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Europe and the race to net zero

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March 2021

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The fast view

- Europe, China, Japan, South Korea and many US states have adopted net zero emissions targets, but there are many paths up this particularly steep mountain. There are different choices to be made, each with different trade-offs, and with different resulting outcomes.
- In this research, we focus on the choices Europe is making. Our method is to draw conclusions about the shape of the system in 2050 from published scenarios derived from several integrated assessment models.
- Europe's destination is clear. It is aiming for a high-renewables, high-electrification outcome, but with a plan to build a hydrogen economy (though not particularly for transportation), and a clear policy choice to use renewable hydrogen. Europe is also heavily incentivising energy efficiency and has seen flat to declining energy demand in recent years. We think of Europe's transition pathway in terms of six key variables:
  - First, there is likely to be a quickening of measures to reduce energy demand in Europe, with scenarios clustering at 0.8%-1.00% per annum. This implies a decline in energy demand in the coming years 10x faster than the average rate of the last three decades.
  - Second, electrification will have to expand significantly. By 2050, net zero scenarios converge on a figure just above 50% of total final demand, up from 19% today.
  - Third, the renewable share of final energy demand, a measure of ambition in pursuing decarbonisation, clusters around 80% in scenarios tending towards net zero.
  - Fourth, the problem of intermittency from variable renewables in Europe can be solved through renewables overbuilding with battery storage, or renewables overbuilding with hydrogen. Europe is going the latter way, which will involve 80% more gross electricity generation relative to the former scenario's 40%.
  - Fifth, carbon capture—both nature-based and engineered options—are used in nearly all scenarios. However, the range of outcomes is vast, and at the median estimate they will account for just 12% of current emissions.
  - Sixth, big decisions have to be made in transport. For passenger vehicles and light commercial vehicles, the path has been set with battery electrification. For heavy trucks, the choices are between battery electrification and hydrogen-based fuels, with the decision on which one to take dependent on institutional factors such as labour laws. Aviation is likely to require fuels, and could be solved by a combination of e-liquids, liquid biofuels, and jet fuels.
- An early comparison of these factors in Europe vs in other regions suggest China is much more likely to rely on demand efficiencies than Europe or the US, while also relying on nuclear to solve the problem of variability. The US is likely to rely most on carbon capture, while also the most likely to keep a role for hydrogen from natural gas with carbon capture. In all cases, Europe, China and the US need to get renewables to over 80% of final energy demand by 2050 to reach net zero.

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As is well known, European countries were the first to commit to legally binding net zero targets. In 2017, Sweden committed to achieving net zero by 2045. In 2018, the UK became the first G7 country to do the same, by 2050 this time.[1] In 2019, those initiatives broadened out into the European Commission announcing its Green Deal, which targets net zero by 2050.

Since then, the rest of the world has joined in. In September 2020, China announced a net zero by 2060 pledge; Japan and South Korea followed with 2050 targets in October. The US has been a notable laggard, but clearly President Biden and a Democratic Congress can do much to reverse the inaction of the last administration. In any case, individual US states have been more proactive. In 2018 California Governor Jerry Brown signed an executive order for a net zero emissions target by 2045.

In other words, the global race towards net zero is on. Much in the same way that countries mobilised for 'total war' in the mid-twentieth century, societies, economies and energy systems are on the cusp of an energy transformation as they are reconfigured or built for a world in which nearly all emissions need to go. There was a moment in the early days of the COVID-19 pandemic when the question was raised whether the current crisis would distract from the decarbonisation agenda. In fact, COVID-19, as perhaps the most simultaneous, synchronised crisis in history, one felt in every corner of the world at more or less the same time, has only reinforced the threat posed by long-term vulnerabilities such as climate change. Climate change, of course, is the ultimate crisis of the Anthropocene, the period when human activity is not just leaving a mark on the physical world, but that may eventually overwhelm it. The crisis is of our own making, but clarifying the net zero pathways is the only way they are going to be solved.

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1. Evans, S., In-depth Q&A: The UK becomes first major economy to set net zero climate goal, Carbon Brief, 12 June 2019.

view

The Paris Agreement and net zero

'Net zero' means reducing global emissions of carbon dioxide (CO_2) to zero either by eliminating CO_2 emissions altogether or by removing CO_2 from the atmosphere. 'Net zero' is easier than 'actual zero' because activities that remove emissions from the atmosphere may eventually be able to cancel out stubborn emissions that are difficult to be rid of.

Net zero targets are crucial if we are to avoid our current trajectory towards 3°C warming by 2100 from pre-industrial levels (defined as 1850-1900), a temperature rise consistent with major environmental, social and economic problems.[2]

Despite the ongoing political mobilization to satisfy the 2015 Paris Agreement targets, they are in fact already insufficient to meet the 'well below 2°C target.' Instead, Paris targets are 'consistent' with pathways resulting in 3°C warming by 2100. According to the Intergovernmental Panel on Climate Change (IPCC), the Paris targets would not limit warming to 1.5°C even if supplemented by very ambitious emissions reductions after 2030.[3] In any case, as of 2019, no major country was meeting its Paris Agreement targets.

What needs to be done instead? To have a two-thirds chance of keeping temperature rises below 2°C this century, the consensus is that the world needs to reduce global emissions by at least 50% by 2050 compared to 1990 levels, and to aim for near net zero by 2100.[4] Needless to say, limiting warming to 1.5°C would require even stronger action. In either case, advanced economies will have to contribute more than the average reduction in these scenarios. The accumulated stock of carbon determines the extent of climate change, and the advanced economies have simply been at it for longer.

In Europe's case, reaching the 'below 2°C' target requires reducing emissions by 80%-95% by 2050 from 1990 levels. Those are the existing objectives for advanced economies as a group, according to the IPCC.[5] To meet a 1.5°C target, the EU would need to reduce emissions by 90%-96% by 2050.[6] Either way, the emissions have to reduce substantially, with negative emissions technologies removing substantial amounts of CO_2 in the latter years of the century.[7]

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2. Lieven, A., Climate Change and the Nation State: The Realist Case, Allen Lane, 2020, p. 2-34.
3. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 14.
4. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 15.
5. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 17.
6. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 17.
7. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2020, p. 17. Such scenarios rely heavily on net negative emissions later on in the century to remove actively CO_2 emissions from the atmosphere.

> Decarbonisation is the goal, but there are many paths up this particularly steep mountain. Countries and regions will differ in the manner and speed in which they approach the summit. There are different trade-offs, with different resulting outcomes.

In this research, we focus on the choices being made in the EU. Given the rich studies that have been commissioned within Europe, our method is to use existing scenario analysis from various integrated assessment models produced by energy system modelers and draw some conclusions about the shape of the energy system in 2050. At the end, we also briefly compare this to the choices being made in China and the United States.[8]

More specifically our method is as follows:

- We set out six key variables that will determine the net zero transition pathway.
- Then we introduce some baseline outcomes by providing forecasts from the International Energy Agency (IEA) World Energy Outlook 2020 and sometimes the BP Statistical Review of World Energy 2020 forecasts.
- We then examine the commitments made in the European Commission strategic plan for climate neutrality. This is the impressively clear and comprehensive 25-page communique from November 2018 titled 'A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy'[9]
- This document was itself backed up by a 393-page document of supporting evidence, detailing eight internally generated decarbonisation scenarios, with different emphases on various technologies, all of which are consistent with 80% emissions reductions by 2050, but only two of which are consistent with net zero.[10]
- Finally, we refer to 'Towards net zero emissions in the EU energy system by 2050,' published in 2020 by the European Commission's Joint Research Centre, the Commission's internal think tank on science-related issues. This is an analysis of 16 internal and external scenarios that reach net zero by 2050. Two scenarios from the Commission's 2018 strategic plan (the internal scenarios in the previous point) are included. The rest are from external groups like the IEA, International Renewable Energy Agency, and the European Climate Foundation.

There are several variables why chosen pathways might look different in different regions.

First, the demand side may grow more or less than expected. There are decisions to be made on incentivising energy efficiency and changing consumption patterns that, if successful, would cause energy demand to decouple from economic activity. On the other hand, if on the supply side, energy can be completely decarbonised, these savings from the demand side become much less valuable. According to the Intergovernmental Panel on Climate Change, scenarios limiting warming to 1.5°C require primary global energy demand to decline by -0.5% p.a. to 2050, with a maximum and minimum range of -0.51% p.a. and 0.48% respectively.[11]

Second, what is the likely level of electrification, and more generally what are the energy carriers of the future? An energy carrier is something that can deliver energy in a usable form. For instance, electricity is an energy carrier, while coal and oil are both energy carriers and forms of energy storage. Net zero will require a vast increase in electrification, but hydrogen generated from electricity (which may then be used to produce e-fuels[12]) is also a potential solution, at least for the most difficult-to-decarbonise processes.

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8. Rogelj, J, Shindell, D., Jiang, K., et. al., 'Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development', Global Warming of 1.5 °C, The Intergovernmental Panel on Climate Change, 2018. p. 100.
9. A clean planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018.
10. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018.
11. Rogelj, J, Shindell, D., Jiang, K., et. al., 'Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development', Global Warming of 1.5 °C, The Intergovernmental Panel on Climate Change, 2018. Tables 2.6 for energy demand, p. 132.
12. E-fuels are synthetic fuels, resulting from the combination of 'green or e-hydrogen' produced by electrolysis of water with renewable electricity and CO_2 captured either from a concentrated source (e.g. flue gases from an industrial site) or from the air (via direct air capture, DAC). E-fuels are also described in the literature as electrofuels, power-to-X (PtX), power-to-liquids (PtL), power-to-gas (PtG) and synthetic fuels.

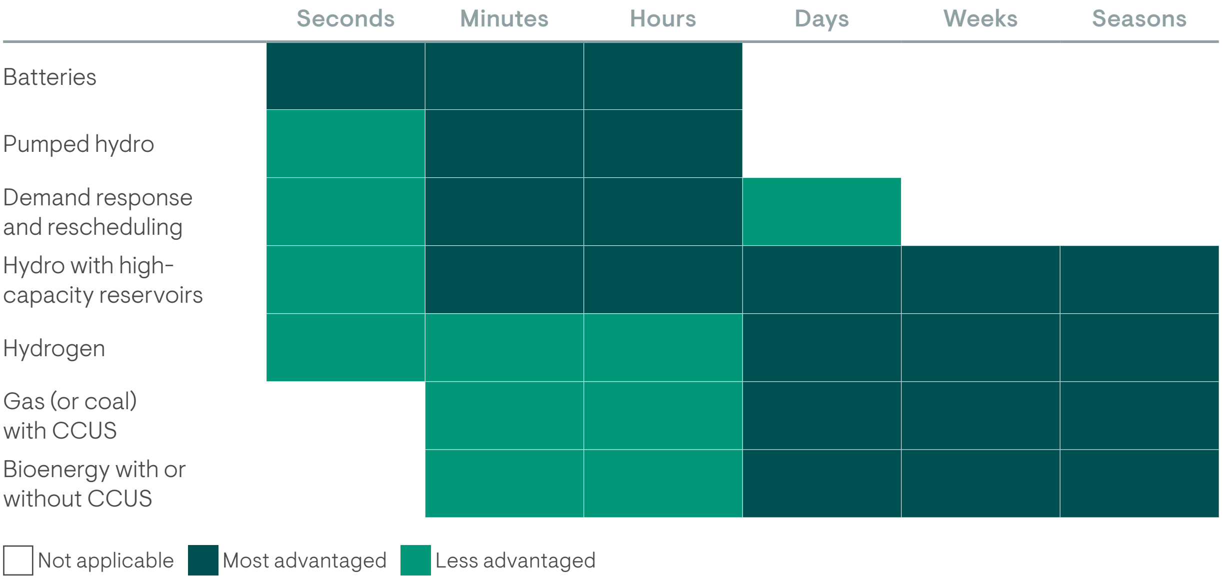
According to the Intergovernmental Panel on Climate Change (IPCC), scenarios limiting warming to 1.5°C see electricity covering 34%-71% (minimum-maximum range) of final energy by 2050, up from about 20% in 2020.[13]

Third, what will be the renewable share of final demand by 2050? This simple number is important simply as a shorthand for the level of ambition and speed that each region is aiming for net zero in the decades ahead. The IPCC report says that in 1.5°C degree scenarios, renewables supply 52%-67% (interquartile range) of final demand by 2050. Coal declines to 1%-7%.

Fourth, what is variable renewable energy's share of electricity production? All net zero pathways require, at the very least, zero-carbon electricity generation, but that can be achieved in two main ways: a high share of variable renewables or a high share of controllable renewables like nuclear and hydropower. If a decision is taken to avoid nuclear energy, then how do energy systems grapple with the variability of wind and solar?

Countries then have a further two choices. They can solve the problem by either a massive renewables overbuilding and some use of battery storage on a timeframe of seconds, minutes, or hours. Or they can pursue a massive renewables overbuilding in the service of hydrogen and e-fuels, which also provide storage, but on a timeframe of days, weeks, and months (see Figure 1). Depending on the choice taken, more or less electricity generation capacity will be required.

Figure 1: Technologies to help balance power systems at different durations



Source: BP Global Energy System at net zero.
https://www.bp.com/en/global/corporate/energy-economics/energy-outlook/net-zero.html

The IPCC report doesn't put a target for variable energy, but it does say that in scenarios limiting warming to 1.5°C, the share of electricity supplied by renewables has to be between 59%-97% (minimum-maximum range) by 2050.

Fifth, to what extent are carbon capture and other negative emissions options a significant driver of emissions reduction?

There are a number of so-called negative emissions options, or actions that remove CO_2 from the atmosphere. Most 1.5°C and 2°C pathways are heavily reliant on negative emissions options at a speculatively large scale before mid-century. There are several knowledge gaps associated with such technologies, and the range of outcomes is large. Effectively, the biggest plug in every country's net zero model is negative emissions from new and untested technologies.

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13. Rogelj, J, Shindell, D., Jiang, K., et. al., 'Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development', Global Warming of 1.5 ºC, The Intergovernmental Panel on Climate Change, 2018, p. 97.

Negative emissions options can roughly be divided into nature-based negative emissions options and engineered negative emissions options. Nature-based options include afforestation and reforestation, soil carbon sequestration, blue carbon habitat restoration, and biochar.[14] Engineered negative emissions options include Bio-energy and Carbon Capture and Storage (BECCS), enhanced weathering, Direct Air Capture and Storage, and ocean fertilisation.

According to the Intergovernmental Panel on Climate Change (IPCC), the overall deployment of BECCS, which excludes carbon sequestration by land use, land use change and forestry, or by fertilisation of oceans— and other negative emissions technologies vary widely across 1.5°C pathways with no or limited overshoot, with global cumulative CO_2 stored through 2100 range from 260GtCO_2 up to 1170 GtCO_2 and the median clustering at 770 GtCO_2 (5th-95th percentile range).[15] Timing also matters. If used in the first half of the century, it neutralises some of the ongoing carbon emissions and therefore slows the accumulation of carbon dioxide in the atmosphere. If used in the second half of the century, after carbon neutrality has been achieved, it is less useful but can also contribute to returning the climate to a 1.5 degree warming level. To the extent that negative emissions options are successful, the outcome of the energy system would be less constrained.

Six, the transition to net zero crucially depends also on how key end-users of energy adapt. Transportation, for instance, is the key sector in developed economies, where it has overtaken power as the biggest source of emissions in recent years. It currently accounts for 16% of total CO_2 emissions globally.[16] Moreover, whereas most energy models are optimistic about the decarbonisation of industrial sectors, they are less so about transport and buildings.[17]

Fully decarbonising transportation will likely require zero carbon ground transportation. That can be done through battery storage or hydrogen. For passenger vehicles and light commercial vehicles, to a large extent the decision has been made with most auto manufacturers already fully invested in electrification. But for heavy trucks it could go either way, with arguments on both sides. To some extent the answer is dependent on the decision taken on the electricity grid (which is actually the way with many of these net zero choices, in which solutions to one part of the problem inform approaches taken in other areas). If there is already significant hydrogen infrastructure, then it will be easier to use hydrogen rather than electricity for trucks. For aviation and shipping, the options are much less clear and the decisions pushed much further out. According to the IPCC report, the share of low-carbon fuels in the total transport fuel mix increases to 40%-58% by 2050 in pathways just overshooting 1.5°C.[18]

Those six factors do not cover everything, of course. For instance, there are difficult-to-decarbonise sectors like agriculture, steel, cement that realistically will not be addressed for a decade or so. Nevertheless, getting a grip on the basic choices underpinning the energy transition is crucial if we are to appreciate the sheer scale of the transformation before us. Understanding these factors will give a clearer picture of what the core building blocks of the future energy system look like.

Of all the regions, Europe has given us the most detail on its chosen pathway.

Europe's destination is clear. It is aiming for a high-renewables, high-electrification outcome, but with a plan to build a hydrogen economy (though not particularly for transportation), and a clear policy choice to use renewable hydrogen ('green hydrogen')

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14. Planting trees is the most cost-effective negative emissions options, according to Aurora and UBS. Yet it is not a straightforward task and less scalable than initially looks. For instance, the rehabilitation of China's Loess Plateau is one of the most impressive ecological rehabilitation projects anywhere in the world. One of the main reasons why is that a group of experts from various backgrounds —national development specialists, ecologists, urbanists, community development specialists, sociologists—all worked together, and for two years all they did was interview community members. More recent Chinese afforestation initiatives, like that in Inner Mongolia's Uxin Banner, prioritised fast-growing monocultures like poplars, the deep roots of which reduced the water table and contributed to desertification. Li, Y., Shapiro, J., China Goes Green: Coercive Environmentalism for a Troubled Planet, Polity, 2020.
15. Rogelj, J, Shindell, D., Jiang, K., et. al., 'Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development', Global Warming of 1.5 °C, The Intergovernmental Panel on Climate Change, 2018, Chapter 2, p. 40.
16. Ritchie, H., and Roser, M., 'Emissions by Sector,' Our World in Data.
17. Rogelj, J, Shindell, D., Jiang, K., et. al., 'Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development,' Global Warming of 1.5 °C, The Intergovernmental Panel on Climate Change, 2018, p. 137.
18. Rogelj, J, Shindell, D., Jiang, K., et. al., 'Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development,' Global Warming of 1.5 °C, The Intergovernmental Panel on Climate Change, 2018, p. 143.

rather than hydrogen from natural gas with carbon capture ('blue hydrogen'). For the EU, thinking of green hydrogen as a core building block as opposed to blue hydrogen makes sense because Europe relies on imported gas. For other countries it will be different—for example in the UK hydrogen investments have focused on blue hydrogen.[19] Europe is also heavily incentivising energy efficiency and has seen flat to declining energy demand in recent years.

Europe is not and has never been one homogenous thing, of course. There are major differences, with the French clearly favouring a high nuclear scenario, the now-departing UK on the fence, and every other country phasing nuclear out. Nevertheless, it is useful to think of the EU as a whole given the strong coordinating role played by the European Commission on policy.

Europe is not and has never been one homogenous thing, of course

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19. Bounds, A., 'Hydrogen project aims to drive UK transition to a low-carbon economy,' Financial Times, 13 January, 2021.

What is Europe's Green Deal?

The Green Deal is an umbrella of tax, spending, and regulatory initiatives pursued during the course of Ursula von der Leyen's European Commission presidency. In summary:

- The EU climate target: In September 2020, the European Commission proposed a plan to revise the EU-wide target for emissions reduction, potentially to 50% - 55% below 1990 levels by 2030.
- The EU recovery plan: The European Commission proposed a €750 billion recovery fund this May. The European Commission will work with European Parliament and Council to agree a future long-term framework and sectoral programmes by early autumn. The new long-term budget will be up and running early 2021.
- Taxation: The carbon border tax adjustment mechanism aims at shielding energy-intensive industries against cheaper imports from countries with less strict climate policies. The revision of the Energy Tax Directive should overhaul the way in which energy products are taxed in the EU. Adoption of both are planned to be in the second quarter of 2021.
- EU Emissions Trading System (ETS) Reform: Reform of EU ETS phase 4 will be implemented in 2021. If the 2030 emissions reduction target is increased, it will be translated to a higher ETS target. Potential carbon border tax will be linked to the price in ETS.
- EU Taxonomy: EU Taxonomy is a classification system for sustainable activities. Its performance thresholds will help grow low-carbon sectors and decarbonise high-carbon ones. The European Commission will establish screening criteria by the end of 2021. The first company reports and investor disclosures using the Taxonomy are due in 2022.
- Other EU Green Deal initiatives: Proposed EU Green Deal strategies including the Circular Economy Action Plan, the 'farm to fork' strategy, and the EU Biodiversity Strategy for 2030 may be adopted in 2021.

What is Europe's Green Deal?

> Let us address each of the six factors that will determine Europe's chosen pathway.

First, Europe faces a slow-growing to falling population. As a mature, energy-poor economy, it has also been at the forefront of incentivising energy efficiency to reduce demand. Therefore it has seen flat to declining energy demand for many years, unlike the US and China. This is likely to continue.

The baseline forecasts from the International Energy Agency Sustainable Development Scenario, which assumes Paris agreement targets are met, show European Union final energy consumption falling by -1.5% annually by 2040 relative to -0.4% in the Stated Policies Scenario, which envisions the energy landscape in the future if current policy ambitions are realised. The gap in fuel required between these two scenarios is vast—the former scenario requires a full 11% less primary energy in 2040 than the latter. To put this in perspective, the 119 GW absolute numbers between those two figures is three-fifths of the EU's current nuclear power output.[20]

According to the BP net zero scenario—which uses a slightly different primary demand figure, rather than a final consumption figure[21]—achieving net zero by 2050 implies Europe achieving a -1.1% decline in energy demand a year by 2040 vs the -0.1% annual rate achieved from 1995-2018—in other words, a quickening of energy demand reduction by over 10 times relative to the last three decades.

Broadly, energy demand can reduce due to increased energy efficiency (e.g. improving the conversion efficiency of a technology), systems efficiency (e.g. circular economy), and/or end-use efficiency measures (renovation of the building stock).

Efficiencies are an important component of getting to net zero, but we should never overstate their possibilities. After all, global energy intensity—a measure of the amount of energy required to generate one unit of output—has increased by a third since 1990, yet global primary energy demand has risen by 60% in the same period.[22]

The 2018 strategic plan from the European Commission, which includes eight Commission-generated scenarios, found a range of final consumption energy demand declines, ranging from 0.8% to 1.4% per year between 2005 and 2050.[23] The least demand reductions were achieved in scenarios with alternative zero-carbon/carbon neutral energy carriers (e.g. hydrogen and e-fuels).

In the 2020 meta-analysis from the European Commission Joint Research Centre of 16 internal and external net zero scenarios, the range of outcomes of demand-side reductions is similarly large, though like the BP numbers they cluster just around 1% p.a. Specifically, the meta-analysis suggests that the reduction in final energy between 2017 and 2050 was anticipated at between 30-60%, with the majority of the scenarios clustering between 30% to 38% (8 out of 16 scenarios). That implies a CAGR reduction of final demand of 0.80% to 0.98% per annum.[24]

To conclude this section, whether you look at primary consumption/demand or final demand/consumption, there is likely to be a substantial quickening of measures to reduce energy demand in Europe. Demand reduction is a big part of Europe's strategy for achieving net zero. Net zero scenarios to 2050 probably require European energy demand to fall between 0.80% and 1.00% per annum. That is lower than some of the more ambitious forecasts, which extend to 1.5% per annum. Nevertheless, even 1% would imply a decline in energy demand in the coming years around 10 times faster than the average rate of the last three decades.

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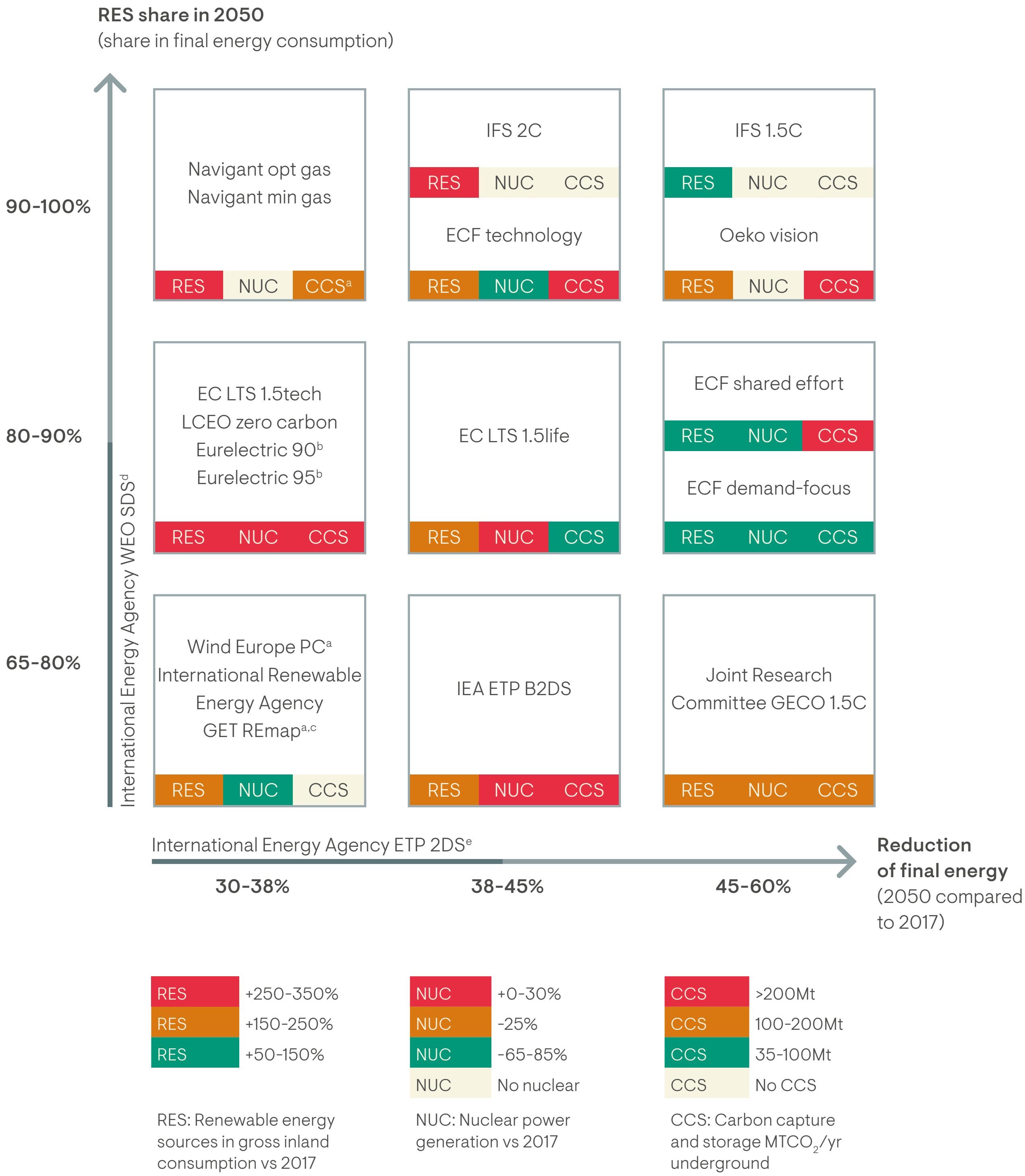
20. World Energy Outlook, International Energy Agency, Annex A3: Energy Demand – European Union, p. 367.
21. The best way to think about this is the difference between the final energy consumed by the user (e.g. household electricity consumption as metered by their homes meter) as compared to the primary energy used to generate the energy consumed by the user (e.g. gas burnt in power station to generate the electricity, with losses from the conversion of gas to power at the power station and losses in transmission and distribution). The more formal way to think about this is that primary energy consumption measures total domestic energy demand, while final energy consumption refers to what end users actually consume. The difference relates mainly to what the energy sector needs itself and to transformation and distribution losses. With thanks to Dan Quiggin for his exceptionally clear formulation.
22. Ritchie, H., Roser, M., 'Energy,' Our World in Data, 2020.
23. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 70.
24. Tsiropoulos, I., Nijs, W., Tarvydas, D., Ruiz, P., Towards net zero Emissions in the EU Energy System by 2050, Joint Research Committee Technical Reports, Joint Research Centre, European Commission, 2020.

Figure 2: European Commission Joint Research Committee scenarios showing reduction in final energy estimates depending on scenarios



a. No data for carbon capture and storage; b. No data on the split between renewables and nuclear; c. 84% GHG emissions reduction, no data for nuclear; d. 72% GHG emissions reduction, based on 2040, reduction of final energy reaches 25% compared to 2017; e. 82% GHG emissions reduction, renewable energy share reaches 50%. Source: European Commission Joint Research Committee. Please note that this chart has been redrawn by Ninety One.

Second, what is likely to be the level of electrification as a percentage of final consumption?

As discussed earlier, an energy carrier is something that can deliver energy in a usable form. At a global level today, electricity makes up just 19% of total final consumption while oil is 41%, coal is 10%, natural gas is 17%, and others are 14%. Those are the International Energy Agency (IEA) numbers.[25]

The IEA's Sustainable Development Scenario, in which the world reaches net zero by 2070, foresees electricity's share to rise to 31% by 2040. The IEA's less ambitious Stated Policies Scenario, which reflects the impact of today's announced policy intentions, sees electricity's share at 24% by 2040.[26]

The BP numbers are slightly different, a product of different aggregation methods. Electricity makes up 24% of total final consumption (excluding non-combusted fuels[27]) by carrier, while oil is 40%, coal is 15%, natural gas is 20%, bioenergy 1% and hydrogen 0%.[28]

In BP's net zero scenario, which foresees an aggressive path to net zero emissions by 2050, electricity rises from around 25% of total final energy consumption in 2018 to 46% by 2040.[29] Hydrogen rises from zero to 5% in this scenario, on track for 16% by 2050. In BP's rapid scenario, the level of electrification by 2040 is much smaller, around 41%.[30]

The Intergovernmental Panel on Climate Change tells us that in scenarios limiting warming to 1.5°C, electricity covers 34% - 71% (minimum-maximum range) of final energy by 2050 with no or limited overshoot, up from about 20% in 2020.[31] The IEA's own forecasts, which suggests that even in the ambitious Sustainable Development Scenario, electricity will not go beyond more than 31% globally by 2040, suggests we fall well short of the most ambitious levels consistent with 1.5° despite the 10 year gap between the two figures (the IEA figures do not go to 2050).

Figure 3: BP projections of carrier share on a global basis

%		2010	2011	2012	2013	2014	2015	2016	2017	2018	2025	2030	2035	2040	2045	2050
Electricity	Rapid	23%	23%	23%	23%	24%	24%	24%	24%	25%	28%	31%	36%	41%	46%	51%
	Net zero	0%	0%	0%	0%	0%	0%	0%	0%	25%	29%	33%	38%	46%	53%	59%
Hydrogen	Rapid	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	3%	5%	7%
	Net zero	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	2%	5%	10%	16%

Source: BP.

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25. Total Final Consumption = the final energy consumed by end-users (e.g. household electricity consumption as metered by their homes meter) as compared to the primary energy used to generate the energy consumed by the user (e.g. gas burnt in power station to generate the electricity with losses in conversion, distribution and transmission). Table A.3 Energy Demand-World, World Energy Outlook 2020, International Energy Agency, 2020.
26. World Energy Outlook 2020, International Energy Agency, 2020, p. 342, 343.
27. Non-combusted fuels are typically, oil, gas or coal for the purpose of feedstocks for petrochemicals, bitumen and fertilisers.
28. Chart Pack Data, BP Energy Outlook 2020 edition, 2020, Sheet 116-R.
29. The International Energy Agency electricity share of total final consumption for 2019 is 19% while BP's figure for 2018 is 25%. These differences stem from different methodologies in estimating final consumption. For instance, the IEA calculations include non-combusted fossil fuels in total final consumption, while BP's do not. Non-combusted fossil fuels = Fossil fuels can be consumed, but not combusted, when they are used directly as construction materials, chemical feedstocks, lubricants, solvents, waxes, and other products. Common examples include petroleum products used in plastics, natural gas used in fertilisers, and coal tars used in skin treatment products. Chart Pack Data, BP Energy Outlook 2020 edition, 2020, Table 116-R and 116-M.
30. BP's rapid scenario assumes the introduction of policy measures, led by a significant increase in carbon prices, that result in carbon emissions from energy use falling by around 70% by 2050 from 2018 levels. The rapid scenario is broadly in line with scenarios that are consistent with limiting the rise in global temperatures by 2100 to well below 2°C above pre-industrial levels.
31. Rogelj, J, Shindell, D., Jiang, K., et. al., 'Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development,' Global Warming of 1.5 ᴼC, The Intergovernmental Panel on Climate Change, 2018, Chapter 2, p. 54.

For Europe, the ambition for electrification is likely to be larger than 31% by 2040 because the starting point is much higher, and Europe has limited energy resources, and so is likely to push for a high use of renewable energies, implying higher electrification. In the International Energy Agency's (IEA) two scenarios, the electricity share of final consumption in Europe rises to 28% - 37% by 2040 from 21% in 2019, or by 7-16 percentage points.

In other words, by 2040, electrification has increased substantially but is relatively limited. Other renewables (including hydrogen) are still relatively small at 3% by this date, while coal, oil and natural gas still make up 33% of total final consumption. The BP scenarios are somewhat less pessimistic.[32]

The European Commission 2018 document's eight scenarios suggest electricity share of final consumption between 40%-55% by 2050, with the median clustering around 50%. The European Commission Joint Research Committee 16 net zero scenarios suggest electricity share of final energy consumption is likely to find itself in 2050 around 35-65%, with the median clustering around 50%.[33]

Importantly, Ursula von der Leyen's European Commission's own ambition has explicitly suggested an electrification target at 53% by 2050.[34] In any case, whether we use the 2040 targets or the 2050 targets, whether we use the IEA numbers, the BP numbers, or the EU internal analyses, the fact that electrification is not expected to rise much further than 50% in the next two decades suggests the many difficulties involved in electrifying everything.

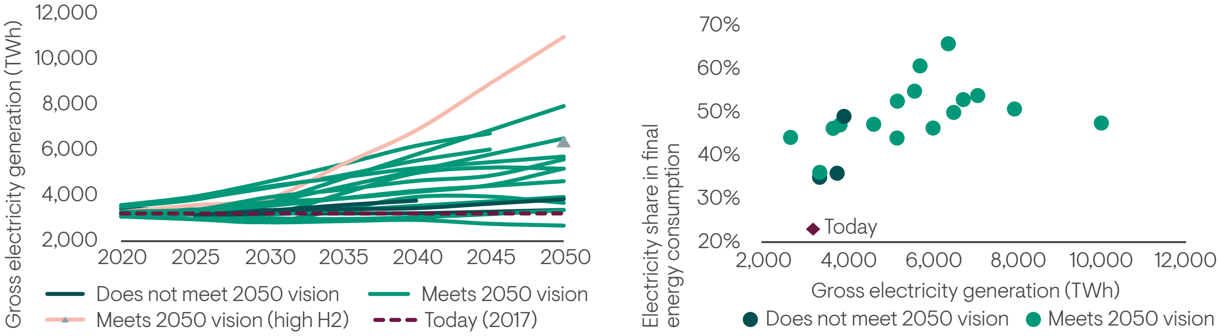
What are the barriers to greater electrification? Basically, not all energy processes and uses can be technically or economically electrified. These include things like high-temperature industrial processes, which are likely to remain stubbornly impervious to electrification. These include the use of heat in refineries, metals (iron and steel, aluminium), non-metallic minerals (cement, ceramics, and glass), paper & pulp, chemicals, food & drink).

At the same time, electricity's share of total primary demand (as opposed to just final consumption) will ultimately have to be much higher, since any strategy to incorporate hydrogen into the energy mix will ultimately be generated by electricity from fossil-free sources.

Meanwhile, there are also inevitable distribution and transmission issues which cause a loss of energy from primary demand generation to final consumption.

To conclude this section, by 2050, electricity's share of total final consumption is likely to be just above 50% (according to the Joint Research Committee analysis, the European Commission's internal scenarios, and the European Commission target). Electricity's share of total primary demand (as opposed to just final consumption) will have to be higher than 50%, since the EU's reliance on hydrogen, including e-fuels, will ultimately be generated by electricity from fossil-free sources. We will discuss just how much higher, but ultimately, electrification has to expand significantly.

Figure 4: European Commission Joint Research Committee Gross electricity generation estimates from 16 scenarios



Source: European Commission Joint Research Committee. Please note that these charts have been redrawn by Ninety One.

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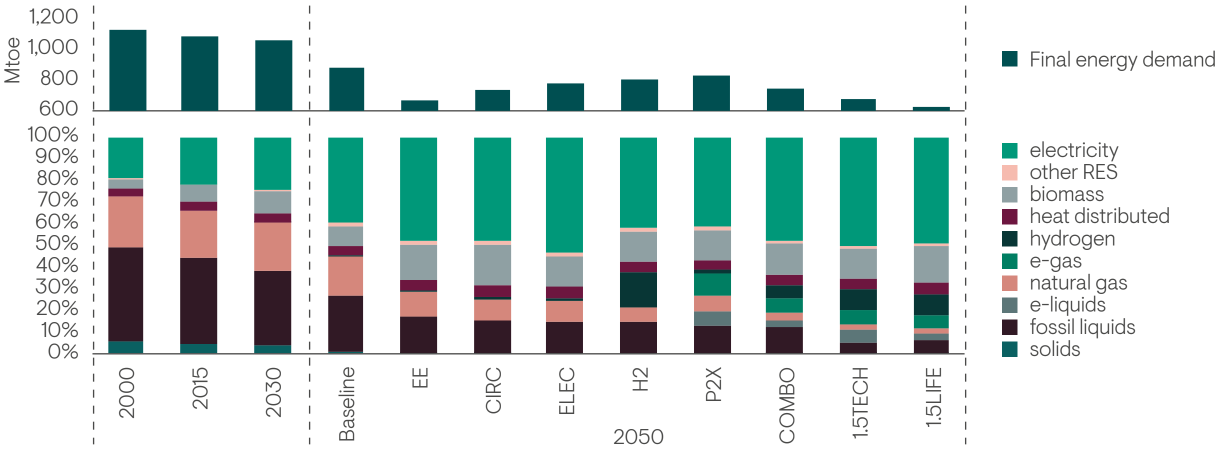
32. BP doesn't break out electrification share at a regional level, but in general, the BP forecasts are less pessimistic than IEA. At a global level, the IEA foresee electricity's share of final consumption rising 5-12 percentage points by 2040, whereas BP sees the global electrification share rising 16-21 percentage points by 2040. We can therefore conclude that BP's European electrification share is likely to be somewhat higher than the IEA's 28% to 37% share of final consumption.
33. Tsiropoulos, I., Nijs, W., Tarvydas, D., Ruiz, P., Towards net zero Emissions in the EU Energy System by 2050, Joint Research Committee Technical Reports, Joint Research Centre, European Commission, 2020, p. 30.
34. A clean planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p.9.

Figure 5: European Commission's 2018 internal scenarios

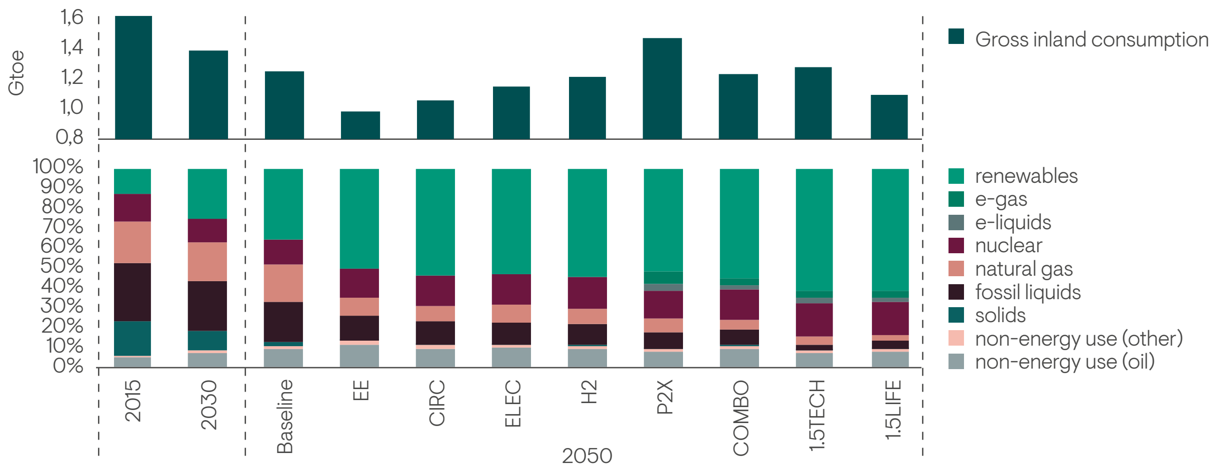


Source: Eurostat.

Third, what is likely to be the renewable share of total demand? This headline number is a shorthand for the level of ambition, and the possible range of outcomes.

In the International Energy Agency Sustainable Development Strategy, renewables (electricity, heat and bioenergy) comprise of 61% of total European final consumption by 2040, up from 34% in 2019. In the BP scenarios, renewables will be anywhere from 63% to 76% of all consumption demand in the same time period (the rapid and net zero scenarios respectively), up from 17% in 2018. By 2050, in the BP net zero scenario, renewables are likely to make up 73% to 88% of energy consumption. In the European Commission's 2018 internal scenarios, renewables (renewables, e-gas, e-liquids, and nuclear) comprise 65% to 85% of gross inland consumption.[35] The hydrogen-centric scenario shows renewables at around 70%, while the two net zero scenarios are over 80%.[36] In other words, the more that decarbonisation relies on supply-based interventions (as opposed to cutting demand, or pursuing unproven 'circular economy' scenarios), and on new technologies like hydrogen, the more renewables are necessary.

Figure 6: European Commission's 2018 scenarios: gross inland consumption



Source: Eurostat.

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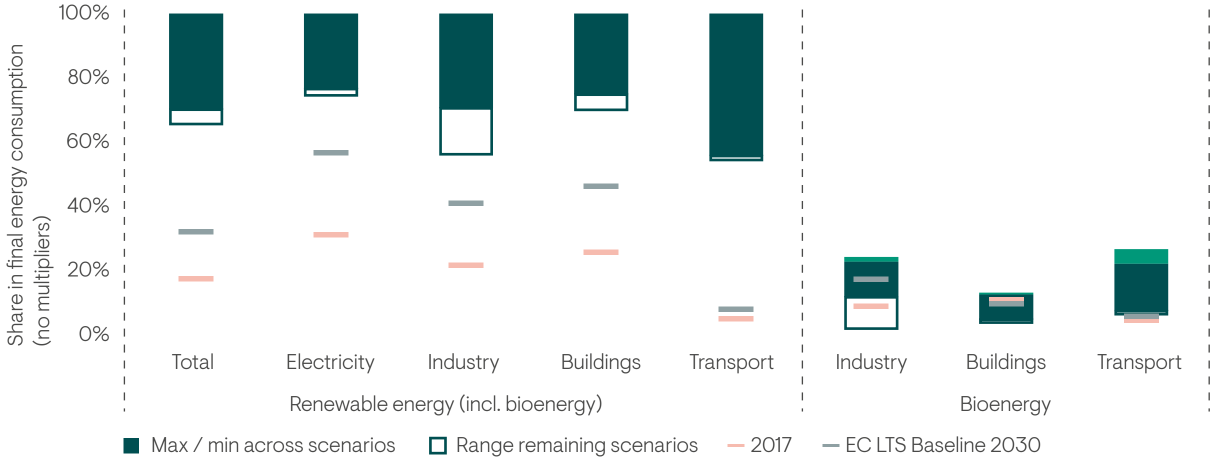
35. Gross inland energy consumption is an EU term that covers: i) consumption by the energy sector itself; ii) distribution and transformation losses; iii) final energy consumption by end users; iv) 'statistical differences' (not already captured in the figures on primary energy consumption and final energy consumption). Gross inland consumption does not include energy (fuel oil) provided to international maritime bunkers. It is calculated as follows: primary production + recovered products + net imports + variations of stocks – bunkers.
36. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p.69.

This is confirmed by the European Commission's 2020 meta-analysis of 16 internal and external scenarios (the Joint Research Committee analysis). There, the consumption of renewable energy in final consumption by 2050 ranges greatly between scenarios (35 percentage points, from 65% to 100%), but most scenarios have a renewable energy share in final energy consumption higher than 80% (13 of the 16 scenarios).[37]

Figure 7: European Commission Joint Research Committee scenarios renewable energy forecasts as a share of total final consumption by 2050



Note: White-filled boxes correspond to the maximum and minimum values across all scenarios for 2050; inner boxes include the remaining scenario values for 2050. The grey marker indicates projections of European Commission LTS Baseline for 2030.
Source: European Commission Joint Research Committee. Please note that this chart has been redrawn by Ninety One.

If renewables only reach 80% of final demand, what does the rest consist of? Mainly residual fossil fuels that are offset by negative emissions technologies.

The advantage of thinking in terms of 'net zero' is that there can still be a role to play for abatement options like afforestation, or gas and coal plants with carbon capture technology, or bioenergy carbon capture and storage (in which a plant fuelled by sustainably-sourced biomass feedstock captures CO_2, thereby generating negative emissions). In general, the literature makes a distinction between nature-based negative emissions options and engineered negative emissions options.

Work by Aurora Energy Research suggests that abatement options could end up playing a significant role in absorbing fossil fuel emissions. Their projects show global primary energy consumption of 18.8 btoe in 2050, of which 15 btoe (or around 80%) is generated from clean energy, 3.8 btoe from fossil fuels, and 1.5 btoe from non-combusted fossil fuel use (e.g. feedstock for products like petrochemicals). The 5.3 btoe generated from fossil fuels (combusted and non-combusted uses) is offset by abatements.[38]

Of course, the presence of abatements should not blind us to the need to mostly decarbonise most energy use. Abatements need to be reserved for difficult-to-decarbonise processes like non-combusted fuel use, and for lagging countries in the emerging world. In comparison with other regions, which are further behind, and more resource endowed, Europe will have to plan to reach net zero with the use of the fewest abatement measures.

In conclusion, renewable share of final energy consumption clusters around 80% of final demand by 2050 in European scenarios tending towards net zero.

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37. Tsiropoulos, I., Nijs, W., Tarvydas, D., Ruiz, P., Towards net zero Emissions in the EU Energy System by 2050, Joint Research Committee Technical Reports, Joint Research Centre, European Commission, 2020, p.20.
38 Can we avoid dangerous climate change?, Aurora Energy Research, September 2019.

List of scenarios discussed

A number of scenarios have been discussed in this document.

The International Energy Agency (IEA) World Energy Outlook 2020 has two comprehensive scenarios, mainly forecasting numbers up to 2040

- The Stated Policies Scenario (STEPS) incorporates the IEA's assessment of all the policy ambitions and targets that have been legislated for or announced by governments around the world
- The Sustainable Development Scenario is based on the same economic and public health outlook as the STEPS, but works backwards from climate, clean air and energy access goals, examining what actions would be necessary to achieve those goals. The near-term detail is drawn from the recent IEA Sustainable Recovery Plan, which boosts economies and employment while building cleaner and more resilient energy systems.

The BP Energy Outlook 2020 have three main scenarios forecasting numbers up to 2050

- Rapid assumes the introduction of policy measures, led by a significant increase in carbon prices, that result in carbon emissions from energy use falling by around 70% by 2050 from 2018 levels. Rapid is broadly in line with scenarios that are consistent with limiting the rise in global temperatures by 2100 to well below 2°C above pre-industrial levels.
- Net zero assumes the policy measures of Rapid are reinforced by significant shifts in societal and consumer behaviour and preferences – such as greater adoption of circular and sharing economies and switching to low carbon energy sources. This increases the reduction in carbon emissions by 2050 to over 95%. Net zero is broadly in line with a range of scenarios consistent with limiting temperature rises to 1.5°C.
- Business-as-usual (BAU) assumes that government policies, technologies and societal preferences continue to evolve in a manner and speed seen in the recent past. In BAU, carbon emissions from energy use peak in the mid-2020s but do not decline significantly, with emissions in 2050 less than 10% below 2018 levels.

There are eight scenarios in the European Commission's 'In-Depth Analysis in Support of the Commission Communication COM(2018) 773. The first five aim for greenhouse gas emissions reduction levels in 2050 of around 80% compared to 1990. The next three are driven by decarbonised energy carriers (-90% declines compared to 1990; consistent with 'well below 2°C'), and two are net zero scenarios that examine the impact of switching from the direct use of fossil fuels to zero/carbon neutral carriers, namely electricity, hydrogen and e-fuels (-100% declines , including carbon sinks, compared to 1990).

- ELEC involves electrification in all sectors
- H2 involves the use of hydrogen in industry, transport and buildings
- P2X (Power-to-X) involves the use of e-fuels in industry, transport and buildings
- EE involves deep energy efficiency in all sectors
- CIRC involves an activation of a more circular economy, using increased resource and material efficiency
- COMBO involves cost-efficient combination of options from the earlier five scenarios
- 1.5TECH is COMBO with more carbon capture and storage and Bio-energy and Carbon Capture and Storage
- 1.5LIFE is COMBO and CIRC with lifestyle changes.

There are 20 net zero scenarios assessed in the European Commission's Joint Research Centre technical report, 'Towards net zero emissions in the EU energy system by 2050.' These scenarios meet the ambition of the European Green Deal to reduce emissions by at least 50% by 2030. 16 scenarios meet the strategic vision for the EU to become a climate neutral economy by 2050.

The 2018 internal scenarios generated by the Commission fulfil a different function to the external ones from 2020. The latter is about comparing different internal and external integrated assessment modelling outcomes to each other in terms of understanding the median outcomes. The former is more about using the same energy model while making different policy choices. The scenarios used are the following. Note the presence of the 1.5Tech and 1.5Life scenarios from the 2018 internal exercise.

- Eurelectric 90 (2018)
- Eurelectric 95 (2018)
- European Climate Foundation Technology (2018)
- European Climate Foundation Demand-focus (2018)
- European Climate Foundation Shared-effort (2018)
- European Commission Long Term Strategic Vision Baseline (2018)
- European Commission Long Term Strategic Vision 1.5Tech (2018)
- European Commission Long Term Strategic Vision 1.5Life (2018)
- International Energy Agency Energy Technology Perspective 2DS (2017)
- International Energy Agency Energy Technology Perspective B2DS (2017)
- International Energy Agency World Energy Outlook 2018 SDS (2018)
- International Renewable Energy Agency GET Remap (2019)
- European Commission Joint Research Centre Global Energy and Climate Outlook 1.5°C (2017)
- European Commission Joint Research Centre Low Carbon Energy Observatory Zero Carbon (2018)
- Navigant Gas for Climate min gas (2019)
- Navigant Gas for Climate opt gas (2019)
- Oeko-Institut The Vision Scenario for the EU (2017)
- Teske et al Achieving the Goals of the Paris Agreement 2C (2019)
- Teske et al Achieving the Goals of the Paris Agreement 1.5C (2019)
- WindEurope Breaking New Ground Paris Compatible (2018)

The Chinese scenarios used in the comparison below come from the Launch of the Outcome of the Research on China's Long-term Low-carbon Development Strategy and Pathway, from the Institute of Climate Change and Sustainable Development at Tsinghua University, led by He Jiankun, from 12 October 2020. This is the initial report setting out the main choices for China's energy pathways. There are 18 reports yet to be written on various sub-topics. In the scenario document there are four scenarios, of which I have leaned on the last two.

- Policy Scenarios is one that follows through the 2030 National Development Commission targets
- Reinforced Policy Scenario are those that strengthen the NDC scenario up to 2030 from the bottom up and step-up the emission reduction efforts
- The 2°C scenario is one that achieves an emission reduction scenario with the global 2°C target by 2050, with per capita CO_2 emission no higher than 1.5 metric tons
- The 1.5°C scenario is one that achieves net zero CO_2 emissions and deep reductions of other greenhouse gases by 2050

The Centre for Climate and Energy Solutions (C2ES) scenarios are focused on the US and provides three scenarios for cutting emissions to levels 80 per cent below 2005 levels. These are not true net zero targets. By 2050 the US is still at 1000 $MTCO_2$ emissions per year, according to these targets.

- **A Competitive Climate:** Strong international pressure in the form of carbon tariffs and growing recognition of the competitive benefits of low-carbon innovation lead to a strong, early U.S. federal response, including an economy-wide price on carbon
- **Climate Federalism:** Responding to economic opportunities and intensifying climate-related disasters, a growing number of U.S. states implement ambitious climate policies, leading to calls from business for a more harmonised national response
- **Low-Carbon Lifestyles:** Increased urbanisation, generational shifts, and technological break-throughs lead to strong market demand for low-carbon consumption products and services, along with the emergence of innovative low-carbon business models

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39. Diringer, E., et al, Getting to Zero: A US Climate Agenda, Center for Climate and Energy Solutions, November 2017, p. 7.

The fourth key decision point is with regards to the scale of variable renewable share of electricity production.

Some regions will choose to use more variable energy to meet their electrification needs, relying on hydrogen and/or battery storage to meet power requirements when energy is not produced. Other regions will use more constant source of energy like hydropower and nuclear to meet their electrification needs. In the former situation, substantially more electricity generation is needed relative to the latter.

As a share of electricity generation, the International Energy Agency Sustainable Development Scenario expects renewables to reach 76% by 2040. As discussed earlier, most external scenarios surveyed by European Commission in 2018 find that Europe's renewables share gets to 81%-85% by 2050, and with International Renewable Energy Agency's global energy transformation, Greenpeace and Oko-Institut Energy Vision getting to almost 100% renewables.[40]

Assuming the EU eventually gets to 80-90% of electricity supplied by renewables, how will that be divided between variable renewables and controllable renewables? Outside of France, and perhaps the now-departing UK, nuclear—the traditional controllable clean energy—is not likely to be an option. So what are the other outcomes?

The core issue is variability. Whereas fossil fuel power plants are controllable or 'dispatchable', i.e. can be dialled up or down to meet demand, the main sources of renewable energy like solar, and wind, are not.

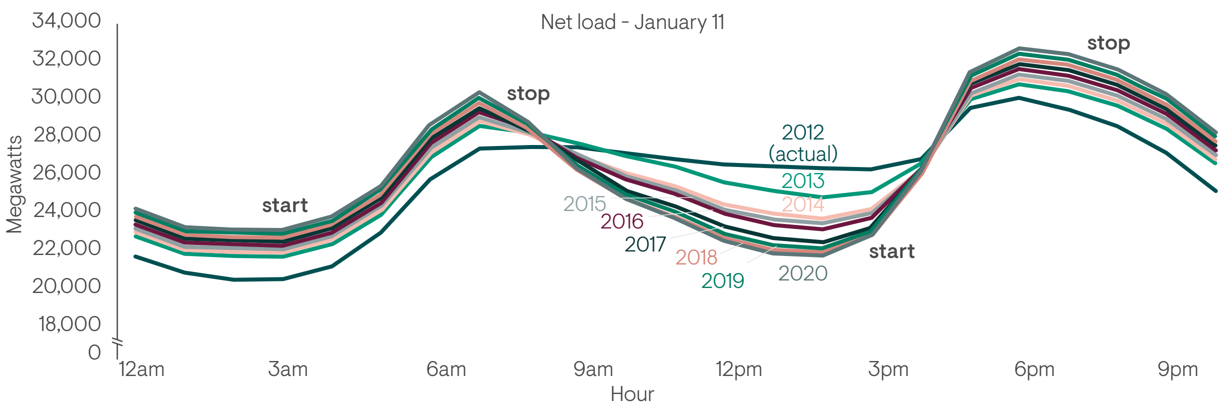
To some extent, solar and wind balance each other out. Where it is not sunny, it is often windy. However, there are periods when solar and wind together are simply not enough. Both cannot provide enough power for peak usage during the day, particularly between 6-9 PM when the sun is typically down and household usage is substantial.

The discrepancy between production and consumption is best illustrated in the so-called Duck Curve, which is how the California Independent System Operator, or grid operator, illustrated the pattern of non-variable energy generation in a variable-energy-heavy system.[41]

What it shows is that net loads produced by non-solar energy producers have been declining in recent years as solar use has grown. Nevertheless, solar is unable to provide power in the early evenings, leading to a steeper and steeper ramp of electricity needed after the sun has set when people arrive back home.

This is why 36% of California's retail electricity sales were served by renewables in 2019, yet during the day with the highest peak demand (August 15), renewables could serve just 26.5% of peak demand.[42]

Figure 8: The so-called Duck Curve of the California grid



Source: California Independent System Operator.

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40. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 76.
41. The figure shows a net load curve for March 31 for years 2012 through 2020. The curve shows the megawatts the system operator must follow on the y axis over the different hours of the day shown on the x axis. There are several distinct ramp periods. A ramp in the downward direction occurs after the sun comes up around 7:00 a.m. when on-line conventional generation is replaced by solar generation (producing the belly of the duck). As the sun sets starting around 4:00 p.m., and solar generation ends, the system operator must dispatch resources that can meet the most significant daily ramp (the arch of the duck's neck). Immediately following this steep 13,000 megawatt ramp up, as demand on the system deceases into the evening hours, the system operator must reduce or shut down generation to meet the downward ramp. Solar Energy's Duck Curve, Institute for Energy Research, 2014.
42. 'California Energy Commission – Tracking Progress,' Energy Commission, State of California, February 2020, and 2019 Statistics, California Independent System Operator, 2019.

How does Europe solve this variability or 'last mile' problem of 100% renewables in electricity generation?

This is a complex question because there are multiple variables at play. Think of it as a series of simultaneous equations with at least three variables: i) the magnitude of electrification in the supply system; ii) the degree of use of hydrogen, e-fuels and other carriers that compete with electricity; which in part depends on iii) the energy choices made by end-users (e.g. if transport electrifies, then that will require more electrification. If transport evolves to use e-fuels, or hydrogen fuel cells, that will require less electricity).

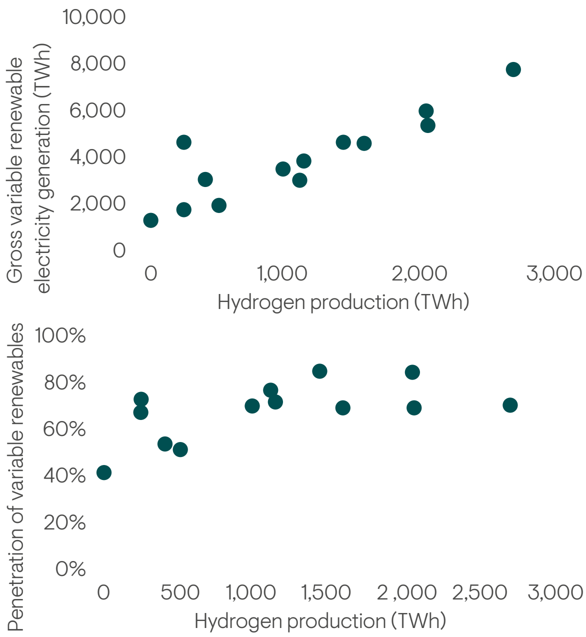
There are important tradeoffs here. Pathways that are more reliant on carbon-free energy carriers require less innovation and investment in the end-use sectors, but also the highest investment needs in the energy supply sectors. Conversely, pathways focused on the demand side change require the least investment in the energy supply sectors.[43]

Solving these simultaneous equations requires integrated assessment modelling. We simplify the broad choices available by focusing on two basic choices that are likely to be posed: a renewables overbuilding scenario, and a hydrogen-centric scenario.[44]

In the renewables overbuilding scenario, the problem is solved by a massive renewables overbuilding and some use of battery storage on a timeframe of seconds, minutes, or hours. In the hydrogen-centric scenario, a push is made to go for a massive renewables overbuilding in the service of hydrogen and e-fuels, which also provide storage, but on a timeframe of days, weeks, and months. Depending on the choice taken, more or less electricity generation capacity will be required.

To give a sense of the magnitudes involved, according to the EU Joint Research Committee analysis of 18 internal and external net zero scenarios, variable renewables always provide 60% to 90% of total renewable electricity, but there is a diverging outcome on their growth, each varying between a factor of 3 and 13. In other words, the volume, but not the penetration, of wind and solar production is driven by hydrogen (see figure 9).[45]

Figure 9: EU Joint Research Committee scenarios showing the interplay of hydrogen and variable renewables.



Note: Including hydrogen demand for e-fuels but not for industrial feedstock. Source: European Commission Joint Research Committee. Please note that these charts have been redrawn by Ninety One.

In the renewables overbuilding scenario, electricity becomes the key carrier for reducing emissions in most sectors. Transport is largely electrified, though within transport aviation and shipping remains difficult. Strong penetration of efficient heat pumps drives further emissions reductions in building.[46]

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43. Communication from the commission: A clean planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018.
44. Communication from the commission: A clean planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018.
45. Tsiropoulos, I., Nijs, W., Tarvydas, D., Ruiz, P., Towards net zero Emissions in the EU Energy System by 2050, Joint Research Committee Technical Reports, Joint Research Centre, European Commission, 2020, p. 34.
46. A clean planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 7 and In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 320.

Here, it is worth examining the EU internal scenario with the highest electrification percentage, known as ELEC. In this scenario, electrification levels reach 53% of final energy consumption by 2050, the highest of all the EU internal scenarios.[47]

Gross electricity generation is 75% above 2015 levels by 2050, vs 45% in a 'business as usual' scenario.[48] By 2070, gross electricity generation is roughly 40% more than what is needed in a baseline scenario, hence the description of this as renewables overbuilding.[49]

In this scenario, electricity storage plays an increasingly prominent role, rising by five times from 65 TWh in 2030 to 335 TWh by 2050, with four-fifths being filled by batteries and pumped hydro storage, and a fifth via hydrogen.[50] The storage is necessary to rebalance variability in the energy system, with batteries being useful for short-term rebalancing, and pumped hydro and hydrogen being particularly useful for longer-term rebalancing.

In the hydrogen-centric scenario, the second simplified case, the final 10-20% of electrification is generated by using renewables to make hydrogen and running that hydrogen through existing fossil fuel plants and gas distribution grids. Hydrogen could be produced at times of low electricity demand providing additional flexibility.

We examine the EU internal scenario with the highest hydrogen use, known as H2. This future assumes a reasonably high share of hydrogen in long mileage cars, coaches and trucks, but a much smaller share in cars and vans, with hydrogen refuelling infrastructure assumed to be deployed by 2050. To the extent that storage is necessary, hydrogen production provides indirect electricity storage.[51]

Hydrogen can be produced in two ways. In the EU scenario, hydrogen would be manufactured using electrolysis. 'Hydrogen is already a common input to some industry processes (notably in chemicals) but currently produced via steam reforming using fossil fuels as input (mostly natural gas) and thus leading to CO_2 emissions.

In a decarbonised future, hydrogen obtained from electrolysis using decarbonised electricity is the preferable option ('green' hydrogen). 'Blue' hydrogen obtained from steam reforming of natural gas coupled with carbon capture and storage (CCS) may also play a role, provided the inherent constraints of CCS are lifted.'[52]

In this scenario, electrification share of final consumption is 41% (much lower than the 50%+ in the earlier scenario). Hydrogen's share is relatively large at 18%, while being negligible in the first scenario (<5%).[53]

However, in this hydrogen-centric scenario, gross electricity generation is 80% larger by 2050 compared to the baseline scenario, as against the 20% increase for the earlier high electrification scenario.[54]

By 2070, gross electricity generation is 75% more for this hydrogen-centric scenario vs the baseline, whereas the high electrification scenario's increase is around 40%.

In other words, a hydrogen-centric scenario would demand much more of a clean power overbuilding as would be required in a straightforward renewables scenario. On the other hand, it would require much less battery storage because more hydrogen would be used as storage. Battery storage required in the hydrogen-centric scenario is projected at 127 TWh vs 195 TWh in the high electrification scenario by 2050.

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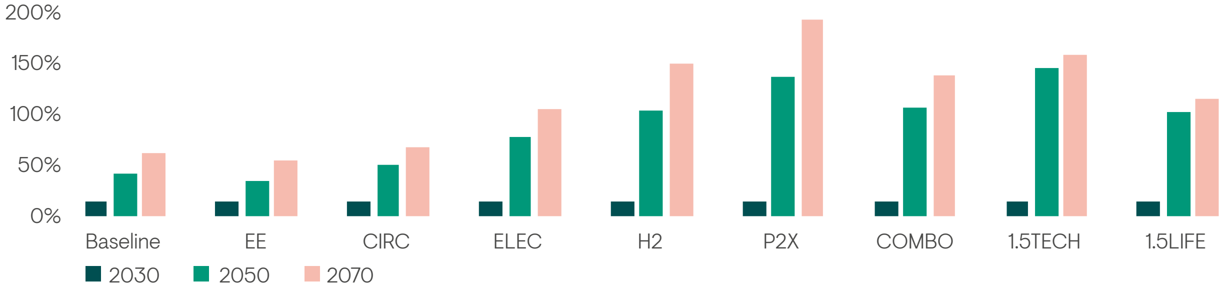
47. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 72.
48. What the European Commission calls a baseline scenario.
49. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 74 & 48. The 40% figure is from the table, sheet main (6560/4600).
50. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 79.
51. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 320.
52. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 64.
53. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 72 (Figure 20).
54. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 47. In absolute numbers, gross electricity generation in the hydrogen-centric scenario would be above 6560 TWh by 2050, vs 5600 TWh in the high electrification scenario by 2050 vs 4600 TWh by 2050 in the baseline scenario.

Figure 10: EU internal scenarios increase in gross electrification compared to 2015 levels



Source: Eurostat.

Moving beyond enumerating these two scenarios, it is fair to say that the EU has already decided on a high-hydrogen scenario. On 8 July 2020, the EU announced that clean hydrogen would play a central role in Europe's new energy economy.[55] The strategy document stated that 'the priority is to develop renewable hydrogen, produced using mainly wind and solar energy. However, in the short and medium term other forms of low-carbon hydrogen are needed to rapidly reduce emissions and support the development of a viable market.'[56]

That strategy document has numbers that are similar to the H2 scenario from 2018. In that document the share of hydrogen in Europe's energy mix is projected to grow from the current less than 2% to 13-14 by 2050.[57] In the H2 scenario, the figure is around 16%, higher than the other scenarios.

In light of the July 2020 hydrogen strategy, it is worth pointing out the other features of that 2018 H2 scenario in further detail. In the 2018 European Commission analysis, the division of carriers was as follows: electricity at just over 40% of final energy consumption by 2050, biomass at around 15%, hydrogen at 17%, natural gas at around 5%, and fossil liquids at about 15%, and the rest met by distributed heat and other sources.[58]

In that same scenario, the division of primary energy sources set renewables at just over half of gross inland consumption, with around 15% going to nuclear, just under 10% going to natural gas, 10% to fossil liquids, and around 10% to non-combusted fuels.[59]

In this scenario, onshore wind makes up 600 GW of power generation capacity by 2050 (just over a quarter), offshore wind 400 GW (17%), solar at 750 GW (32%), other renewables at 250 GW (11%), nuclear at 150 GW (6%), fossil fuels at 200 GW (9%). The H2 scenario from 2018 is not even a net zero scenario, so in a net zero scenario, the capacities required, as detailed above, will be larger.

Interestingly, the EU's new offshore wind strategy also hews somewhat to the H2 2018 scenario. On November 19, 2020, the European Commission published its offshore wind strategy, which sees offshore wind in the EU-27 going from 12GW today to 60GW by 2030 and 300GW by 2050. In other words, a 25X increase over the current installed base.[60] That 300 GW for offshore wind excludes the UK, which the c. 400 GW target figure from H2 scenario in 2018 includes. Given that the UK is expected to reach 75-80 GW by 2050, what was predicted in the H2 scenario in 2018 is close (+/- 20GW-25GW) to the European Commission's thinking on the subject today.[61]

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55. A Hydrogen Strategy for a Climate-neutral Europe, European Commission, 2020.
56. Powering a Climate-neutral Economy: Commission sets out Plans for the Energy System of the Future and Clean Hydrogen, European Commission, 2020.
57. A Hydrogen Strategy for a Climate-neutral Europe, European Commission, 2020. Footnote 5. This cites the following document, Moya, J., et al., Hydrogen use in EU decarbonisation scenarios, Joint Research Centre, European Commission, 2019.
58. A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 72 (Figure 20).
59. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 69 (Figure 18)
60. Venkateswaran, D., Becker, M., et al, The EU's Offshore Wind Strategy-an ambitious 25X capacity expansion target by 2050, Bernstein Research, 23 November 2020.
61. Venkateswaran, D., Becker, M., et al, The EU's Offshore Wind Strategy-an ambitious 25X capacity expansion target by 2050, Bernstein Research, 23 November 2020, p 3. Also Figure 24 in In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p.77.

In conclusion for this section, the renewables share of electricity must tend towards 100% in a net zero world. Yet wind and solar are intermittent technologies, while nuclear is not a long-term option in many European countries. How will the problem of consistent electricity generation from renewables be solved? We think there are ultimately two options: renewables overbuilding with battery storage, or renewables overbuilding with hydrogen. In the former situation, less electricity generation (about 40% more by 2050 relative to the baseline scenario) and more battery storage will be required, while in the hydrogen-centric scenario, gross electricity generation will be 80% more by 2050 relative to the baseline, while less battery storage will be required. Meanwhile, announcements this year of the offshore wind and hydrogen strategy suggest the EU is not too far from the H2 scenario it laid out in its 2018 internal scenario planning exercise.

Fifth, the role of engineered carbon capture and storage (CCS). CCS is where the net in the net zero comes in. Emissions can never be reduced to zero, e.g. certain agriculture based non-CO_2 emissions cannot be eliminated. Therefore, as IPCC reports have indicated, removing CO_2 from the atmosphere has to be part of a long-term solution, even though the focus has to be on achieving emissions reductions as quickly as possible.[62]

In Europe, forecasts for engineered (as opposed to nature-based) carbon removal are used in all the European Commission internal scenarios to abate CO_2 emissions in 2050. Nevertheless, the amounts differ significantly depending on the scenario in use. The amount of CO_2 captured ranges from around 44 $MTCO_2$ to 600 $MTCO_2$, (or between 1% and 16% of current emissions) with the hydrogen-centric scenario that we have identified as being a good mirror for Europe's energy ambitions requiring the lowest amount of CCS, mainly underground storage.[63]

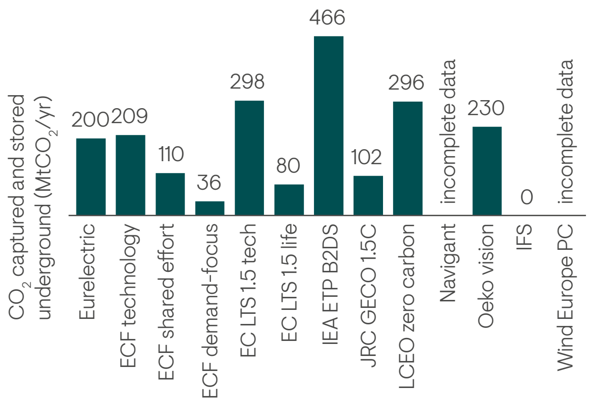
In the EU Joint Research Committee external scenarios, almost all scenarios rely on CCS to abate CO_2 emissions in 2050. In six of 16 scenarios, CO_2 captured and stored is more than 200 $MTCO_2$ per year. Carbon removal by 2050 can reach up to 466 $MTCO_2$. Much of this will depend on the level of development achieved in CCS technologies.

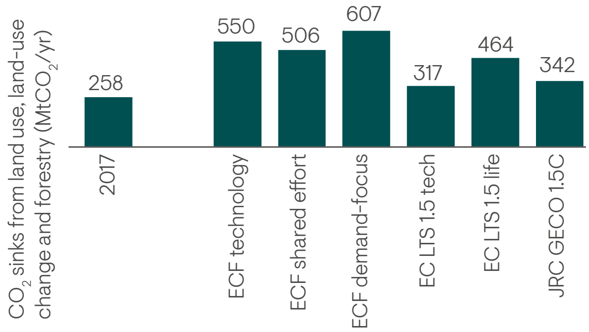
The main barriers with CCS are first, cost, and the risk of leakage.

Land use changes and forestry (LULUCF) have some potential as well, with scenarios expecting an increase in LULUCF sinks by 25% to 135%, compared to 258 $MTCO_2$ in 2017.

In conclusion, the range of carbon removed from CCS options is substantial, from 44 $MTCO_2$ to 600 $MTCO_2$, with the median clustering around 200 $MTCO_2$. Similarly, the range of carbon removed from land use changes is wide. At the median estimate (200 $MTCO_2$ for underground carbon storage, and 250 $MTCO_2$ for land use changes), carbon removal would still be relatively small (12% of current emissions).

Figure 11: EU Joint Research Committee scenarios of carbon-removed





Note: Joint Research Committee GECO 1.5C includes power, industry and other; in European Commission LTS and LCEO zero carbon, CO_2 is captured and reused (not shown in the figure). Navigant mentions the need for CCS in steel and cement production, with potential CO_2 supply of 113 and 179 $MTCO_2$ per annum, respectively.
Source: European Commission Joint Research Committee.

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62. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 193.
63. In-depth analysis in support of the Commission communication: A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission, 2018, p. 192.

In the sixth factor, the decarbonisation of end-demand is a crucial input into how energy systems organise **themselves**. Many projections are generally optimistic for the industry sectors, but less so for buildings and transport sector.[64] Choices made about energy supply, e.g. the extent to which batteries are used vs hydrogen, impacts the range of options open to transportation, and vice-versa.

The International Energy Agency World Energy Outlook finds that for Europe, the transport sector's transition to net zero will involve energy demand reducing 44% to 223 Mtoe by 2040 from 392 Mtoe in 2019, of which oil declines by 73%, and electricity rises ten-fold, while bioenergy and other fuels increase somewhat. Electricity is 31% of total transport demand in the EU by 2040.

The discussion on transport in European Commission communique 773 from 2018 suggests that electrification alone will not be the silver bullet. The communique notes that given that batteries have a low energy density, their heavy weight makes them ill-suited for aviation and shipping. For long-haul trucks, it is unclear whether batteries will reach the required cost and performance level. So alternative fuels will be necessary.

There is also clearly a role for transitional fuels. While hydrogen-based technologies (such as e-fuels and fuel cells) may be competitive in the medium to long-term, LNG with high blends of bio-methane could become an alternative in the near-term.

In the long-term, aviation, shipping and trucking—the particularly difficult-to-decarbonise transport sectors—could shift to advanced biofuels and e-fuels. The potential advantage of e-fuels is that they can be stored and used in multiple ways across different economic sectors. Within e-fuels, the advantage of e-liquids is high energy density but also their direct use in conventional vehicle engines, relying on the existing refuelling infrastructure.

Nevertheless, reserving the consumption of e-fuels and hydrogen for the transport modes that need them most would help limiting the power sector resources, which increase with their production and deployment.

Electrification alone will not be the silver bullet.

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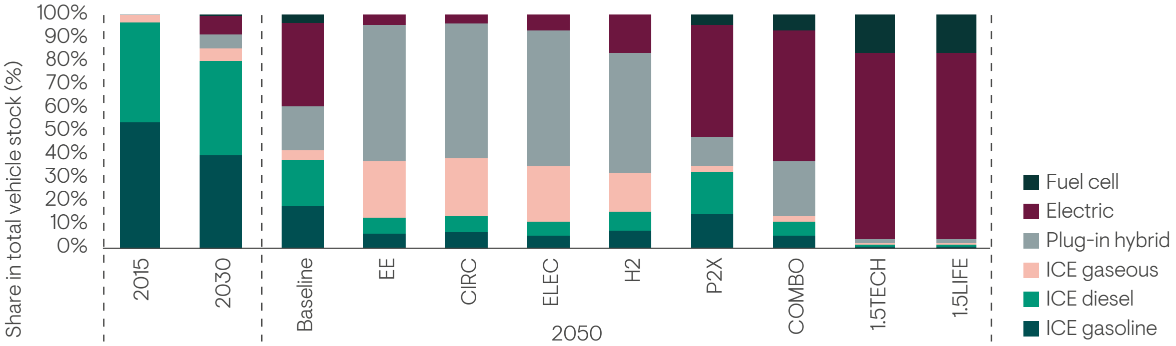
64. Rogelj, J, Shindell, D., Jiang, K., et. al., 'Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development,' Global Warming of 1.5 °C, The Intergovernmental Panel on Climate Change, 2018, p. 137.

Overall, the transport sector's net zero pathway is arranged with a mixture of electrification, hydrogen, biofuels, and synthetic fuels. Here we examine some figures for several modes of transport.

Passenger vehicles: In the two net zero scenarios in the European Commission's 2018 internal scenarios, battery electric cars dominate the drivetrain technologies disproportionately, with the remainder mostly given to hydrogen fuel cells (the 1.5Life and 1.5Tech scenarios). In the hydrogen-centric scenario, by 2050 electric cars occupy 65% of vehicles, with plug-in hybrids retaining around 20% of vehicles, with combined diesel and gasoline over 10%, though with more efficient biofuels and perhaps e-fuels.

Figure 12: EU internal scenarios in total cars stock by drivetrain technology



Source: Primes. Please note that this chart has been redrawn by Ninety One.

For light commercial vehicles, the net zero scenarios are again dominated by battery electric vehicles and fuel cells. In the hydrogen-centric scenario, fuel cells occupy 45% of the total stock of light commercial vehicles, even more than passenger vehicles.
In many ways, the sweet spot for hydrogen are pickup trucks and vans.

For heavy goods vehicles, the scenarios represent the greater uncertainty regarding the technology. Currently, this is dominated by conventional diesel powertrains, which are still expected to be dominant in 2050, taking up 30% to 55% of the stock of heavy goods vehicles. In the two net zero scenarios, diesel and gas make up 60% to 65% of HGV stock, with hybrids taking that number to 90%. However, the expectation is that the fuels going into these engines will be entirely carbon-neutral because they are a mixture of e-fuels and biofuels.

In 2017, International Energy Agency analysed scenarios for the future of trucks. By 2050, drivetrains remain varied, with electrification becoming important for light trucks, especially for urban delivery, and a variety of technologies—from conventional diesel, hybrids, LPG/CNG and some electrification—being used for medium and long-haul heavy duty trucks. While the report states that the price of fuel cells can be brought down to become competitive, the uncertainty is still large. No obvious technology winner appears for trucks. The role of social institutions is potentially key in deciding how the technology develops. Battery electrification could be more popular in Europe relative to the US because of labour laws that require truckers to rest every 4.5 hours, whereas in the US that is less likely to take place.

For aviation, jet fuel engines are expected to dominate the powertrain technologies. The challenge here is enormous. The net zero scenarios can only be fulfilled by a faster penetration of bio-kerosene and e-liquids taking place by 2050, reaching 55-57% of the fuel mix (23-45% for bio-kerosene and 10-34% for e-liquids). Electric aircraft only materialise in very small numbers. Energy demand continues to rise.

Demand reduction in the transport sector plays a role too. By 2050, the baseline/business-as-usual scenario in European Commission 2018 internal scenarios shows transport energy demand decreasing by 24% by 2050 compared to 2005, mainly due to the impact of the proposed CO_2 standards on overall vehicle fleet efficiency, but also due to improvements in the efficiency of the transport system. Oil products remain dominant, providing 75% of the final energy demand in 2050, down from over 90% currently. Electricity would provide around 11% of the energy consumption by 2050, driven by the uptake of electric vehicles and further progress in the electrification of rail. Liquid biofuels would maintain a relatively stable share over time (around 6% of the fuel mix), while gaseous fuels including biomethane would provide around 6% of energy demand by 2050. Hydrogen is projected to represent around 2% of the transport energy demand by 2050.

In the two net zero scenarios, higher reductions in energy demand are achieved by 2050 relative to 2005 (45% and 50%). Meanwhile, liquid biofuels consumption is poised to increase by 17-26%, more than in the other scenarios. Hydrogen is part of the transport fuel mix in all scenarios, rising to 15-16% in the net zero scenarios, though not for cars. E-fuels represent 15-26% of the fuel mix in a net zero scenario. Natural gas's share is <4% by 2050. Overall, liquid and gaseous biofuels, hydrogen and e-fuels would represent about 56-59% in the scenarios reaching net zero by 2050 by 2050.

In terms of fuels consumed for transport, in a net zero scenario we move from a world dominated by oil products to a world with roughly half the energy demand dominated by electricity, liquid biofuels, hydrogen, and e-liquids and e-gas. Oil products play a residual role.

When we look at the net zero internal and external scenarios for transportation analysed by the European Commission, we come to similar conclusions.

There is a strong role for demand reduction: most net zero scenarios expect transport to consume around one-third of the energy it consumes today (40% to 80% reduction in most scenarios between 2017 and 2050). In most scenarios, the sector's electricity consumption increases approximately by a factor 10 and together with biofuels they cover about 60% of the sector's energy demand excluding international aviation and maritime bunker fuels.

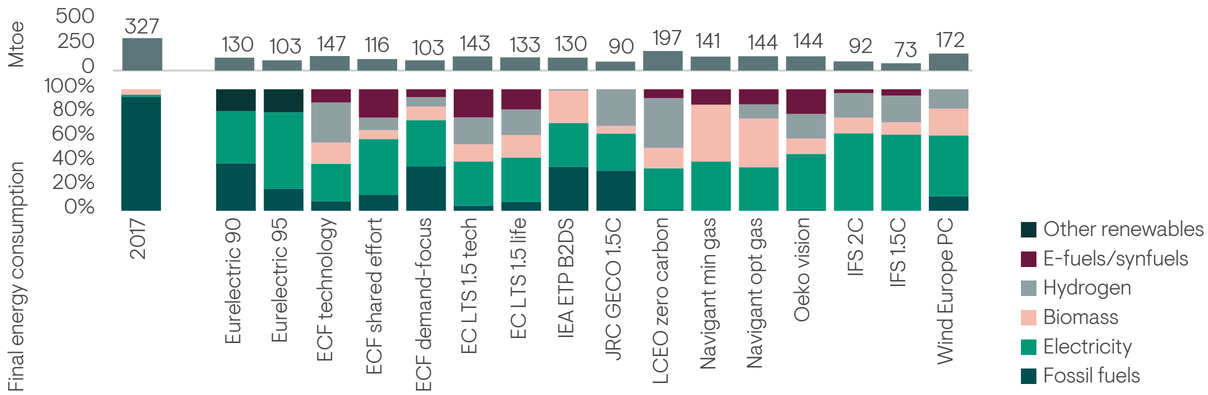
Hydrogen and e-fuels are fully deployed and become key elements in decarbonising transport; they supply from 15% to 50% of the sector's energy needs. Oil is still used in transport in most scenarios (2 to 50 Mtoe, 1% to 16% of today's consumption; only 6 out of 17 scenarios phase out oil completely).

The 10 scenarios that achieve net zero emissions in the EU by 2050 all seem to follow a different route in decarbonising transport. Three scenarios still use fossil fuels but have significant reduction in the car fleet. The two European Commission scenarios still use oil and increase passenger road transport activity compared to 2050. The remaining five scenarios completely phase out oil.

In conclusion, for passenger vehicles and light commercial vehicles, to a large extent the path to decarbonisation has been set, with most auto manufacturers already fully invested in battery electrification. Hydrogen could have been a possibility for light commercial vehicles, but it will likely take a backseat to electrification, given the current European Commission policy configuration. For heavy trucks, no obvious technology winner appears in terms of drivetrains—the choices are between battery electrification and hybrids (including e-fuels), with diesel still in significant use. For aviation, the technological challenges remain enormous.

In terms of fuel choices (as opposed to drivetrains), the expectation is that fuels going into the engines will eventually be entirely carbon-neutral because they will be a mixture of e-fuels and biofuels. However, a transition more reliant on electrification or fuel cells, rather than biofuels and e-fuels, would have benefits in terms of reduced stress on land or energy resources. On the other hand, an important advantage of both e-fuels and advanced biofuels is their direct use in conventional vehicle engines, relying on the existing refuelling infrastructure. The big decisions are very much still to be made and depend on technological and manufacturing breakthroughs.

Figure 13: European Commission net zero scenarios transport sector final energy consumption



Note: 'Other renewables' includes non-emitting secondary fuels such as biomethane, biodiesel, bioethanol, hydrogen and others in Eurelectric. Source: EC Joint Research Committee. Please note that this chart has been redrawn by Ninety One.

Will Europe's clearer vision and first mover advantage give them a competitive advantage on manufacturing in the future?

The net zero transition is being undertaken on its own terms, and for its own sake. But for it to happen it must clearly not contradict longstanding social aspirations for economic growth, industrial competitiveness and high employment. The US$18 trillion question, therefore, is whether, if Europe does make the appropriate steps forward in pursuing net zero emissions, Europe's clearer vision and first mover advantage will give them a competitive advantage on producing tradable goods in the future.

In other words, will Europe ultimately be better placed to steal a march on its competitors by starting early in producing products suitable for a zero carbon world (in the way that European onshore and offshore wind pioneers like Orsted, Vestas and Siemens Gamesa seem to have done)? Or does this just imply increased production costs, more disruption to existing businesses and therefore make Europe even less competitive than it already is by adding carbon costs to high and inflexible labour costs (in the way European heavy industry seems to be challenged by climate change)? If the net zero transition imposes too high costs compared to other countries, it risks simply displacing carbon-intensive economic activity from Europe to other regions—in effect, harming the European economy while making little difference to global emissions.

Both scenarios are possible, but the outcome likely depends on three factors. First, whether carbon border taxes can be made to work—as a way of imposing a fee on products imported from other countries without an equivalent carbon pricing plan. This is to ensure that businesses face a level playing field against imports from countries that are not doing their bit to reduce emissions.

There are many sceptics about the possibility of a carbon border tax, not least in industry, but it is worth noting that the European Commission is already factoring in €5 billion to €14 billion in carbon border revenues per year in the "latter stage" of the 2021-2027 planning period as a way of paying for the EU's Next Generation fund, which accrues at the European level[65]. The debt is accruing, and will need to be paid for.

Second, it probably depends on whether consumer behaviour will change to give European companies new revenue opportunities. Will we pay more for a zero carbon iPhone, for instance? Clean technology will ultimately lower operating costs—with McKinsey for instance, projecting a decline of €260 billion a year in Europe by 2050 in total operating expenditures, with most of the savings to be had in transportation, power and heating/cooling. These would offset increases in the cost of food and flights for holidays[66]. The balance of payments deficit Europe chronically runs for energy would shift dramatically, transforming Europe's relations with the Middle East and Russia. Yet the same report suggests these prizes will require €28 trillion in investments over the next 30 years. So there is clearly a financing hump to be overcome to reach that point. Will European consumers be willing enough to fund that energy transition—in effect getting the same output for more cost?

(In a way, discussing the behaviour of the 'European consumer' or the 'Asian consumer' may become more anachronistic in the coming years given the emergence of behavioural change on an increasingly global basis due to higher levels of connectivity. There is a non-zero chance of a broader backlash against consumption, and given the head-start that European consumers have made, European firms may be better placed for that particular scenario).

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65. European Commission, Financing the Recovery Plan for Europe, May 27, 2020.
66. McKinsey, How the European Union could achieve net-zero emissions at net-zero cost, December 3, 2020.

Finally, it depends on the pace and direction of travel of other regions. If other countries also want to get to net zero but start later then there might be some catch-up investment that has already been done in Europe that will benefit those other regions. The parallel is the positive spillover effects that German investment in solar technology in the late 2000s gave to the global industry in terms of economies of scale, or to a lesser extent how the investment in offshore wind undertaken by the UK in the 2010s powered the offshore wind industry.

The case studies of solar and offshore wind suggest that an increase in demand, even for those who are large first movers, does not ultimately guarantee homegrown champions in the relevant technology, with solar cell and module producers today largely concentrated in China and Southeast Asia, and with the offshore wind supply chain spread out over Danish, Spanish and Chinese firms. That suggests that if European policymakers are going to pursue ambitious net zero policies relative to their counterparts, they need to ensure that the benefits of European policies accrue to European companies.

Put all this together and the conclusion is a mixed one. As a result of the net zero targets, one has to start from the baseline that Europe's competitiveness is going to fall. That is because businesses in the region with more ambitious emissions reduction technologies are going to face higher costs from the transition. These costs cannot be passed on entirely to consumers without a hit to domestic demand for those products, or for other products in the domestic market, and consequently a loss in output. This will affects export competitiveness, particularly for the most price sensitive tradable goods.

However, there are three mitigating factors, which European policymakers will have to lean on heavily, to ensure that the transition proves to be a positive impulse for the European economy rather than a negative one. First, Europe will have to implement a carbon border tax in a way that is consistent with its trade relations and without excessive bureaucracy. That would prevent European companies from being penalized by the energy transition. Second, European consumers will have to be encouraged to spend more for innovative products that lower carbon, which arguably requires both a cultural shift and policy support. Finally, it will depend on the pace and direction of travel of other regions. To the extent that firms in other regions would rather free-ride on European innovation by delaying their own net zero transitions, European policy will have to be more aggressive in ensuring that the benefits of Europe's ambitious climate targets accrue to European companies. The long-term benefits of an early transition to net zero are plausible, but the short-term transition is dangerous without the appropriate policies.

The impact of these scenarios should be chastening and sobering. They imply a major shift towards decarbonisation that European societies have committed to and are already making steps towards. The good thing is that Europe's destination is clear. It is aiming for a high-renewables, high-electrification outcome, but with a plan to build a hydrogen economy (though not for transportation), a clear policy choice to use renewable hydrogen, and to encourage and/or take advantage of declining energy demand. The global race for net zero is on, and the targets show just how much society—European or otherwise—is yet to be transformed.

Conclusion

Factors impacting shape of net zero transition pathway			Europe	China	US	Conclusion
National target			Net zero by 2050	Net zero by 2060	None. Patchwork at state level	
Main reference document			European Commission Communique 773, Supporting data and JRSC document	ICCSD Launch Document	"Pathways to 2050: Alternative scenarios for decarbonising the US economy," C2ES	
	Why it matters	**IPCC reference**				
1. Energy demand trajectory	Some regions will choose to rely more or less on energy efficiencies and demand reductions vs others.	In scenarios limiting warming to 1.5°C, primary energy demand declines by -0.1% p.a, with a maximum and minimum range of -1.7% p.a. and 0.54% respectively.	Steady from a high base. -1.1% decline in primary energy demand a year by 2050 in a net zero scenario (BP) vs -0.1% p.a. from 1995-2018 (BP). Delta = 1%. Eight out of 16 external and internal scenarios clustered on a decline in final consumption of 0.80% to 0.98% per annum.	Substantial reduction from high growth. 0.1% increase in primary energy demand a year by 2050 in a net zero scenario (BP) vs 5.8% increase from 1995-2018. Delta = 5.7%. The Tsinghua plan is less ambitious but still strong relative to China's history. The Tsinghua plan shows primary energy consumption rising by 0.3% p.a.- 0.5% p.a. in a 1.5 degrees and a 2 degrees scenario respectively.	Moderate declines relative to history. -1.1% a year decline in energy consumption a year by 2050 (BP) vs +0.4% p.a. from 1995-2018 (BP). Delta =1.5% (moderate).	China's plan assumes the biggest decrease in energy consumption, which may reflect the inefficiencies of an energy system at an earlier stage of transformation as well as a more aggressive commitment to tackling decarbonisation.
2. Electricity share of final consumption vs other carriers (e.g. hydrogen)	The basic choice here is between regions with a high degree of electrification and those with a lower degree of electrification. Without electrification, the choices are fossil fuels, or hydrogen, including e-fuels.	In scenarios limiting warming to 1.5°C, electricity covers 34% - 71% (minimum-maximum range) of final energy by 2050 with no or limited overshoot, up from about 20% in 2020.	Electricity is likely to be just above 50% of final energy consumption. The Commision has targeted 53% by 2050. A composite of internal and external net zero scenarios collected by the EC for Europe suggest electricity share of final energy consumption in 2050 is around 35-65%, with the median clustering around 50%.The remaining final consumption is likely carried by a declining percentage of fossil fuels as well as green hydrogen including e-fuels. Electricity share of final consumption is likely 28%-37% by 2040, according to IEA.	Electricity is 55-68% of final energy consumption by 2050. The share of electricity in final energy consumption will increase to about 55% in the 2 degrees scenario and 68% in the 1.5 degrees scenario, both by 2050 and both from about 25% today. There are no stated targets for hydrogen, but hydrogen is mentioned as important for the transition from a 2 degrees scenario to a 1.5 degrees scenario. The Chinese electrification share will end-up higher than the European share because of Europe's likely higher use of hydrogen and e-fuels. Electricity share of final consumption is likely 35% 42% by 2040, according to IEA.	Electricity is likely 23%-29% of total final energy consumption by 2040, according the IEA World Energy Report, as against Europe's 28%-37% by 2040. The expectation is that the US will continue to lag Europe on electrification going into 2050, and therefore have electricity under 50% of final energy consumption by 2050. The remaining final consumption is likely carried by a declining percentage of fossil fuels as well as blue hydrogen, which the US will promote as a way of developing its domestic energy base.	China has the highest share of electrification by 2040, a reflection of the Chinese state's aim for high nuclear generation, battery electrification in transport, and a less explicit commitment to hydrogen, at least for now.

Factors

Factors impacting shape of net zero transition pathway			Europe	China	US	Conclusion
	Why it matters	**IPCC reference**				
3. Renewables as a share of final demand	This headline number is a shorthand for the level of ambition for each region in the decades ahead.	The IPCC report says that renewables supply 52%-67% (interquartile range) of final demand by 2050, with coal declining to 1%-7%.	In 13 of 16 net zero internal and external scenarios produced by the EC, renewables are over 80% of final energy demand by 2050. If 2040 is the benchmark, then renewable share of total demand is 42% to 62%, according to the IEA. The remainder is fossil fuels.	Renewable share of total energy demand is 70%-85% by 2050 in a 2 degrees scenario and 1.5 degree scenario respectively. The renewable share of electricity is expected to be 90% by 2050 in both a 1.5 and 2 degree scenario. If 2040 is the benchmark, then renewable share of total demand is 25% to 46%, according to the IEA. The remainder is fossil fuels.	Renewable share of total demand is 26% to 50% by 2040, according to the IEA. The remainder is fossil fuels.	In net zero scenarios, Europe, China and the US need to get renewables to over 80% of final energy demand by 2050. The US and China are likely to be behind Europe by 2040, on current projections.
4. Variable renewable share of electricity production	Some regions will choose to use more variable energy to meet their electrification needs, relying on hydrogen and/or battery storage to meet power requirements when energy is not being produced. Other regions will use more constant sources of energy like hydropower and nuclear to meet their electrification needs. In the former situation, more electricity generation is needed relative to the latter.	The IPCC report doesn't put a target for variable energy, but it does say that in scenarios limiting warming to 1.5°C, the share of electricity supplied by renewables is 59%-97% (minimum-maximum range) by 2050.	Variable renewable share of total electricity production by 2040 is 41%-51%, according to the IEA. Nuclear and hydro share is 29-30%. In the hydrogen-centric strategy that Europe is adopting, electricity would be channeled into hydrogen and e-fuels. The share of electricity generation that cannot be met with variable renewables is met with hydrogen run through existing fossil fuel power plants. Electricity generation would have to rise by 3X in this hydrogen-centric scenario.	Variable renewable share of total electricity production by 2040 is 27%-48%, according to the IEA. Nuclear and hydro share is 21-26% The pathway reveals a strong role for nuclear generation, with generation rising by 7x by 2050, understandable given that the ICCSD is in part under the aegis of the nuclear industry. Ultimately,the ICCSD plan envisions getting renewables to 90% of electricity production by 2050 in both a 2 degrees and 1.5 degrees scenario.	Variable renewable share of total electricity production by 2040 is 33%-57%, according to the IEA. Nuclear and hydro share is 19-23%.	Variable renewable shares are likely to be highest in Europe, which is pursuing a hydrogen-centric economy, and the US, which has strong wind resources.

Factors impacting shape of net zero transition pathway	Why it matters	IPCC reference	Europe	China	US	Conclusion
5. What role for carbon capture excluding land-use changes?	This is one component of the 'net' in 'net zero'. To the extent that carbon capture can be used, the energy system would not need to be transformed as quickly.	The overall deployment of CCS varies widely across 1.5°C pathways with no or limited overshoot, with cumulative Co2 stored through 2050 ranging from zero up to 300 GtCO2 (minimum-maximum range) of which zero up to 140 GtCo2 is stored from biomass. This defintion of CCS is excluding agriculture and forestry sinks.	The scenarios see CCS at between 44 MTCO2 to 600 MTCo2, with the median clustering at 200MTCO$_2$. Or 5% of current emissions.	Substantial investment in negative emissions technologies. 510MTCo2e to 880 MTCo2 by 2050, or 6-9% of current carbon emissions are removed using CCS and BECCS in a two degree scenario and 1.5 degree scenario respectively.	In the US, by 2050, CCS and BECCS will remove 375 MtCo2 - 625 MTCo2 per year in the C2ES scenarios, which do not aim for net zero. This is 8-13% of emissions by 2050.	Carbon capture ex-land use changes ends up being a substantial driver of emissions reductions, especially in United States.
6. What happens to transportation?	The decarbonisation of end-demand is a crucial input into how energy systems organise themselves. Ninety One projections are generally optimistic for the industry sectors, but not for buildings and transport sector (IPCC, page 137). The extent to which batteries are used vs hydrogen impacts the amount of electricity that needs to be generated.	The share of low-carbon fuels in the total transport fuel mix increases to 40%- 58% by 2050 in 1.5°C-overshoot pathways.	Battery electrification for passenger vehicles and light commercial vehicles. For trucks, there is no obvious winner, wiith batteries, hydrogen, biofuels, e-liquids and e-gas all in play. For aviation and shipping the technological challenges are enormous. By 2040, low-carbon fuels in the total transport fuel mix increases to 25%-58%, according to the IEA.	The main strategy is electrified transport, though a full analysis is yet to come. The main ICCSD report will be followed by 18 sectoral reports diving deeper into the possible solutions, one of which will focus on transportation. By 2040, low-carbon fuels in the total transport fuel mix increases to 22%-46%, according to the IEA.	The strategy is less determined, but for passenger vehicles is likely to revolve around electrified transport. For trucks, the US is likely to go the hydrogen route because of weaker labour laws. By 2040, low-carbon fuels in the total transport fuel mix increases to 32%-56%, according to the IEA.	The range of estimates is enormous for each region, reflecting the uncertainty of outcomes. Overall, US, China and Europe are mainly pursuing battery electrification for passenger vehicles and light commercial vehicles. For trucks they are likely to split, with the US pursuing more hydrogen and Europe more battery electrification.

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CS_211 01/2021