IEA - Net Zero by 2050: A Roadmap for the energy sector

Executive Summary

The IEA prepared a roadmap at the request of the UK government, who is presiding the 26th Conference of the Parties (COP26) of the UN's Framework Convention on Climate Change, taking place in Glasgow during November 2021.

The roadmap laid by the IEA is "one of many", as the report likes to remind us now and then, and although it mentions "there's no one-size-fits-all approach to clean energy transitions", it does little to show how the solutions proposed affect different economies, how assumptions on technologies vary between regions or who would pay for the changes implied.

Lot of emphasis is put on the need for governments to lead this transition: laying out major climate and energy policies, investing to speed up the time-to-market of new technologies, planning and incentivizing major infrastructure changes, steering users into solutions (i.e. with taxes, banning cars from certain places or taxing road congestion), among others.

Most of the document seems to be targeted for policy makers. Results are presented but usually without any economics or assumptions that justify why a solution is chosen versus another. The questions the energy sector may be asking itself nowadays (i.e. how to address renewable intermittency and back-up costs, EVs vs H_2 trucks for long distance haul, etc.) are not addressed specifically or are only mentioned with general remarks.

The pathway presented looks to achieve net zero from energy-related and industrial process emissions without relying on offsets from outside the energy sector[1] (i.e. forestation[2]) and with little reliance on negative emission technologies. It also tries to maximize technical feasibility by implementing mature technologies first: most of the emission reductions by 2030 come from readily available technologies today, but in 2050 almost half of the reductions come from technologies that today are at the demonstration or prototype phase.

To do this, the IEA proposes to mobilize 90 billion usd of public funding as soon as possible to have demonstration projects ready before 2030. Currently, roughly 25 billion usd are committed.

By doubling historical investment and a dramatic shift in consumer habits, it builds a system that uses 7% less energy in 2030 with an economy 40% bigger. By 2050, the world uses 8% less energy than today with an economy more than twice as big and with a population that is 2 billion larger.

According to the Net Zero Emissions (NZE) scenario, capital investment in energy should rise from 2.5% of GDP in recent years (2.3 trillion usd[3]) to 4.5% by 2030 (5 trillion usd). The majority is spent on electricity generation, networks and electric end-user equipment.

Besides reducing emissions, this massive capital expenditure looks to take electricity to most end-uses, which would demand less energy by making a more efficient use of energy, compared to current solutions. Besides gains from electrification and use of more efficient equipment, the NZE scenario proposes behavioral changes[4] from users to further reduce emissions. These behavioral changes represent -1.7 Gt CO_2eq by 2030 and -2.6 Gt CO_2 eq by 2050 (less than 8% of total reductions).

As a result from all the measures mentioned above, energy intensity (energy supply/ 1000 usd of GDP) drops from 4.5 GJ/1000 usd GDP in the past years, to 3 GJ/1000 usd GDP in 2030 and 1.7 GJ/1000 usd

[1] The energy and industrial sector account for 33.9 Gt CO_2eq, which are around three quarters of total GHG emissions. The other largest source of emissions is agriculture, forestry and other land use, accounting for 10-12 Gton CO_2eq.

[2] IEA metions a potential offset of 1.3 Gt CO_2eq

[3] Of which 836 billion usd were fossil fuels.

[4] Behavioral changes are changes in ongoing or repeated behavior by consumers which impact energy demand, i.e.: flying less, reducing indoor temperature settings in buildings, more use of public transport, etc.

GDP in 2050. This implies an annual improvement of energy intensity of 4.2% between 2021 and 2030, compared to 1.6% in the last decade. Without energy efficiency, behavioral changes and electrification measures, final energy consumption would be 300 EJ higher in 2050, almost 90% higher of the 2050 level in the NZE scenario (344 EJ).

According to IEA, NZE is built on the following principles:

- The uptake of all the available technologies and emissions reduction options is dictated by costs, technology maturity, policy preferences, and market and country conditions.
- All countries co-operate towards achieving net-zero emissions worldwide.
- An orderly transition across the energy sector. This includes ensuring the security of fuel and electricity supplies at all times, minimizing stranded assets where possible and aiming to avoid volatility in energy markets.

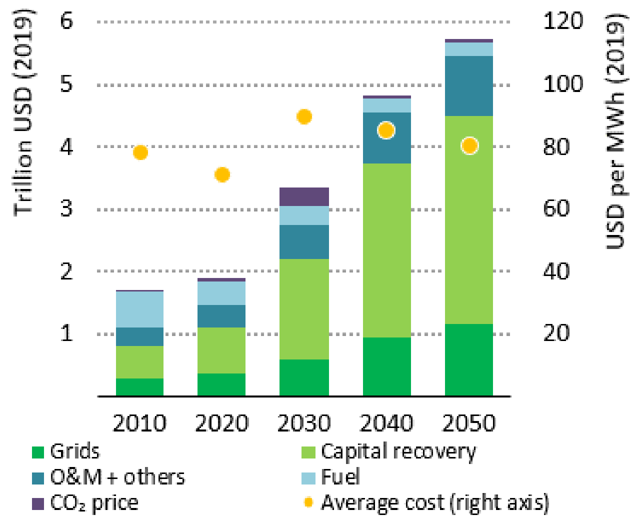
Even though the report may have tried to lay out a neutral scenario to reach net-zero under certain conditions, it arrived at one conclusion that grabbed most of the headlines: producers may need to stop bringing new fields online beyond 2021. The report then becomes highly political, as it may be used to pressure financiers and shareholders to push for reduced upstream funding.

Oil, gas and coal production is expected to drop significantly due to CO_2 prices (see next char). Oil and natural gas supply becomes concentrated in a small number of low-cost producers and oil would trade at a wellhead price of 35 usd/bbl in 2030 and 24 usd/bbl in 2050. This implies a big level of coordination between leading economies and policies (like carbon pricing mechanisms) to avoid carbon leakages. There's no mention of the carbon border adjustments needed to avoid carbon leakage. Expectations are put on countries to achieve great global coordination to achieve this.

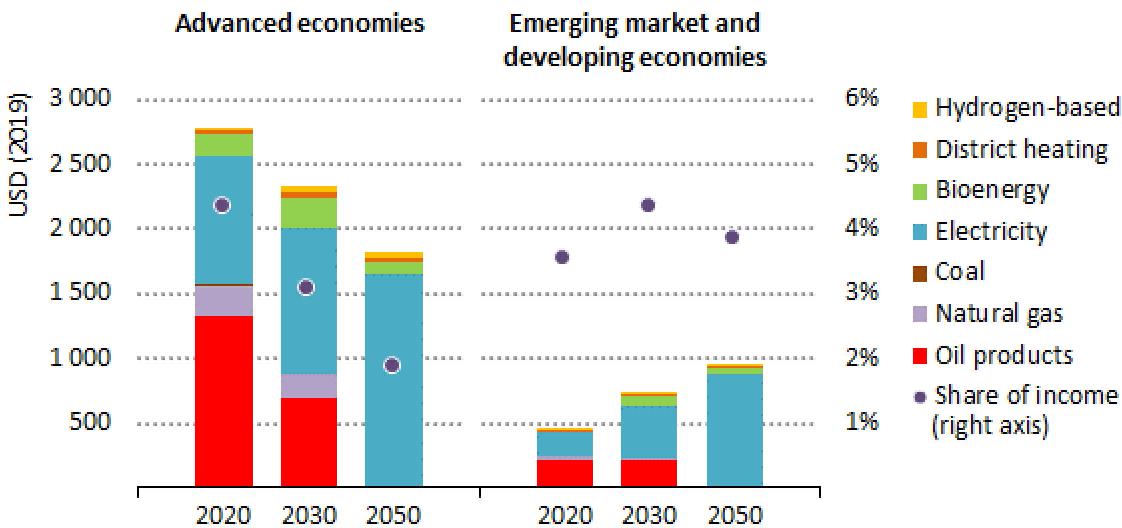
Carbon pricing	**2025**	**2030**	**2040**	**2050**
Advanced economies (usd/ton CO2)	**75**	**130**	**205**	**250**
Natural Gas (usd/MMBTU)	*+4*	*+7*	*+11*	*+13*
Oil (usd/bbl)	*+38*	*+65*	*+103*	*+125*
Coal* (usd/ton)	*+149*	*+258*	*+407*	*+496*
China, Russia, Brazil & S.Africa (usd/ton CO2)	**45**	**90**	**160**	**200**
Natural Gas (usd/MMBTU)	*+2*	*+5*	*+8*	*+11*
Oil (usd/bbl)	*+23*	*+45*	*+80*	*+100*
Coal (usd/ton)	*+89*	*+179*	*+317*	*+397*
Other emerging market and dev economies (usd/ton CO2)	**3**	**15**	**35**	**55**
Natural Gas (usd/MMBTU)	*+0*	*+1*	*+2*	*+3*
Oil (usd/bbl)	*+2*	*+8*	*+18*	*+28*
Coal (usd/ton)	*+6*	*+30*	*+69*	*+109*

**Additional costs for coal are calculated using the average emissions per tonne between bituminous coal and lignite coal.*

Power generation is one of the few technologies where costs assumptions are addressed: by 2030 the assumed LCOEs for wind range between 35-55 usd/MWh, while the ones for solar PV are in the 20-45 (both without considering back-up), which are reasonable values considering we are already seeing similar prices in some regions today. Batteries and grid infrastructure are mentioned as important, but the impact of these two items in the final price of energy is not discussed.



There is a single mention of global electricity costs, which shows they would rise from 71 usd/MWh to almost 90 usd/MWh in 2030 and finally fall to 80 usd/MWh in 2050. Electricity supply becomes much more capital intensive due to the massive increase in renewables and the corresponding need for more network capacity and sources of flexibility. Battery and transmissions costs (and other assumptions regarding these two points) are a constant omission throughout the document.



According to IEA, the average annual bill in advanced economies declines from 2,800 usd in 2020 to 2,300 usd in 2030, thanks to a strong push in energy efficiency and cost-effective electrification. In emerging markets, there is a huge increase in demand because of economic growth, rising income and universal access to electricity. Average bills grow by 60% by 2030 and more than double in 2050. As a percentage of income, it stays relatively flat, but this level of energy bills could mean that governments face huge backlash in emerging economies.

Hydrogen and hydrogen-based fuels[5] are expected to play a role in several sectors: fertilizers, heavy transport, power generation, steel and blending with natural gas. IEA expects demand to be at 212 MMton by 2030 and at 535 MMton by 2050, from 87 MMton today. Both blue and green hydrogen are expected to have a significant role in the net zero pathway, accounting for 40% and 60% of total hydrogen production by 2050 respectively. Even though cost decline assumed by IEA is similar to other projections, demand is more optimistic (specially by 2030). It's questionable the pace of adoption of hydrogen by 2030 due to costs. According to IEA they will be 1.5-3.5 usd/kg (11 to 26 usd/MMBTU) for production, without

[5] Ammonia and synthetic fuels.

considering transport or storage, which would be prohibitive in some applications and economies. There are no economical comparisons made with other solutions as to understand if hydrogen was the best alternative in each proposed application.

Electric car sales increase eighteen fold between 2020 and 2030, accounting for over 60% of sales, which is not in line with other private projections that stand for significantly less than half of market penetration**.** Annual battery production for EVs leaps from 160 GWh today to 6,600 GWh in 2030. This seems too optimistic by two reasons, first according to other EV sales projections reaching half of what IEA estimates by 2030; and secondly because IEA assumes battery capacities more than doubles in ten years, tough the largest number of EVs in China is being sold with small battery capacity. IEA expects demand for critical minerals grows almost sevenfold between 2020 and 2030. This seems optimistic considering the time required to develop these resources, to test new cleaner extracting technologies and for countries to develop policies and laws regarding mining. Lithium demand in particular is expected to grow 30 times of what is today by 2030 and 100 times in 2050.

Steel, along with cement, chemical production and other heavy industries are the last sectors to get decarbonized. Almost 60% of the emissions reduction in IEA's NZE scenario come from technologies that are today either in pilot or demonstration stage. On top of that, "the ease with which many industrial materials and products can be traded globally means that markets are competitive and margins are low. This leaves little room to absorb additional costs […]. It will take time to develop robust global co-operation and technology transfer frameworks or domestic solutions to enable a level playing field for these technologies."

The bottom line is: the IEA prepared **one possible scenario**, with minimal CCUS and off-set solutions, prior to COP26. The result of the scenario is a world where there is no more oil & gas development needed and there is a high electrification of most end-uses. To achieve this scenario there needs to be a great degree of cooperation between the leading economies to stop carbon leakage. At the same time, the document mentions the need for each government to lay out their particular roadmap, with major climate and energy policies, investing, planning, taxes to incentivize a great deal of behavioral changes in users.

Many of the things mentioned seem highly optimistic and it is hard to follow the IEA's reasoning in the scenario they proposed as they do not show most of the assumptions used to arrive at the solutions, or the consequences these changes would have in different regions or economies.

What the IEA says matters. Its forecasts are used by oil companies to shape investment strategies, by governments to create energy policies and by stock market investors who want to understand the future.

Opec said in a memo that the report's message "stands in stark contrast with conclusions often expressed in other IEA reports and could be the source of potential instability in oil markets if followed by some investors,". It labelled the report as "overly ambitious in terms of its assumptions and results," but conceded it "will certainly influence investment decisions, which may curb demand (growth) for fossil fuels."

The American Petroleum Institute argued that any pathway to net-zero "must include continued innovation and use of natural gas and oil, which remains crucial to displacing coal in developing nations and enabling renewable energy."

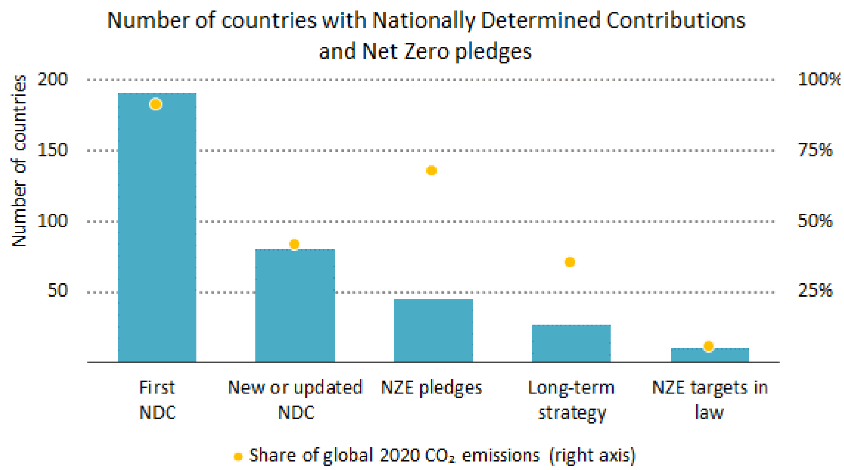
IEA chief Fatih Birol addressed some of the criticisms in a LinkedIn post[6]: "This misses what the IEA is about," he wrote. "For many years, we have been focused on shaping a secure and sustainable energy future for all, which requires transitioning to clean energy. A secure energy future demands this — a world

[6] https://www.linkedin.com/pulse/back-future-story-behind-ieas-net-zero-roadmap-fatih-birol?trk=public_profile_article_view

ravaged by climate change from fossil fuel emissions won't be secure." He further added: "It is important to understand that our work isn't a binding prescription. Our Net Zero Roadmap is designed to illuminate the essential debates on energy and climate in societies around the world and inform policy makers so they understand the implications of their actions – and of their inaction. Our Roadmap sets out a pathway to net zero by 2050. We do not claim it is the only one. Different countries are in very different places on the path to net zero, and each will chart its own course. The IEA is ready to help countries design their own national roadmaps – and to support the international coordination and cooperation that a successful global transition to net zero will require."

2. Today's pledges fall short

There has been a rapid increase over the last year in the number of governments pledging to reduce greenhouse gas emissions to net zero. Net zero pledges to date cover around 70% of global GDP and CO_2 emissions. However, fewer than a quarter of announced net zero pledges are fixed in domestic legislation and few are yet underpinned by specific measures or policies to deliver them in full and on time.



The Stated Policies Scenario takes account only of policies that are in place or have been announced by governments. Annual energy-related and industrial process CO_2 emissions rise from 34 Gt in 2020 to 36 Gt in 2030 and remain around this level until 2050. If emissions continue on this trajectory, with similar changes in non-energy-related GHG emissions, this would lead to a temperature rise[7] of around 2.7°C by 2100.

The Announced Pledges Case assumes that all announced national net zero pledges are achieved in full and on time, whether or not they are currently underpinned by specific policies. Global energy-related and industrial process CO_2 emissions fall to 30 Gt in 2030 and 22 Gt in 2050. If emissions continue this trend after 2050, with similar action on non-energy-related GHG emissions, it would lead to a temperature rise in 2100 of around 2.1°C. This scenario also highlights that existing pledges, even if delivered in full, fall well short of what is necessary to achieve net-zero emissions globally by 2050.

[7] Temperature rise refers to the estimated increase in Global Mean Surface Temperature (GMST) averaged over a 30-year period, expressed relative to pre-industrial levels.

3. Net Zero Emissions (NZE) Scenario

CO_2 Emissions

Global energy-related and industrial process CO_2eq emissions in IEA's NZE fall to around 21 Gt CO_2eq in 2030 and to net-zero in 2050, from 33.9 Gt CO_2eq today. Cumulative energy related emissions reduction between 2020 and 2050 are 460 Gt and, assuming parallel action from forestry, agriculture and other land use sectors, emissions reduction of 500 Gt is achieved, which is consistent with limiting temperature increase to 1.5°C with 50% chance. These changes take place while the global economy more than doubles through to 2050 and the global population increases by 2 billion.

The fastest and largest reductions in global emissions in the NZE are initially seen in the electricity sector. Electricity generation was the largest source of emissions in 2020 (40%), but emissions drop by nearly 60% in the period to 2030, mainly due to major reductions from coal-fired power plants, which are replaced with solar and wind capacity. By 2040, the electricity sector achieves net zero emissions.

Emissions from the buildings sector fall by 40% between 2020 and 2030 thanks to a shift away from the use of fossil fuel boilers, and retrofitting the existing building stock to improve its energy performance. But this sector only represents the 8% of GHG emissions in 2020.

Emissions from industry and transport, which account for 25% and 21% of total emissions in 2020 respectively. Emissions from these two sectors fall by around 20% over the 2020-2030 period, but their pace of emissions reductions accelerates during the 2030s as the roll-out of low-emissions fuels and other emissions reduction options is scaled up.

Nonetheless, there some areas in transport and industry in which it is difficult to eliminate emissions entirely (such as aviation and heavy industry) and both sectors have a small level of residual emissions in 2050. These residual emissions are offset with applications of BECCS and DACCS[8] (1.9 Gt by 2050).

The IEA indicates, in its pathway's building principles, that its strategy to achieve net zero is to uptake all available technologies and that emissions reduction options are dictated by costs, technology maturity, policy preferences, and market and country conditions. One would then expect to find throughout the document details regarding these decisions of a technology over another but, although some assumptions or boundary conditions are made explicit, the reader is left with more questions than answers.

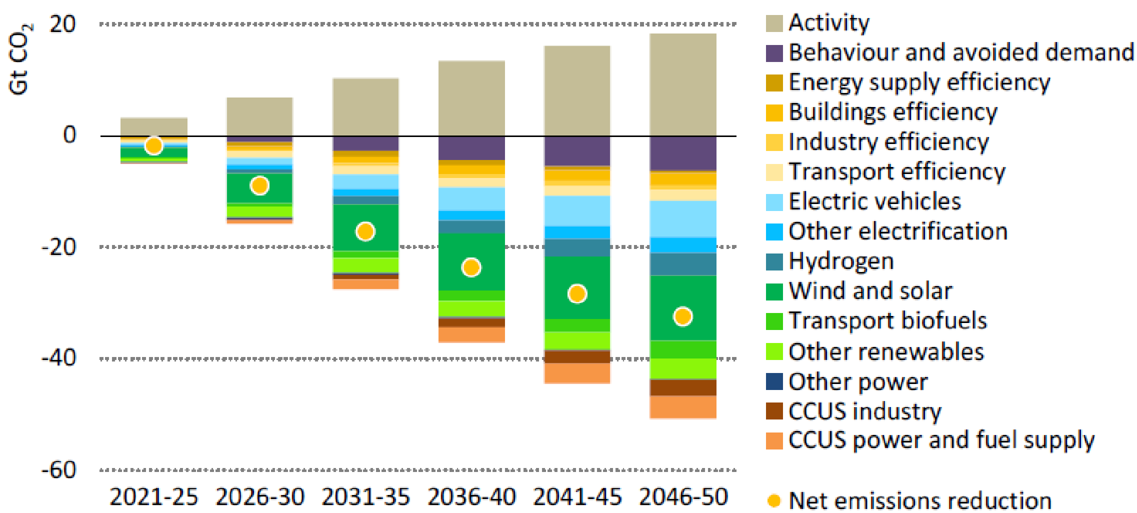
Between 2026-2030: 33% of emissions reduction comes from wind and solar energy, 17% from efficiency improvements; 12% from other renewables (bioenergy, concentrated solar power, geothermal, marine), 8% from electric vehicles adoption, another 8% from behavior and avoided demand[9], 6% from CCUS and 6% from other electrification. Hydrogen accounts for 4% of emissions reduction, 4% for biofuels for transport and other power generation, the remaining 2%.

Between 2046-2050: 23% of emissions reduction comes from wind and solar energy, 14% from CCUS, 13% from electric vehicles adoption, 12% from behavior and avoided demand, 11% from efficiency improvements and 8% from hydrogen. The remaining reductions are from other renewables (7%), electrification (6%) and biofuels for transport (6%).

Average annual CO2 reductions from 2020 in the NZE

[8] BECCS: Bioenergy Equipped with CCUS. DACS: Direct Air Capture with CCS.

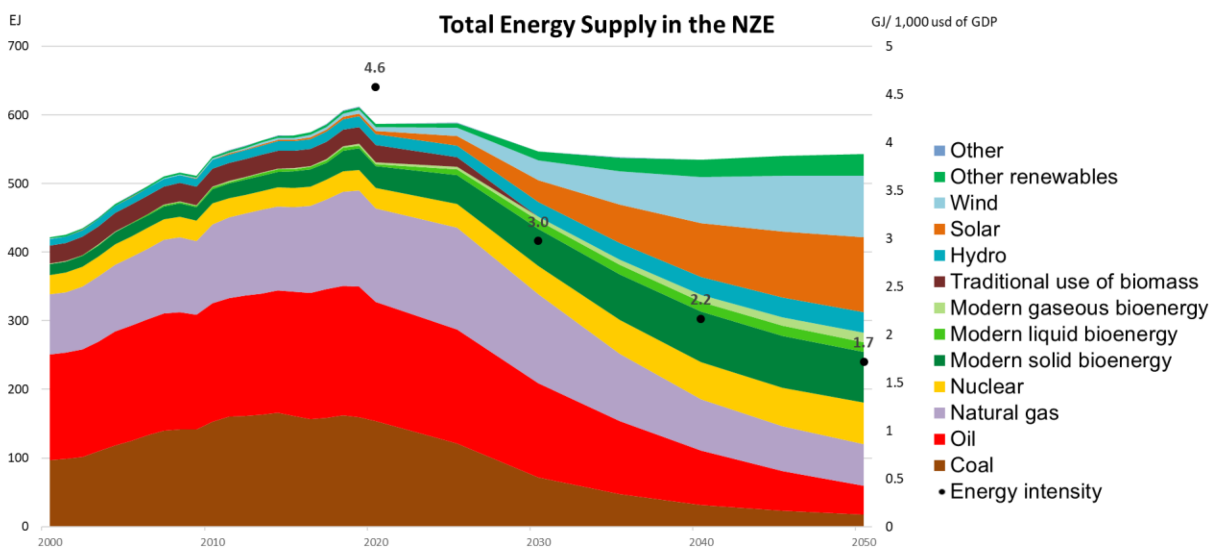
[9] Behavior = change in energy service demand from user decisions, e.g. changing heating temperatures.
Avoided demand = change in energy service demand from technology developments, e.g. digitalization.



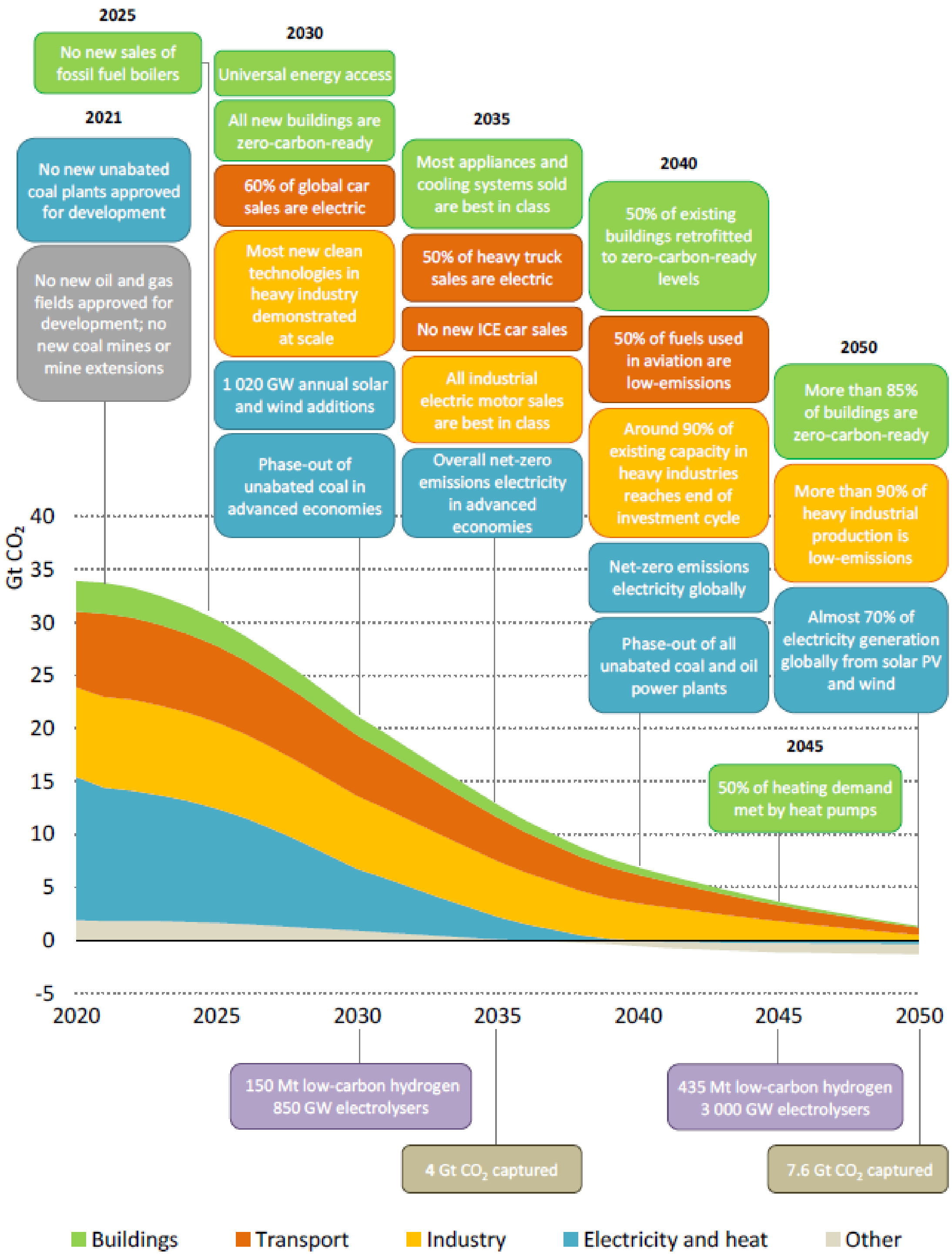
The IEA estimates that 55% of the cumulative emissions reductions in the pathway are linked to consumer choices, such as purchasing an EV, retrofitting a house with energy-efficient technologies or installing a heat pump. Behavioral changes, particularly in advanced economies – such as fewer car trips or foregoing a long-haul flight provide around 4% of the cumulative emission reductions.

Energy Supply

Total energy supply falls to 550 EJ by 2030, 7% lower than 2020. This occurs despite significant increases in the global population and economy because of a fall in energy intensity (the amount of energy used to generate a unit of GDP). This is achieved through a combination of electrification, a push to pursue all energy and materials efficiency opportunities, behavioral changes that reduce demand for energy services, and a major shift away from the traditional use of bioenergy. After 2030, electrification continues to reduce energy intensity, but there is not much opportunity to continue increasing efficiency. Besides, beyond 2030 the production of new low-carbon fuels increases (hydrogen, synthetic fuels) which tends to push up energy use.

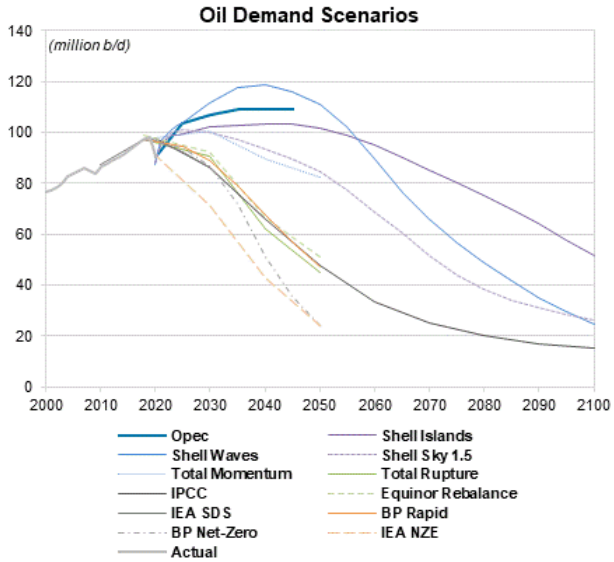


Key milestones in the pathway to net zero

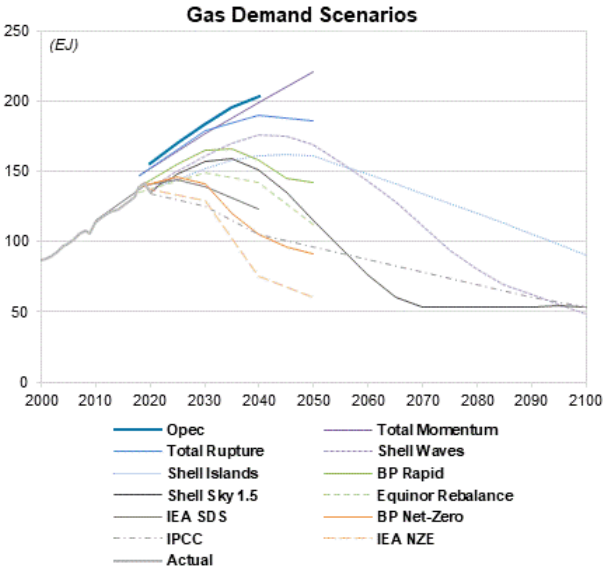


Oil & Gas

IEA's NZE presents one of the grimmest scenarios for the oil and gas industry to date compared to previous projections made by OPEC and other majors: no new project sanctions and exploration for oil, gas or coal are necessary beyond 2021. By 2050, fuels account for just 20% of energy consumed, from almost 80% today.



Actual oil demand since 2000 and projections to 2100 in million barrels per day in a choice of scenarios. Source: Companies and above institutions, Energy Intelligence



Oil demand drops by 20% in 2030 to 70 MMbbl/d and 75% in 2050 to 24 MMbbl/d, down from roughly 90 MMbbl/d today. Oil prices would fall sharply, from around 70 usd/bbl today, to 35 usd/bbl in 2030, 28 usd/bbl in 2040 and 24 usd/bbl in 2050.

Gas demand drops by 55% to 1,750 Bcm from 3,900 Bcm today, after reaching a peak of 4,200bcm in mid-2020s. This clearly suggests a limited role for gas as a bridge fuel. Natural gas prices stay flat at 2 usd/MMBTU in the US, while hovering between 3.5 and 5 usd/MMBTU in EU and Asia.[10]

More than half the natural gas use in 2050 is for hydrogen production with CCS (*blue hydrogen*). In power generation, by 2030 gas accounts for 13% of global energy generation (from 23% today) and by 2050 gas accounts for 2%.

The IEA sees no need for many of the LNG facilities currently under construction or in planning phase. In IEA's view, LNG trade increases from 420 Bcm today for the next five years reaching 500 Bcm, but falling to 160 Bcm by 2050. The surviving producers are the ones with the lowest cost and lower emission resources: Middle East, Russia and Australia, with the US losing most of its share.

As a consequence, gas infrastructure would follow a similar fate after 2030, with some assets being able to be re-purposed to carry low-carbon gas molecules.

Oil and natural gas supply becomes concentrated in a small number of low-cost producers. Despite of this and low prices for hydrocarbons, demand stays low. This implies a big level of coordination between leading economies and policies to avoid carbon leakages. Such policies, like carbon pricing mechanisms and carbon border taxes are barely mentioned in the document.

[10] By 2050 a 10% blending with synthetic methane for buildings, industry and transport is incorporated, which only considering cost of hydrogen feedstock at 1 usd/kg, would increase natural gas price by 1 usd/MMBTU.

This seems particularly difficult to apply in countries where O&G exports make up for most of the state income or where National Oil Companies are less vulnerable to legal or shareholder pressure if the policies mentioned above are not correctly enforced.

About 50% of the fossil fuel use in 2050 is in plants equipped with CCUS (3.5 Gt of CO_2). This comprehends converting natural gas to hydrogen, electricity generation and industrial use, mainly to extend operations of young facilities and reduce stranded assets.

Another 30% of the fossil fuel use in 2050 is for non-energy purposes, where fuel is not combusted and so does not result in any direct emissions (chemical feedstocks, lubricants, paraffin waxes and asphalt). This happens even if the pathway accounts for an uptake in plastic recycling[11].

The remaining 20% is used where technology options are scares (fuel aviation).

Electrification (power generation, grid, demand)

The direct use of low-emissions electricity instead of fossil fuels is one of the most important drivers of emissions reductions in the NZE, accounting for around 20% of the total reduction achieved by 2050. Global electricity demand more than doubles between 2020 and 2050 with the biggest absolute growth occurring in merchant hydrogen production (+12,000 TWh/yr[12]) closely followed by the industry sector (+11,000 TWh/yr). Most of the use in the industry is for low and medium heat and the use of electricity in secondary scrap-based steel production.

The lion's share of the work relies on renewables: by 2030 1,120 GW of renewables would need to be installed per year, more than four times the record set in 2020. By 2050 almost 90% of power generation comes from renewables, with solar PV and wind accounting for nearly 70%.

Annual investment in transmission and distribution grids expands from 260 Busd today to 820 Busd in 2030.

The IEA says solar PV, onshore and offshore wind would be cheaper on a levelized cost of electricity (LCOE) basis than gas-fired combined cycle power stations, unabated coal-fired units or nuclear by 2030 in all the world's major economies, including the US, China, India and the EU (no results shown for other regions). Though the LCOEs shown do not include battery costs or transmission costs associated with the deployment of renewables. Battery and transmissions costs (and other assumptions regarding these two points) are a constant omission throughout the document.

As renewables become more abundant, capacity factors for gas and coal plants drop, while capacity factors for renewables stay relatively flat. Capex cost for most technologies stay flat, except for solar PV and wind off-shore which drop between 1 and 6% per year. Capex for wind on-shore barely drops in any of the markets, which is quite puzzling.

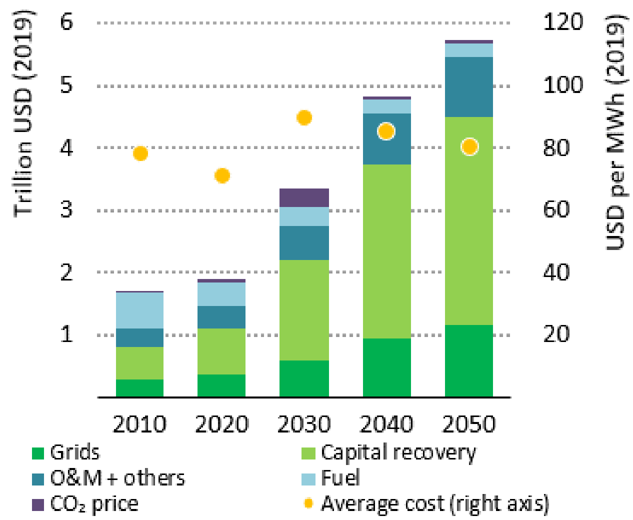
The assumed Wacc for Nuclear, Coal and Gas generation is 7-8% in all markets, while for wind and solar it leans more towards 4%, which we found quite reasonable comparing it to current actual numbers.

Taking all these points into consideration, by 2030 the assumed LCOEs for wind range between 35-55 usd/MWh, while the ones for solar PV are in the 20-45. Which are prices we are seeing today in some regions.

[11] Global reuse of plastics in secondary production increases to 14% in 2030, from 8% in 2020. In 2050 it increases to 35%.

[12] Greater than the current total annual electricity demand of China and the US combined.

There is a single mention of global electricity costs, which shows they would rise from 71 usd/MWh to almost 90 usd/MWh in 2030 and finally fall to 80 usd/MWh in 2050. Electricity supply becomes much more capital intensive due to the massive increase in renewables and the corresponding need for more network capacity and sources of flexibility.



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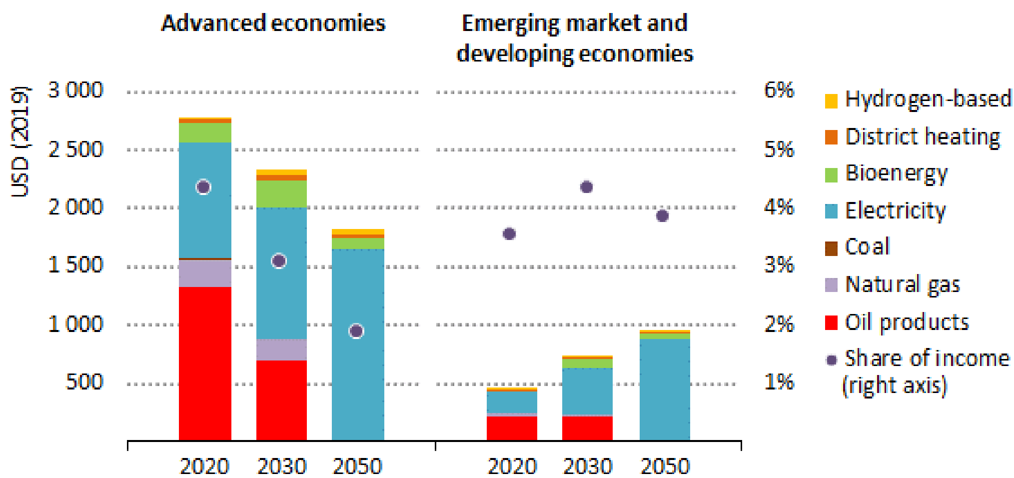


Carbon Capture

Carbon capture and carbon direct removal (CDR[13]) play a relatively small role in the IEA's NZE. The scenarios assessed by the IPCC[14] have a median of around 15 Gt CO_2 captured in 2050 using CCUS (more than double than IEA's), while CDR in IPCC scenarios range from 3.5 to 16 Gt of CO_2 (versus 1.9 Gt CO_2 in IEA's NZE).

Around 95% of the CO_2 captured is stored permanently underground and 5% is used in synthetic fuels. According to IEA, global geological storage capacity is considerably above what is necessary to store the cumulative CO_2 captured in the NZE. Though it is not addressed how geographically close those storages sites are relative to emissions centers, for example.

It is assumed that CO_2 captured volumes increase marginally in the next 5 years from the current 40 MMton/y and then there is a rapid expansion reaching 1.6 Gton captured in 2030. By 2050, 7.6 Gt of CO_2 is captured, of which 5.2 Gt is captured from fossil fuels (2.6 Gt from industries, 1.3 Gt from H_2 production,

[13] Direct Carbon Removal includes Direct Air Capture with CCS (DACCS) and Bioenergy Equipped with CCUS (BECCS)

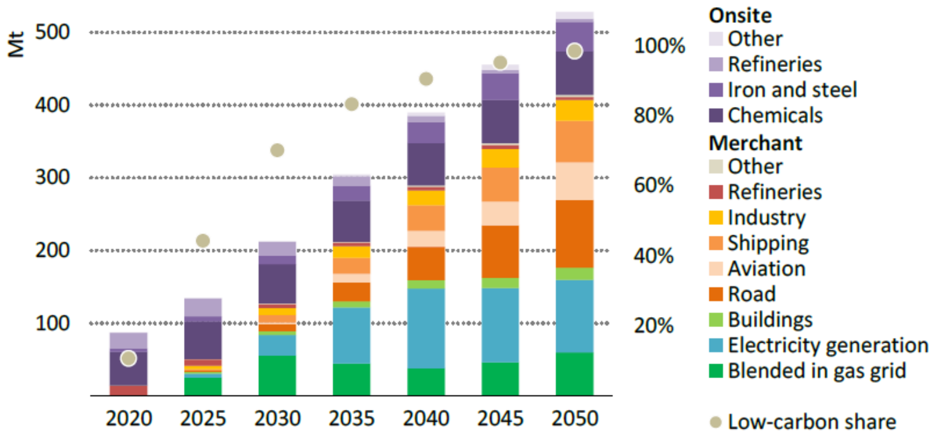
[14] Intergovernmental Panel on Climate Change. In 2018 a report was made with 90 scenarios, of which 18 were net-zero. The comparison shown above only considers these 18 vs IEA's NZE.

0.9 Gt in power generation, 0.4 Gt in other uses), 1.4 Gt is captured from bioenergy and 1Gt is captured directly from the air.

A failure to develop CCUS for fossil fuels would require 15 trillion usd of additional investment between 2021 and 2050 in wind, solar and electrolyser capacity to achieve the same level of emission reductions. This means cumulative global energy investment in the energy sector would be around 10% greater.

Hydrogen and hydrogen-based fuels

Hydrogen demand increases from today's 87 MMton (2020) to 212 MMton by 2030 and 535 MMton by 2050[15]. These estimations seem to be rather optimistic in relation to other projections, specially by 2030[16].



Today hydrogen applications are basically chemicals production (ammonia for fertilizers mainly) and refining. In consistency with oil production reduction, hydrogen demand for refineries is reduced by a 30% by 2030 and by almost 80% by 2050. In the case of hydrogen for fertilizers and other chemicals, its production increases by a 30% by 2050.

New applications for hydrogen arise through the years. By 2030, 55 MMton H_2 are blended in the natural gas infrastructure (15% blend in volumetric terms in average), representing 25% of hydrogen demand. We can infer this would increase costs by 0.5 to 1.5 usd/MMBTU[17], without taking into account the cost of retrofitting current infrastructure and end-use applications.

In the electricity sector, hydrogen and hydrogen-based fuels provide an important low-carbon source of electricity system flexibility. Although these fuels provide only around 2% of overall electricity generation in 2050, this translates into very large volumes of hydrogen and makes the electricity sector an important driver of hydrogen demand (30 MMton H_2 in 2030 and 100 MMton H_2 in 2050). It's hard to understand if this 2% is reasonable since the document makes no effort to show how hydrogen competes in the power generation market and its role as an energy storage option.

Transport accounts for 10% of hydrogen demand in 2030 and almost 40% in 2050. This is mainly due to the role of H_2 in trucks[18] (one third of fuel use in trucks by 2050 along with direct use of H_2); the use of ammonia in shipping (over 60% of total fuel consumption is from hydrogen or hydrogen-related fuels) and the production of synthetic fuels for aviation. The impact of higher costs in transport by trucks and shipping is not addressed, neither the needs for infrastructure development. In the case of aviation fuels, the less costly alternative is actually biofuels but due to their limited availability, hydrogen to produce synthetic

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[15] Hydrogen demand by 2050 in IEA's NZE scenario is over 80% higher than the median of IPCC Scenarios, almost 80% higher than IEA's Sustainable Development Scenario 2019 (300 MMton H_2) and almost 35% higher than BP's Net Zero scenario 2020 (about 400 MMton H_2). However, it is similar to the most optimistic projections (i.e. Hydrogen Council 2017 and Barclays 2020 scenarios).
[16] For most projections, by 2030 demand is closer to 100 MMton H_2.
[17] By 2030, hydrogen costs are estimated between 1.5 and 3.5 usd/kg.
[18] In the case of trucks, it is assumed hydrogen outcompetes batteries when daily driving distances are over ~500km.

kerosene is also used and some aviation emissions are tackled with CDR (without being clear when and why they choose one alternative over the other).

In the case of industry, hydrogen demand increases from 20 MMton in 2030 to 70 MMton in 2050 (13% of total demand), mainly driven by its use in steel production.

In terms of hydrogen supply, almost 70% of H_2 production is low carbon (from roughly 1% today) by 2030, grey hydrogen costs increase significantly[19] due to the IEA's proposed carbon prices[20]. By 2050, over 98% of the hydrogen is low carbon. IEA's pathway gives blue hydrogen a significant role beyond transition: by 2030 almost 50% of low-carbon hydrogen production is from coal or natural gas with CCUS and by 2050 this share is reduced to 40%, and the remaining 60% is produced via water electrolysis (it acknowledges this ratio will vary substantially among regions). IEA claims the reason for preferring one over the other depends on economic factors and on whether CO_2 storage is available.

Hydrogen produced through water electrolysis by 2030 requires installing electrolysis capacity of 850 GW, when today is less than 0.5 GW and main electrolyser companies are starting to build the firsts gigafactories. Current hydrogen strategies target an electrolysis capacity of about a 20% of IEA's estimation and projects in pipeline account for roughly 5% of IEA's estimation. Considering this significant increase in electrolyser capacity development, there is no information in the document regarding the technology assumed (PEM, alkaline, other?) and the requirement of precious metals (i.e. platinum for PEMEC).

By 2050, electrolysis installed capacity should increase to 3,600 GW, with an electricity consumption of 14,500 TWh[21] (20% of global electricity supply) largely from renewable resources (95%). Natural gas use for hydrogen production with CCUS is 925 bcm in 2050, or around 50% of global natural gas demand.

Hydrogen production costs from electrolysis are assumed to fall from 3.5-7.5 usd/kg today to around 1.5-3.5 usd/kg in 2030 (11-26 usd/MMBTU) and 1-2.5 usd/kg in 2050 (7.5-19 usd/MMBTU), without taking into account transport or storage. These costs seem to be in line with most reports, including electrolyser costs and efficiency improvements. In order to achieve the higher end of hydrogen costs by 2050, electricity should cost at least less than 45 usd/MWh. Similar costs are estimated for producing H_2 with natural gas with CCUS (1-2 usd/kg H_2), but probably with lower storage costs.

IEA also states global trade in hydrogen develops over time, with large volumes exported from gas and renewables-rich areas in the Middle East, Central and South America and Australia to demand centers in Asia and Europe with a cost of transport of 1 to 3 usd/kg by 2050. Again, there is no clear information regarding volumes traded, how they are estimated or even how this 15 to 41.5 usd/MMBTU (hydrogen production costs plus transport) compete with other alternatives across different regions.

Electric Vehicles, Batteries, Lithium

Electric vehicle (EV) car sales increase eighteenfold between 2020 and 2030, hitting more than 55 million EVs sold annually by then, accounting for over 60% of sales versus 4.6% last year. However, the most optimistic private projections turn out to be more conservative, reaching approximately 30% market share by 2030 (32 million units sold according to BMI[22]) and reaching 71% by 2040 (83 million according to BMI). Meanwhile, SFA[23] is at lower values for its projections, 15 million in 2030 (13%) and 40 million (31%) in

[19] If hydrogen is produced from the steam methane reforming pathway, the additional costs for CO_2 prices would be between 0.9 to 1.3 usd/kg in most cases. If hydrogen is produced from coal, the additional costs could be about two times the ones indicated for natural gas.
[20] See Carbon Prices chapter.
[21] It assumes a load factor of 46%.
[22] BMI stands for Benchmark Mineral Intelligence, is a price reporting agency based in London and provider of specialist information for the supply chain of lithium ion batteries for electric vehicles.
[23]SFA Oxford is a world-renowned authority on platinum-group metals and provides in-depth market intelligence on battery raw materials and hydrogen.

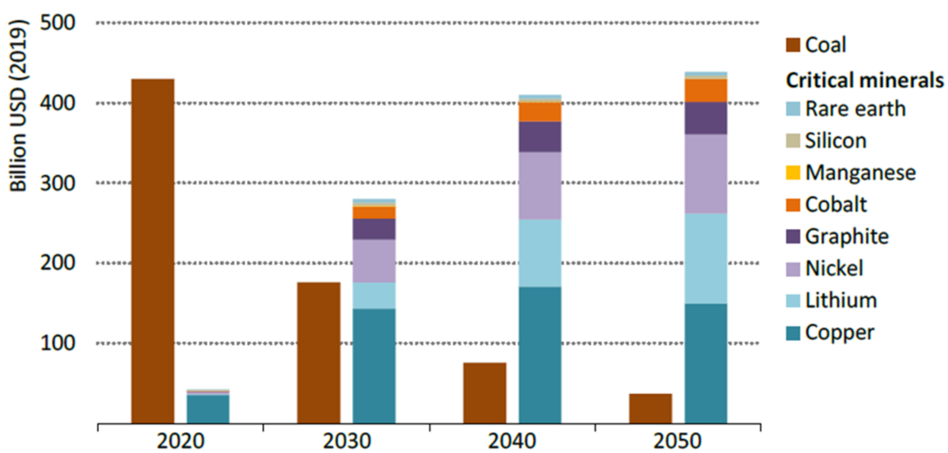
2040. The gaps in the estimates could mean that the NZE plan is too optimistic and therefore difficult to be achievable with the objective of arriving with an almost completely electrified fleet by 2050.

The electrification of heavy road transport is slower because it depends on batteries of higher density than those currently available on the market. Other factors such as the weight of batteries, the high energy and power requirements, and limits on driving autonomy also affect electrification, but fuel cell advancements make significant progress primarily after 2030. Thus, fuel-cell vehicles and EVs account for 30% of sales, up from less than 0.1% in 2020. Biofuels appear as an alternative in the energy transition during 2020 until developments manage to scale up technology in fuell cells and electrification and lower costs.

Annual battery production for EVs leaps from 160 GWh today (about 53 kWh battery capacity per Ev) to 6,600 GWh in 2030 (reaching up to 120 kWh average battery capacity per EV) – the equivalent of adding almost 20 gigafactories of 35 GWh each, every year for the next ten years. These projections are not in line with forecasts made by BMI and SFA, who indicate a demand for batteries for 2030 of 1,744 GWh and 1,828 GWh, respectively. BMI stands for a stable average of 53 kWh per vehicle capacity, and for 2030 SFA raises up to 120 kwh, the same level as IEA[24]. Only by 2040, BMI indicates reaching 5,000 GWh due to EV sales projection.

Governments must guarantee a stable electricity supply to the grid to avoid demand peaks (a possible secondary effect of the massive adoption of chargers in urban areas), as well as the renewable sources of supplying this energy. IEA estimates that EV public charging units will go from 1 million in 2020 to 40 million by 2030. SFA places public and private charging at 140 million units by 2030, and the EU aims to have 1 charger per 10 EVs~~.~~

Demand for critical minerals (copper, lithium, nickel, manganese, cobalt and rare earths) grows almost sevenfold between 2020 and 2030 in the IEA's NZE. This seems optimistic considering the time required to develop these resources, to test new cleaner extracting technologies and for countries to develop policies and laws regarding mining.



Today's production is highly concentrated in a small number of countries[25] making supply vulnerable to political instability and export restrictions. There's also concerns on land-use, social backlash, competition for scarce water, corruption and even human right abuses and child labour (as with cobalt from the DRC).

[24] Currently in China the best-selling electric car has just 14 kWh of battery capacity, so it seems optimistic assuming that the massiveness in big cities would be achieved in larger battery capacities and therefore increase the overall capacity average from 53 kWh up to 120 kWh.
[25] https://www.linkedin.com/pulse/how-make-sure-critical-minerals-enabler-bottleneck-clean-fatih-birol

There are only 9 mentions of the word 'lithium' in the whole document. One of the mentions is that demand of lithium for use in batteries grows x30 to 2030 and is more than 100 times high in 2050. In the BMI projection the growth is about x10 to 2030, and ~x30 to 2040.

The lithium market (today 4 Bn[26]) is expected to reach 27 Busd by 2030 and 71 Busd by 2040 according to BMI's volume demand projection. As for IEA estimations, no prices or volumes assumptions are mentioned.

Steel

CO_2 emissions from heavy industry decline by 20% by 2030 and 93% by 2050 in the NZE. Optimizing the operational efficiency of equipment, adopting the best available technologies for new capacity additions and measures to improve material efficiency play an important part in this. However, since there are limits to how much emissions can be reduced by these measures, almost 60% of emissions reductions in 2050 in the NZE are achieved using technologies that are under development today.

The ease with which many industrial materials and products can be traded globally means that markets are competitive and margins are low which leaves little room to absorb additional costs. According to the IEA it will take time to develop the global co-operation required and technology transfer frameworks or domestic solutions to enable a level playing field for these technologies. Heavy industries use capital-intensive and long-lived equipment, which means facilities usually have a lifetime of over 40 years. If net zero is to be achieved 2050, there is a narrow window for action (one cycle of investment decision).

IEA's pathway assumes that in the steel industry, electricity and other non-fossil fuels account for nearly 70% of final energy demand in the sector by 2050, up from just 15% in 2020. This shift is driven by technologies such as scrap-based electric arc furnaces (EAF), hydrogen-based direct reduced iron (DRI) facilities, iron ore electrolysis and the electrification of ancillary equipment. The share of coal in total energy use drops from 75% in 2020 to 22% by 2050 in the NZE, of which 90% is used in conjunction with CCUS.

Technologies that are currently on the market deliver around 85% of emissions savings in steel production to 2030. They include material and energy efficiency measures and a major increase in scrap-based production. After 2030, the bulk of emission reductions come from the use of technologies that are under development, including hydrogen-based DRI and iron ore electrolysis. Several CCUS-equipped process technologies are also deployed.

Carbon Price

Little is said about carbon prices and other policies that will drive investments in the proposed net zero pathway. It is mentioned that "*a broad range of energy policies and accompanying measures are introduced across all regions to reduce emissions in the NZE. This includes: renewable fuel mandates; efficiency standards; market reforms; research, development and deployment; and the elimination of inefficient fossil fuel subsidies. Direct emissions reduction regulations are also needed in some cases".* But without much further detail or any specific recommendation.

The IEA's NZE does assume the implementation of CO_2 prices across all regions. They are expected to be introduced in the immediate future across all advanced economies for the electricity generation, industry and energy production sectors (130 usd/ton by 2030 reaching 250 usd/ton by 2050). Lower prices are assumed for China, Russia, Brazil and South Africa (90 usd/ton by 2030 and 200 usd/ton by 2050) and, for other developing countries, it is assumed that they pursue more direct policies to adapt and transform their energy systems and so the level of CO_2 prices is lower than elsewhere (reaches 55 usd/ton by 2050).

[26] IEA stands that today's lithium market value is 1Bn, not in line with current lithium production (314.000 tns) and prices (aprox. usd 13.000 /tn). However, further IEA projections get close to BMI's to about 32.6 B by 2030, 83.8 Bn by 2040 and finally (not addressed by BMI) 112.4 Bn by 2050.

It is not explained how this carbon taxes are estimated: are they fixed to what is necessary for sustainable technologies to outcompete current emitting technologies? Do they stop oil and natural gas from being demanded globally to the level the NZE assumes? Also there is no mention regarding carbon border adjustment mechanisms to avoid the potential carbon leakages that could arise from the different carbon prices among regions.

To understand the impact of these carbon prices, we calculated the additional costs they would imply for natural gas and oil relative to their average emissions and the impact in power generation in the case of coal. The proposed carbon prices seem to be consistent with decreasing fossil fuels demand (and keeping them low) and enhancing the uptake of renewable electricity. By 2030, most of the electricity produced with natural gas[27] would have an additional cost of around 30 to 60 usd/MWh and between 90 to 130 usd/MWh when produced with coal.

Oil price by 2050 is almost 25 usd/bbl, so when the carbon tax is included that price could reach 125 to 150 usd/bbl, which is twice as much as it is today.

CO2 prices for electricity, industry and energy production in the NZE and impact in fossil fuel costs

	2025	2030	2040	2050
Advanced economies:				
Carbon price	**75**	**130**	**205**	**250**
Equivalent to:				
Natural Gas (usd/MMBTU)	*+4*	*+7*	*+11*	*+13*
Oil (usd/bbl)	*+38*	*+65*	*+103*	*+125*
Coal (usd/MWh)	*+72*	*+124*	*+196*	*+239*
Selected emerging market and developing economies*				
Carbon price	**45**	**90**	**160**	**200**
Equivalent to:				
Natural Gas (usd/MMBTU)	*+2*	*+5*	*+8*	*+11*
Oil (usd/bbl)	*+23*	*+45*	*+80*	*+100*
Coal (usd/MWh)	*+43*	*+86*	*+153*	*+191*
Other emerging market and developing economies				
Carbon price	**3**	**15**	**35**	**55**
Equivalent to:				
Natural Gas (usd/MMBTU)	*+0*	*+1*	*+2*	*+3*
Oil (usd/bbl)	*+2*	*+8*	*+18*	*+28*
Coal (usd/MWh)	*+3*	*+14*	*+33*	*+53*

*China, Russia, Brazil and South Africa.
Additional costs for coal are calculated as usd/MWh produced in a power generation open cycle facility.

[27] Combined cycle.