide management**.



Source: COM: Industrial Carbon Management, 2024

Carbon dioxide removal (CDR)

E.g. afforestation, direct air capture and sequestration (DACS), bioenergy+CCS (BECCS)

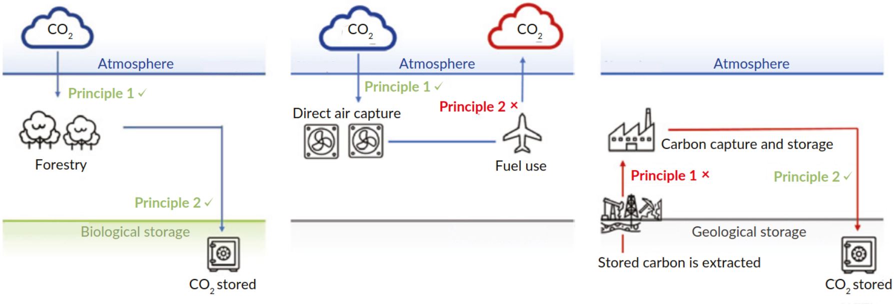
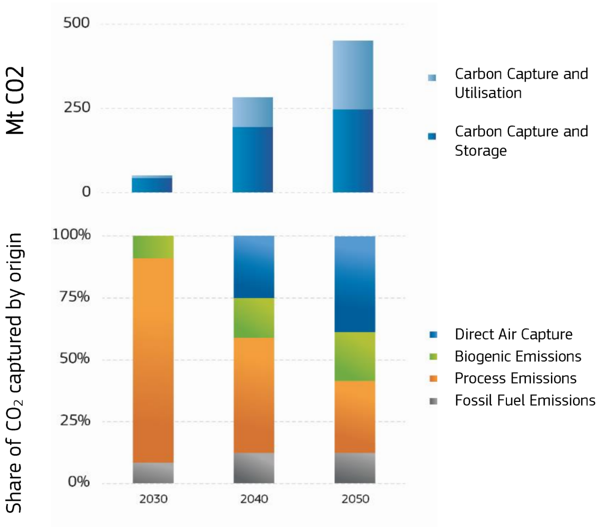


Figure 1.1. *To be defined as Carbon Dioxide Removal (CDR), a method must capture CO_2 from the atmosphere (Principle 1) and durably store it (Principle 2). An example of a method which satisfies both principles, and hence qualifies as CDR, is afforestation/reforestation (left). There are several approaches that satisfy only one of these principles, and hence are not CDR, but which count as Carbon Capture and Utilisation (e.g. Direct Air Capture to fuels (middle) or as fossil Carbon Capture and Storage (right). Source: Zero Emissions Platform (2020)[12].*

Source: State of CDR, 2023

Carbon management in EU policy

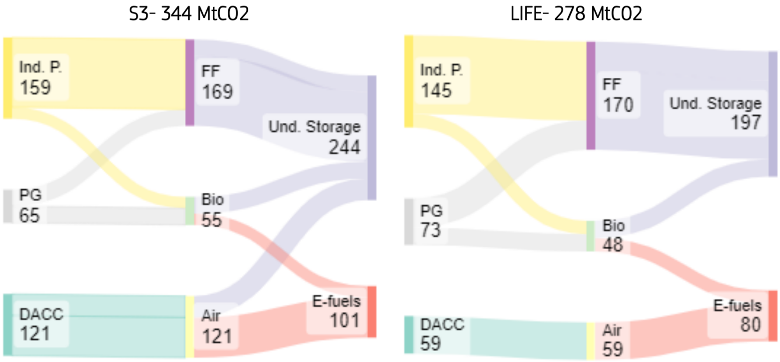


- EU Commission's planning for 2030 has 50 $MtCO_2/a$ sequestration (in Net-Zero Industry Act), rising to $\sim$250 $MtCO_2/a$ in 2050
- 2050: around 450 $MtCO_2/a$ total capture from point sources and air
- 2050: around 200 $MtCO_2/a$ CCU
- 2050: around 100 $MtCO_2/a$ CDR
- NB: Neither DAC or BECCS have been demonstrated at scale!

Source: COM: Industrial Carbon Management, 2024

Carbon dioxide management in 2040

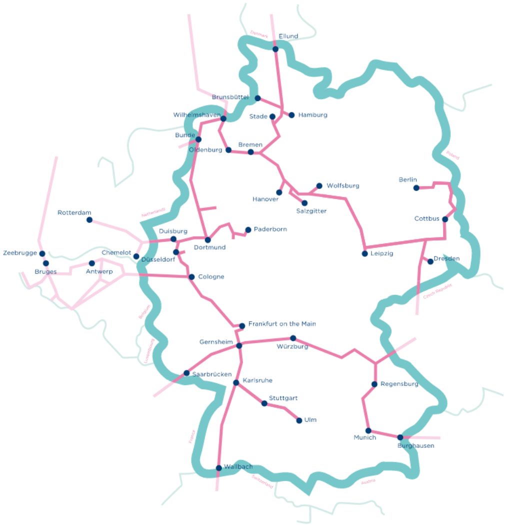
Potential role of carbon dioxide management in 2040: carbon captured from industry, power plants, biorefineries and air. Some transported to sequestration sites, rest used for e-fuels.



Note: "Ind. P." stands for Industrial processes and include fossil carbon from industrial processes as well as carbon of biogenic origin coming from the upgrade of biogas to biomethane. "FF" stands for "fossil fuels". "PG" stands for "power generation". "Bio" refers to CO2 produced by the combustion of biomass in power generation and produced during the upgrade of biogas into biomethane. "DACC" stands for "Direct Air Capture

Source: European Commission 2040 target impact assessment, 2024

Potential carbon dioxide network for Germany

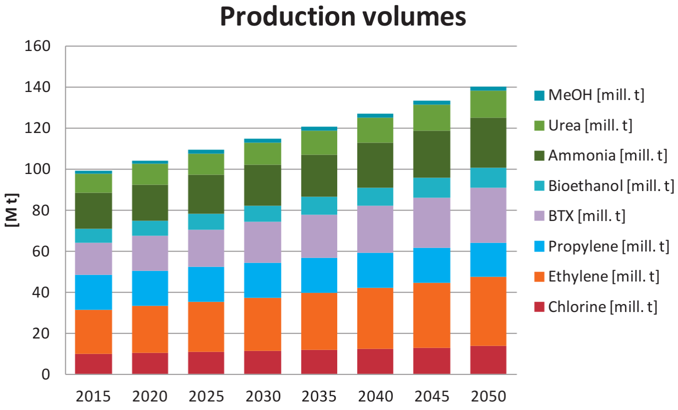


- A Startnetz to transport up to 50 $MtCO_2$ per year in Germany is planned by OGE.
- CO_2 is transported cold and under pressure as a liquid.
- CO_2 networks already existing in the United States, primarily to transport CO_2 for enhanced oil recovery.

Source: **OGE, 2024**

Chemicals

Forecast for chemicals production in Europe:

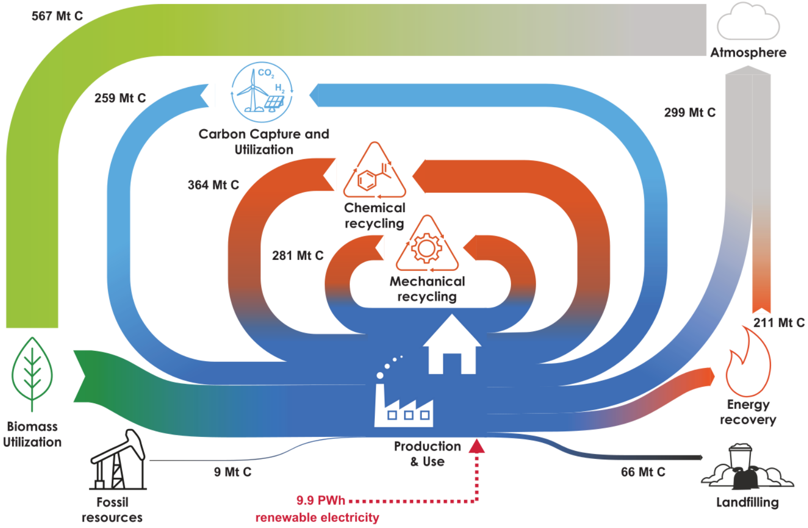


- Fossil fuels are used for process heat in the chemicals industry, but also as a **feedstock** for chemicals like ammonia (NH_3), ethylene (C_2H_4) and methanol (CH_3OH or MeOH)
- Ammonia, used for fertiliser, can be made from hydrogen and nitrogen using the Haber-Bosch process
- Ethylene, used for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

Source: DECHEMA

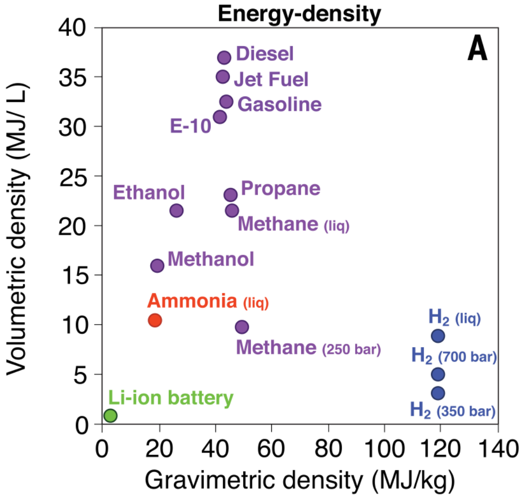
Recycling plays an important role for plastics

For all materials: reduction, reuse and recycling help to reduce energy consumption.



Source: Meys et al, 2021

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

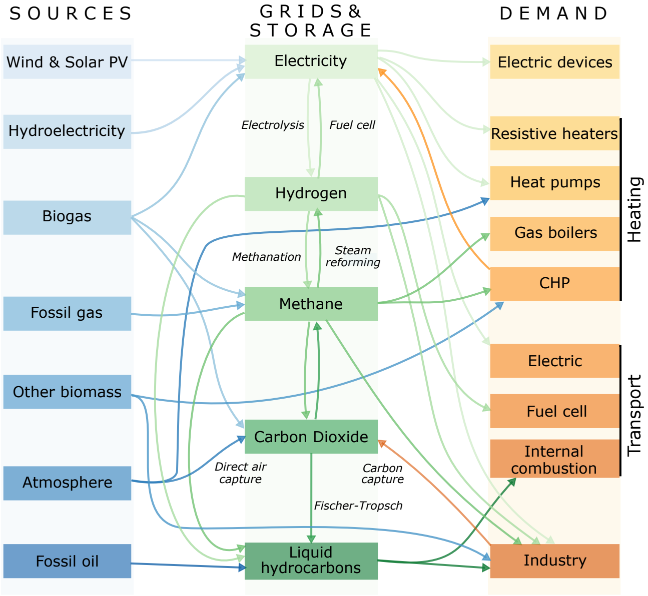
Defossilising non-electric industry processes, aviation, shipping

We assume higher recycling levels as well as process- and fuel-switching:

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	Recycling; synthetic methane/ol, naphtha and hydrogen
Other industry	Electrification; process heat from biomass
Shipping	Electrification; methanol, ammonia, liquid hydrogen
Aviation	Electrification; kerosene from Fischer-Tropsch

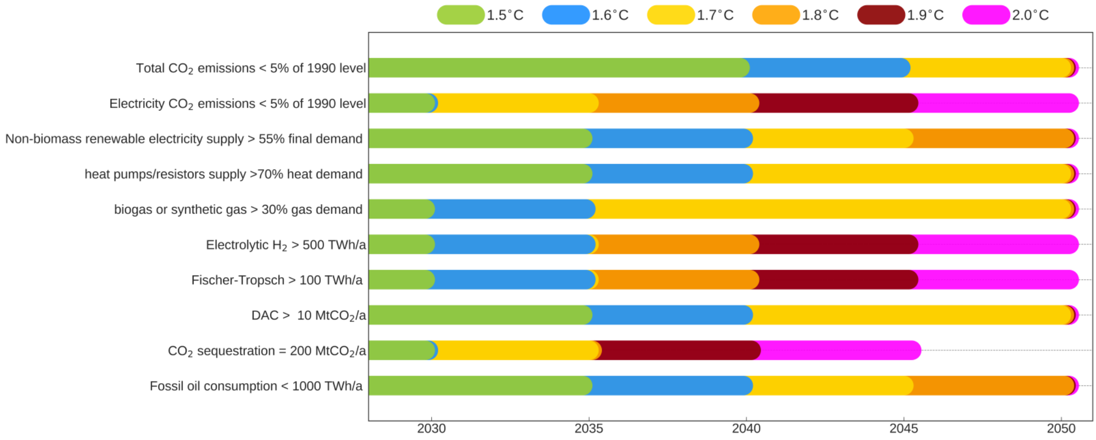
Carbon is tracked through system: 90% of industrial emissions are captured; direct air capture (DAC); synthetic methane and liquid hydrocarbons; transport and sequestration 20 €/tCO_2

Including all sectors needs careful management of carbon



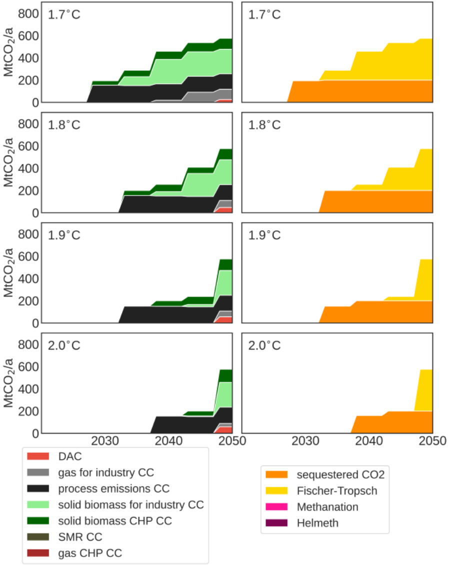
Results on appearance of technologies; depends on temperature target

When key transformations occur depends on the carbon budget.



Source: M. Victoria et al, 2022

Carbon management (CCU/S) becomes increasingly important

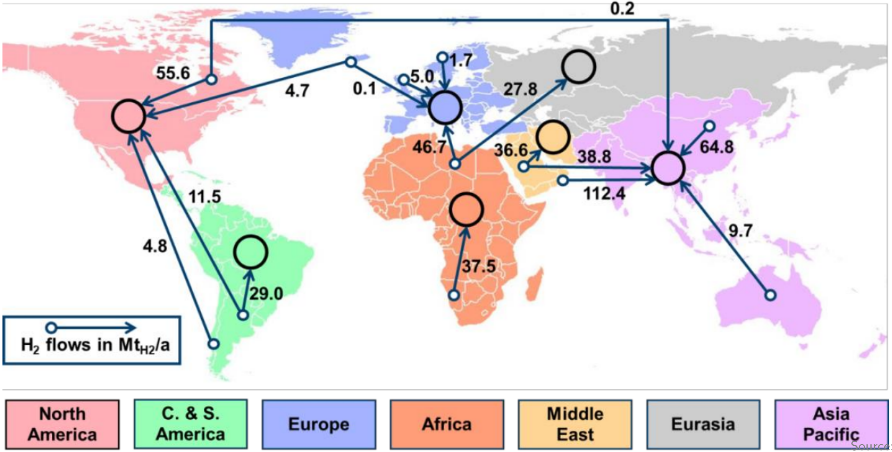


- **Carbon capture** (left): from process emissions, but also from heat production in industry and for combined-heat-and-power (CHP) plants
- **Sequestration** limited to 200 $MtCO_2/a$ (enough to cover today's process emissions)
- Further captured carbon is **used** for Fischer-Tropsch fuels (kerosene and naphtha)
- The tighter the CO_2 budget, the more is captured, and at some point **direct air capture** (DAC) also plays a role
- If sequestration is relaxed to 1000 $MtCO_2/a$, then CDR compensates unabated emissions elsewhere

Source: M. Victoria et al, 2022

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

Synthetic fuels from outside Europe?

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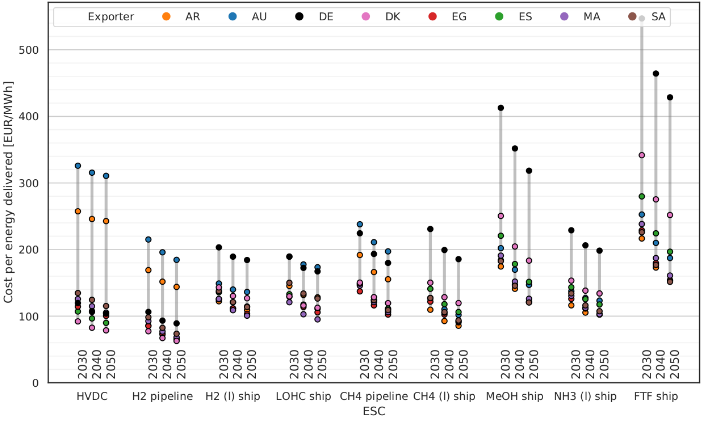
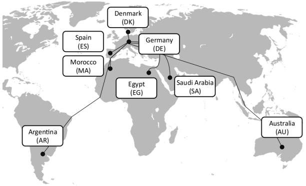
Green hydrogen with pipeline transport costs around ~ 80 €/MWh in model. Shipping green hydrogen from **outside Europe** in liquid, LOHC or NH_3 form may not compete on cost (depends e.g. on WACC), but scarce land in Europe may still drive adoption.





Source: Hampp et al, 2021

Role of biomass

Role of biomass

In the **current** German energy system, biomass sources consist mostly of dedicated energy crops like corn, rapeseed or fuelwood. Biomass is either used directly for heat and power, or processed by anaerobic digestion for biogas or processed into gasoline and diesel substitutes.

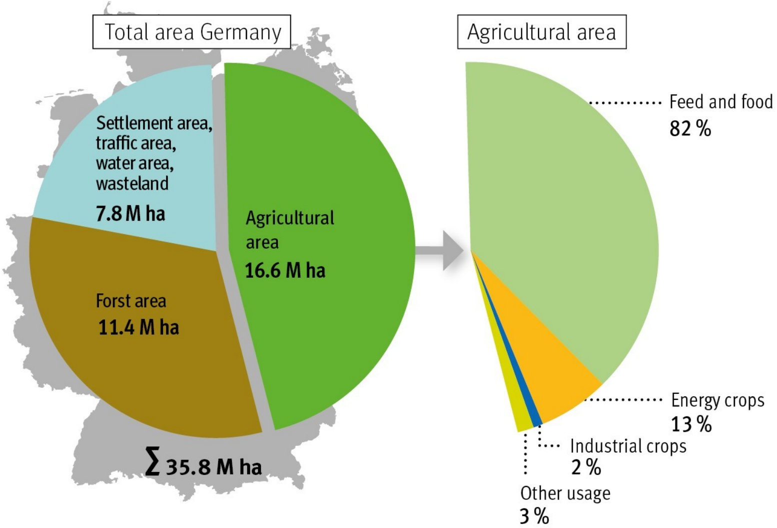
Energy crops are **controversial** because there are emissions from fertiliser and harvesting, and they displace land that could otherwise be used for food.

The **future use of biomass** would need to change as current uses (power, land vehicles) electrify. Use should be prioritised where carbon is needed, e.g. in dense fuels for shipping and aviation, carbonaceous feedstocks for industry, and carbon dioxide removal (CDR).

The **future feedstocks** should be chosen to avoid direct land use, e.g. by using wastes and residues from agriculture, such as straw from grain production, or manure from animals.

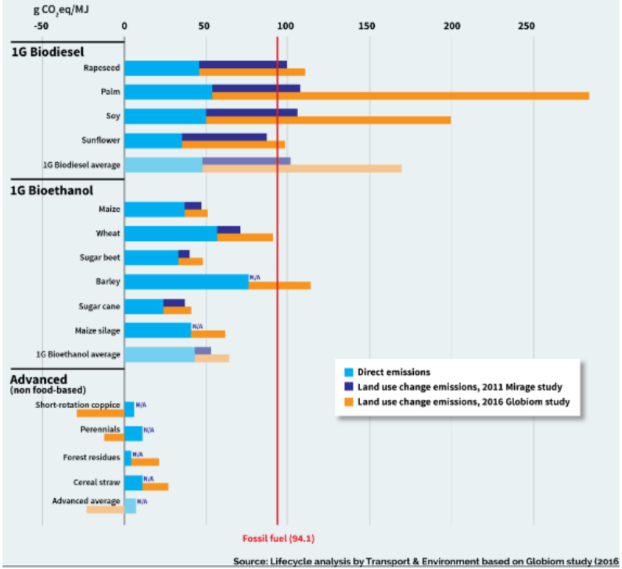
Land use for biomass in Germany

Around 7% of land in Germany used for energy and industrial crops (mostly maize, rapeseed).



Source: FNR, 2024

Lifecycle emissions for different biomass sources



- Depending on how land use is accounted (controversial!) many first generation biofuels have emissions as bad as fossil.
- Imported palm and soy particularly bad.
- Second generation advanced wastes and residues are significantly better.
- European policy is adjusted appropriately since RED II.

Source: Transport & Environment, 201x

Open Energy Modelling

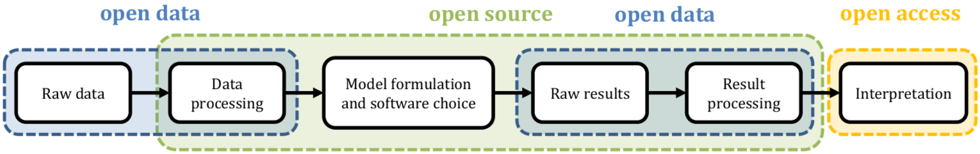
What is open modelling?

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,

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

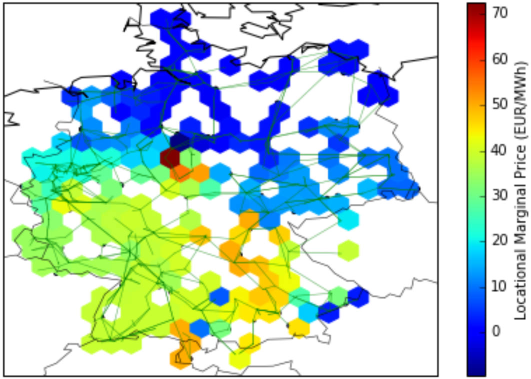
Python for Power System Analysis (PyPSA)

Technische Universität Berlin

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

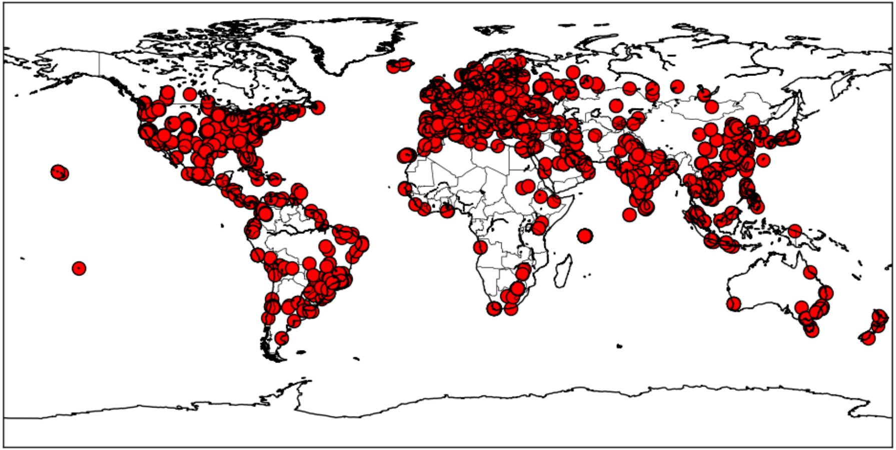
- Static **power flow**
- **Linear optimal power flow** (LOPF) (multiple periods, unit commitment, storage, coupling to other sectors)
- **Security-constrained LOPF**
- Total energy system **capacity expansion optimisation**

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

Technische Universität Berlin

- 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**