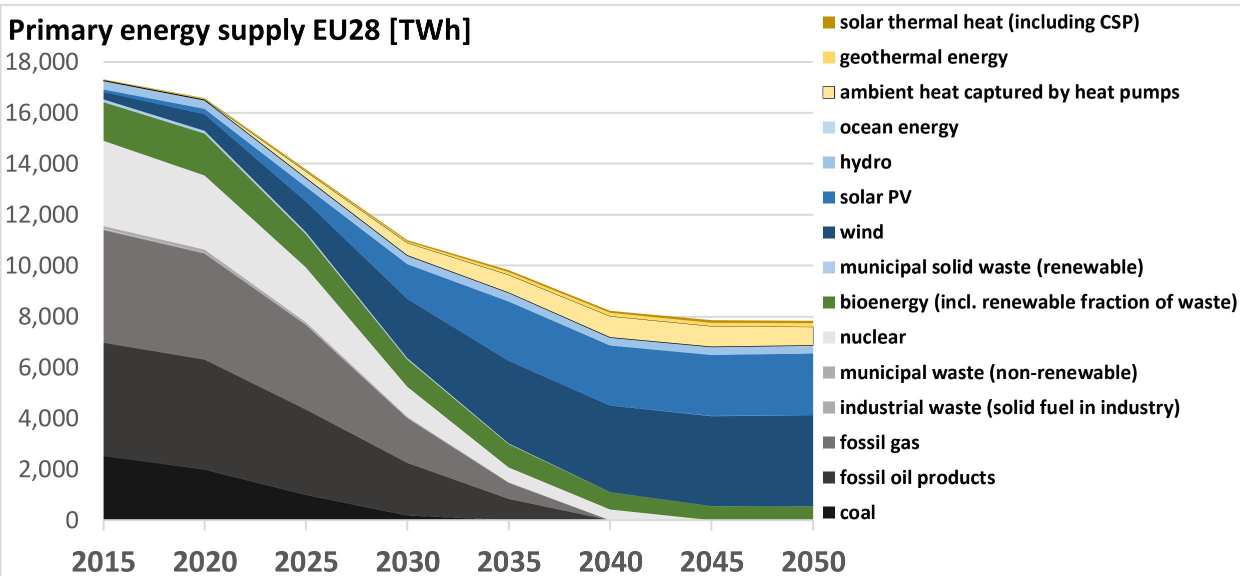
Building a Paris Agreement Compatible (PAC) energy scenario

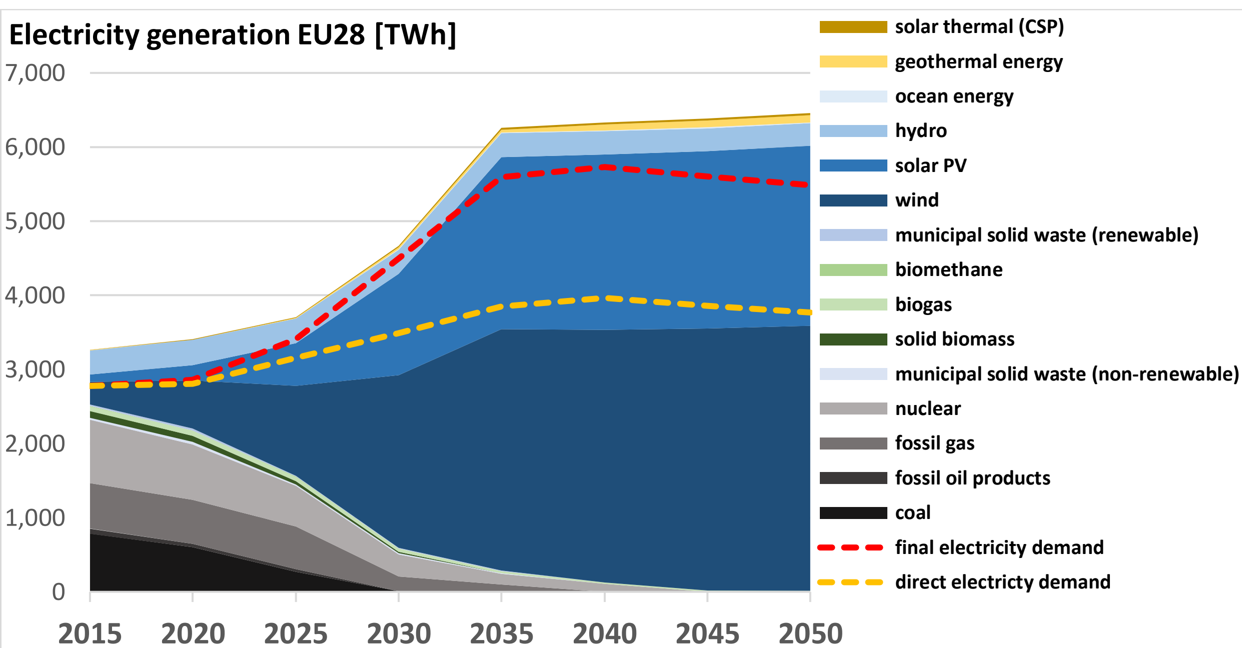
CAN Europe/EEB technical summary of key elements

June 2020

2. Energy supply

The second chapter presents the primary energy supply that covers the sector-specific energy demand as presented in chapter 1. Primary energy covers consumption of the energy sector itself, losses during transformation (i.a. from gas into electricity) and distribution of energy, and the final consumption by end users. Losses from converting the primary energy into other energy carriers are not yet deducted, neither losses of transmission and distribution, e.g. from district heat networks or leaking gas pipelines. In the following subchapters, the specific supply and conversion of different primary energy sources is assessed. Total supply of primary energy halves from 2015 to 2050 with renewables becoming the major source by 2030. Solar PV and wind by then also supply most electricity, covering an increasing direct demand and the additional electricity demand for producing non-fossil gases through electrolysis (see "final electricity demand" below).





2.1 Phasing out coal

Key assumptions

It is as indispensable[1] as inevitable that most of the hard coal and lignite consumption will be phased-out by the year 2030.

- National coal phase-out plans for electricity generation exist in most EU Member States. These will be implemented or even anticipated by power plant operators because of high carbon prices and low economic attractiveness.[2] Coal fired power plants that supply district heat tend to be retired later.
- The increase of the carbon price and renewable capacities will strongly reduce the full load hours of the remaining coal capacities. Most of them will be retired by 2030. Very few reserve capacities remain.[3] Neither retrofitting of existing coal capacities nor new mines are considered economically viable.
- Renovation will lead to a quick replacement of individual heating based on coal. In industry, energy savings as well as electrification and renewable hydrogen will substitute the most important coal supply in the steel, cement and ceramics industries. The introduction of CCS is not considered realistic.

Evolution of energy supply

Coal-fired power plants have become risky assets for most operators in most countries.[4] In addition, air quality legislation leads to earlier shutdowns. In 2030, only 7 TWh of electricity are produced by remaining capacities in Germany, Poland, Estonia and Czechia. These are used as back-up capacities with very low full load hours.

In the energy-intensive industry, the phase-out of coal will progress only slightly slower than in electricity generation. Coal supply falls from 394 TWh in 2015 to 140 TWh in 2030 to disappear by 2035. This development is largely due to developments in the steel industry. Firstly, the reduced steel demand cuts coal consumption. Besides this trend, a massive increase of the electric arc furnace route for steel production together with the introduction of the Direct Reduction of Iron (H-DRI) process reduces the coal supply for blast furnaces.[5]

Integration of members' and experts' feedback

The coal-phase out trajectory was developed in close collaboration with experts and members. Assumptions were discussed at the PAC scenario workshops.[6] Key figures for the electricity sector are based on the Europe Beyond Coal campaign's database of coal-fired power plants.[7] In addition to the Öko-Institut's market modelling (see page 38), several country-specific studies were considered to substantiate the phase-out trajectory.[8]

Sensitivities and limitations

Depending on the short- and mid-term evolution of the EU Emission Trading System (ETS) carbon price, capacities for electricity generation could be retired even more quickly. A potential fuel switch of coal-fired power plants from coal to

1 Climate Analytics: Global and regional coal phase-out requirements of the Paris Agreement, September 2019.

2 Carbon Tracker: Powering down coal. Navigating the economic and financial risks in the last years of coal power, November 2018; Sandbag: The cash cow has stopped giving: Are Germany's lignite plants now worthless? July 2019.

3 This was confirmed by Öko-Institut's electricity market modelling with PAC scenario assumptions and a carbon price of €84/t.

4 Carbon Tracker: Apocoalypse now, October 2019; Carbon Tracker: Lignite of the living dead, December 2017.

5 Material Economics.

6 CAN Europe/EEB: Summaries of PAC scenario workshops and General Assemblies workshops.

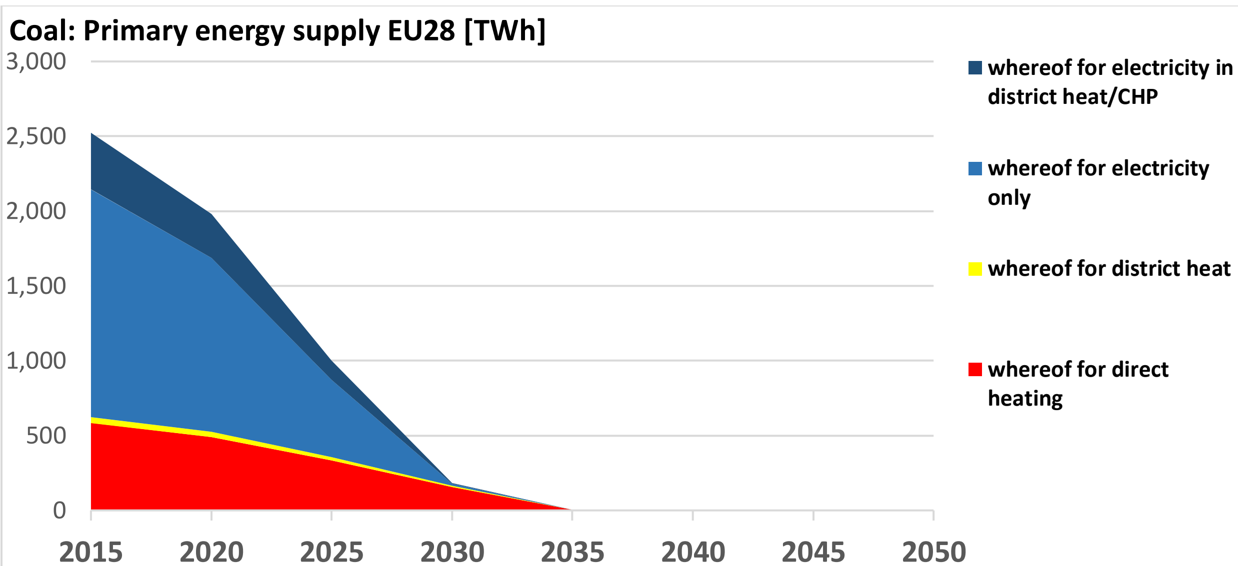
7 Europe Beyond Coal: European Coal Plant Database. Status: 12 July 2019. Country-specific updates were integrated by May 2020.

8 Forum Energii: PEP2040 scrutinized by Forum Energii. Comments and recommendations, Nov. 2018; Energynautics: Czech power grid without electricity from coal by 2030, May 2018; REKK et al.: Accelerated lignite exit in Bulgaria, Romania and Greece, May 2020; Bartholdsen et al.: Pathways for Germany's low-carbon energy transformation towards 2050. In: Energies, 2019, 12, 2988, Aug. 2019.

biomass has not been analysed in detail. Given the environmental risks associated with it, such a conversion or co-firing should be avoided.[9]

Key results[10]

- NGOs' policy demand of phasing out coal by 2030 will mostly be implemented: In electricity generation, renewables and the carbon price drive the quick phase-out in almost all Member States by 2030. Support schemes such as capacity mechanisms can delay this trend only by a few years.
- Poland and Germany are the two Member States that dominate the remaining hard coal and lignite capacities. In 2030, Poland produces 2 TWh and Germany 4 TWh of electricity from coal.
- As the use of coal in industry is mainly concentrated in a limited number of energy-intensive steel production sites, their gradual modernisation during normal investment cycles will bring about a switch from coal to renewable electricity and hydrogen (see also chapter 1.1 on industry's energy demand).



9 Sandbag: Playing with fire. An assessment of company plans to burn biomass in EU coal power stations, Dec. 2019.

10 Findings in this chapter also include the extraction and combustion of oil shale which statistically accounts as hard coal. In the EU, it is used for electricity generation in Estonia only. In 2030, oil shale fired capacities of 659 MW remain in Estonia with <1 TWh of electricity produced according to Öko-Institut's electricity market modelling. It is possible that these capacities will be retired earlier.

2.2 Phasing out fossil gas

Key assumptions

The continued use of fossil gas puts the EU's climate and energy goals at risk. In addition to the decreasing demand for electricity generation and in buildings, an active fossil gas phase-out by 2035 needs to be pursued.[11]

- A further increase of fossil gas supply for electricity generation to replace coal power plants is not foreseen given the availability of cheaper renewable electricity supply. Full load hours slump by 2030.[12]
- The PAC scenario assumes that fossil gas supplied for heating buildings in the residential and tertiary sector will be strongly reduced by 2035 because of the high rate and depth of renovation that trigger the replacement of fossil gas boilers. Any uptake of fossil gas supply in transport is not realistic.
- The impact of methane leakage from fossil gas infrastructure on global warming increases pressure to rapidly cut fossil gas supply.[13] The introduction of CCS is not considered realistic.

Evolution of energy supply

Together with fossil oil products, fossil gas in 2015 was the most important source of primary energy supply of the EU. In industry, fossil gas dominates with 1,077 TWh supplied in 2015 (34% of industry's final energy demand). As a consequence of reduced material demand, increased energy efficiency, electrification and introduction of non-fossil gases (renewable hydrogen, synthetic methane), supply goes down to 203 TWh in 2035 (8% of final demand) and will be entirely phased out by 2040.

While 41% of the residential sector's and 36% of the tertiary sector's final energy demand in 2015 was covered by fossil gas, the share drops to 9% in 2035. The remaining 136 TWh in the residential sector and 84 TWh in the tertiary sector will eventually disappear from the mix by 2040 because of the high rate and depth of renovation that trigger the replacement of fossil gas boilers for individual heating. Cooking will be largely electrified or switched to biomethane.

The share of fossil gas in electricity generation falls from 22% (616 TWh) in 2015 to 2% (96 TWh) in 2035. Remaining capacities however will not always immediately be mothballed. They might still be used to burn non-fossil gases (renewable hydrogen, synthetic methane) to offset variable renewable electricity generation during very few hours of peak demand.

Integration of members' and experts' feedback

During the collective PAC scenario building process, members and experts highlighted the need for proactive fossil gas phase-out policies of Member States in order to achieve the ambitious trajectory. Instruments such as a ban on gas boilers and financial incentives for transitioning cities to fossil-free heating are a prerequisite.[14]

[11] E3G: Pathway to a climate neutral 2050: Financial risks for gas investments in Europe, February 2020; E3G: Deep decarbonisation and the future of gas in the EU, March 2019; Global Witness: Overexposed: How the IPCC's 1.5°C report demonstrates the risks of overinvestment in oil and gas, April 2019; FoEE: Can the climate afford Europe's gas addiction? November 2017.

[12] This was confirmed by Öko-Institut's electricity market modelling with PAC scenario assumptions and a carbon price of €84/t.

[13] Energy Watch Group: Natural gas makes no contribution to climate protection, September 2019.

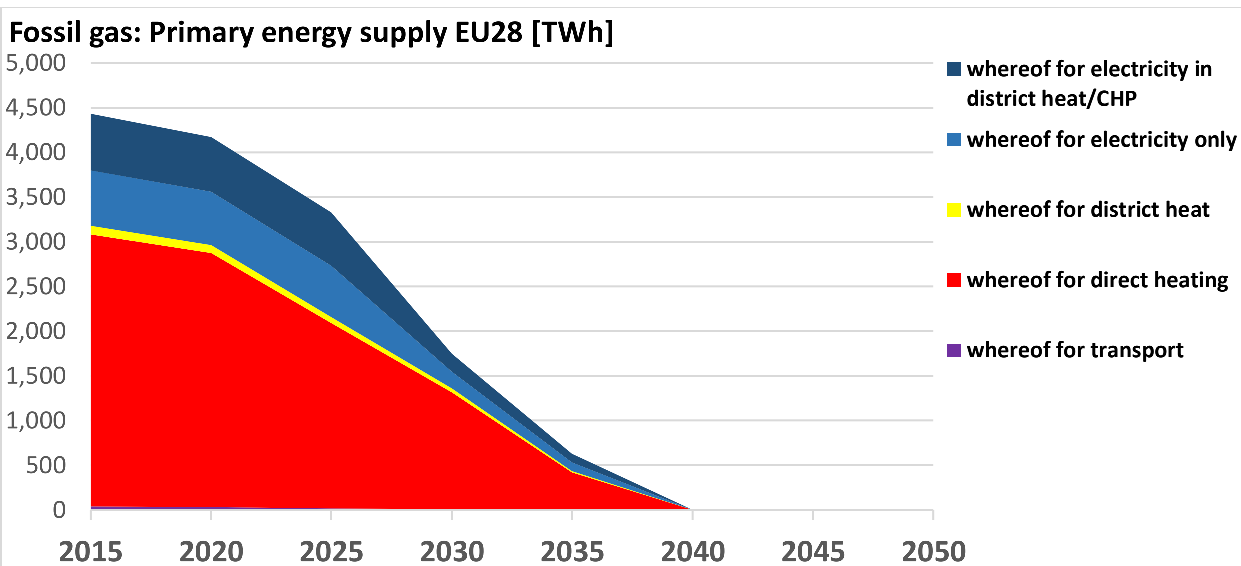
[14] CAN Europe/EEB: Summaries of PAC scenario workshops and General Assemblies workshops.

Sensitivities and limitations

Uncertainties remain with regards to the pace of fossil gas phase-out. The oversupply of cheap fossil gas streaming to Europe makes a quick shift to its alternatives challenging in the residential and tertiary sectors. Households' investment decisions tend to favour continued use of the heating technology that they already are familiar with, in particular if Member States subsidise installing new gas boilers in households. Existing fossil gas infrastructure exerts inertia, meaning that established operators and gas suppliers successfully keep their consumers tied to incumbent distribution chains. Alternatives such as new and efficient district heating networks often would need to be anticipated and facilitated first in lengthy spatial planning processes. Against this backdrop, policies and measures are a decisive element for the role of fossil gas.

Key results

- Electricity generation from fossil gas decreases by 84% from 2015 to 2035. Fossil gas is not needed as a "bridge fuel". Immediate leap-frogging from coal to renewable electricity generation is possible.
- Renovation pushes fossil gas out of buildings' energy supply. Final energy demand for fossil gas in the residential sector drops by 90% from 2015 to 2035 (-86% in tertiary). Electrification and non-fossil gases fully substitute fossil gas in industry between 2035 and 2040.
- High carbon prices and EU and Member States' commitment to phasing out fossil gas is crucial for the trajectories shown in the PAC scenario.



2.3 Phasing out fossil oil

Key assumptions

The absolute domination of fossil oil products in the transport sector is not compatible neither with the Paris Agreement's 1.5°C objective nor with the EU climate and energy targets,[15] therefore:

- Fossil oil disappears from the transport sector's energy supply by 2040 thanks to massive electrification combined with fuel-switching.[16]
- Ongoing modernisation of production processes and higher energy efficiency lead to a gradual phase out of oil in industry and agriculture. Circular economy principles accompany the phase out in the chemicals industry, also with regard to its role as a raw material.[17]
- Fossil oil will be phased out for space heating and hot water in buildings with the gradual replacement of old and inefficient heating oil boilers due to renovations.

Evolution of energy supply

Fossil oil products in 2015 were the most important source of primary energy supply. By 2030, fossil oil will remain by far the dominating energy supply in transport. In 2015, it covered 93% of final energy demand (3,385 TWh). Even after a steep market introduction of electric vehicles, 60% of final demand is still covered by fossil oil in 2030. With a further massive upscaling of renewable electricity, of renewable hydrogen and liquid synthetic fuels, its share decreases to 28% in 2035. Fossil oil products then are phased out by 2040.

In agriculture, fossil oil covered 50% of final energy demand in 2015 (162 TWh), falling to 47 TWh in 2035. It will be partly substituted by renewable electricity and by liquid biofuels for farming machinery, leading to an entire phase-out between 2035 and 2040. Fossil oil supply for heating in buildings has a less important role. Similar to the phase out of fossil gas boilers, the renovation of buildings leads to a fast switch to renewable heating such as heat pumps and renewable district heating. Fossil oil supply will reduce by 95% between 2015 and 2035 in the residential sector (-80% in tertiary).

Fossil oil supply in industry is often limited to processes that can be electrified or that can switch to biomass or non-fossil gases.[18] In electricity generation, fossil oil loses its marginal role as reserve capacity and for islands.

Integration of members' and experts' feedback

Based on a comparison of cost factors and technology readiness, members and experts attending the PAC scenario workshops and providing feedback suggested a very quick ramping up of electric vehicles and thus an advanced phase-out of fossil oil in road transport.[19]

15 Global Witness: Overexposed: How the IPCC's 1.5°C report demonstrates the risks of overinvestment in oil and gas, April 2019.

16 Transport and Environment: How to decarbonise European transport by 2050, November 2018.

17 Material Economics.

18 In 2015, the non-energy use of fossil oil products in the chemicals industry (707 TWh) is 25 times higher than the direct use for energy supply. In contrast with the latter, fossil oil will remain in non-energy use for the production of raw materials. Circular economy approaches however allow for a phase-out by 2050. In energy statistics, the non-energy use of fossil fuels in the chemicals industry is not accounted with regards to emissions or shares of energy carriers.

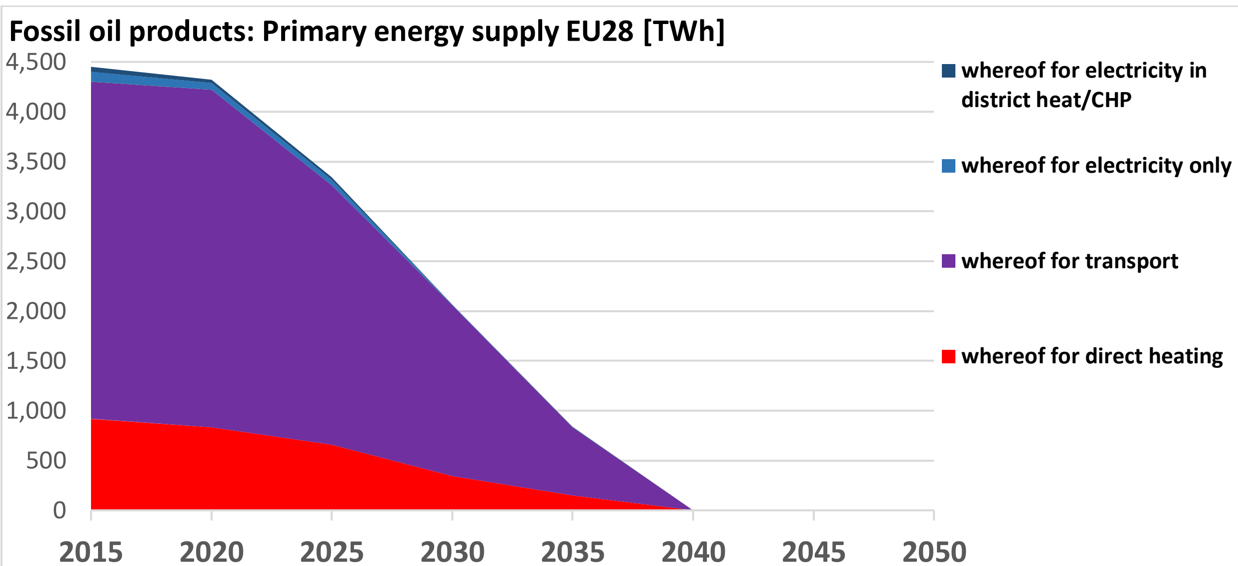
19 CAN Europe/EEB: Summaries of PAC scenario workshops and General Assemblies workshops.

Sensitivities and limitations

The availability of alternatives to fossil oil in aviation is limited to second generation liquid biofuels and liquid synthetic fuels. Their competitiveness has not been assessed in detail. The analysis of economic and regulatory conditions for phasing out the fossil oil product kerosene by 2040 lies beyond the exercise of this first PAC scenario.

Key results

- Fossil oil quickly loses its dominating role in the transport sector by 2035, shrinking to 28% of final energy demand. This is followed by a full phase out by 2040, provided liquid synthetic fuels are scaled-up from the beginning of the 2030s to substitute kerosene in aviation.
- Like in the case of fossil gas, deep renovations quickly squeeze fossil oil out of the supply mix for heating and hot water in buildings. Final energy demand for fossil oil in the residential sector drops by 95% from 2015 to 2035 (-80% in tertiary).
- Phasing out fossil oil in industry is less challenging than leaving fossil gas. It slumps from a share of 8% in final energy demand in 2015 to 2% in 2035.



2.4 Phasing out waste incineration

Key assumptions

- Waste incineration will be phased out by 2040, assuming a 20-year lifetime of incinerators and taking into account a gradual implementation of the circular economy approach and shrinking waste volumes.

Evolution of energy supply

Burning solid municipal waste in waste incinerators for electricity and heat production only plays a minor role in the EU's energy mix.[20] In light of the implementation of the circular economy legislation in the EU, the available residual waste will decline while the biomass share of waste will partly be redirected towards biogas generation or solid biomass CHP at lower investment and operating costs. Electricity generation falls from 48 TWh and gross final heat consumption from 96 TWh in 2015 to zero in 2040. Waste as a solid fuel in industry disappears by 2040.

Integration of members' and experts' feedback

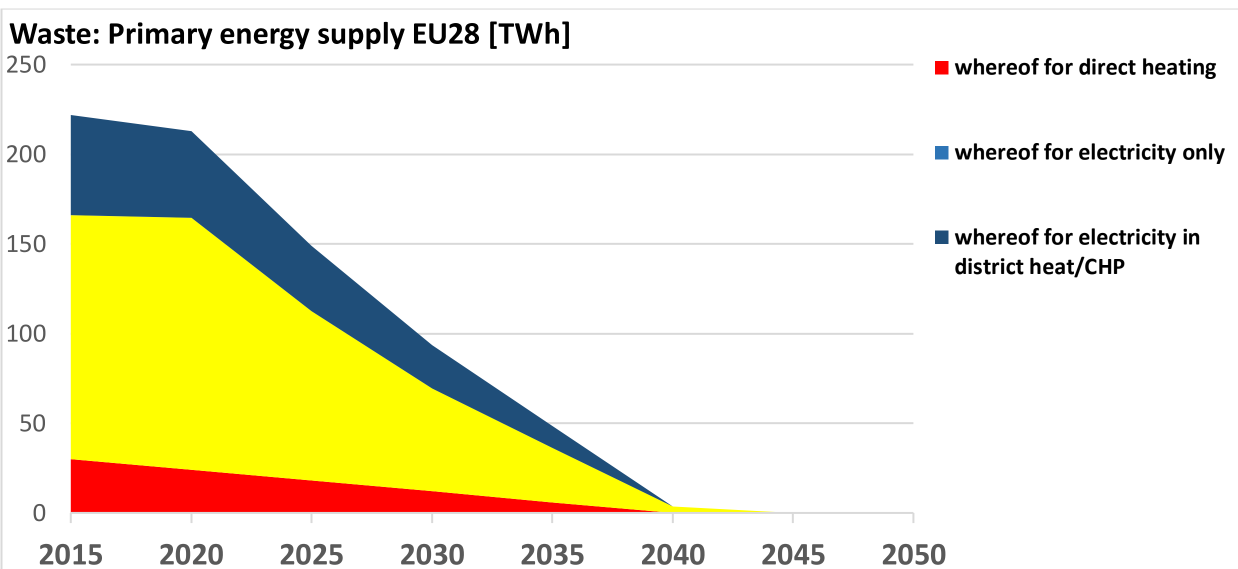
Members and participants of the scenario workshops confirmed the phase-out trajectory for waste incinerators. Keeping a continuously high level of waste demand would undermine targets for higher recycling rates.

Sensitivities and limitations

Poor data quality of installed capacities and operating parameters of waste incinerators need to be improved.

Key results

- The EU continues its circular economy approach, reduces waste and leaves waste incineration by 2040.



20 Eurobserver: Renewable municipal waste barometer, November 2014; ENTSO-E: Transparency platform, November 2019. Given the average biomass share in solid municipal waste, 43% of energy supplied is renewable energy.

2.5 Phasing out nuclear power

Key assumptions

- Newly added capacities are not realistic due to high investment costs and competition of renewables.
- Lifetime is limited to 40 years unless governments and/or operators explicitly announce schedules.
- Increasing costs of maintenance, of the fuel chain and decommissioning incentivise earlier retirements.

Evolution of energy supply

National phase-out plans will be implemented. In countries without such plans, the expected retirement of capacities is based on the country profiles published by the World Nuclear Association.[21] For economic and security reasons, lifetimes are not extended anymore. After 40 years of operation, most capacities are retired as investment in modernisation and maintenance costs are higher than expected income from wholesale markets.[22] Only capacities at an advanced stage of construction will be completed.

Installed capacities in France alone in 2015 exceeded the sum of installed capacities in all other EU Member States. Provisions of the *Programmation pluriannuelle de l'énergie* 2018 (PPE) apply: at least 12 reactors from defined sites will have to be retired between 2027 and 2035 to reduce the share of nuclear power to the legally fixed maximum threshold of 50% of French electricity consumption. Following an option under the PPE, two additional reactors will be retired between 2025 and 2026 as foreseen by PPE in case of oversupply on the European wholesale electricity market. The lifetime of remaining capacities will be mostly limited to 40 years, because after the fourth decennial inspection, further modernisation is economically not viable for the operator EDF.[23]

Electricity generation decreases from 857 TWh in 2015 to 109 TWh in 2040 and disappears by 2045. Only very few capacities built after 2000 remain in the electricity mix between 2040 and 2045, mainly in France and UK.

Integration of members' and experts' feedback

Retirement trajectories were discussed and slightly adapted in exchange with members' national experts.

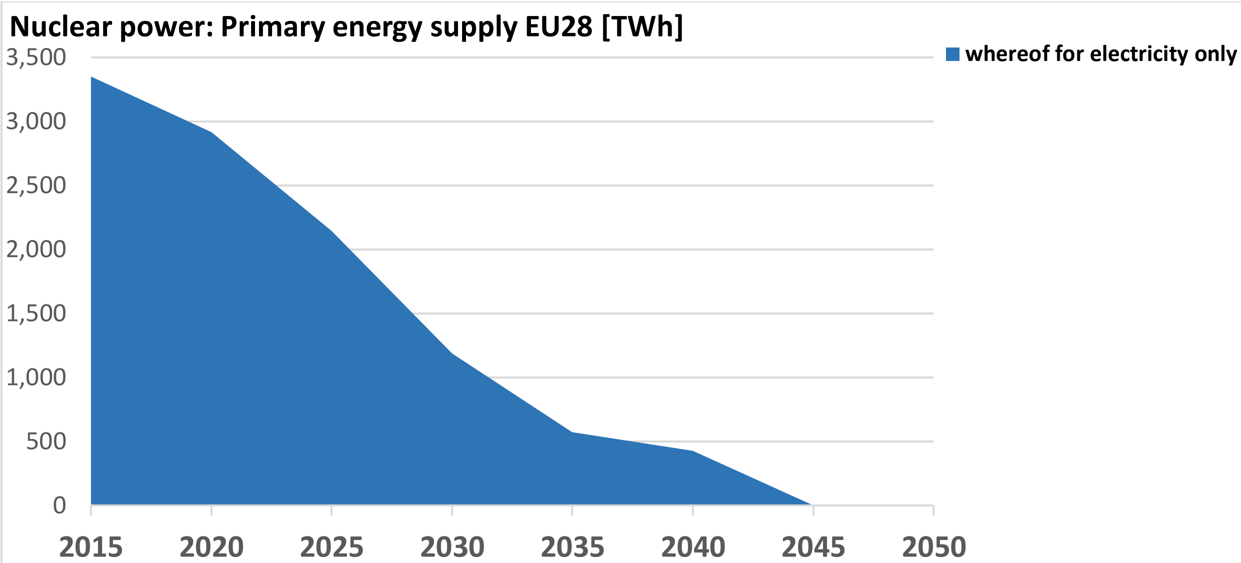
Sensitivities and limitations

Nuclear power is strongly dependent on national policy frameworks and still enjoys direct and indirect subsidies. For countries without clear phase-out plans, governments' commitment to support this technology is crucial.

Key results

- A minority of EU Member States keeps nuclear power in the mix. Except for the few reactors added after 2000, all capacities will be retired by the year 2040.
- Its share in electricity generation drops from 26% in 2015 to 6% in 2030 and remains marginal in 2040.

21 World Nuclear Association: Country profiles, Sept. 2019; https://www.world-nuclear.org/information-library/country-profiles.aspx
22 Öko-Institut: The Vision Scenario for the European Union. 2017 Update for the EU-28, February 2018; Négawatt: Scénario négaWatt 2017-2050. Dossier de synthèse, January 2017.
23 Négawatt.


Nuclear power: Primary energy supply EU28 [TWh]
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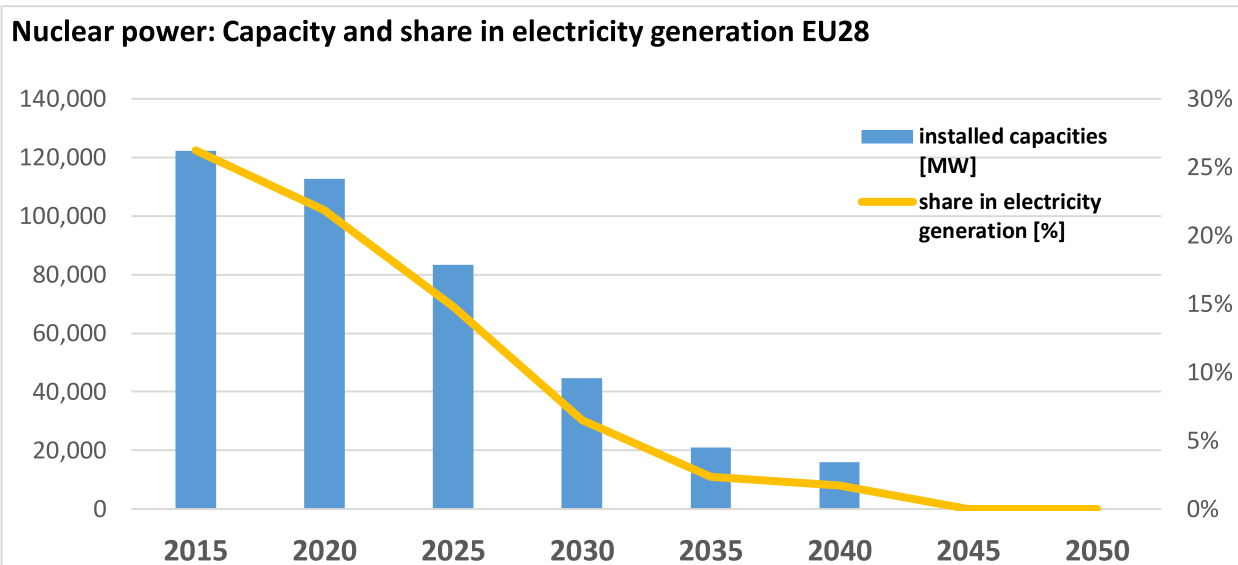
Nuclear power: Capacity and share in electricity generation EU28
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installed capacities [MW]
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2.6 Mobilising bioenergy

Key assumptions

Biomass is an abundant resource with a very limited sustainable potential for energy. Therefore, the PAC scenario implies clear boundaries for bioenergy use:

- In line with EEB's and CAN Europe's principles on sustainable bioenergy use, an increase of forest harvests is excluded. For reasons of forest ecology, areas left out of harvesting increase and a maximum of 70% of residues is available for energy needs. Co-firing and electricity-only use is replaced by cogeneration.[24]
- Only waste and residues with climate benefits and no alternative use feed the biogas production.[25] Due to reduction of waste streams, no substantial increase of available fermentable waste is expected.
- So-called first generation biofuels are phased-out by 2030. Second generation biofuels are limited to aviation and self-consumption in agriculture, with low land footprint and stringent sustainability criteria.

Evolution of energy supply

In order to phase out coal and fossil gas during the 2030s, bioenergy carriers are kept or redirected towards hard to decarbonise industry sectors such as steel, ceramics, cement and glass. Bioenergy steadily covers around 10% of industry's reducing final energy demand between 2015 and 2050. While biomethane supply increases, solid biomass for direct heating in industry is more than cut in half between 2015 (280 TWh) and 2050 (114 TWh). Solid biomass is however shifted towards a non-energy use as raw material input in the chemicals industry (270 TWh in 2050). This allows to substitute fossil oil products in a circular economy approach.[26] In the residential sector, individual heating with solid biomass (15% of final energy demand in 2015) decreases due to energy savings and switching to other more efficient individual renewable heating systems or connection to district heating.

Biogas is mostly used in small CHP units. As a relatively costly but dispatchable energy carrier, they can turn into "gap fillers" to produce more flexibly and offset variable solar and wind. In the 2030s, most biogas is upgraded to biomethane in order to substitute fossil gas in distinct industry sectors' processes that require methane.

Supply of liquid biofuels reaches a peak in 2020 with 278 TWh to strongly slump to 39 TWh in 2050. The dominant use for blending of first generation biofuels in road transport ends with the quick market introduction of electric vehicles. Biofuel use is reoriented towards hard to decarbonise aviation. In addition, by 2030, 30 TWh are self-consumed in agriculture to substitute fossil oil products in farming machinery.

Integration of members' and experts' feedback

Priorities for bioenergy use in different sectors were substantiated and adapted in exchange with members and PAC scenario workshops. This included a gradual phasing out of bioenergy from individual and district heating.[27]

24 CAN Europe, EEB et al.: Pitfalls and potentials. The role of bioenergy in the EU climate and energy policy post 2020. NGO recommendations, April 2015; EEB: Burnable carbon. What is still burnable in a circular, cascading, low carbon economy? June 2017.

25 ICCT: The potential for low-carbon renewable methane in heating, power, and transport in the European Union, October 2018. Sequential crops could be a valuable feedstock for biogas production provided they do not drive unsustainable farming practices.

26 Material Economics.

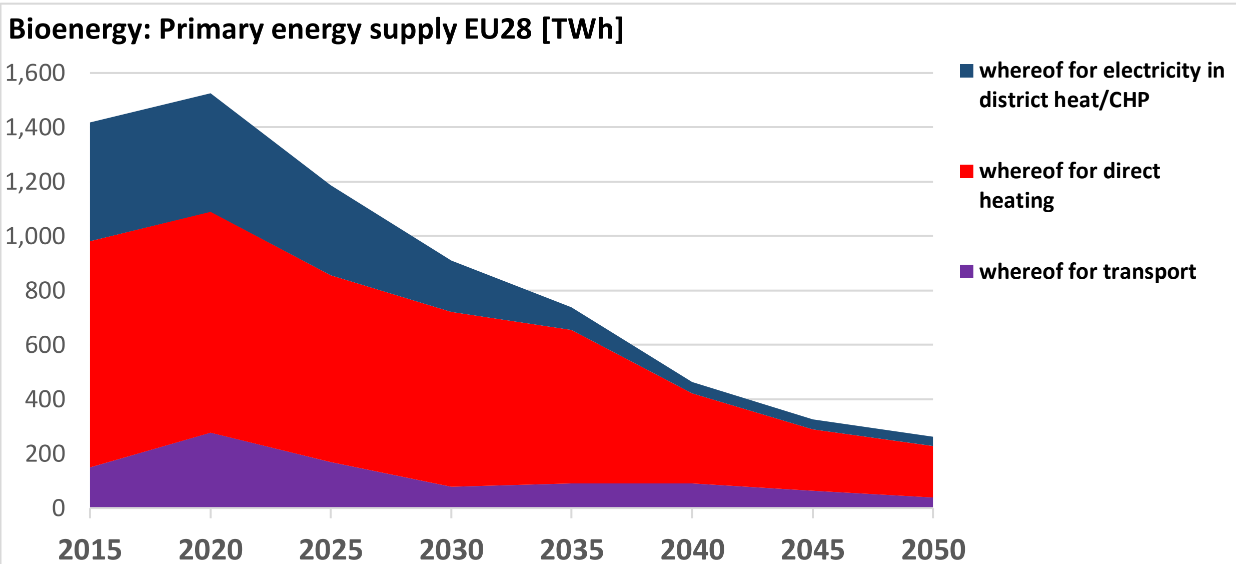
27 CAN Europe/EEB: Summaries of PAC scenario workshops and General Assemblies workshops.

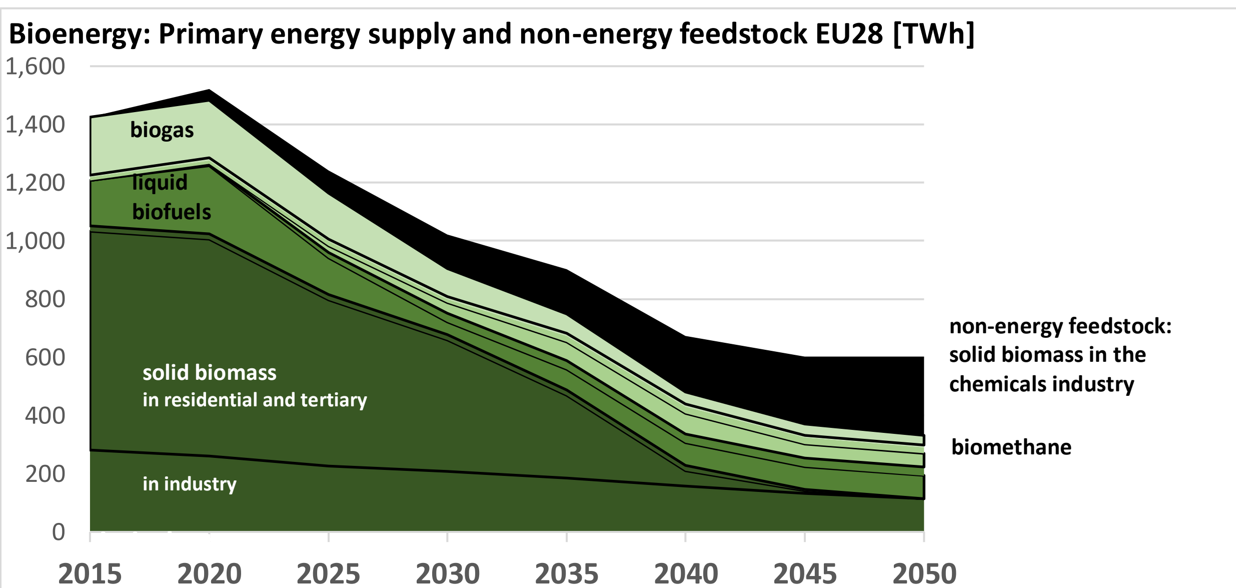
Sensitivities and limitations

The decrease of bioenergy in heating depends on future costs and flexibility needs that are difficult to assess. Deep renovation could offer an opportunity to shift away solid biomass from inefficient individual heating.

Key results

- Primary energy supply of bioenergy decreases by almost two thirds between 2015 and 2050. Its share in primary energy supply falls from 9% to 6% in 2050. If the use of solid biomass as non-energy feedstock in the chemical industry is included, supply still more than halves.
- Bioenergy plays an important qualitative role thanks to its flexible and versatile energy carriers that respond to specific demands of sectors and processes where no renewable alternative is accessible.
- Sustainable bioenergy quantitatively loses in importance but respects the boundaries of its potentials.





2.7 Mobilising solar energy

Key assumptions

- Solar photovoltaic (PV) is the cheapest and easiest to scale up renewable technology. Further decreases in installation costs turn solar self-consumption into a major driver for electrification. The PAC scenario largely takes over assumptions on solar PV potentials from the Energy Watch Group (EWG)/LUT model.[28]
- Solar thermal heat grows less strongly than solar PV. Its shares in district heating play an increasing role. The PAC scenario takes over assumptions on solar thermal potentials from the Heat Roadmap Europe.[29]
- Concentrated solar thermal power (CSP) remains limited to a few southern European countries with sufficient solar irradiation and suitable locations.

Evolution of energy supply

The solar PV electricity generation increases more than ten-fold from 103 TWh equalling a 3% share in electricity generation in 2015 to 1,368 TWh (30%) in 2030. Just after wind energy, it becomes the EU's second electricity source with 2,360 TWh representing 37% of electricity generation in 2040.

Solar thermal heat remains an energy source used for individual heating in the residential and tertiary sector. Building renovation and replacement of inefficient fossil heating systems triggers a switch to solar thermal installations. They double their supply from 25 TWh in 2015 to 58 TWh in 2050. In addition, solar thermal heat is increasingly supplied through expanding district heat networks with a maximum of 21 TWh reached in 2040.

Electricity generation from CSP increases from 5 TWh in 2015 to 17 TWh in 2030 and 24 TWh in 2040. Its contribution to European electricity generation however is marginal and does not exceed 0.5%.

Integration of members' and experts' feedback

In a number of countries short-term market forecasts indicate a slower uptake than projected by the EWG/LUT model.[30] Solar PV growth rates during the 2020s consequently were reduced and further uptake was delayed.

Sensitivities and limitations

Neither the share of ground-mounted solar PV nor its space demand have been assessed more in detail. While environmental risks are negligible, potential synergies and conflicts with agriculture's needs have to be clarified.

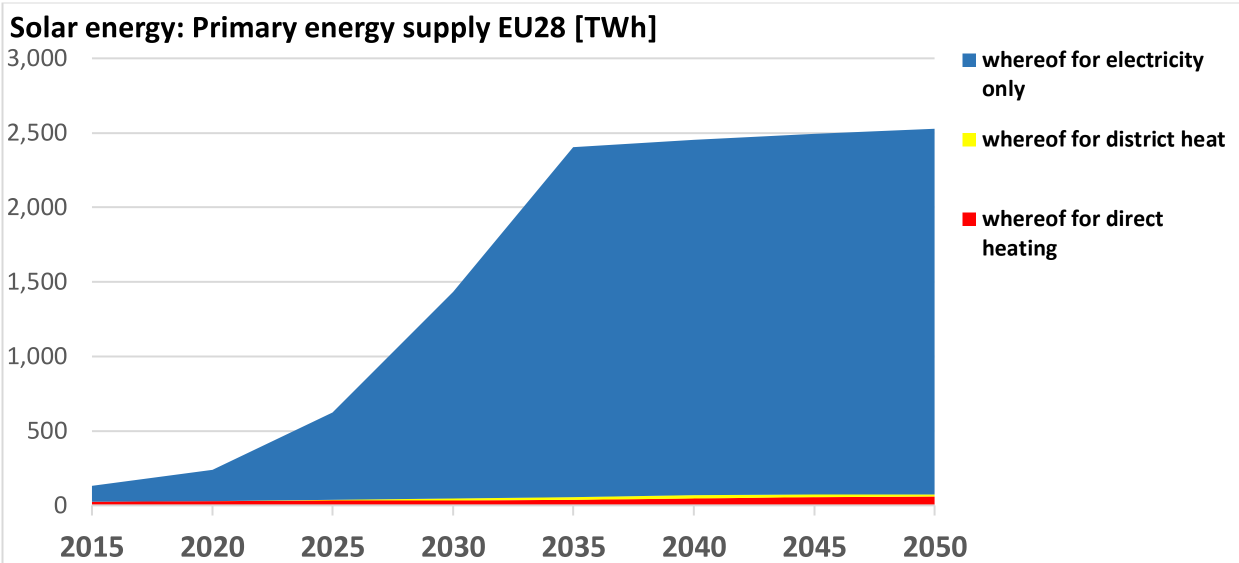
Key results

- Solar PV makes solar energy the second most important electricity source of the PAC scenario by 2030. After a quick ramp-up until 2030, it covers up to 38% of electricity generation in 2050.
- Solar thermal heat supply more than doubles until 2050. It reaches new consumers in the tertiary sector and in industries with low temperature demand thanks to the expansion of district heat networks.

28 EWG/LUT: Global Energy System based on 100% Renewable Energy. Energy Transition in Europe across Power, Heat, Transport and Desalination Sectors, December 2018.

29 Aalborg University: Heat Roadmap Europe 4.

30 Solar Power Europe: Global Market Outlook for Solar Power 2019-2023, July 2019; Eurobserver: PV barometer 2020, April 2020.


Solar energy: Primary energy supply EU28 [TWh]
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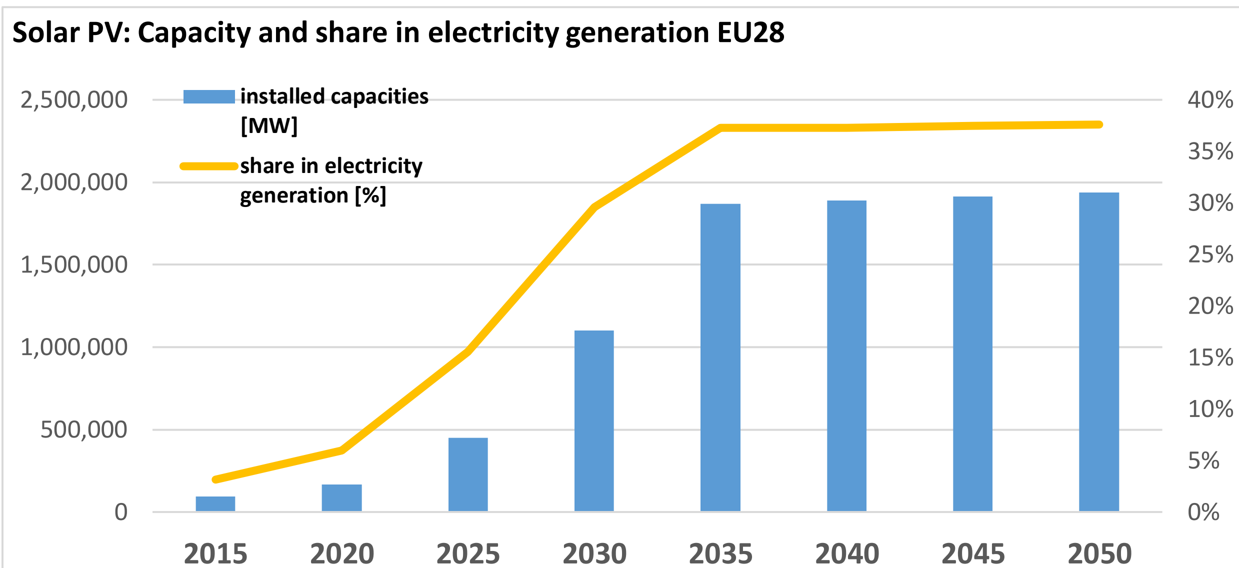
Solar PV: Capacity and share in electricity generation EU28
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installed capacities [MW]
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15%
10%
5%
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2.8 Mobilising wind energy

Key assumptions

- Electricity generated by wind turbines onshore and offshore is one of the cheapest renewable technologies. Further decreases in installation costs make it a driver for electrification. The PAC scenario largely takes over assumptions on onshore wind potentials and capacity factors from EWG/LUT.[31]
- Offshore wind potentials and capacity factors are taken over from BVG Associates and the International Energy Agency (IEA), following the European Commission's estimation of up to 450,000 MW of capacity. The PAC scenario assumes that this potential will partly be mobilised.[32]

Evolution of energy supply

The quick upscaling of onshore wind electricity generation leads to a more than six-fold increase from 267 TWh to 1,829 TWh between 2015 and 2030. The share of onshore wind in electricity generation increases from 8% to 40%. Onshore wind then is the EU's most important electricity source, reaching 2,591 TWh in 2040 (41% of electricity generation).

Offshore wind electricity generation rises even faster from 35 TWh in 2015 to 497 TWh in 2030, equalling an increase from 1% to 11% of electricity generation. Every fifth kilowatt-hour of wind power comes from an offshore turbine in 2030. Offshore wind farms contribute 818 TWh in 2040 (13% of electricity generation).

Integration of members' and experts' feedback

In a number of countries short-term market forecasts indicate a slower uptake of onshore wind capacities than projected by the EWG/LUT model.[33] Growth rates during the 2020s were reduced and further uptake delayed.

Sensitivities and limitations

Novel floating foundation technologies that are not yet introduced in the market allow installations in deeper waters (>70 m) and in areas with sea ice. Such technology innovations could further advance offshore wind shares.

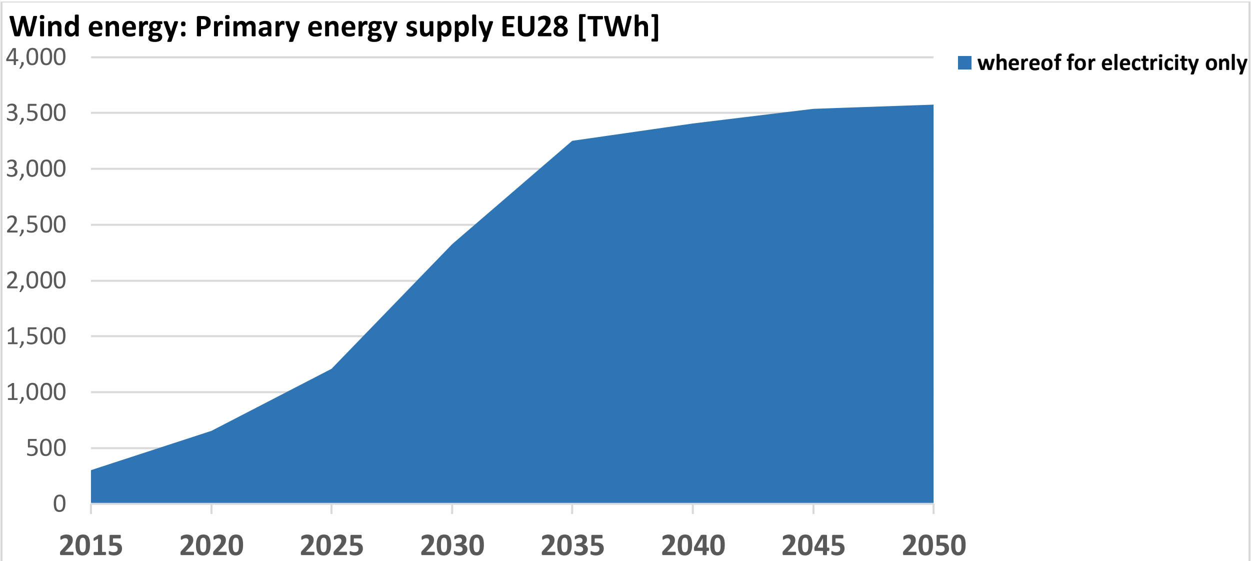
Key results

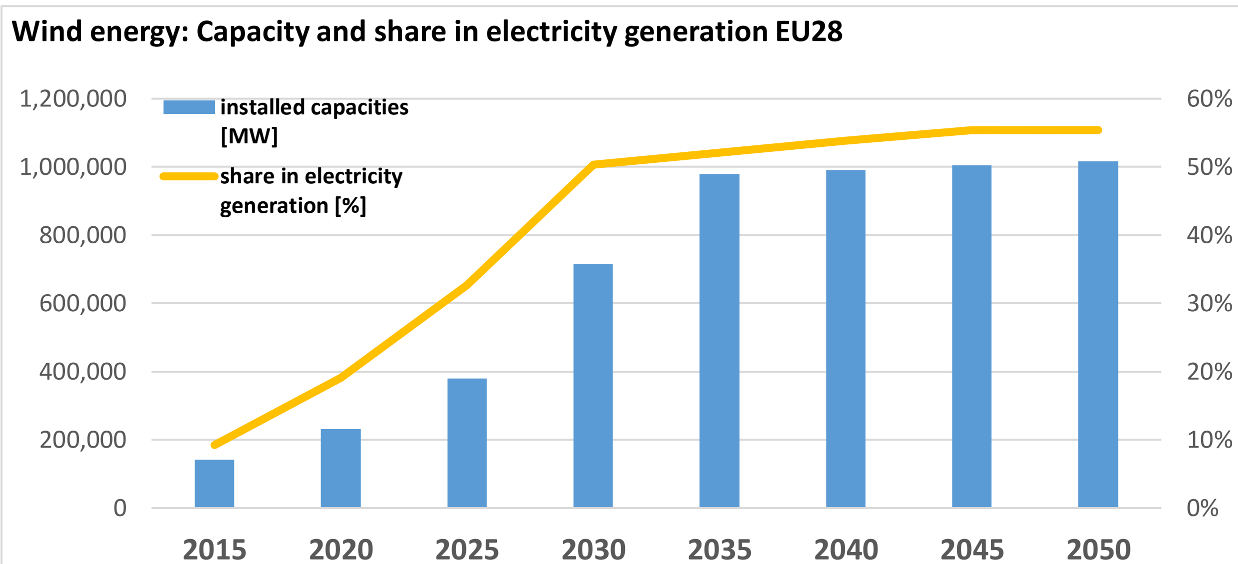
- Due to a speedy multiplication of capacities both onshore and offshore, wind energy becomes the EU's most important source of primary energy supply in 2030 with 2,326 TWh, just before fossil gas and oil.
- If onshore wind capacities are scaled-up according to the PAC scenario trajectory, only a third of the 450,000 MW offshore wind capacity potential needs to be mobilised to make wind energy the most important source of primary energy supply in 2030. A higher offshore wind share is however possible.

31 EWG/LUT.

32 Wind Europe/BVG Associates: Our energy, our future. How offshore wind will help Europe go carbon-neutral, November 2019; European Commission: A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. In-Depth Analysis. COM(2018)773, November 2018.

33 Wind Europe: Wind energy in Europe in 2018. Trends and statistics, February 2019; Eurobserver: Wind energy barometer 2020, March 2020.


Wind energy: Primary energy supply EU28 [TWh]
whereof for electricity only
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
2015
2020
2025
2030
2035
2040
2045
2050


Wind energy: Capacity and share in electricity generation EU28
installed capacities [MW]
share in electricity generation [%]
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
60%
50%
40%
30%
20%
10%
0%
2015
2020
2025
2030
2035
2040
2045
2050

2.9 Mobilising hydropower

Key assumptions

- Capacities of run-of-river, reservoir or mixed hydro[34] power will not increase from 2020 onwards.
- A slight linear increase for all hydro power capacities from 2015 to 2020 is integrated into the PAC scenario to mirror power plants already in construction.
- The PAC scenario assumes a 10% loss in electricity production due to environmental requirements and climate change. Capacity factors are taken over from the EWG/LUT model.[35]

Evolution of energy supply

Even under keeping a constant level of hydropower capacity, its electricity generation decreases. Climate change will affect water availability for hydropower. Depending on the temperature increase, hydropower production in Europe could go down by around 6% under a moderate warming scenario and by 13% under high warming scenarios[36]. Additionally, the implementation of the Water Framework Directive (WFD) through minimum flow requirements and other mitigation measures might affect the overall hydropower production by around 3%[37]. Therefore, the PAC project shows a slight decrease in hydropower production, even with constant capacities.

Integration of members' and experts' feedback

In general, feedback from members and experts has been supportive on PAC scenario's assumption not to increase hydropower capacity beyond 2020. Some EU28 countries have already increased their installed capacity between 2010 and 2015 and are planning additional increase by 2020[38]. Therefore, when possible, figures have been updated with most recent data from Eurostat, and installation rates have been extrapolated until 2020.

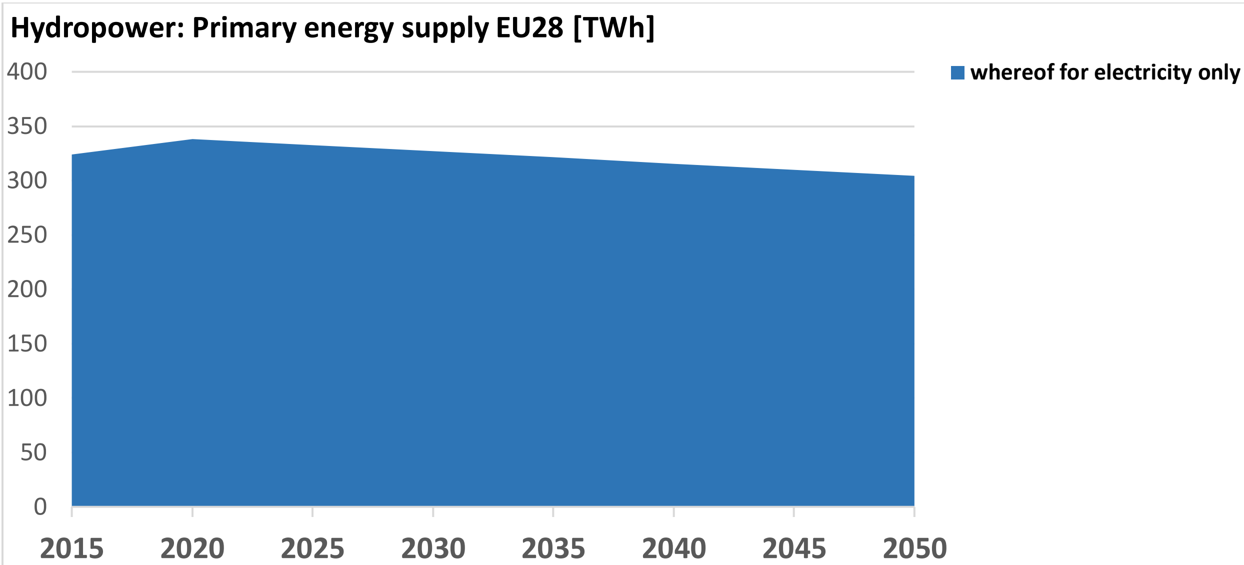
Sensitivities and limitations

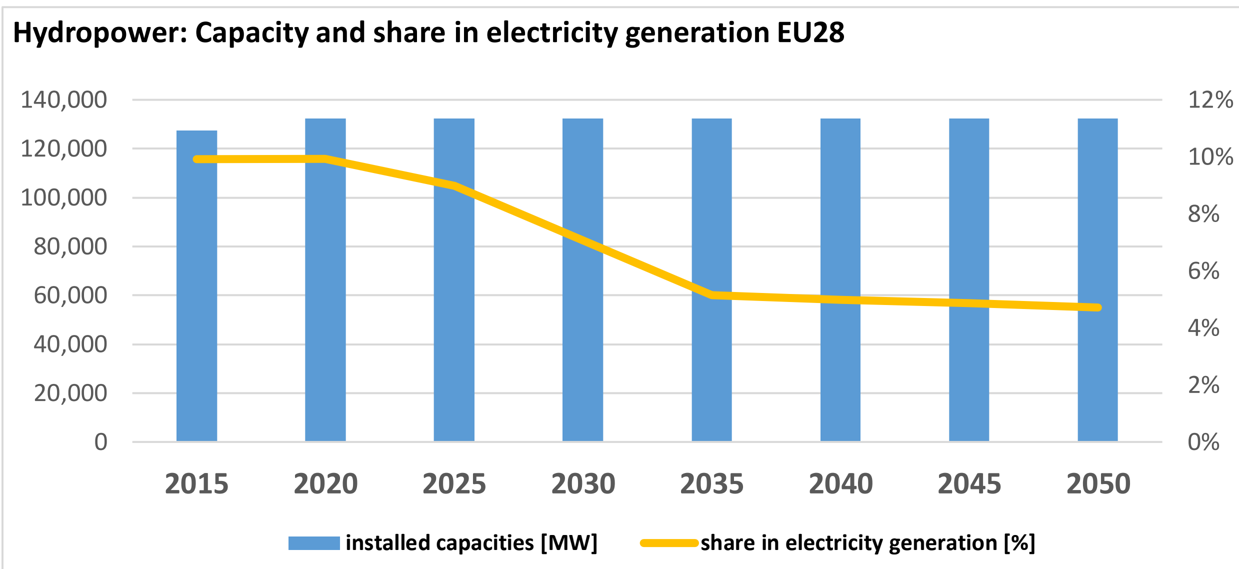
The PAC scenario has chosen deliberately conservative assumptions on new hydropower projects. Actual post-2020 installed capacity might be higher.

Key results

- Unless upgrade of existing facility, no further hydropower expansion happens beyond 2020.
- Hydropower production will drop by 10% due to climate change and environmental requirements.

34 Hydro plants with natural water inflow into an upper reservoir where part or all equipment can be used for pumping water uphill
35 EWG/LUT.
36 COACCH: The economic cost of climate change in Europe: Synthesis report on COACCH interim results, November 2019.
37 Arcadis/Ingenieurbüro Floecksmühle: Hydropower generation in the context of the EU water framework directive, May 2011.
38 ECN: NREAP database, https://ecn.nl/collaboration/nreap/2010/data/index.html.


Hydropower: Primary energy supply EU28 [TWh]
whereof for electricity only
400
350
300
250
200
150
100
50
0
2015
2020
2025
2030
2035
2040
2045
2050


Hydropower: Capacity and share in electricity generation EU28
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
12%
10%
8%
6%
4%
2%
0%
2015
2020
2025
2030
2035
2040
2045
2050
installed capacities [MW]
share in electricity generation [%]

2.10 Mobilising ocean energy

Key assumptions

- Although tidal, wave, ocean thermal and salinity gradient energy are still in their infancy, conditions for market introduction are good. Assumptions are mainly taken over from the European Commission and short-term market analysis.[39]

Evolution of energy supply

The accessible ocean energy potential of 3,360 MW installed capacities is mainly mobilised between 2025 and 2030. Electricity generation reaches 2 TWh in 2025 and multiplies five-fold to reach 10 TWh in 2030. The share of ocean energy in final electricity demand remains marginal with a maximum of not more than 0.2%.

Integration of members' and experts' feedback

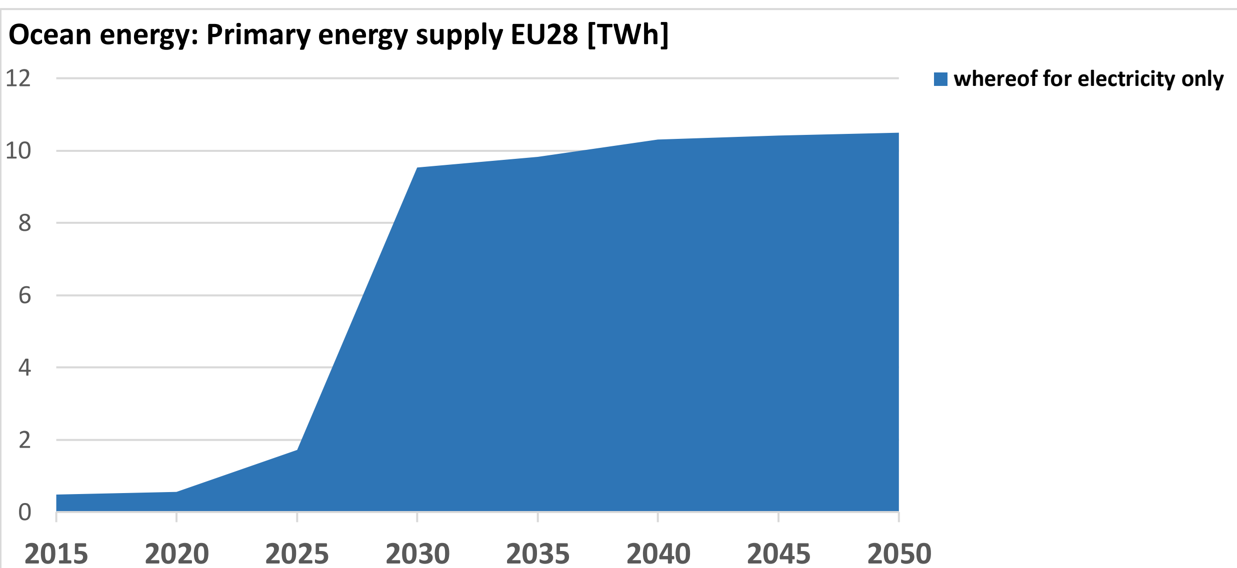
Members and experts from the ocean energy industry confirmed key assumptions of the PAC scenario.

Sensitivities and limitations

Research and industry currently cannot provide robust trajectories for the development of ocean energy capacities beyond the year 2030. In a simplified approach, the PAC scenario assumes that ocean energy technologies until 2050 will continue electricity generation at least on the same level as in 2030.

Key results

- Ocean energy is at the brink of market introduction with a positive outlook. It complements Europe's offshore energy portfolio in the coastal regions but plays a marginal role in European energy mix.



[39] European Commission/Wavec: Market Study on Ocean Energy, May 2018; Eurobserver: Ocean energy barometer, November 2018.

2.11 Mobilising ambient and geothermal energy

Key assumptions

- Ambient heat captured by heat pumps is the key driver for electrification of heating mainly in residential and tertiary sectors. Technology developments also allow an increased share for industries' low temperature processes. Heat pump potentials are based on Heat Roadmap Europe.[40]
- The PAC scenario assumes that 1 kWh of gross heat production from heat pumps entails 0.7 kWh of ambient (aero- or geothermal) heat captured by heat pumps and 0.3 kWh of direct electricity demand.[41]
- In contrast to ambient energy captured by heat pumps, deep geothermal energy potentials are primarily mobilised through cogeneration. The PAC scenario is based on assumptions from the European Technology & Innovation Platform Deep Geothermal (ETIP DG) and the EWG/LUT model.[42]

Evolution of energy supply

Heat pumps that capture ambient (aerothermal and shallow geothermal) energy quickly ramp up their energy supply from 25 TWh in 2015 to 497 TWh in 2030. They become the most important renewable energy supply for heating buildings in the residential and tertiary sectors after 2030, leaving solid biomass behind them.

Deep building renovation induces a steady switch from individual fossil heating systems to heat pumps. They are the first choice for individual heating. However, starting from the middle of the 2020s, a quarter of energy supplied by heat pumps is also distributed through the growing district heat networks. Up to 117 TWh are consumed in industry in 2040, covering 5% of industry's final energy demand.

Deep geothermal energy projects are more difficult and take more time to be mobilised than individual heat pumps. Primary energy supply in 2030 (81 TWh) nevertheless is four times higher than in 2015. Until 2050, supply triples to reach 247 TWh, mainly due to a stronger uptake of geothermal CHP feeding also into district heat networks. Electricity from geothermal CHP plants however only covers a maximum of 2% of final electricity demand by 2050.

Integration of members' and experts' feedback

In a number of countries short-term market forecasts indicate a slower uptake of geothermal electricity generation capacities than projected by the EWG/LUT model. Growth rates during the 2020s were adopted and further uptake delayed.[43]

40 Aalborg University: Heat Roadmap Europe 4.

41 The electricity demand of heat pumps is already included in final electricity demand and not a renewable energy source as such. It is thus not included in the aforementioned numbers. The electricity consumed by heat pumps to harvest the renewable energy source of ambient (aerothermal and geothermal) energy however will have a 100% renewable electricity mix by the year 2040.

42 ETIP DG: Implementation Roadmap for Deep Geothermal, April 2019; EWG/LUT.

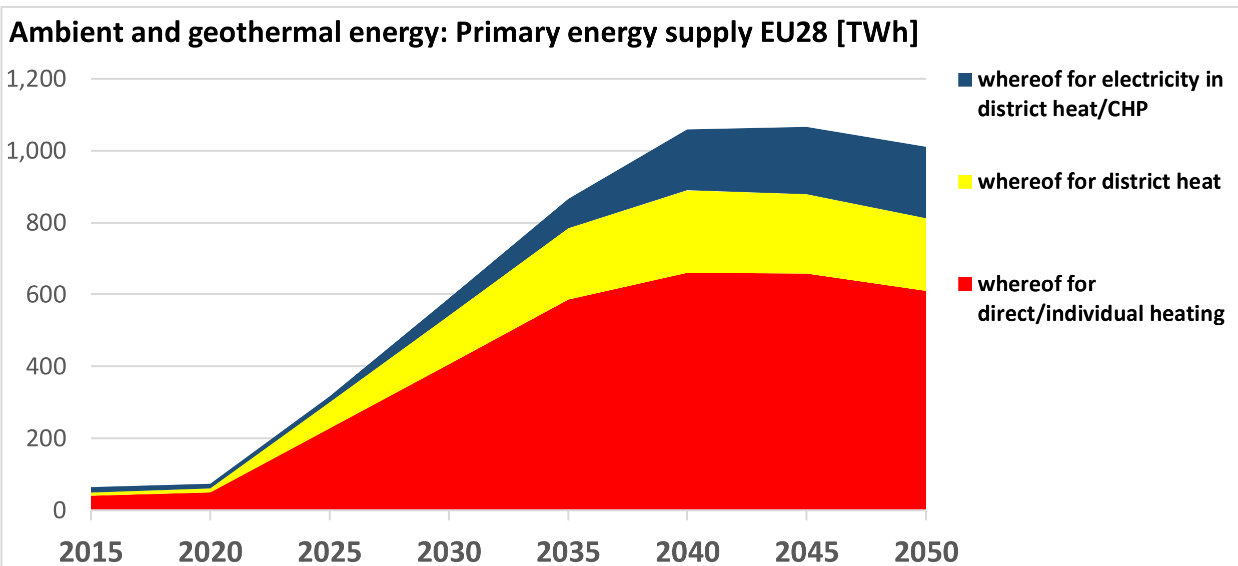
43 Eurobserver: Heat pumps Barometer, Nov. 2018; European Geothermal Energy Council: Geothermal market report, June 2019.

Sensitivities and limitations

Implementing deep geothermal electricity projects in many Member States is still economically relatively risky. Only half of the expected growth of capacities that was projected in the previous 2020 National Renewable Energy Action Plans (NREAPs) has been achieved. Stable support schemes are crucial for the deployment of the trajectories described in the PAC scenario.

Key results

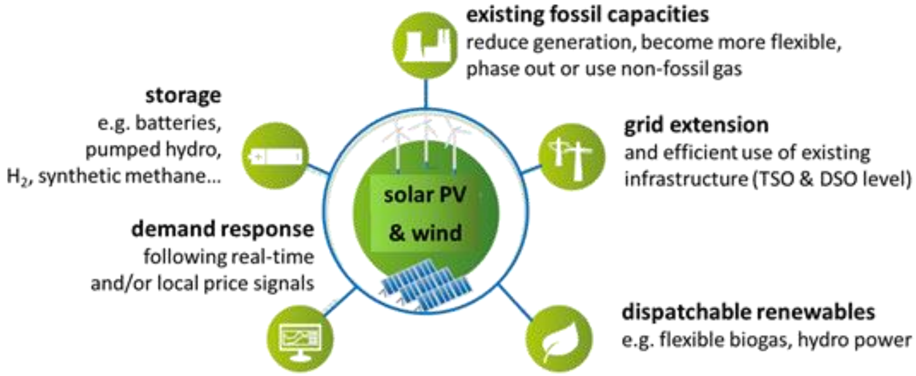
- The deep renovation of buildings presents an opportunity for installing heat pumps as an easy to deploy heating technology. Heat pumps efficiently increase the use of renewable electricity for heating. They cover 15% of gross final heat consumption in 2030 and 54% in 2040.
- It is more challenging to scale up CHP plants and heating stations using deep geothermal potentials. In the PAC scenario, primary energy supply of geothermal energy increases more than ten-fold from 21 TWh in 2015 to 247 TWh in 2050.



Electricity market modelling with different flexibility options

The PAC scenario projects an energy system that largely relies on the variable renewable energy sources solar PV and wind. The higher their share in the energy mix, the more relevant is the assessment of adequacy: Electricity supply needs to meet demand at every moment in time. The interplay of different flexibility options needs to interact smoothly to always guarantee a stable grid and security of supply.

Flexibility options mobilised in the PAC scenario



Graphic: AEE

On an annual base, electricity generation perfectly matches demand. Solar PV installations and wind turbines naturally cannot be dispatched. Their output often varies strongly on seasonal and daily base. Therefore, an hourly modelling is required. For this purpose, PAC scenario data is fed into the PowerFlex electricity market model run by Öko-Institut. It simulates cross-European wholesale electricity markets. In this modelling exercise, the swift expansion of the net transmission capacities of cross-border electricity grids is taken over from the TYNDP 2018 Global Climate Ambition 2040 scenario. The increased cross-border exchange of electricity helps prevent shortages or curtailment. In the year 2030, 63.5 TWh of renewable electricity however cannot be delivered to end consumers. Most excess renewable electricity is used by flexible electrolysers to produce renewable hydrogen (see chapter 2.12).

In addition, other flexibility options help to balance demand and supply in 2030:

- Pumped hydro storage (54 TWh stored and 39 TWh reinjected into the grid in 2030)
- A broad market introduction of ever cheaper solar PV batteries (76 TWh stored in 2030 with 343,108 MW of installed generation capacity) allows to shave peak load and ease the grids through self-consumption. Batteries of electric vehicles were not considered as a flexibility option in this model run.
- Demand side flexibility schemes will incentivise consumers as in industry to shift their demand to those time periods when there is an oversupply. In this PowerFlex model run it was assumed that 5% of any national peak demand could be shifted for one hour.
- A flexible operation of fossil gas fired power plants also contributes to balancing demand and supply. Fossil gas capacities for electricity generation will however continue to decrease and eventually be phased out by 2035. Flexible biogas cogeneration also could contribute as a flexibility option but was not part of this model run.
- Heat networks and flexible power-to-heat could offer additional flexibility but were neither considered in this model run.

2.12 Producing non-fossil gases and fuels

Key assumptions

- Non-fossil gases and fuels are based on hydrogen that is exclusively produced with renewable electricity. In order to respond to specific demands of industry and transport sectors, renewable hydrogen can be converted into renewable ammonia, synthetic methane and liquid synthetic fuels.[44]
- All non-fossil gases are linked with important losses of primary energy input. Efficiencies of electrolysers and conversion processes gradually improve. Levelised costs of renewable hydrogen production however remain relatively high compared to direct electrification and constrain market introduction.[45]
- Against the background of limited potentials and low efficiencies, the PAC scenario restricts the use of non-fossil gases to sectors and processes that cannot use renewable electricity directly and that do not have any alternative to substitute fossil fuels, i.e. to energy-intensive industries and parts of transport.

Evolution of energy supply

Demand for renewable hydrogen firstly occurs in the energy-intensive industry processes that require an energy carrier with high energy density such as steel, chemicals, non-ferrous metals and pulp, paper and printing. By 2030, 6% of industry's final energy demand is covered by 161 TWh of renewable hydrogen. Between 2035 and 2050, renewable hydrogen demand remains stable in these sectors with 320 to 340 TWh, covering 15% of demand. In addition, synthetic methane is introduced to a minor extent to replace fossil gas in certain industry processes such as in cement, ceramics, glass, non-ferrous metals and pulp, paper and printing.[46] In 2030, 37 TWh of synthetic methane are consumed in the industry. Demand doubles to reach 63 TWh to 81 TWh between 2035 and 2050, covering up to 4% of industry's final energy demand.

In the transport sector, renewable hydrogen is scaled up at comparable pace to cover 131 TWh of demand in 2030 (5% of transport's final energy demand), increasing to 250 TWh in 2050 (13% of demand). It is mainly used to substitute fossil oil products in heavy freight where electric drives are not fully deployed, and in fuel cells in mid-distance shipping. In parallel, renewable hydrogen is converted to renewable ammonia for long-distance shipping (maximum of 86 TWh in 2050, 4% of the transport sector's final energy demand).

For aviation, liquid synthetic fuels are the only short-term renewable alternative besides liquid biofuels to phase-out the fossil oil product kerosene. Aeroplanes become the most important consumer of renewable gases and fuels with 192 TWh of liquid synthetic fuels consumed in 2030 (7% of transport's final energy demand), rising to 374 TWh (20% of demand) in 2050, while electric aircraft are firstly used to substitute the use of biofuels.

44 CAN Europe: Position on the use of gas in the future energy system, January 2020. Sustainably sourced biogas and biomethane also are non-fossil gases but covered in chapter 3.6. Hydrogen produced through steam methane reformation with fossil gas currently dominates European hydrogen consumption in industry. In the PAC scenario data, the current fossil hydrogen demand is not disclosed as such explicitly but included in the industry's primary energy demand.

45 ICCT; International Energy Agency: The future of hydrogen, June 2019; Cambridge Econometrics/Element Energy/European Climate Foundation: Towards fossil-free energy in 2050, March 2019; Agentur für Erneuerbare Energien (AEE, German Renewable Energies Agency): Metaanalyse Erneuerbare Gase in der Energiewende, March 2018; Agora Energiewende/Enervis: Power to gas/Power to liquid calculator, February 2018.

46 Material Economics; European Commission: A clean planet for all; AEE: Erneuerbare Energie für die Industrie. Renews Kompakt, June 2017; UK Department of Energy and Climate Change/Department for Business, Innovation and Skills: Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050. Glass, Ceramic sector, Food and Drink, March 2015.

Integration of members' and experts' feedback

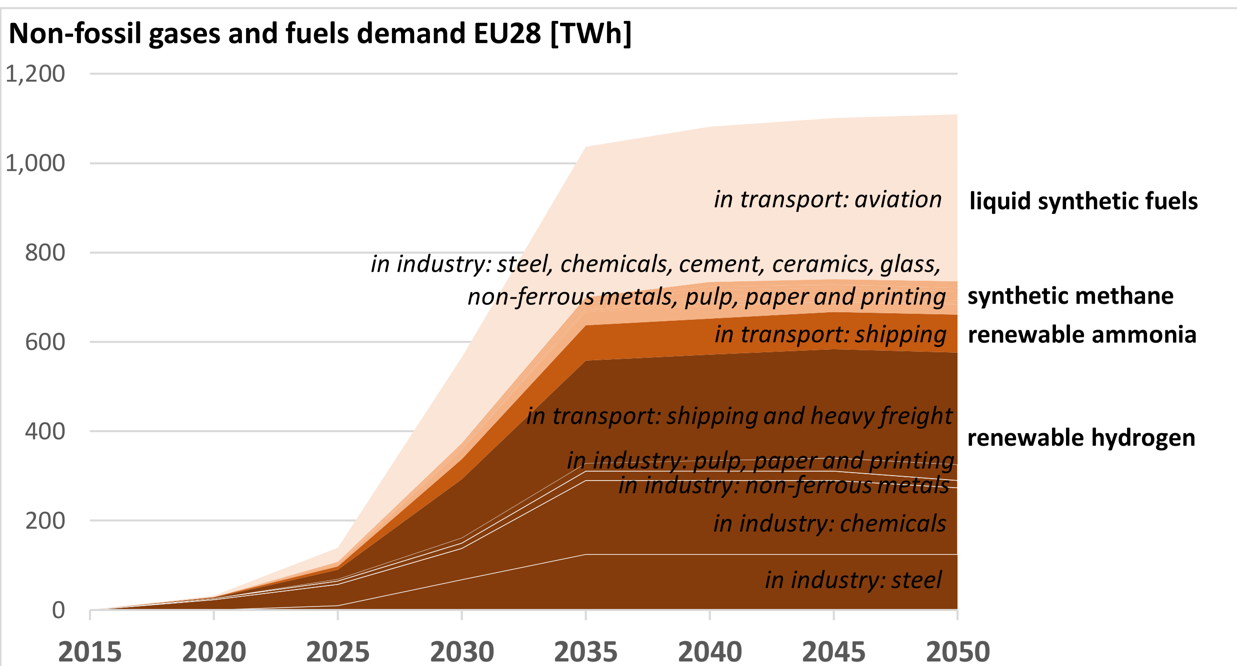
Members and participants of the PAC scenario workshops agreed that, given the availability of more efficient and easier to deploy solutions, non-fossil gases and fuels would not play any role in the residential and tertiary sectors, neither in agriculture. Additional electricity needed for producing renewable hydrogen should come from domestic EU potentials. Imports of renewable hydrogen from beyond the EU should be avoided.[47]

Sensitivities and limitations

Potential imports of renewable hydrogen are not included in the PAC scenario. Depending on costs, infrastructure and policy frameworks, such imports might play a role in the future. A complex set of economic and environmental parameters still would need to be assessed in order to explore its feasibility and desirability.

Key results

- Non-fossil gases have climate benefits only if they are exclusively produced with renewable electricity and replace fossil fuels in distinct demand sectors where there is no other sustainable alternative such as renewable heat or direct electrification with renewable electricity.
- Already during the 2020s, first relevant shares of renewable hydrogen have to be introduced to accompany the phase-out of coal and fossil gas in energy-intensive industries. In view of their poor efficiency, non-fossil gases however will only play a limited role compared to direct electrification.
- Compared to industry, renewable hydrogen, renewable ammonia and in particular liquid synthetic fuels cover a higher share of transport's final energy demand (up to 37% in 2050). Only a very swift and broad scaling up of renewable hydrogen generation allows for the ambitious fossil oil phase out in transport.



47 CAN Europe/EEB: Summaries of PAC scenario workshops and General Assemblies workshops.