POSSIBLE

Ways to Net Zero

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Ways to Net Zero

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Profile Books

Contents

UNITS OF ENERGY

For simplicity I have standardised on a single way of measuring energy flows and total amount of energy used or generated. When reading about energy you might see different units, such as Joules or 'barrels of oil equivalent', but I have converted everything to multiples of watts and watt hours.

- **What is an energy (or power) flow?** Flows are the rate at which energy is being transferred (often called 'power'.) We could be talking about something tiny, such as the power of a light bulb right up to the total amount of energy being used in a country. An LED light bulb might be rated at 5 watts power, for example, while the UK typically uses about 35 gigawatts of electricity. A gigawatt is a thousand million watts.
- **What is the amount of energy used?** We usually express the total amount of energy used or generated in terms of watt hours. A light bulb running at 5 watts will consume 5 watt hours in the course of an hour. The UK's total electricity use in the same period would be 35 gigawatt hours. (A country's total consumption of energy is typically about five times as much as its use of electricity.)
- **Multiples of watts** Each of the main units of power and energy mentioned in this book is a multiple of one thousand of the next lower unit on the list:

kilowatt	1,000 watts
megawatt	1,000,000 watts
gigawatt	1,000,000,000 watts
terawatt	1,000,000,000,000 watts

Units of energy such as Kilowatt hour (kWh) or Terawatt hour (TWh) are similarly multiples of watt hours.

TYPICAL POWER AND ENERGY MEASURES

- **The latest generation of offshore wind turbines** have a maximum power generation capacity of around 10 megawatts of electricity. The average rate of electricity consumption of a typical domestic house in Europe might be 400 watts.
- **The world's annual electricity consumption** is around 28,000 terawatt hours (estimates vary quite a bit.)
- **The total energy in the oil used per year** around the world is around 50,000 terawatt hours, or more than the total amount of electricity used. Gas has a similar value.

Throughout the book, I've tried to express numbers with a comparator figure, to give a sense of scale and to help assess a technology or idea's significance.

INTRODUCTION

Possible

Ways to net zero

The path to a zero carbon world is now well understood. Wherever possible, all the activities that use energy, ranging from heating homes to operating heavy trucks, will be switched from fossil fuels to electricity. And this electricity will come from renewable sources – principally solar panels and wind turbines but also hydro-electric power and geothermal energy from the ground in some countries. Nuclear power may also have a continuing role.

Huge, almost unimaginable, amounts of new capacity will be needed. Perhaps the output of wind and solar farms will exceed fifty times today's level (though we're still only talking about using less than one percent of the world's surface.)

Expressed in this simple way, this ambition sounds attainable, if challenging. But we face two apparently intractable problems. Neither the wind or the sun are available all the time and, although batteries will be useful, they will never be able to provide the power to cover long periods of low production from renewable sources. An additional challenge is that some of our energy uses cannot be electrified. We'll still need large amounts of gaseous and liquid fuels for such activities as steel-making, long-distance shipping and aviation.

This is where hydrogen comes in. Made from electricity in huge electrolysers, at times when the power networks have abundant surpluses, 'green' hydrogen can meet both of these problems head on. First, it will act as a large-scale store of energy available at those times when renewables are in short supply. The stored hydrogen can be burnt in gas turbines or reacted in fuel cells to make extra electricity when it is needed. Generating hydrogen from electricity and then turning it back into power when needed is an inefficient process that loses much of the energy. Nevertheless, it is probably the best way of ensuring enough electricity is available at all times. In the chapters following, I explore how this can work, and how it might be supplemented by other storage.

The second use for hydrogen is as the key energy source when making direct substitutes for fossil fuel. Chemically combined with sources of carbon (in well-understood engineering processes), it can make many different types of fossil fuel replacements, such as synthetic aviation fuel. Similarly, it can substitute for fossil-derived energy in such activities as making chemical fertilisers.

For those activities that we cannot move to electricity or low carbon hydrogen – the cement industry, for example, and perhaps aviation – we will need some form of carbon capture and storage. This is one of the fastest-moving areas of climate technology. Traditional approaches envisaged capturing carbon at the major sources of emissions, such as power station chimneys. Today there are also dozens of companies looking at capturing carbon directly from the air or the sea using a wide variety of innovative techniques.

There is now widespread agreement on this central route that the world needs to take to net zero: the electrification of all possible energy uses to reduce emissions, with hydrogen working alongside to cover most other needs. That takes us a long way towards our eventual aims. As Kingsmill Bond of the

Mega Green – China's largest solar green hydrogen facility, in Kuqa, Xinjiang Province, can store 210,000 cubic metres of hydrogen. GETTY IMAGES

Rocky Mountain Institute said when I interviewed him for this book: 'The route to 80 percent decarbonisation is relatively easy. The final 20 percent is more problematic.' But Kingsmill isn't worried. 'Here's how change works', he said. 'The easiest problems are solved first, leaving the difficult questions. Once the easy stuff has been dealt with, it usually becomes simpler to resolve the more challenging issues.'

Those remaining difficult parts of the transition are what much of this book is about. Are there enough key raw materials in the ground to make such things as the wind turbines, the electrolysers and the batteries the world will need? How will the world move away from animal agriculture? Can we shift from an economy in which tiny percentages of plastics are recycled to a completely circular industry with full reuse? How can we stop using coal in the steel industry? What is the best way to capture the CO_2 we will need to extract from the air? And how do we persuade electorates that acting decisively on climate is in our best interests?

None of these challenges has an easy answer, and some look intimidatingly difficult. Many of the solutions, too, will come with substantial costs, particularly in the early years. But there is a potential route forward in each case, and often a range of alternative ways around each of the main obstacles to net zero. As we begin to solve the easier challenges of decarbonisation, I hope this book will help show that a comprehensive solution is possible.

PART ONE

ELECTRIC WORLD

CHAPTER ONE

100 percent renewables

Building a power system for a fully electrified world

The transition to a world with a 100 percent renewable electricity system will encounter some high hurdles. However, the underlying fact is that wind, solar and hydro-electricity are now cheaper in most parts of the world than power generated by fossil fuels. And, in all probability, the cost advantages of renewables will continue to grow over time.

It is not just proponents of renewables who make this argument. The UK government, not always a fan of low carbon power, published its latest estimates in October 2023 for the cost of gas generation compared to wind and solar.[1] These figures showed that new onshore wind farms are expected to provide the cheapest source of power by the mid-2020s, at around £38 a megawatt hour. Electricity from gas turbines would be more than three times as costly as onshore wind, once a tax on carbon emissions (factored into these estimates) is added. Indeed, generators using gas will probably pay more for the fuel alone than the total cost of onshore turbines. Solar power photovoltaics (PV) in the UK comes out about 10 percent more expensive than onshore wind in these government estimates, and offshore wind around 20 percent higher. Both of these are still far cheaper than gas generation.*

In the US, where the price of natural gas is a fraction of what Europe has to pay, the raw cost of wind and solar electricity in the best locations is also lower than generation at gas turbine power stations. The investment bank Lazard publishes annual research on the comparative figures for the main generating technologies. The 2023 report showed that onshore wind and solar might have costs as low as $24 per megawatt hour of electricity output, compared to $62 for electricity from a fully depreciated gas power plant.

While both solar and wind will require complementary energy storage to overcome their intermittency, the Lazard analysis suggests that this would only increase the minimum cost to around $45 per megawatt hour, still well below the level of a typical US gas-fired power station, even before adding in any charges for sequestering the CO_2 issuing from the plant.

Other parts of the world show similar patterns. The recent outbreak of global inflation and higher interest rates has not undermined the economic attractiveness of solar and wind. The International Renewable Energy Agency (IRENA) wrote in August 2023 that the global average cost of electricity delivered by onshore wind fell in 2022 by 5 percent from the level of a year earlier.[2] At $33 (£27) per megawatt hour, this makes wind far cheaper than fossil fuel electricity in all parts of the world that do not have access to extremely cheap natural gas. Solar electricity also saw a global cost reduction

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* The government estimates are expressed in 2021 prices. Inflation since then will have added to the cost of both wind and solar installations, but the conclusions still hold.

in 2022, falling by 3 percent to around $49 ($40) a megawatt hour, although offshore wind saw a small increase as supply chains were strained.

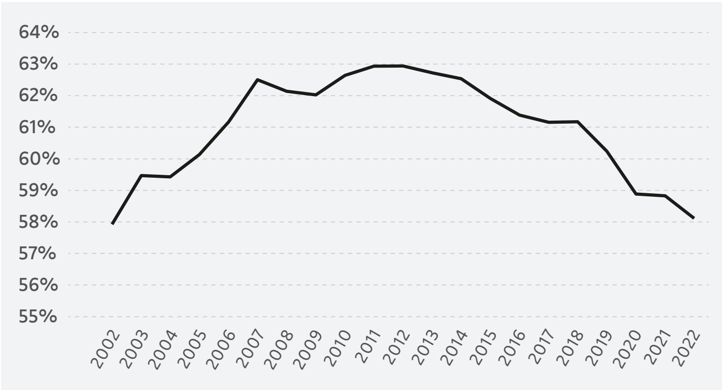
These figures are world averages and individual countries show quite a range of figures. The decline in cost has been most marked in China, responsible for almost half the new solar power installed globally in 2022. But, even in a year of more economic and geopolitical disruption than has been seen for decades, the cost of renewables has continued its downward slide in most countries of the world.

IRENA also notes how much improvement we've seen in solar and wind prices. In 2010, the average global cost of onshore wind was 95 percent higher than the lowest fossil fuel alternative. By 2022, the mean cost of onshore wind had fallen to the point where it was less than half the cheapest fossil fuel source. The decline in solar PV power is even more staggering. In 2010, PV was seven times more expensive than the cheapest electricity produced from gas or coal. But, by 2022, it was on average 29 percent lower cost than the cheapest fossil electricity.

The inevitable rise of renewables I wrote a book enthusing about the prospects for solar power in 2015, when capacity additions totalled about 50 gigawatts of new PV panels per year. In mid-2023, the International Energy Agency (IEA)* projected a figure of about 290 gigawatts of new solar photovoltaics installations for the year – almost six times as much. Some other forecasts are even higher. The competitive price of electricity from solar farms is accelerating the rate of installations around the world.

* The IEA is an inter-governmental organisation, based in Paris, that provides policy recommendations on global energy. Its 31 nation members comprise 75 percent of world energy use.

FOSSIL FUEL SHARE OF GLOBAL ELECTRICITY GENERATION



Fossil fuels peaked in global electricity generation in 2011 and their downward trajectory since then has become clear.
Energy Institute's Statistical Review of World Energy

That said, autumn 2023 saw reversals in the fortunes of some low carbon electricity suppliers, particularly in the offshore wind industry. One major and troubling event was the withdrawal of global leader Ørsted from two proposed American wind farms off the coast of New Jersey. The company cited rising financing costs, supply chain problems and a worldwide shortage of the vessels necessary to install the offshore foundations and towers.[3] At the same time, Ørsted announced a decision to go ahead with another large US offshore wind project. However, after a decade of cost reductions, the message was that building offshore wind farms has become more challenging.

To some people, these problems in offshore wind are a signal that the renewables industry will fail to maintain its striking record of continuous reductions in costs. I'd argue that is too pessimistic a view. Yes, higher interest rates have severely affected the economics of projects such as huge offshore wind farms that require billions of dollars of external finance, and the rapid growth of the industry has created shortages, disruptions and spikes of inflation in many places around the world. But the underlying manufacturing and installation costs of a wind turbine continue to get cheaper per unit of electricity produced. There's no obvious reason why the long downward slide in wind and solar costs should slow any time soon.

Solar and wind improvements We can expect new materials to reduce the price of solar panels sharply within the next decade. The most likely improvement lies in the use of 'perovskites' to thinly coat the conventional silicon wafers used in PV. These simple and inexpensive chemicals add to the output of a panel by capturing portions of the sun's spectrum that cannot be used by today's panels, thus adding to the electricity generated.

The potential of perovskites has been well understood for at least a decade, and various types are now being developed by research institutions and private companies. The principal obstacles to commercialisation have been the need to protect the panel from water ingress and to stop high light levels degrading the perovskite. Progress on these issues is speeding up, and in November 2023 Chinese researchers said they had found a route to stabilising the new material.[4] Oxford PV, a global pioneer in the use of perovskites, says that it will start commercial scale production in 2024, aiming to deliver a 20 percent increase in the output of a standard PV panel for very little extra cost. This will particularly improve the financial attractiveness of installing PV in confined spaces, such as small domestic roofs.

With wind turbines, cost and performance improvements are likely to come from continuing to increase their size; as the US Department of Energy says, 'The bigger, the better.'[5] Wind speeds are higher further away from the ground and a taller tower allows longer blades, assisting in the collection of more energy from the air flow past the turbine. Individual turbines are getting more powerful, both onshore and offshore. The US turbine manufacturer GE says that its latest product range for offshore will be able to produce up to 18 megawatts of power (enough at peak power for the typical use of over 40,000 UK homes.) By contrast, the earliest offshore turbines, installed in 1991 off the coast of a Danish island in the Baltic Sea, each had about one fortieth of that output.

I've suggested that wind and solar are already cheaper than gas- and coal-fired power and are likely to become even cheaper in the future. This will encourage an accelerating shift towards the use of low carbon technologies to make electricity. Energy costs are an important part of any economy, so using wind and solar growth to push down the prices paid by households will improve people's living standards.

One recent analysis by independent researchers predicted that by 2030 retail electricity prices in major European economies could be expected to fall 11–18 percent from pre-pandemic levels, as the share of renewables in the energy mix increases.[6*] Importantly, this work also suggests that the growth of wind and solar in Europe requires no subsidy support, or even a carbon tax on fossil fuel power generation. The installation of renewables makes good commercial sense already.

Despite the falling price of renewables, my sense is that governments should also continue to sponsor research and development of various forms of nuclear power. Both fission and fusion approaches might become cost competitive with wind and solar at some point. The evidence for this is very unconvincing at present (after eagerly attending lectures on

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* I contacted the researchers Manuel Losa and José Abad to ask about this. Their response was clear: 'we believe that the energy transition should have a positive impact on economic growth as it should structurally reduce energy prices. This decline in energy prices will improve productivity and purchasing power gains for corporations and households, respectively.'

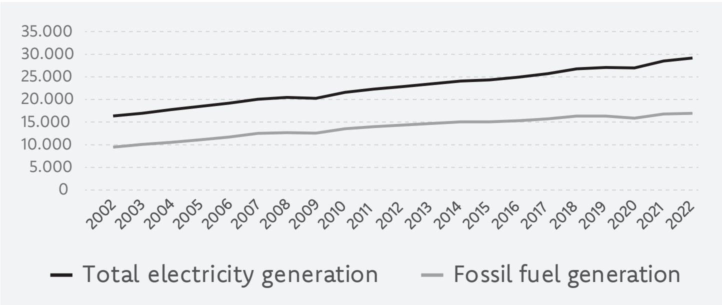
The bigger, the better: wind turbines at the Seagreen Offshore Wind Farm, Scotland's largest and the world's deepest fixed wind farm, under construction in the North Sea. GETTY IMAGES

the future of nuclear energy over the last few years, I have yet to hear a single proponent of either small fission reactors or large fusion plants offer any form of detailed analysis of the eventual cost per unit of electricity produced.) Nevertheless, it would be foolish to rule out technologies which could eventually match wind and solar, with the advantage of reasonably reliable stability in electricity output.

How much more electricity do we need?

At present the world makes and uses about 27,000 terawatt hours of electricity a year. In advanced economies, power needs are likely to double or more as energy use shifts towards electricity, particularly for heating and for road transport. In developing countries, usage will rise severalfold. All in all, it is

GLOBAL ELECTRICITY DEMAND (TERAWATT HOURS)



One of the challenges of net zero: global electricity demand is growing. ENERGY INSTITUTE'S STATISTICAL REVIEW OF WORLD ENERGY

reasonably likely that the world will want to generate at least 90,000 terawatt hours of electricity by 2050, to meet net zero.

Is this figure – using an energy system almost entirely reliant on renewables and hydrogen – attainable? At the moment, renewable energy from wind and solar (excluding hydro-electric power) is only responsible for about 12 percent of world electricity production, and electricity is, of course, only a fraction of total energy use.[7] Fossil fuels still provide over four-fifths of the world's total energy requirements.[8] Analysts argue that coal and oil production have come close to their peaks and will clearly decline from now on, but switching energy use 100 percent to renewables by 2050 does at first sight look highly improbable.

So why should we be cautiously optimistic that energy use will be switched to renewable electricity?

The compound growth phenomenon In 2022, the amount of global electricity produced by solar PV increased by 26 percent, according to the International Energy Agency. This increase took production up to 1,300 terawatt hours, or over 4 percent of today's global electricity generation. Even this amount seemed difficult to envisage even a decade ago.

The full impact of compound growth rates is always difficult to comprehend. Nevertheless, the arithmetic is clear that – if the increase continued at the current rate – solar power would get the world up to 90,000 terawatt hours of electricity within about twenty years, well before the 2050 target for net zero. In other words, the current rate of expansion of solar power is sufficiently fast to achieve net zero without help from any other electricity sources. This is the reason that the IEA recently said that solar was now growing fast enough to meet the agency's decarbonisation targets.[9]

Wind power is not growing as fast as solar, but still increased by 14 percent in 2022. Even this continued growth rate would be sufficient to mean that wind power alone would meet all the world's electricity needs in 2050, without assuming any growth in solar PV, hydro-electric or nuclear electricity.

Is the expansion in renewables likely to continue for the next decades? I discussed this issue with Hannah Ritchie, the senior researcher at Our World in Data,[*] an organisation that publishes highly comprehensive and reliable information on the energy transition. She asserted that the increase in solar and wind installations is a self-reinforcing trend and that, as more renewables are installed, their cost tends to fall, increasing their attractiveness for future capacity additions. There are no obvious reasons why solar and wind cannot continue to increase in importance, she says; their growth is 'reliably exponential' and high rates of yearly increase in new solar and wind capacity will persist, meaning that a very large fraction of world electricity will come from these sources, complemented by hydro-electric and nuclear power. The fall in cost is likely to continue, Hannah adds, even though higher interest rates have slowed recent progress.

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* Many of the statistics used in this book are sourced from Our World in Data.

The climate scientist Tim Lenton made a similar point in a recent interview. He argued for the idea of 'positive tipping points', or increasingly rapid shifts from fossil fuels to lower carbon technologies, as shown by the move away from coal-fired power generation in the UK, or that towards electric vehicles in some Nordic countries. The journalist covering his work said that 'his research suggests that technological change can occur very quickly with policies that get green technologies to "tipping point" thresholds – and that this could turbocharge the green transition'.[10]

China and international competition We shouldn't underestimate the importance of competition between countries trying to grab the largest share of new industries. China is central to the whole energy transition, asserts Kingsmill Bond of the Rocky Mountain Institute, and it is the key driver of change. The country's commitment to growing low carbon sources of electricity, including nuclear power, was the key factor pushing the US into action in 2022 with the climate policies of President Biden's Inflation Reduction Act (IRA.)

In turn, the obvious surge of investment activity in the United States as a result of the IRA has pushed the EU into much greater financial and political commitments to decarbonisation. European countries are competing to attract investment in low carbon industries such as EV (electric vehicle) batteries, hydrogen electrolysers and pipelines, and carbon capture

The role of hydrogen

In September 2023, Britain's Royal Society published work by a group led by Chris Llewellyn Smith, one of the country's most distinguished scientists.[11] The report concluded that the cheapest route to full decarbonisation of the UK's electricity system would be to pair wind and solar with low carbon ('green') hydrogen. Professor Llewellyn Smith's calculations show that the most economical way of operating an energy network would be to have an electricity system composed of 20 percent solar farms and 80 percent wind turbines, plus substantial energy storage principally employing hydrogen. Unlike some other researchers, or the UK government, he doesn't think it is necessary to retain any gas-fired power stations. 'Renewables plus hydrogen' will be fully sufficient, provided there is adequate storage capacity to cope with the years when wind speeds are unusually low.

Llewellyn Smith's central idea is that when wind or solar are abundant, more electricity will be produced than the UK needs, or can profitably export via interconnections to Ireland and continental Europe. At these times, electrolysers will use electricity to split water into its constituent parts, the gases oxygen and hydrogen. This hydrogen gas can then be stored, probably in deep caverns underneath the ground created in the middle of impermeable salt deposits. The gas has a very high energy value and can be converted back to electricity. So when electricity is in short supply the hydrogen will be used to supplement other sources of power, either using a process of combustion, such as in a gas turbine, or through a chemical reaction in what is known as a fuel cell.

The use of hydrogen as a storage medium in this way is not cost-free. The system will need a huge quantity of electrolysers as well as adequate storage caverns and distribution pipelines for the hydrogen produced. And the cost in terms of energy is also high. The electricity we get back out will probably be around 45 percent of what is put in. This sounds very inefficient, but there are no obvious alternatives capable of storing several months of surplus electricity. Batteries would be vastly more expensive. (See the following chapter for more on this.)

Hydrogen in the UK system Llewellyn Smith has estimated that the UK electricity system will need to generate about twice as much power as it does today when everything possible has been switched to electricity. This will both meet the needs for moment-to-moment electrification of the economy, including heating and transport, as well as providing the hydrogen necessary to buffer the intermittent renewable sources of power for long periods of time. He demonstrates convincingly that the cost of electricity from a 'renewables plus hydrogen' energy system is lower than prices from the fossil fuel based alternative.

Llewellyn Smith also comments that adding nuclear power to the mix cannot be expected to decrease the costs of UK electricity supply. The price required to justify the construction of new power plants is far greater than needed by renewables. And he also asserts that the UK government's strategy of using gas-fired power stations as the backup for when the country does not have enough solar or wind will similarly offer no benefit to the costs of running the energy system, as well as making it impossible to achieve zero emissions.

According to Llewellyn Smith, the UK alone will need almost 90 gigawatts of electrolyser capacity. Even using optimistic assessments of electrolyser prices, installations of this size will have a total cost of £20–25 billion.[12] Building up the hydrogen storage industry will require careful direction from governments, good market design and substantial capital investments. However, there is no obvious commercial reason why the electricity system cannot cost-effectively use hydrogen to maintain constant availability of power.

Hydrogen will also be needed as a key energy source for many industrial uses. These include steel, aviation, shipping and some high temperature applications in industry (these challenging areas for net zero are discussed in later chapters.)

Green hydrogen infrastructure Development of infrastructure for making green hydrogen using water electrolysis is moving

Refhyne, Europe's biggest hydrogen electrolysis plant, launched by Shell in Wesseling, Germany, will produce around 1,300 tonnes of hydrogen per year. GETTY IMAGES

ahead globally, although not yet at a pace which suggests it has reached the 'positive tipping point' described by Professor Tim Lenton. The biggest single project in construction at the time of writing is a 4 gigawatt site at the Neom development in Saudi Arabia, which will be capable of producing about 100 tonnes of hydrogen a day. My own work suggests that the world will need as much as 500 milllion tonnes a year.

Other countries actively backing the new hydrogen industry include Germany, Canada and the US, all of whom are seeking to build large facilities that will help push down the cost. The German hydrogen strategy envisages subsidising new electrolysers and transmission pipelines to add as much as

2.5 gigawatts of new capacity a year, and having 10 gigawatts installed by 2030.[13] Germany also sees the need for major imports of hydrogen, coming from places such as North Africa and Scandinavia, where low electricity costs means it will be cheap to use electrolysers.

'Renewables plus hydrogen' will give the world a reliable and larger supply of electricity to allow the electrification of many of the major energy uses, such as personal and light commercial transport and building heat.

Electric vehicles

The amount of energy used in transport of all types exceeds the world's current production of electricity and is responsible for about a quarter of all global emissions. Most of this is from the operation of road vehicles, particularly private cars. Electrification of transport is a high priority.

As with solar and wind, the world is seeing an exponential growth in electric cars and vans. In September 2023, they represented about 17 percent of all global vehicle registrations.[14] Two years earlier, the figure was just 10 percent.[15] And a further two years before that, in September 2019, the share had dipped to as little as 2.3 percent after China had reduced its incentives.[16] Although EV sales are still concentrated in Europe and China, volumes are increasing rapidly in other parts of the world, including the US and parts of Asia. The IEA noted that 2022 sales in India, Thailand and Indonesia were triple those of 2021.[17] Worldwide sales growth in 2023 was probably about 35 percent, even though sales in some countries, such as the UK, showed relatively slow growth.

In a few countries, car purchases are now largely EVs. Plug-in vehicles represent over 90 percent of the total car sales in Norway. The much larger Swedish car market is running at over 60 percent electric, while the Netherlands is approaching a

50 percent share. These countries, and others like them, show that electric vehicles can dominate the automobile industry, and surprisingly quickly.

In many other countries, including most of Western Europe, the market share of EVs in mid-2023 was above a quarter. In China the figure was 38 percent, and José Pontes, who runs the world's most complete database on electric vehicle markets, said that China now represents about 60 percent of world EV sales.[18]

Cheaper, smaller EVs EVs sold outside Asia still tend to be more expensive than equivalent combustion engine cars, holding down the growth in sales. This will change over the next few years as Chinese exports flood into Western markets at prices that will severely undercut local manufacturers. (This replicates the disruptive arrival of cheap Chinese solar panels in the West in 2009, which pumped up the speed of growth of solar electricity.)

In China lower priced EVs are already directly competitive with similar petrol cars. A 2023 study suggested that the typical EV sold there was priced at less than €32,000, while the equivalent number in Europe was about €56,000.[19] The difference is partly because EVs in Europe tend to be aimed at upmarket customers, while manufacturers in China are targeting the mainstream buyer. This is changing. In November 2023, Renault announced its first electric car under €20,000 for sale in Europe. Other manufacturers are developing cheaper vehicles to compete against Chinese exports. Electric cars will eventually be fully competitive on the sales forecourt.

Running costs will also probably be much cheaper, although this depends on the relative prices of electricity and petrol. In the long run, EV prices are likely to fall as battery costs shrink and, in addition, yearly operating expenses may also decline. For example, EV insurance costs, which are currently higher in many parts of the world because of the higher price of replacing the car, will tend to diminish as the price of new vehicles falls below petrol vehicles. Maintenance costs are also markedly lower.

Electric vans and trucks Moving to EVs for personal transport will be one of the easiest parts of the 'electrify everything' movement. It should also be possible to make a swift transition to electric vans for local delivery, particularly in cities that provide incentives for low-pollution vehicles (or penalties for pollution.) Electric mid-weight vehicles are also shifting to electricity. European sales of electric trucks of more than 16 tonnes grew by more than 200 percent in 2022, although the numbers are still a tiny fraction of the total market.[20] Volvo Trucks is one of the manufacturers most eager to switch to fully electric production, saying that it aims to have battery-powered vehicles forming half of its sales in 2030. The very heaviest long-distance lorries will be more of a problem (see *Chapter 13*), but here, too, it seems possible that a high proportion of long-distance freight transport can be switched to electricity within a couple of decades.

Almost all financial commentators see the battery EV share continuing to increase year on year, partly because of national policies around the world that will block petrol and diesel sales, but also because of the increasing view among the major car manufacturers that internal combustion engines have a very limited future. Volkswagen, the largest non-Chinese car company, will launch its last petrol car in 2026 and intends to stop selling them entirely in about 2033. Renault is even more aggressive, planning to cease all non-electric sales by 2030.[21] Research and development into the improvement of petrol engines has almost stopped at every manufacturer.

The charging challenge Vehicle charging infrastructure in many countries is still not sufficient to meet the expected levels of electricity demand in a 100 percent EV world, but the signs are that charger installation rates will grow rapidly. China saw a nearly 50 percent increase in public charging points in 2022.[22] In the rest of the world, the rate of increase was even faster, albeit from a lower starting point.

The global rate of growth of chargers is now at least comparable to the increase in EV sales, implying that finding a vacant charging point is becoming easier for the typical electric car driver. Much remains to be done, particularly making charging more feasible for apartment dwellers and those without private driveways, but public policy around the world now recognises the importance of building a widespread

WattEV's charging station at the Port of Long Beach – the USA's largest of its kind for electric, heavy-duty trucks. GETTY IMAGES fast-charging infrastructure to encourage the takeup of EVs. Governments and industry also acknowledge the need for even faster charging rates for heavy trucks and other commercial vehicles. A greater problem, perhaps, is ensuring that national electricity grids are capable of handling demand (as discussed in *Chapter 3*.)

Active travel The electrification of surface transport, particularly private cars, needs to be accompanied by a resolute attempt to increase 'active travel', such as walking and cycling, and also to boost the provision of public transport, a particular weakness in UK urban centres.[23] This will reduce the need for cars, improve public health and cut living expenses.

This is a point I'll make several times: just because we may have a technological option for reducing emissions through electrification doesn't mean that this is the only route that should be taken. Much of the world would be a happier and healthier place if the usage of private cars was significantly reduced. The benefits extend well beyond the climate change impact. Downtown areas in many cities have been revived by pushing cars out of the centre. Pollution has been reduced with positive effects on public health.[24]

Electrifying heat

Providing energy to homes and commercial buildings, mainly for heating and hot water, accounted for nearly 25 percent of global energy use in 2018, according to the IEA.[25] While most of the world's oil is used to fuel surface transport, low-temperature heating in buildings, including our homes, is generally provided by gas.

In many building types, heating (and cooling) can be decarbonised relatively easily. It can either be provided by community networks in which hot water is piped from central generation stations out to buildings and homes in very highly insulated pipes. Or the heating can be electrified efficiently by the installation of heat pumps either at the building itself or in a small local network.

Heat pumps for all? Heat pumps extract heat from ambient outside air or from below the ground and use it to warm the inside of houses and larger buildings. These devices use electricity to provide the energy needed. They are efficient and in the right circumstances can deliver up to four times as much heat into the building as they use in the form of electric power. In most countries this means that customers will save money by using electricity rather than burning natural gas for heating. The UK is an outlier, because its electricity prices are so much higher than its historically relatively low gas costs.

Heat pumps are being rapidly adopted in many European countries, replacing fossil fuel sources. The analyst Jan Rosenow reported that Finland leads the field in Europe, with 70 units per 1000 households installed in 2022 (up 120 percent on the previous year.) [26] [27] Almost 50 percent of Finnish homes are now heated by heat pumps. And if heat pumps work well in freezing north European countries, they'll succeed anywhere.

The trade association for the European industry wrote that heat pumps now provide heating for almost 20 million buildings on the continent, or around 16 percent of Europe's residential and commercial stock.[28] One forecast sees this total rising to almost 50 million buildings by 2030. Heat pumps have now passed beyond Tim Lenton's 'positive tipping point'.

There will undoubtedly be problems pushing penetration up to 100 percent of all buildings that need heating or cooling. British consumers are particularly sceptical. But the evidence is increasingly strong that this technology can allow a large-scale move away from gas in all parts of the world. Heating can join transport in moving to electricity and away from gas.

Heat pumps don't just work for domestic houses. Large megawatt-scale installations now heat office buildings, shopping centres and even factories. They can also be used for many low temperature industrial heating applications such as driving off water in the paper-making process.

High–heat industries Later chapters of this book look at industries in which decarbonisation will be arduous because electrification will be expensive or difficult to achieve. Generally speaking, activities which require heating to temperatures of more than about 1,000°C may be particularly likely to struggle to shift to electricity. This includes ceramics manufacture, glass-making and some types of chemical processing. But, for many other sectors – food processing, for example – electrification can provide the necessary source of energy. The latest generations of heat pumps that can generate heat at up to perhaps 400°C can assist in decarbonising much of industry.

In some countries, provision of medium-temperature heat can also be provided directly by solar energy. The heat from the sun is collected in what is known as 'concentrating solar power' (CSP) installations in which the energy is concentrated and temperatures of up to 400°C can be achieved.[29] The remaining difficult challenges are restricted to a small number of specific industrial activities which require higher temperatures (see *Chapter 7*.)

How fast can we electrify?

The International Energy Agency is not an organisation prone to bouts of over-optimism. But its director, Fatih Birol, made the following comments at the launch of the IEA's 2023 World Energy Outlook: 'The transition to clean energy is happening worldwide and it's unstoppable. It's not a question of *if*, it's just a matter of *how soon* – and the sooner, the better for all of us. Governments, companies and investors need to get behind clean energy transitions rather than hindering them. There are immense benefits on offer, including new industrial opportunities and jobs, greater energy security, cleaner air, universal energy access and a safer climate for everyone.' [30]

The IEA forecasts that the electrification of the world economy will bring almost ten times as many electric vehicles to the roads by 2030, that global solar production will exceed the total electricity output of the US and that the share of renewables in world electricity generation will approach 50 percent. Heat pumps and other electric heating systems will be outselling fossil fuel boilers globally by that date and three times as much investment will go into offshore wind alone as the total new capital expenditure on new gas- or coal-fired power stations.

The energy transition is speeding up and electrification and the production of hydrogen will give the world the opportunity to begin cutting emissions. One 2023 study even suggested that the rapid growth of renewables in China will mean the country's CO_2 output could fall from 2024 onwards, a landmark on the road to global net zero.

But renewable electricity doesn't solve all problems and there are areas where decarbonisation will need more than the replacement of fossil fuels by renewables. The following chapters will look at these problems and set out an array of possible solutions, including (in *Chapters 14* and *15*) the fast-emerging technologies for removing CO_2, which we will need as part of our overall plan to keep the world's warming to the globally agreed target of 1.5°C.

CHAPTER TWO

Energy storage solutions

When there's no sun, or wind: the intermittency challenge

Our electricity system is designed so that supply adjusts at a moment's notice to changing demand. A gas-fired power station is particularly good at varying its output in response to shifting needs during each hour of the day. Before the advent of intermittent renewable sources, a relatively small number of large power stations were called into action by the electricity markets and their output flexed up and down as required by industrial and household consumers.

This is changing as renewables become a larger and larger fraction of total supply. No longer can we rely on being able to change the amount of electricity generated in response to fluctuations in usage. As a result, across the world we're seeing three major trends:

- **Much greater volumes** of energy storage. Supply and demand for energy will be more difficult to match as the share of renewable electricity rises. A large part of the balancing will take place by storing electricity and then using it when necessary.