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# Pathways

## Decarbonisation of electricity generation: The foundation stone for achieving net zero

June 2022

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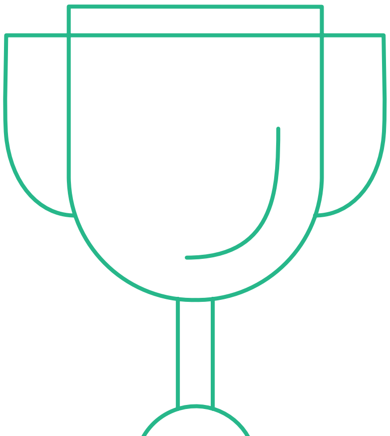
# Introduction:<br>The task ahead and the opportunities



Humanity's strategy for reaching net zero could be crudely described as "electrify everything we can and decarbonise electricity generation". There is, of course, much more to it than this. But it is true that the virtual elimination of carbon emissions from electricity generation is a necessary condition for reaching net zero. It is not a sufficient condition, but with electricity generation expected to be roughly 50 per cent of total final energy demand in 2050 (and possibly more if green hydrogen becomes viable), it would get us a decent chunk of the way there.

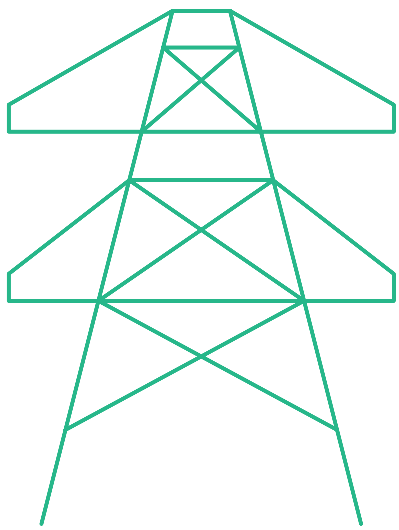
In this paper, which is the second in our "path to net zero" series,[1] we examine the outlook for the electricity sector in a net zero scenario, including how much of the economy can reasonably be electrified by 2050, what the technical challenges are with decarbonising electricity generation, and how much capital it is likely to require to achieve this outcome.

From a technical perspective, particularly if we include the production of green hydrogen in our thinking, large swathes of economic activity can be electrified. Different technologies are available; however, their contribution will be bound by their limitations: hydro is dependent upon topography and precipitation, geothermal is dependent on geology, biomass offers limited sustainable potential, and nuclear is expensive. This means there is a huge focus on wind and solar as the mainstays of the decarbonisation process, technologies that have proven cheap and with resource potentials far exceeding human energy needs. There is no technical reason why, supported by energy storage, these technologies cannot effectively fully decarbonise electricity generation.

The real question is the cost, which defines how quickly we, as a society, wish to decarbonise. Large amounts of capital investment will be necessary. The average of the estimates by the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), and Bloomberg New Energy Finance (BNEF) suggest a total capital need of $US53.4 trillion out to 2050, which is more than half of all the capital managed by asset managers globally today.[2] For investors with the appropriate expertise and investment horizon, this represents one of the largest sector investment opportunities of the next three decades.

1. Our earlier paper, "Pathways – The path to net zero: The challenges and opportunities for real assets investors", November 2021, can be found here.
2. BCG, "Global Asset Management 2021" (July 2021).

# The future energy and electricity system



Energy is foundational to economies and societies. We need it to heat our homes, cook our food, use appliances and devices, and move ourselves and goods around. It has also played an epoch-changing role at times – cheap, accessible coal played an important role in sparking the first industrial revolution, and the discovery of oil and the mastering of drilling techniques to access it changed our societies, transport systems, and economies immeasurably in the 20th century, particularly in the aftermath of World War II.

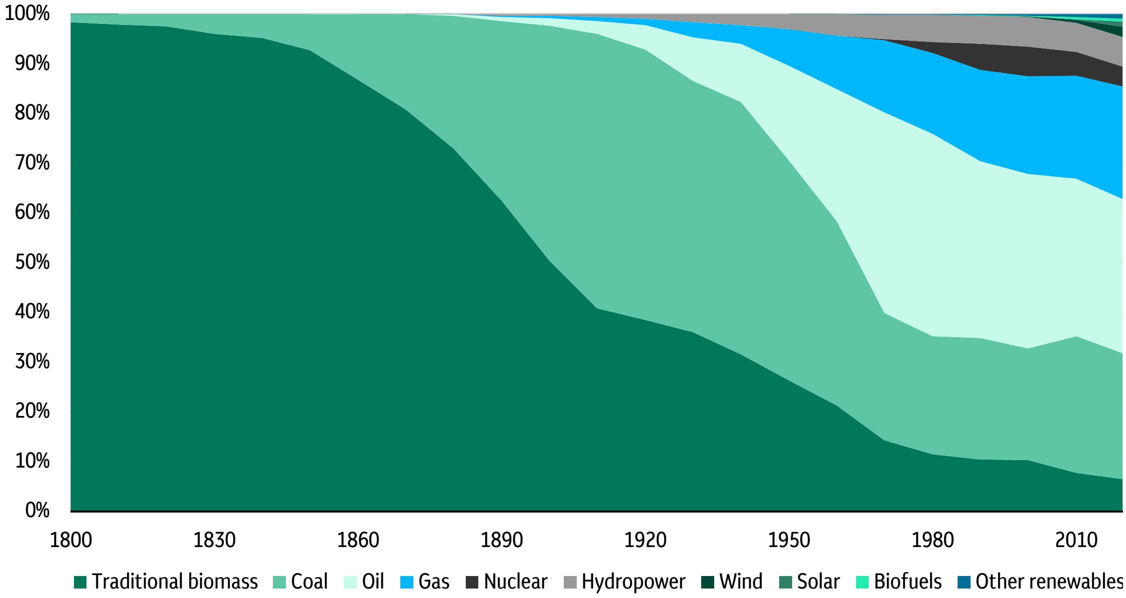
Indeed, the mix of energy that the world relies on has changed significantly over time, as new sources of cheap energy have become available, and the structure of our economies and the types of energy they need have evolved. Figure 1 shows the world's energy supply mix over the past 220 years. Several points are noteworthy:

- Prior to the industrial revolution, traditional biomass – wood – was the overwhelming source of energy.
- Coal's share of the energy mix rose sharply from around 1850 onwards, as the industrial revolution spread to Germany and the US.
- Oil's rise came after 1950, as cheap Middle Eastern oil began to dominate global supply, the world adopted automobiles in great numbers, and the internal combustion engine (ICE) became ubiquitous.
- Gas has grown significantly in importance in the past half century as pipelines to capture and use it were built, its compelling economics were recognised, and its relatively clean nature (compared with coal and oil) grew in importance.
- Renewables, even today, are a small share of primary energy consumption. They are a larger share of final[3] consumption, though, and are growing rapidly.

The important point here is that while the energy transition will require large changes in the energy sources we rely on and the technologies we use, seismic shifts such as this are neither new nor unique to the current period.

3. Final consumption refers to the energy ultimately used by our societies and economies, while primary energy demand is the total amount of energy used to produce that final, end-use energy. The difference is primarily the energy losses that come from thermal, mostly fossil fuel-based power generation.

Figure 1:
World's primary energy supply mix over the past 220 years




Source: Our World in Data (June 2022).

## Economic activity and energy demand

Given its importance for economic activity, it is not surprising that growth in energy consumption correlates with growth in gross domestic product (GDP). Indeed, the correlation between the growth in the world's energy consumption (measured on a final demand basis) and growth in global GDP (measured on a purchasing power parity (PPP) basis) was 0.91 between 1980 and 2020 (Figure 2). Energy consumption grows more slowly, however, as we tend to become more energy efficient over time, something that is reflected in the sizeable negative intercept term (-2.0 per cent) in a regression of energy demand growth against GDP growth.

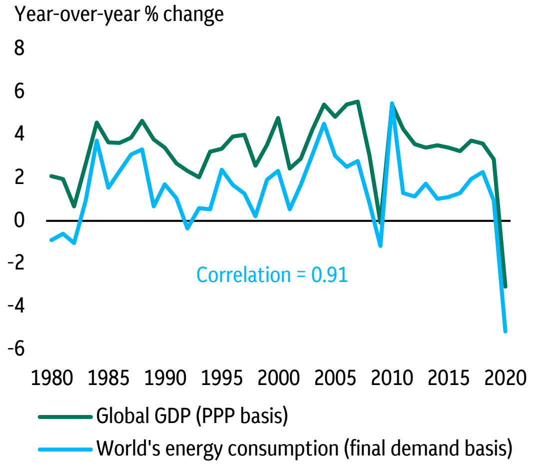
*Growth in global final energy demand = -2.0% + 1.0*global GDP growth*

This is due in part to improving energy efficiency over time, the result of technological advancement and changes in behaviour, but changes in economic structure also play a role. Economies with higher levels of GDP per capita tend to have larger services (or tertiary) sectors and the energy-intensive industrial (or secondary) sector is a smaller proportion of economic activity compared with economies at an earlier stage of development.

There also may be an "energy saturation" effect at play, whereby marginal economic activity requires less and less energy. This is the idea that we need only so much energy for heating, cooling, cooking, lighting, and appliance use. Once people have reached that saturation point, growth in demand for energy slows down, potentially quite dramatically. Indeed, some of the world's most developed economies – mainly in Europe – have seen a decline in demand for energy over the past 20 years.[4] Statistically, these effects are likely to lower both the intercept term and the co-efficient on GDP over time.

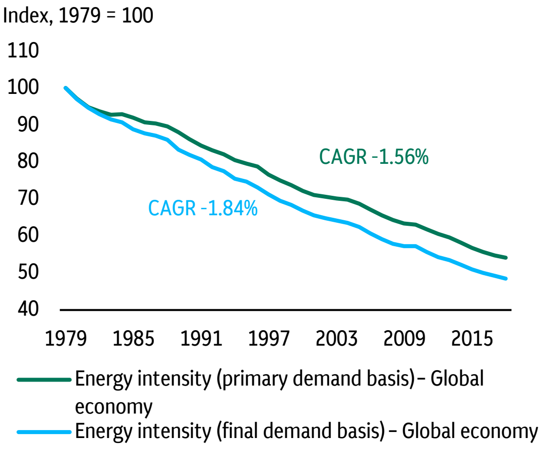
All these effects amount to a strong downtrend in energy intensity over time. Between 1979 and 2018[5] the energy intensity of the global economy – energy used per unit of GDP – declined between 1.5 per cent and 1.9 per cent per year, depending on which measure of energy demand one uses (Figure 3). The decline has also been remarkably consistent, with energy intensity rising in only one of those 40 years, for both metrics.[6]

Figure 2:
Energy consumption and economic activity are highly correlated




Sources: International Monetary Fund (IMF) World Economic Outlook (WEO) database (June 2022), BP's Statistical Review of World Energy (June 2022).

Figure 3:
The energy intensity of our economies has declined consistently over time




Sources: Macquarie Asset Management calculations, IMF WEO database (June 2022), BP's Statistical Review of World Energy (June 2022), IEA data and statistics (June 2022). CAGR = compound annual growth rate.

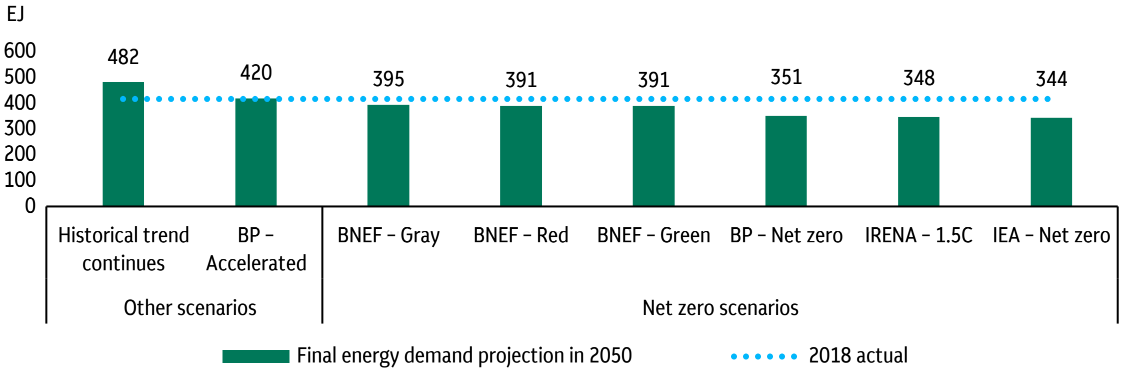
4. Primary energy demand 1999-2019 (to avoid the artificially low base of 2020 for comparison) from BP's Statistical Review of World Energy 2021.
5. This is the last year for which we have data for both primary and final energy demand.
6. 1984 for primary energy consumption and 2010 for end-use energy consumption.

## Energy consumption and the energy transition

The transition to a net zero world is a multidecade project, which means the task is to decarbonise not simply today's $US103.9 trillion global economy,[7] which has a final energy consumption of 423 exajoules (EJ) per year,[8] but rather an economy that is roughly 2.2 times that size in real terms.[9]

One question that flows from this is how much energy the global economy will be consuming in 2050. If the historical relationship of the past four decades shown above continues, final energy demand in 2050 is likely to be around 482 EJ. But most forecasters expect, in their net zero scenarios, that energy consumption will actually fall over the next three decades (Figure 4). Indeed, all forecasters shown in Figure 4 believe energy demand will be in the 340-395 EJ range in 2050 – the IEA's net zero emissions scenario predicts energy consumption of 340 EJ in 2050, 19.6 per cent below the level of 2022[10]; in BP's net zero scenario, energy consumption falls to 351 EJ in 2050, 17.0 per cent lower than 2022[11]; BNEF models three scenarios – Green, Gray, and Red – with energy consumption declining to 391 EJ in the Green and Red scenarios and 395 EJ in the Gray scenario[12]; and in IRENA's 1.5C scenario, energy consumption is 348 EJ in 2050, 17.7 per cent lower than its 2022 level.[13]

Figure 4:
End-use energy demand projections by forecaster

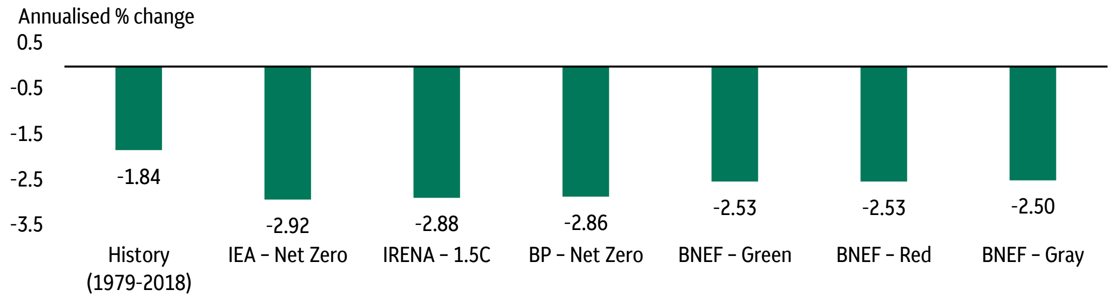



Sources: Macquarie Asset Management calculations, BNEF's New Energy Outlook (NEO) 2021 (July 2021), IRENA's "World Energy Transitions Outlook: 1.5C Pathway" (June 2021), IEA's "Net Zero by 2050: A Roadmap for the Global Energy Sector" (June 2021), BP's Energy Outlook 2022 (March 2022). Other scenarios include BP's accelerated case, which assumes $CO_2$ equivalent emissions fall to around 10 $GtCO_2e$ by 2050.

7. The IMF's estimate of the size of the global economy in 2022.
8. This 2022 figure is calculated by taking the last actual data point we have for 2018 and projecting forward based on energy consumption's historical relationship with GDP.
9. Assumes that labour productivity growth averages over 2020-2050 what it did during 1980-2020 and that global growth downshifts in line with the slower growth in working-age population as the world's population ages.
10. IEA, "Net Zero by 2050: A Roadmap for the Global Energy Sector" (June 2021).
11. BP, "Energy Outlook 2022" (March 2022).
12. BNEF NEO 2021 (July 2021).
13. IRENA, "World Energy Transitions Outlook: 1.5C Pathway" (March 2022).

These all represent an acceleration in the rate of decline in the energy intensity relative to what has been achieved historically. After falling by 1.8 per cent per year between 1979 and 2018, most forecasters have energy intensity declining by almost 3 per cent per year between now and 2050 (Figure 5). In addition to the efficiency and saturation trends mentioned above, part of this expected acceleration is likely due to the expected electrification of large amounts of economic activity.

Figure 5:
Implied changes in energy intensity – Historical versus forecasted




Sources: Macquarie Asset Management calculations, BNEF's NEO 2021 (July 2021), IRENA's "World Energy Transitions Outlook: 1.5C Pathway" (June 2021), IEA's "Net Zero by 2050: A Roadmap for the Global Energy Sector" (June 2021), BP's Energy Outlook 2022 (March 2022).

## Electrification – How far and how fast

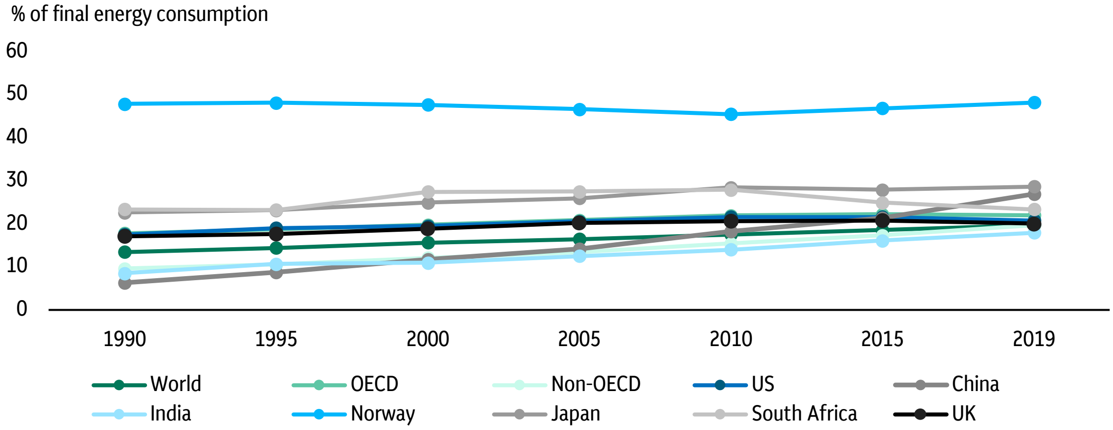
Over the next three decades, we believe the electrification process is likely to be most intense in transport (particularly light-duty vehicles), heating, and parts of industry. Electrification has a double-barreled impact on energy consumption:

- From a final demand perspective, a lot of this comes from the more energy-efficient nature of electric motors compared with ICEs and heat pumps compared with boilers.
- From a primary demand perspective, the replacement of thermal (fuelled) power plants with non-fuelled power plants such as hydro, solar, and wind reduces primary energy demand for electricity generation by avoiding the elevated conversion losses of thermal power plants.

As of 2019, electricity accounted for 19.7 per cent of final energy consumption globally, although there is considerable variation by region and country (Figure 6). Norway's degree of electrification of almost 50 per cent is at a level roughly in line with what is required from the global energy system to achieve net zero emissions (see below for more detail). Norway benefits from abundant hydroelectric power, from which almost all (98 per cent) of its electricity is generated. Its industry and household sectors are also highly electrified relative to other countries, and it leads electric vehicle (EV) take-up in proportionate terms with 90 per cent of 2021 car sales being EVs,[14] thanks to some heavy implied carbon taxes on ICEs.[15]

14. BNEF, "Electric vehicle outlook 2022" (June 2022).
15. See "The Norwegian Vehicle Electrification Policy and Its Implicit Price of Carbon", Lasse Fridstrom (January 2021).

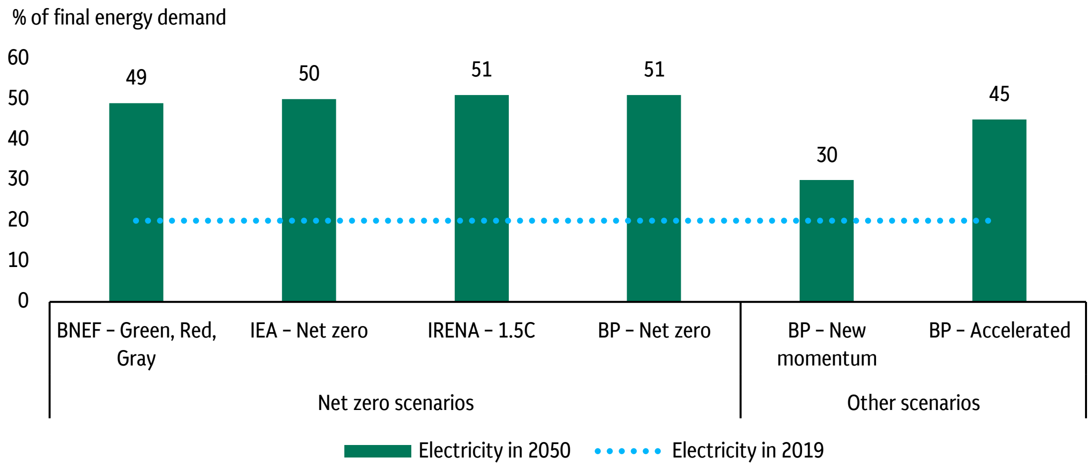
Figure 6:
Electricity as a share of final energy consumption by region and country




Source: IEA data and statistics (June 2022).

Forecasts for the percentage of final energy consumption that will come from electricity in 2050 are also in a tight range, this time around 50 per cent – the IEA expects 50 per cent; BNEF, 49 per cent; BP, 45-51 per cent depending on the scenario; and IRENA, 51 per cent (Figure 7).

Figure 7:
Direct electrification as a percentage of final energy consumption in 2050 by forecaster



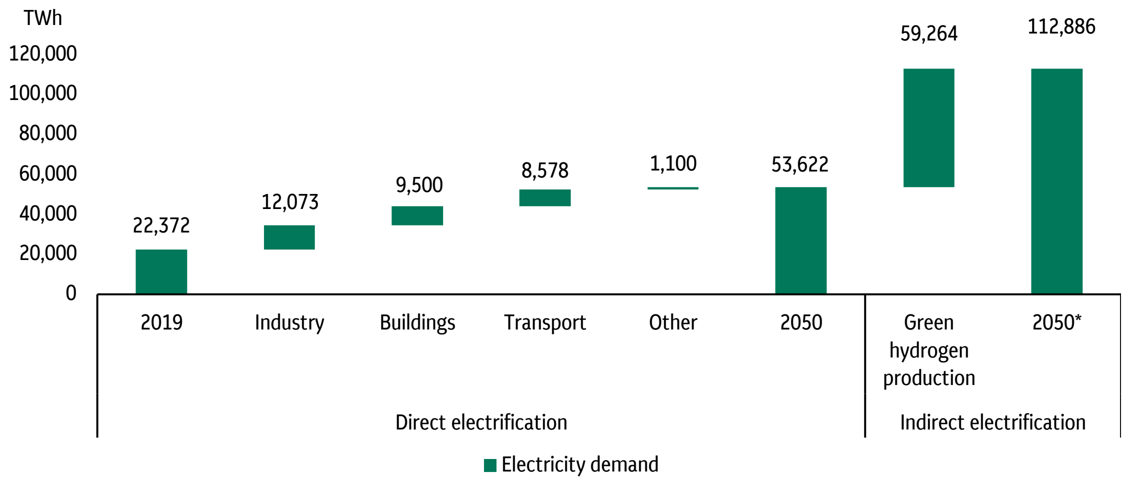

Sources: Macquarie Asset Management calculations, BNEF's NEO 2021 (July 2021), IRENA's "World Energy Transitions Outlook: 1.5C Pathway" (June 2021), IEA's "Net Zero by 2050: A Roadmap for the Global Energy Sector" (June 2021), BP's Energy Outlook (March 2022). Other scenarios include BP's accelerated case, which assumes $CO_2$ equivalent emissions to fall to around 10 $GtCO_2e$ by 2050.

**What are the key drivers of electrification? Figure 8 shows BNEF's breakdown by sector.**

- **Buildings:** In 2019, the buildings sector was responsible for a large share of electricity demand, with 10,505 terawatt hours (TWh) consumed across residential and commercial buildings. But there is significant potential to electrify and decarbonise further using heat pumps and direct electric boilers and heaters.
- **Industry:** In 2050, the largest demand for electricity could come from industry as switching to electric boilers and furnaces becomes more common. This could result in a doubling of electricity consumption, from 9,616 TWh in 2019 to 21,689 TWh in 2050.
- **Transport:** With significant scope for electrification of light-duty vehicles in particular, electricity demand could increase significantly to 8,911 TWh in 2050, implying that around 95 per cent of passenger vehicles will be electric by 2050.

The main uncertainty for electricity demand comes from indirect electrification prospects. If green hydrogen becomes viable, then electricity demand could reach 59,264 TWh in 2050, more than double its 2019 level. If this materialises, then the share of electricity in final energy demand could reach as much as 71 per cent in 2050.[16]

Figure 8:
Direct and indirect drivers of electricity demand in 2050




Source: Macquarie Asset Management calculations, based on BNEF's New Energy Outlook (NEO) 2021 (July 2021).
* BNEF Green scenario under which hydrogen is manufactured via water electrolysis powered by wind and solar.

16. Refers to BNEF Green scenario. BNEF, "New Energy Outlook" (July 2021).

# Technical challenges on the decarbonisation road

With most analysts expecting electricity demand to reach around 50 per cent of final energy demand by 2050, critical questions arise from a decarbonisation point of view: Can we have an electricity generation system based overwhelmingly on wind and solar? Can such a system provide us with the necessary amount of power and provide it reliably and cost effectively?

At the same time, with 50 per cent of energy demand remaining in non-electric uses, such as for heat and transportation fuels, there is the additional question of whether green hydrogen will significantly contribute to the energy transition over the next three decades. It can substitute for fossil fuels, both directly in terms of being a fuel (for industry, transportation, and heating) and indirectly by being used to create sustainable synthetic fuels (transport). The size of its contribution depends on a range of variables. If hard-to-electrify segments of the economy become powered by green hydrogen[17] we could see much higher demand for electricity than is currently assumed by most analysts. In this section we examine these issues as well as their implications for the transition.

## Can the electricity system achieve 100 per cent decarbonisation?

There are low- or zero-carbon energy sources beyond wind and solar. But hydro is dependent upon topography and precipitation, geothermal is reliant on geology, and biomass offers limited sustainability potential. Nuclear is expensive, as is carbon capture and storage today. Meanwhile, wind and solar's available resources vastly surpass global energy needs. It is estimated that 0.22 per cent of the landmass covered in photovoltaics (PV) would satisfy global energy demand.[18] One critical question therefore is, technically speaking, can an electricity system be run using only wind and solar? In short, the answer is yes, in our view, although its cost may increase towards the tail end of the decarbonisation process.

In this section we outline some of the challenges of an electricity network based solely on wind and solar power and the potential solutions to those challenges. The key challenge is dependency on meteorological conditions which cause the output of wind and solar to fluctuate seasonally, within the 24-hour daily cycle, and even by the minute when weather conditions shift suddenly.

Solar has a daily cycle, resulting in some output every day, but it is still subject to volatility from weather patterns and variations in cloud cover. Its output is also effectively zero at night. Wind has longer and less predictable cycles – it can blow for days or even weeks on end but then be quiescent for a similar length of time. But, unlike solar, it does have the advantage of being able to supply power for a full 24-hour cycle.

17. Green hydrogen refers to hydrogen produced from water electrolysis, a process that consumes electricity to split water into hydrogen and oxygen.
18. https://www.sciencedirect.com/science/article/pii/S266711312200002X

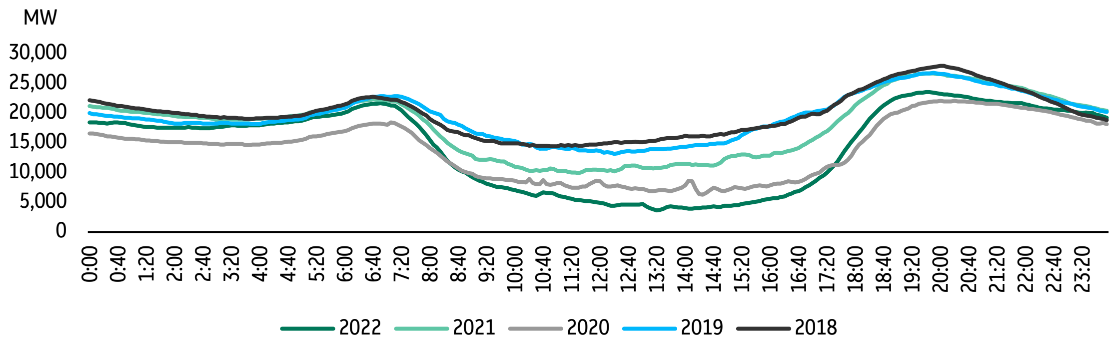
**Challenge 1 – Short-term variability.** Renewable electricity generation from an individual asset can change by the minute when wind speeds slow or clouds move past a solar installation. Such rapid fluctuations can make these intermittent power sources difficult to handle for the grid operator, as any fluctuation has to be instantaneously compensated by another power generation asset.

Grid stability is not a new problem, however. A greater share of renewables in the energy supply mix intensifies the challenge, but having fast frequency response has always been necessary for grid stability and the maintenance of a reliable electricity supply. Utility-scale batteries, which are already in use, can alleviate much of this concern, primarily because of their extremely fast response time, which can be measured in seconds or even fractions of seconds. Flywheels have the potential to replace the natural spinning reserve lost by decommissioned turbines, should batteries prove insufficient.

**Challenge 2 – Diurnal mismatch problem or "duck curve"**. The load curve of a system typically has a trough at night when people are sleeping, a small peak early in the morning as people make breakfast and prepare for work or school, and a larger peak in the early evening when people return from work and turn on appliances and lights and cook food. Thermal power generators are well placed to deal with these intraday fluctuations due to their ability to increase output on command (although there is a lag, the size of which varies by the type of plant). But it is different with renewables. Solar supply increases rapidly after sunrise, maximizes around noon or early afternoon, and then decreases quickly as the sun dips towards the horizon late in the day. At night its output is effectively zero.

The result is an intraday mismatch between when power is produced and when it is needed – in the early mornings and evenings, solar's output is low while demand is high. The resulting "net load", i.e. demand from the system not met by renewables power, has a quite sharp peak in the mornings and evenings but is low during the day. As renewables penetration of the energy mix rises over time this effect intensifies, as shown in Figure 9 below. It is called the "duck curve effect" because the lines on the graph take on the appearance of a duck over time.

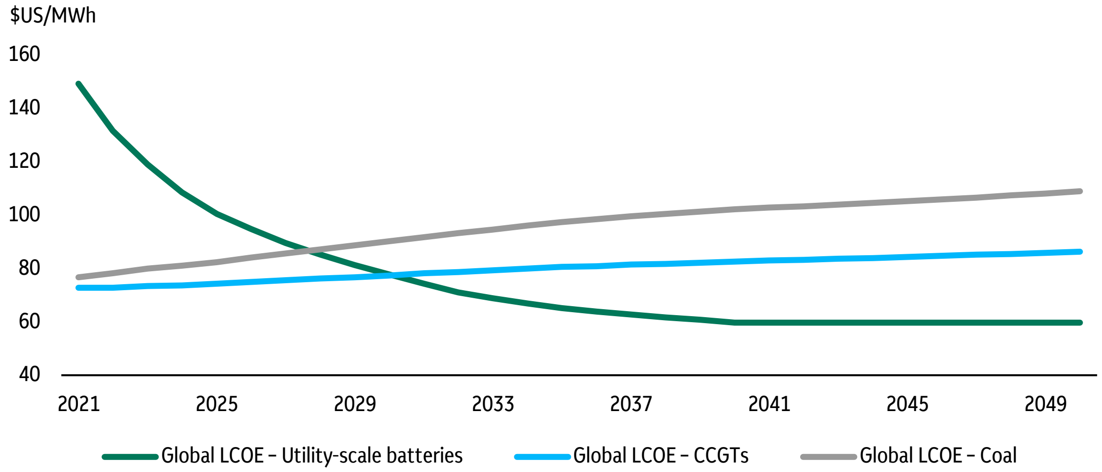
Figure 9:
The "duck curve" of the net electricity load in California




Source: California Independent System Operator (June 2022). Data refer to the same calendar day in April throughout the period between 2018 and 2022.

Thermal plants, particularly gas turbines, are able to supply the fluctuating net load and have been the main option to date. But as the peaks in the curve become steeper and shorter, the economics of thermal plants deteriorates, spreading a large, fixed cost over less and less output and pushing the ramp rates of these turbines to their limits. The cost of peak power then begins to rise. But energy storage is another option. The economics of batteries is well suited to daily cycling and although they are currently more expensive than combined cycle gas turbines (CCGTs) on a levelised cost of electricity (LCOE) basis, that is set to change around 2030 (Figure 10).[19]

Figure 10:
Outlook for LCOE of utility-scale batteries



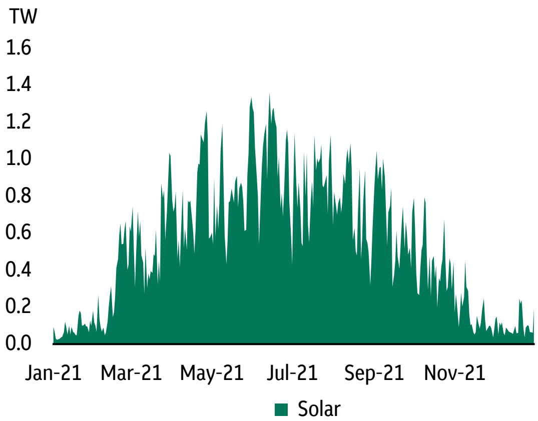

Sources: BNEF LCOE database (June 2022), IMF WEO database (June 2022). Notes: 1. This is a four-hour battery with 50 per cent capacity. 2. Global LCOE is calculated as a GDP-weighted average of US, China, Germany, France, UK, Japan, and India.[20]

**Challenge 3 – Seasonal supply shortfalls.** In hot climates, solar power generation, from a seasonal perspective, tends to correlate well with demand – air conditioning use is usually higher in the summer months when the power output from solar is greater (Figure 11). It may also correlate well within the day, as air conditioning use tends to increase into the early afternoon, which is when solar power often reaches its zenith.

In moderate and cold climates, solar power generation tends to correlate poorly with demand, as there is less need for air conditioning in the summer but a large need for heating in the winter. In certain regions wind may be better correlated with seasonal demand (Figure 12), but there is still a large amount of variation in output day to day, week to week, or even winter to winter.

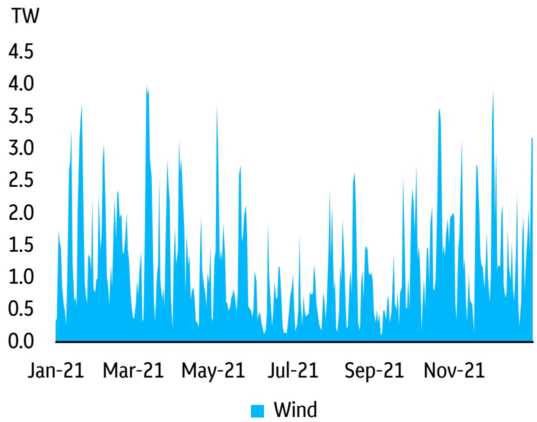
19. It is worth noting that the cycling assumptions can play a role in battery economics.
20. For utility-scale batteries, France is not included because data on costs are not available. For coal, both France and the UK are not included in the calculation for the same reason.

Figure 11:
Solar power generation in Germany




Source: www.energy-charts.info (June 2022).

Figure 12:
Wind power generation in Germany

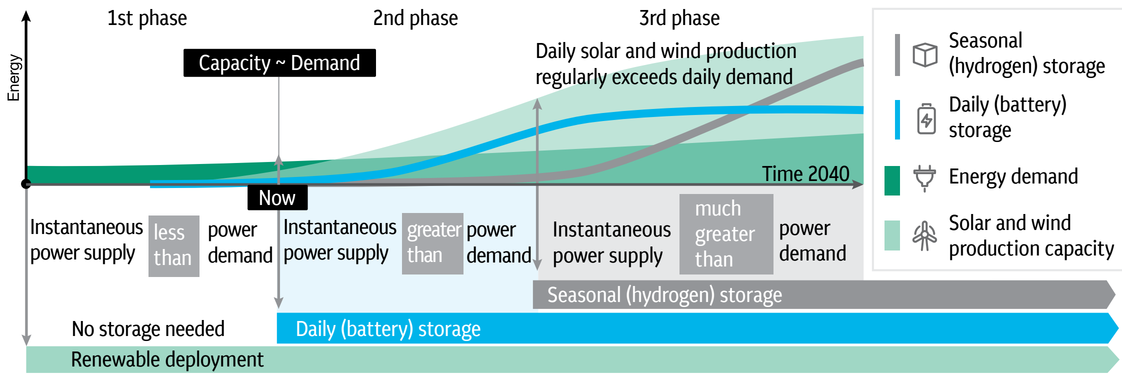



Source: www.energy-charts.info (June 2022).

The economics of batteries is not well suited to seasonal energy storage, as infrequent cycling results in excessive amortisation costs per unit of energy stored. In some specific markets, pumped hydro storage (PHS) can serve this long-duration storage requirement. However, PHS is very geographically specific. For areas without the requisite topographical features, a different technology would be needed. Large amounts of energy can be stored through chemical storage and green hydrogen (i.e. hydrogen made from renewables-powered electrolysis) could meet this need, although it is currently expensive. Another option is simply to overbuild wind power capacity sufficiently to meet demand even during the less favourable season. These challenges mean that an energy transition driven by wind and solar is likely to proceed in three distinct phases (Figure 13) that will play out over decades.

**Phase 1.** This phase begins when renewable energy sources first enter the energy system and continues up until the point at which energy storage is required. In phase 1, the intermittent power supply from renewables can be managed by dispatchable generators modulating their outputs to ensure electricity supply matches demand. Intermittent power output is generally below the load level (though some "curtailment" of surplus renewable power happens later in the phase), and traditional generators remain the mainstay of electricity supply. Almost all battery storage deployed is for ancillary grid services, and not energy shifting.

Figure 13:
The three-phase energy transition




Source: Macquarie Asset Management analysis.

**Phase 2.** This phase starts when cost-effective energy storage meaningfully enters the electricity network for energy shifting. Batteries increasingly replace peaker plants, making greater renewables deployment possible. In this phase, energy storage is used for shifting energy within a 24-hour window, such as storing excess solar production during the day for use during the peaks in demand in the evening and at night, or for storing excess wind power when output is above normal or required levels.[21] Renewables are capable of meeting all demand in summer (the seasonally favourable period due to the extra energy generated by solar) at the end of phase 2, but not all year round due to the reduction in solar output and increase in demand during winter in colder regions. In some markets, particularly in the sunbelt of the world, this may effectively be enough to fully decarbonise the power sector, as seasonable storage may not be required.

**Phase 3.** The final phase begins at the point where the usefulness of 24-hour storage caps out. However, in markets where seasonal variations in renewables generation and demand are significant, long-duration storage, clean energy imports, or considerable overbuild of renewable capacity will be required to meet winter demand.

Seasonal storage requires large amounts of energy to be stored for long periods of time at a cost-effective rate per kilowatt hour (kWh). This is unlikely to be achieved with storage systems that have capital expenditure (capex)-dominated costs of storage and instead favours storage systems with low per-kWh capex but potentially significant variable per-kWh costs, such as green hydrogen production and storage.

21. Wind has fewer cycles than solar, and battery economics are heavily dependent on regular cycling. That said, towards the latter stages of the energy transition, when wind generation capacity is a larger proportion of total energy than it is today, wind will be above required levels far more often than it is now.

## Impact of hydrogen production on the electricity system

A potentiality that could really move the needle for electricity demand is if green hydrogen becomes viable by 2050. Indeed, according to some estimates, green hydrogen could more than double electricity demand in 2050 compared with a situation in which green hydrogen does not become competitive.[22]

Hydrogen is the most abundant element in the known universe, accounting for about 75 per cent of its mass and around 90 per cent by atom count.[23] On Earth, hydrogen is less abundant, but it is still available in huge quantities. The challenge is that it is usually attached to something else – hydrocarbons or water – and it needs to be separated from them to be used as pure hydrogen that burns cleanly, producing only water as a by-product.

Hydrogen has multiple potential use cases:

1. **Transport.** Hydrogen fuel cells are already used to power buses. Batteries appear to have the jump on hydrogen for light-duty vehicles, but there is the possibility that fuel cells become more widely adopted for heavy-duty vehicles such as trucks. Sustainable, synthetic fuels derived from hydrogen using Fischer-Tropsch[24] processes, for example, can also be used in aviation and shipping.

2. **Buildings.** Hydrogen can be mixed with natural gas, or indeed replace it in full, to heat buildings, although in the latter case hydrogen-compatible boilers would be needed.

3. **Industry.** The fossil fuels currently used in furnaces and boilers could be replaced by hydrogen. In steel, for example, hydrogen can be used as a reducing agent, replacing the coal that is traditionally used in a blast furnace[25] and currently responsible for 8 per cent of global carbon dioxide ($CO_2$) emissions.[26]

4. **Seasonal storage.** A fully decarbonised energy system must provide electricity, heat, and fuel around the clock and year round. Battery storage can complement renewables during the day and night cycles, while hydrogen can play an important role in storing energy to deal with the seasonal swings.

In 2020, global hydrogen demand was around 90 million tonnes (Mt),[27] almost all of which was produced from fossil fuels (grey hydrogen), a process that is very $CO_2$ intensive. But hydrogen can also be produced by using an electrolyser to run a current through water ($H_2O$) to break the bonds

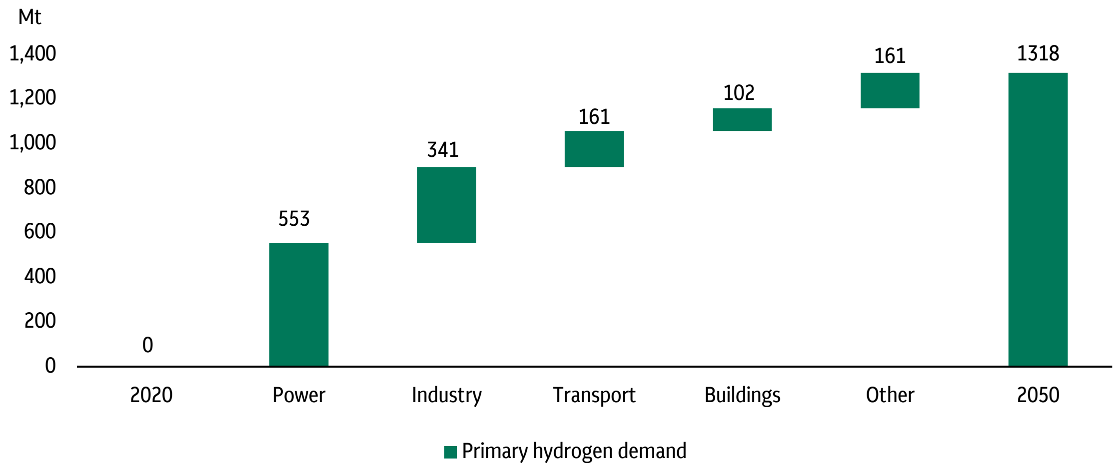
22. Based on the BNEF Green scenario in the NEO 2021 (see Figure 8).
23. Los Alamos National Laboratory (https://periodic.lanl.gov/1.shtml).
24. The Fischer-Tropsch process is a fully proven technology that was first invented in 1925 and was used by both Germany and the UK during World War II to produce synthetic fuel, with Germany producing as much as 124,000 barrels per day in 1943. Indeed, synthetic fuel accounted for half of Germany's total oil production during the war (see Daniel Yergin, The Prize – The epic quest for oil, money and power, page 327). But when the war ended, and with the advent of cheap Middle Eastern oil, the need for it declined. The Fischer-Tropsch process allows the conversion of a mixture of carbon monoxide (CO) and hydrogen ($H_2$) into liquid hydrocarbons (e.g. gasoline) under high temperatures and high pressure in the presence of a catalyst (e.g. iron).
25. Carbon plays an important role in the cast iron and steel industry, contributing to the hardening of the metal. Therefore, it will likely remain an alloying element. The quantities required for alloying are a small share of the carbon (coal) currently used in iron and steel production.
26. McKinsey & Company, "Decarbonization challenge for steel" (June 2020).
27. IEA, "Hydrogen: More efforts needed" (November 2021).

between the hydrogen (H) and the oxygen (O). If the electricity used is produced with clean energy, such as from renewables, the hydrogen is clean. Its vast potential as a fuel, and its zero-carbon nature, make it extremely attractive from an energy transition perspective. A key issue today is its cost. At present green hydrogen is a nascent industry with low scale and a high cost structure, making it uncompetitive with grey hydrogen and with natural gas, although its cost could drop quickly if the sector scales up.

We believe the competitiveness of hydrogen depends on a range of factors: the capex and operating-expense costs of electrolysers; the price of electricity; the price of fossil fuels, particularly natural gas; and the level of any carbon price. A full analysis of the cost trajectory and prospective competitiveness of green hydrogen is beyond the scope of this paper[28] but if capex costs and the cost of renewable power fall at the rates that some analysts expect, it could be that sometime between 2030 and 2050 green hydrogen is not only cheaper than grey (produced from fossil fuels) and blue hydrogen (produced from fossil fuels but with the carbon output neutralised by carbon capture and storage), but also cheaper than natural gas.[29]

If this tipping point eventuates, we could see, given its multiple use cases, a sizeable expansion in the demand for, and production of, green hydrogen. With it taking around 50 megawatt hours (MWh) of electricity to produce 1 tonne of hydrogen, this could have a large impact on electricity demand. Indeed, by some estimates this could more than double electricity demand by 2050, largely eliminating the use of fossil fuels.

Figure 14:
**Green hydrogen demand projection by sector**




Source: Macquarie Asset Management calculations, based on the Green scenario in BNEF NEO 2021 (July 2021).

28. See our upcoming Pathways paper on hydrogen, where we will explore these issues in more detail.
29. BNEF, "1H2022 Hydrogen Market Outlook: Exponential growth ahead" (February 2022).

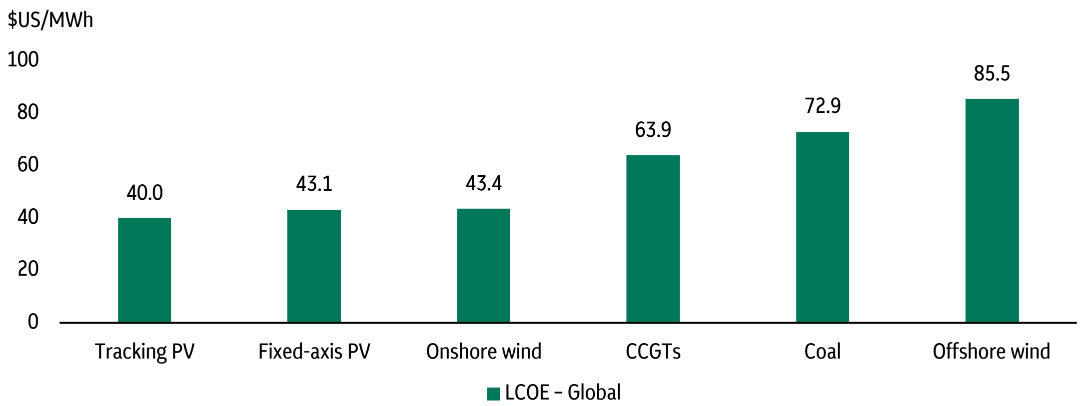
# Capital need of the energy transition

Completing the energy transition is going to require large amounts of capital. For renewables to supply all the world's electricity in 2050, wind and solar capacity will need to expand from around 1,539 gigawatts (GW) in 2020[30] to 22,723 GW by 2050.[31] This will need to be supported by a large amount of energy storage, and grids will need to be reinforced and extended. In this section we analyse the amount of capital needed in each of these areas.

## Wind and solar – The $US20 trillion question

With electricity expected to account for 50 per cent of total final energy use in 2050, demand is expected to increase from 22,372 TWh (as of 2019) to 53,622 TWh, a compound annual growth rate (CAGR) of 2.9 per cent for 31 years. With renewables now materially cheaper than most other forms of electricity, the great bulk of this extra energy is likely to come from solar and wind. At the global level it is now only offshore wind that is more expensive than gas and coal, while, on average, solar and onshore wind are around 41 per cent and 33 per cent cheaper than coal and gas, respectively, on a LCOE basis (Figure 15).

Figure 15:
LCOE by power source

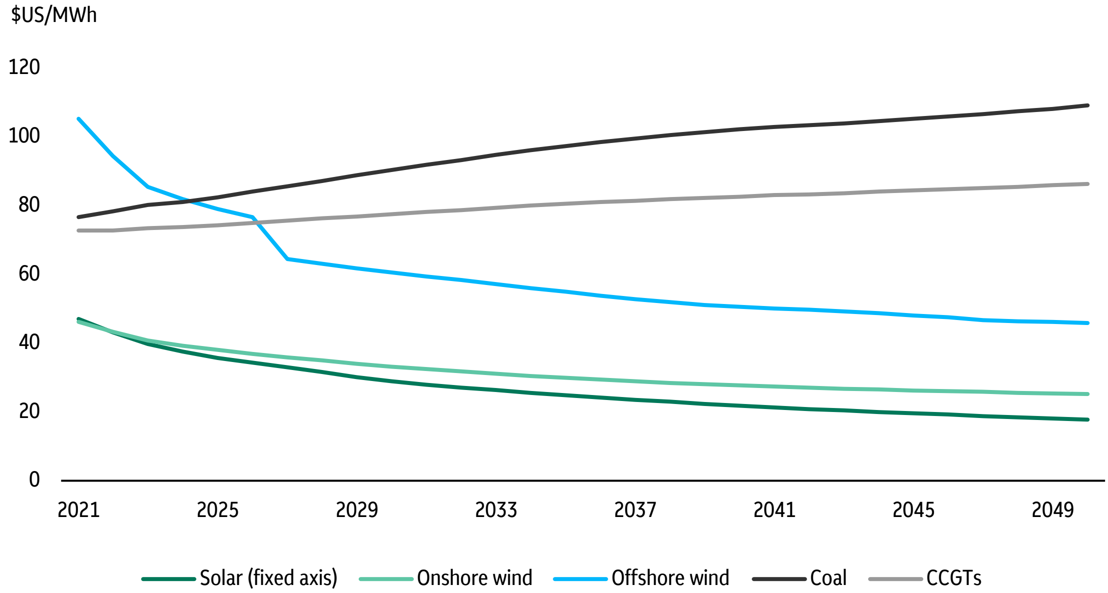



Sources: BNEF LCOE database (June 2022), IMF WEO (June 2022). Note: Global LCOE is calculated as a GDP-weighted average of US, China, Germany, France, UK, Japan, and India, subject to the data availability for each technology.

30. BNEF database (June 2022).
31. IEA, "Net Zero by 2050: A Roadmap for the Global Energy Sector", Figure 3.11, page 118 (June 2021).

Moreover, looking ahead, both solar and wind are likely to decrease in price quite substantially, while there is much less cost improvement in coal and gas. Between 2021 and 2050 renewables (solar, onshore wind, offshore wind) are expected to decrease in cost by between 45 per cent and 62 per cent, while coal and gas are expected to increase (Figure 16). By 2050 the cost of solar is expected to be less than 20 per cent of the cost of coal.[32]

Figure 16:
LCOE by technology, 2021 to 2050

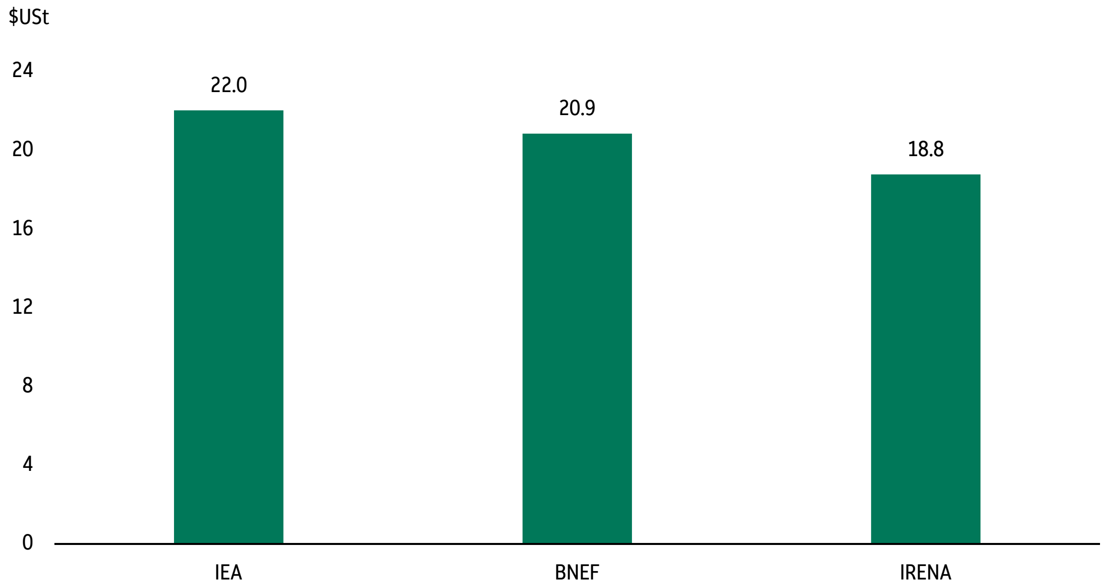



Sources: BNEF LCOE database (June 2022), IMF WEO (June 2022). Note: Global LCOE is calculated as a GDP-weighted average of US, China, Germany, France, UK, Japan, and India, subject to the data availability for each technology.

32. It is worth bearing in mind that visibility on the cost of different generation technology declines beyond a few years ahead.

Adding the capacity necessary to meet this electricity demand will require a huge amount of capital. For wind and solar alone this will require $US22.0 trillion according to IEA,[33] $US20.9 trillion according to BNEF,[34] and $US18.8 trillion according to IRENA[35] (Figure 17). This makes for an average estimate of $US20.6 trillion out to 2050 which, to put in perspective, is roughly the size of the annual US GDP. It is worth noting that the full amount required for investment in power generation over this period is significantly larger than this. The average of the three BNEF net zero scenarios gives a total investment requirement of $US38 trillion once other sources of power such as hydro, nuclear, gas, geothermal and biomass are included.[36]

Figure 17:
Capital requirements for renewables




Sources: BNEF's NEO 2021 (July 2021), IRENA's "World Energy Transitions Outlook: 1.5C Pathway" (June 2021), IEA's "Net Zero by 2050: A Roadmap for the Global Energy Sector" (June 2021).

33. For the IEA we can only find capacity estimates for wind and solar but we have estimated the cost of this out to 2050, assuming current capex cost falls at the same rate as the cost of power on an LCOE basis.
34. Based on the average of BNEF three net zero scenarios (Green, Gray, and Red), although for the Green scenario we exclude the hydrogen-driven generation requirement.
35. IRENA, "World Energy Transitions Outlook: 1.5C Pathway", Figure 3.2, page 102 (June 2021).
36. In business-as-usual cases the cost of this component is much greater.

## Grids – Almost as capital hungry as wind and solar

Grids are one of the few remaining natural monopolies. In many developed countries, however, they are run by private companies deploying private capital, but the operating environment and returns available are heavily regulated. These assets are often regulated on a regulated asset base (RAB) model, where the owner receives a return based on the amount of allowed capital deployed, with some flexibility around a central return for over- and under-delivery on key objectives set by the regulator, which are often related to customer service, operational performance, or both.

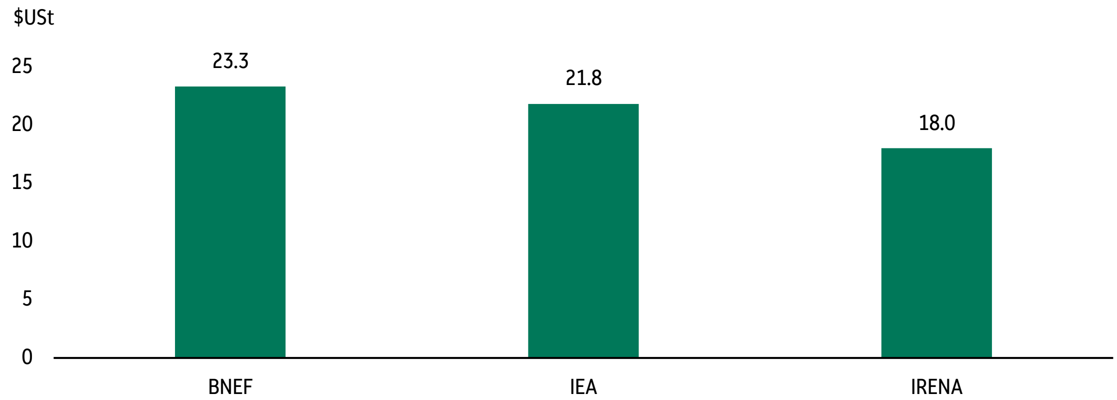
If the private company believes it can manage its capital structure well and hit key performance targets, the scope to add to that capital base is one of the opportunities embedded in such an asset. In this sense the energy transition, which will require significant amounts of capital to be placed into grids for expansion, reinforcement, and maintenance, represents an opportunity. There are multiple drivers of this increasing capital need:

- **Replacement of existing grids.** Many electricity grids in the developed world are now old, and replacements will be needed over coming decades. In the US the average age of the grid is 40 years old, with more than a quarter of it over 50 years old.[37]
- **Buildout of grids in emerging markets.** Many emerging markets are underserved by grids, and extending grid reach in these areas will be a major contributor to growth in the global grid infrastructure.
- **Decentralisation.** The shift to renewables-based power will mean that the base for power generation changes. The natural resource flows that are key for wind and solar output are not necessarily located in the same place as the thermal power plants they are replacing, which have different requirements from their external environment. At the same time, the number of generation units is set to increase, as renewables power plants tend to be smaller in size than thermal plants. Both of these factors will add to demand for distribution and transmission infrastructure.
- **Digitalisation.** The digitalisation of transmission and distribution infrastructure represents an opportunity to improve its efficiency and durability. But it also requires investment, and this will make a meaningful contribution to the growth in required capex going forward.

All told, BNEF estimates that under its net zero scenarios[38] grid extension, replacement, and reinforcements will require $US23.3 trillion by 2050. The IEA and IRENA have similar but slightly smaller estimates – the IEA expects $US21.8 trillion[39] and IRENA $US18 trillion. The capital requirement grows strongly over the period, with annual expenditure reaching almost $US1 trillion per year by 2050.[40]

37. Christine Oumansour, “Modernising ageing transmission” (April 2020).
38. The average of the Green, Gray, and Red scenarios.
39. See page 82 of IRENA’s “World Energy Transitions Outlook: 1.5C Pathway” (June 2021).
40. BNEF estimates required capex of $US960 billion per year in the 2040s, while the IEA estimates it at $US800 billion.

Figure 18:
Capital needs of grids by 2050




Sources: BNEF's NEO 2021 (July 2021), IRENA's "World Energy Transitions Outlook: 1.5C Pathway" (June 2021), IEA's "Net Zero by 2050: A Roadmap for the Global Energy Sector" (June 2021).

## Energy storage – The smaller cousin but still significant

There are many different energy storage technologies, all of which have different technical advantages and disadvantages and different cost structures.[41] But in the context of the storage requirements for the energy transition, batteries appear to be the most attractive available technology in the short term, with possible exceptions where there is availability for PHS expansions. Batteries can serve multiple functions in the energy transition and in many cases the revenues generated from these different activities can be "stacked", which helps improve the economics of an investment in batteries. These functions include:

- **Energy shifting.** This involves buying energy at the cheap time of the day and selling it at the expensive time of the day. Greater use of intermittent power sources will likely increase the demand (and therefore reward) for shifting energy from times of excess supply to times of excess demand.
- **Renewables firming.** Batteries can also help to smooth the rapid fluctuations in renewables output that can occur over short periods of time due to weather events. This effectively increases the power's market worth and the price attainable by the supplier.
- **Power outage ride-through.** A consumer who is exposed to an unreliable grid (whether flickering, brownouts, or full blackouts) would benefit from having an energy storage system to call on in times of weaker power supply.

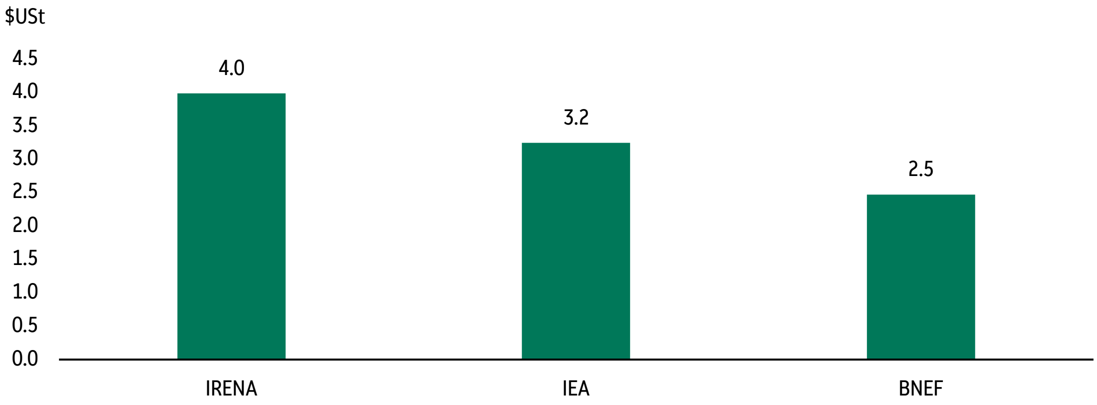
41. See our Pathways paper, "Batteries, energy storage and the future of electricity networks" (September 2019), for more details.

- **Capacity charge avoidance.** A capacity charge is the charge the consumer faces for connection to the grid. It is meant to cover the cost of the grid infrastructure. For commercial consumers, this charge is a function of peak use, as that determines the infrastructure need. These charges can be considerable, so the consumer is strongly incentivised to reduce peak use. It is like energy shifting, but under a different pricing regime. During peak use, customers deplete their storage to limit the power drawn from the grid and recharge the storage later when their use is below peak. This reduces the maximum power the customer needs to draw from the grid and therefore the capacity charge to be paid.
- **Self-consumption.** The rise of solar panels on rooftops has created the "prosumer", a market participant that is at once both producer and consumer. These rooftop solar owners are increasingly poorly remunerated for feeding electricity into the grid. This incentivises the storing of ostensibly zero marginal cost excess solar production during the day for consumption during the evening and night, avoiding having to buy that electricity from the utility.
- **Transmission and distribution upgrade deferrals.** Batteries can be used to decongest transmission and distribution lines and nodes. This can delay infrastructure upgrades, which has value to the infrastructure owner.
- **Ancillary services.** Small fluctuations in grid frequency and voltage create inefficiencies. Given batteries' rapid response time they are ideally suited to frequency and voltage management. This has been a good revenue generator for batteries to date. It is worth noting, however, that the importance of this type of activity for batteries will decline over time. The ancillary services revenue line is largely fixed, so the proliferation of batteries attached to the grid could see a pronounced decline in the per battery revenue available for this service.

The amount of battery storage that will ultimately be needed depends on a range of factors including their cost evolution, their success at the different technical requirements in a broad range of markets, the cost evolution of wind and solar, and the cost of competing storage technologies. The IEA, under its net zero scenario, estimates that $US3.2 trillion,[42] or around $US114 billion per year, will be required for batteries by 2050, while the average of the BNEF's three net zero scenarios implies a need of $US2.5 trillion in energy storage.[43] IRENA, on the other hand, expects that about $US133 billion per year, or $US4 trillion in total, will be needed (Figure 19).

42. IEA, "Net Zero by 2050: A Roadmap for the Global Energy Sector", Figure 4.2, page 155 (June 2021).
43. Although another $US200 billion is required for PHS.

Figure 19:
Capital needs for batteries by 2050

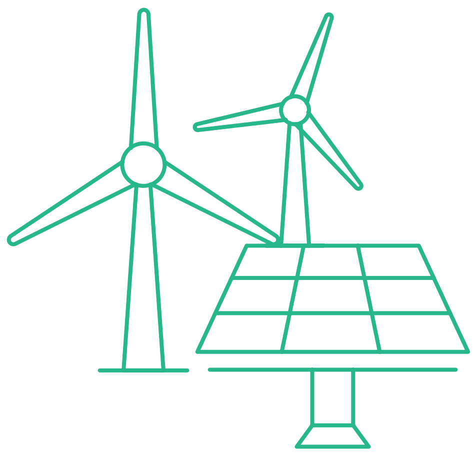


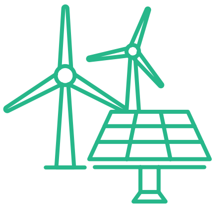

Sources: BNEF's NEO 2021 (July 2021), IRENA's "World Energy Transitions Outlook: 1.5C Pathway" (June 2021), IEA's "Net Zero by 2050: A Roadmap for the Global Energy Sector" (June 2021).

The average of the major forecasters suggests that some $US20.6 trillion will be needed for renewables capacity expansion, $US21.0 trillion for grids, and $US3.2 trillion for batteries by 2050. This is a total capital need for renewables, grids, and batteries of $US44.8 trillion. Beyond that, roughly another $US8.6 trillion will be needed for other power sources and technologies such as nuclear, hydro, geothermal, biomass, and gas. This means that a total of about $US53.4 trillion will be needed to transition the electricity sector to net zero by 2050. To put this in context, it totals more than half the global capital managed by asset managers today.[44]

44. BCG, "Global Asset Management 2021" (July 2021).

# Conclusion: Wind and solar to drive decarbonisation





With electricity consumption expected to account for roughly half of total final energy demand in 2050, the decarbonisation of the electricity sector is essential to the energy transition and achieving net zero. If green hydrogen turns out to be viable, there is upside to this estimate. From a technical perspective, there is no barrier to the overwhelming bulk of this electricity need being met by wind and solar, in conjunction with daily and seasonal energy storage.

Estimates suggest that some $US44.8 trillion will be required for the extra solar and wind capacity, energy storage need, and the expansion and reinforcement of grid infrastructure, with another $US8.6 trillion needed for other technologies. This is a sizeable amount of capital, and for investors with the appropriate expertise and investment horizon this potentially represents one of the largest sector investment opportunities of the next three decades.

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**For more information, or to speak to the authors of this issue, Daniel McCormack, Aizhan Meldebek and Thomas Studer, please contact your Macquarie Asset Management Relationship Manager.**