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RESEARCH NOTE

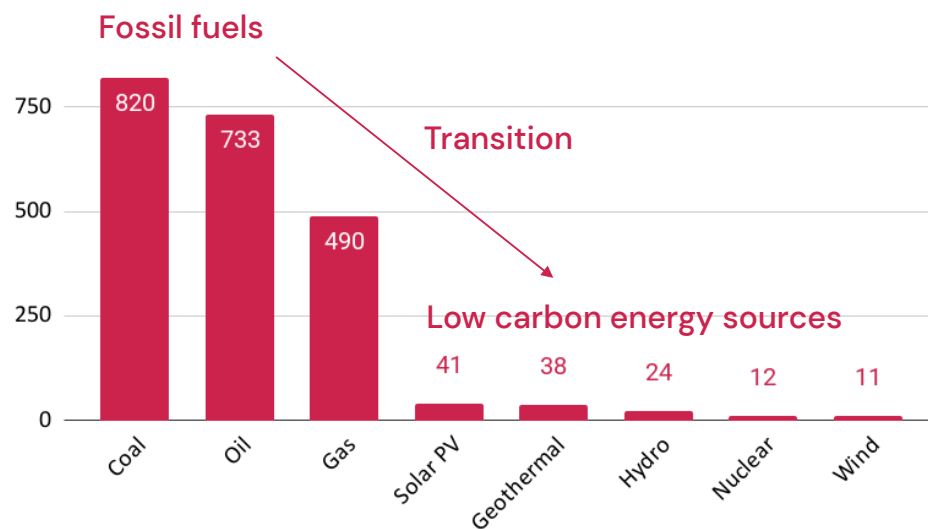
HOW FAST CAN WE TRANSITION?

WE MUST CHANGE THE ENERGY SYSTEM, AND WE MUST DO IT FAST

The call for an energy transition surged in the wake of the “oil shocks” in the 1970s. At the time, it referred to the need for Western countries to reduce their dependence on oil and gas. But as evidence of climate change accumulated, the term began to include the broader necessity to shift away from all types of fossil fuels to low-carbon energy sources, such as wind, solar, hydro or nuclear power. Fossil fuels being responsible for 78% of all carbon dioxide emissions from human activities, stopping burning them is indeed crucial to limit the negative consequences of climate change¹.



Fig. 1. Lifecycle greenhouse gas emissions of various electricity generation sources in kg CO2 equivalent per MWh. Data from IPCC AR5² and WNA³.



Despite growing concerns, the world mix still relies on fossil fuels for about 80% of its primary energy consumption, with no sign of significant reduction to date. And even though global installed solar PV and wind capacities have increased about sevenfold and threefold respectively between 2011 and 2019⁴, renewable energy deployment needs to be stepped up.

Indeed, according to the IPCC, to limit global warming to 1.5°C, with no or limited overshoot, global emissions must decline by about 43% from 2019 levels by 2030 and then reach net zero by the early 2050s. In scenarios that limit global warming to below 2°C, net zero can be postponed to the early 2070s but emissions still need to decline by about 27% by 2030⁵. Such levels of decarbonisation will require aggressive deployment rates for renewable energy sources, particularly wind and solar.

The IPCC ranks the development of wind and solar energies among the best mitigation options available⁵. Both the International Energy Agency's (IEA) 'Net Zero by 2050' scenario and the International Renewable Energy Agency's (IRENA) 1.5°C Pathway anticipate that renewables will play a major role in decarbonisation, amounting to 33% of emission reductions during this decade⁶ and 25% by 2050⁷.

The key question, therefore, is whether low-carbon energy technologies can be deployed at the scale and speed required. Even if this work focuses on climate change mitigation, it should not be forgotten that both economic and geopolitical motivations, such as those following the crisis in Ukraine, may provide further incentives to accelerate the low-carbon energy transition. More generally, four out of five people live in countries that import fossil fuels, which means that they would stand to benefit from a transition to local renewable energy sources. In particular, China and India are the largest and third largest fossil fuel importers and are strongly committed to a transition⁸.

WHERE WE ARE NOW

While the share of renewables in the global electricity mix remained at around 20% during the 2000s, it has grown to 28% in the last decade thanks to the rapid development of solar PV and wind energy. In 2000, more than 90% of renewable electricity came from hydro-power. Solar PV and wind energy now represent a third of renewable electricity generation, and around 9% of total electricity generation^{9,10}.

Renewable electricity capacity additions have outpaced those of non-renewables since 2014. **Solar PV and onshore wind power are dominating the growth, with cumulative installed capacities exceeding 800 GW for both of them in 2021⁷**. Their growth is fast: at around 21% and 13% per year, respectively over the last three years (Fig. 2). 133 GW of new solar PV capacity were commissioned in 2021. However, so far, renewables are mainly helping to meet the ever-increasing total energy demand – mainly from industrialising countries – rather than actually replacing fossil fuels. Moreover, as technology adoption follows S-shaped



curves, growth rates will eventually decrease as the share of renewables in the energy mix increases¹¹.

Capacity is defined as the amount of energy per second a generator can produce when running at its maximum power. It is measured in kilowatts (kW), megawatts (1 MW = 1000 kW) and gigawatts (1 GW = 1000 MW). As illustrated in Fig. , the typical capacities of a solar PV unit, a wind turbine and a nuclear reactor are a few kilowatts, megawatts and gigawatts, respectively. To date, hydropower is still the largest renewable power source in terms of installed capacity (1230 GW).

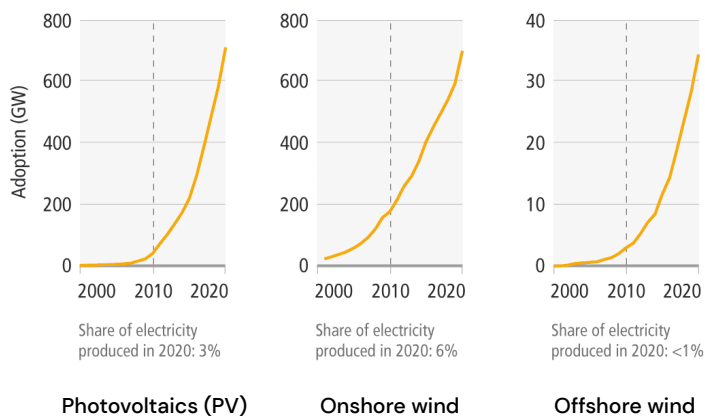


Fig. 2. Cumulative global adoption for each technology, in GW of installed capacity. Figure adapted from IPCC AR6 Group III.

Contrary to other works that considered other indicators, such as the production of primary energy¹² or the amount of national electricity supply per year¹³, this note focuses on installed capacities, since they are the key parameter for energy network dimensioning. It is recalled that, for the same amount of installed capacity, wind produces about twice as much electricity as solar PV, due to a difference in capacity factors⁵.

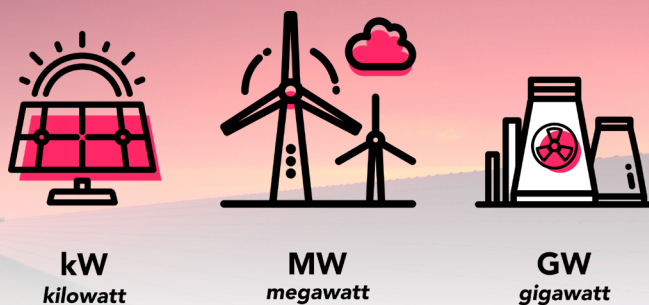


Fig. 3. Typical capacities of a solar PV unit, a wind turbine and a nuclear reactor are a few kilowatts, megawatts and gigawatts, respectively. Deploying 1 GW of low-carbon capacities therefore involves building about one nuclear reactor or a few hundred wind turbines or a few hundred thousand solar panels or any equivalent combination.

WHERE WE NEED TO GO

Net zero by 2050 scenarios from the IEA, IRENA and BP all agree that installed solar and wind capacities must be close to 9000 GW in 2030 and to 22000 GW in 2050, with deviations of less than 1000 GW^{7,10,14}. This implies significant annual capacity additions, around 700 GW per year on average. The global pathway proposed by the IEA, for instance, implies reaching annual capacity additions of 630 GW of solar photovoltaics (PV) and 390 GW of wind by 2030. In its 2022 outlook, BP features a net-zero scenario in which the effort is more spread out over time, which allows them to assume 40% lower capacity additions in 2030, around 630 GW/yr for wind and solar combined. But then, BP's scenario expects the addition pace to keep increasing beyond 2030 while the IEA anticipates that it will never exceed the value reached in 2030. In any case, **the effort to be made is nearly equivalent to installing the world's current capacities every year from 2030 to 2050.**



Annual capacity additions (GW)	2020	2030	2050
Total solar PV	134	630	630
Total wind	114	390	350
<i>Of which offshore wind</i>	5	80	70

Table 1. Source: International Energy Agency (2021), Net Zero by 2050, IEA, Paris.

At the regional level, Asia, North America, and Europe will account for more than 80% of installations by 2030. They will need to ramp up installations by three to five times while other regions, while the Middle East and Africa will have to scale up by 13-fold⁷.

ARE WE ON TRACK?

The divergence between the pathway to achieve net zero emissions by 2050 and what has been pledged by countries all over the world is referred to as the ‘ambition gap’, while the difference between pledges and current measures is known as the ‘implementation gap’. To determine whether the world is on track to implement the capacities required in the time available, it is therefore necessary to examine both the levels of ambition and implementation in every country.

To date, 67 countries have committed to becoming carbon neutral over the next decades¹⁵. The IEA’s ‘Announced Pledges Scenario’ aims to model a trajectory in which pledges are fully implemented in time¹⁰. It projects that installed solar and wind capacities will stay around 60% of what is needed in net zero pathways. BP’s ‘New Momentum’ scenario, which is designed to capture the global energy system’s current trajectory, is even more pessimistic as it expects capacity additions in stated policies to be only a third of the net zero target by 2030, and half

of it by 2050¹⁴. Even 25% higher capacity additions, as in the so-called ‘Accelerated case’ also considered by the IEA, would fall short of the net-zero target by around 30%. **This emphasizes the need to strengthen renewable energy deployment ambitions.**

Just as ambition, implementation is also not up to the mark. In its report “Renewables 2021. Analysis and forecast to 2026” released in December 2021, the IEA expects PV capacity to be around 1800 GW in 2026, with net additions around 200 GW per year, and wind capacity to be close to 1300 GW in 2026, with net additions around 100 GW per year. Though already significantly higher than historical deployment rates — from 2015 to 2020, average additions amounted to about 100 GW per year for solar PV, and 60 GW per year for wind — this would likely not be sufficient to meet announced pledges in 2030. All this shows how much more still needs to be done to tackle the renewable deployment challenge we face.

BOX 1. Beyond renewables, the issue of the transition speed is also key for nuclear power. In France, for instance, as many as 14 EPR2 reactors may be built between 2035 and 2050. So far, EDF have proposed to build new reactors by pairs on existing sites to reduce their cost, at the rate of a pair every 4 to 5 years. This implies an average capacity addition around 1 GW per year. Only after this first phase, meant to recreate an efficient nuclear industry in France, the construction may accelerate up to two pairs every three years (~2 GW/yr). According to the French nuclear industry, this is the maximum speed possible¹⁶. Interestingly, this is significantly less than what France managed to accomplish in the 1970s and 1980s (5 GW/yr).

ARE TARGETS REALISTIC?

To determine whether required deployments are within reach, capacity additions must be examined at the national level. In Europe for instance, a recent report from RTE, the French electricity transmission system operator, gives the average renewable capacity additions planned by 2030 for five comparable countries (Table 2). In average, they are around 3 GW/yr for solar and 1 to 2 GW/yr for wind¹⁶. The highest targets have been set by Germany for solar (4.6 GW/yr), by the UK for offshore wind (3 GW/yr) and by Spain and France for onshore wind (2.1–2.2 GW/yr).



Annual capacity additions (GW) planned on average by 2028–2030	Solar	Onshore wind	Offshore wind	Total
France	3.5	2.1	0.7	6.3
Germany	4.6	1.7	1.2	7.5
Spain	2.3	2.2	0.2	4.7
Italy	3.0	0.8	0.1	3.9
UK	2.0	1.1	3.0	6.1
Average	3.1	1.6	1.0	5.7

Table 2. Source: RTE¹⁶.

The plans of these five countries are equivalent, in terms of capacity additions, to the construction of more than 3 nuclear reactors per year per country. One could therefore question their feasibility. However, they are fully compatible with maximal deployment speed achieved in the past. France, for instance, was able to build around 5 GW of nuclear energy per year in the 1970s and 1980s, and Germany has managed to deployed about 7 GW per year of wind and solar energy since 2008. **Policy targets are thus in line with past performances.** More generally, a review of 17 decarbonization scenarios has confirmed that most of them call for expansion of global generation capacity at rates consistent with historical experience¹⁷. This approach has notably showed that total global capacity additions are roughly proportional to global GDP. This relationship allows us to confirm that the latest BP and IEA net-zero scenarios have deployment rates in line with or slightly above what can be inferred from historical data (300–700 GW per year in 2050).



Looking at the data from BP’s Statistical Review of World Energy 2021 and IRENA’s Renewable Capacity Statistics 2021, we find that two countries have even reached capacity additions higher than 10 GW per year: China and the U.S. After a few years at around 40 GW per year for solar and 20 GW per year for wind, China broke records in 2020 by installing 56 GW of PV capacity and 71 GW of wind power¹⁸. Even if these figures are due to an exceptional rush of connections before the phase out of subsidies, China should easily reach its target of 1,200 GW of renewable capacity in 2030.

The U.S. capacity additions also set a record in 2020, with 17 GW added for solar, and 13 GW for wind. In its Solar Futures Study released in 2021, the U.S. Department of Energy (DOE) considers a scenario in which solar capacity additions reach 45 GW per year on average for the 2020–2030 period¹⁹. Nonetheless, it is clear that China and the US are outliers. We find that all other countries have significantly lower deployment rates, most of them building no more than 1 GW per year of both solar and wind capacities, as shown in Fig. 4. **Solar PV is clearly dominating the growth**, as we find 15 countries with capacity additions higher than 1 GW per year for solar, only 6 countries have capacity additions above 1 GW per year for wind power — all of them being also among the 15 top countries for solar deployment.

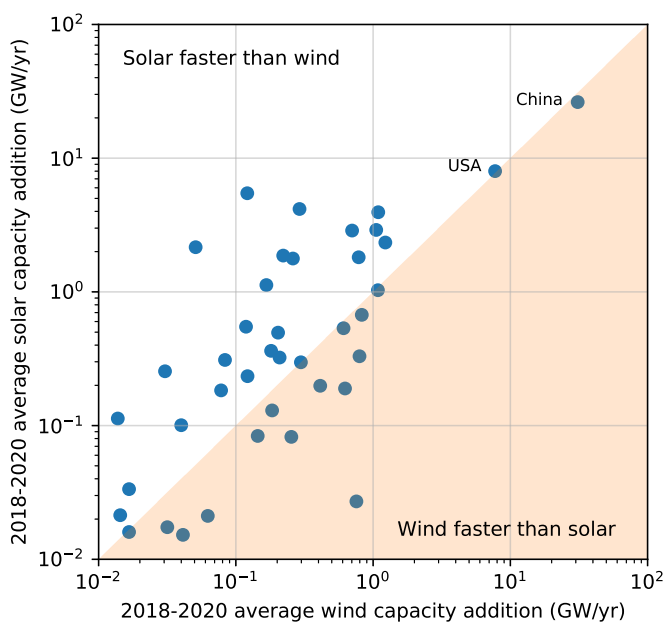
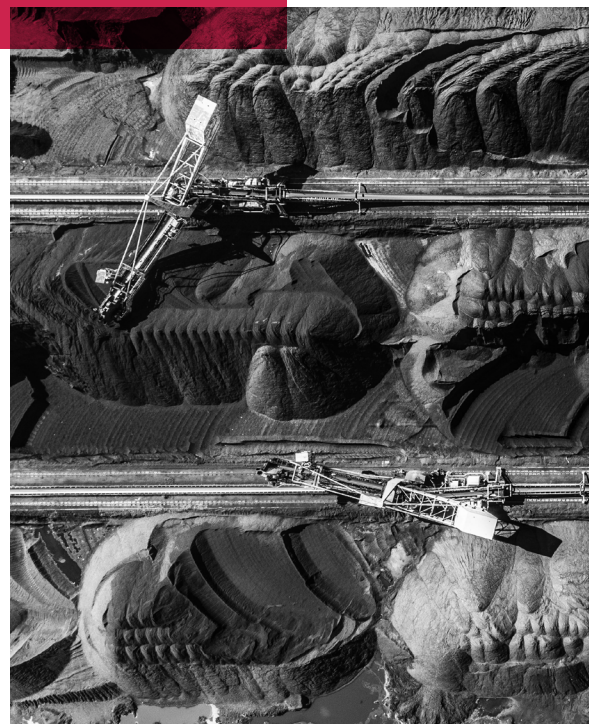


Fig. 4. Average capacity additions over the last 3 years (2018, 2019, 2020) of solar PV as a function of wind. Data from IRENA²⁰.

COSTS ARE A KEY DRIVER OF TRANSITIONS

The problem with energy systems is that they have considerable inertia. Historical analysis shows that the average duration from the invention of a technology to the time its share in the energy mix peaks or reach 80% is nearly a century²¹. For instance, it took coal 70 years to rise from 5% of the world's energy mix to its peak share – 55% in the 1910s – before it was supplanted by oil. Moreover, the ongoing energy transition is in no way comparable to past transitions due not only to the speed required, but also to its nature. Indeed, for the first time in history, new energy sources must completely replace existing ones, and not just add to them. Moreover, the ongoing transition has also to be deliberate, rather than the unplanned consequence of the fortuitous emergence of new energy sources^{22,23}.



Historic examples show that **the fastest transitions occur when new technologies offer a better service at a lower cost**. This process can be even more accelerated if demand is surging at the time of the uptake and if there are no major technological lock-ins. This was for instance the case of gas and kerosene lighting that have replaced primitive tallow candles in only a decade²⁴.

The cost reductions, floor cost limits and growth potential of key renewable and energy storage technologies have systematically been underestimated in IEA's scenarios, likely giving policy-makers the impression that renewables are and will always be expensive technologies²⁵. However, since 2010, the global weighted-average levelised costs of utility-scale solar PV electricity, onshore and offshore wind energy have fallen continuously since 2010 by around 85%, 68% and 56%, respectively^{5,7}. Historically, the cost reduction of solar PV is the most impressive, having fallen by a factor of 10,000 from the first commercial application on a satellite in 1958⁵.

As a result, **renewables are now increasingly below the costs of conventional fossil fuel generation and become the default option for capacity additions in almost all countries**, which was not necessarily the case until recently (Fig. 5). Utility-scale solar PV projects that will be commissioned this year could have an average price of USD 0.04 per kilowatt hour (kWh), which is almost 30% less than coal-fired power plants, the cheapest fossil-fuel competitor. The recent increase in fossil fuel costs makes renewables even more competitive⁷. Their development should also be supported by the cost decline of stationary energy storage technologies. A recent study has notably shown that the real price of lithium-ion batteries, scaled by their energy capacity, has declined by about 97% since their commercial introduction in 1991²⁶.

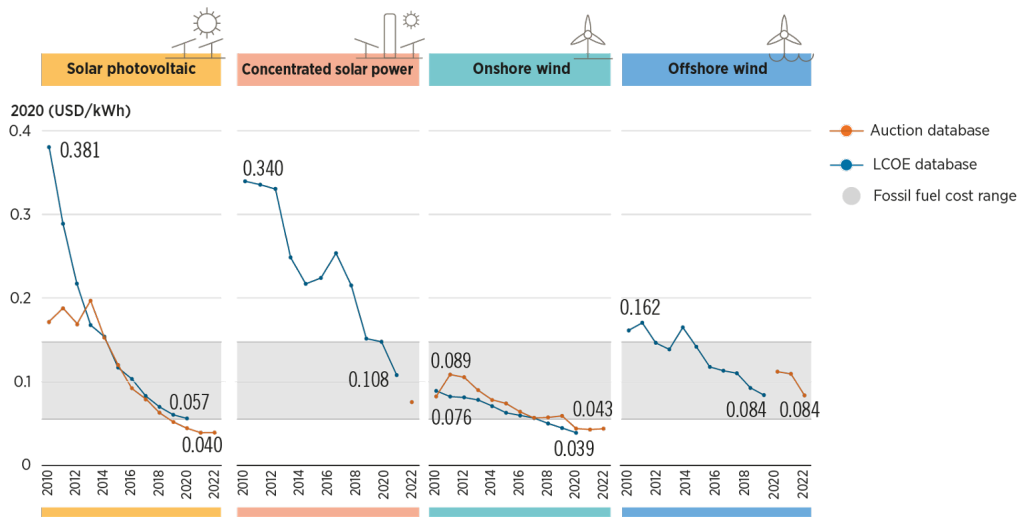


Fig. 5. Global weighted-average levelised cost of electricity (LCOE) and power purchase agreement (PPA)/auction prices for solar PV, concentrated solar power (CSP), onshore wind and offshore wind, from 2010 to 2023. Figure reproduced from IRENA⁷.

The fundamental driver of this change is that energy technologies follow learning curves, also known as Wright's law. While technologies start out very expensive, their price declines as the cumulative capacity installed grows (Fig. 6). This is mainly due to technological improvements and economies of scale. As renewables are modular small-unit size technologies, there is empirical evidence that they have more opportunities for learning, and thus for significant cost reductions and fast adoption²⁷. The example of nuclear in France shows that new nuclear reactors would be built much slower than historical ones notably because of complex designs, stricter safety requirements, long authorisation delays and losses of industrial competence¹⁶.

In some cases, once a technology reaches cost levels similar to its direct competitors, cost reductions stop, and stable market shares are established. But in the case of renewables, **several works anticipate that the decrease will continue in the next decades**^{14,25}.

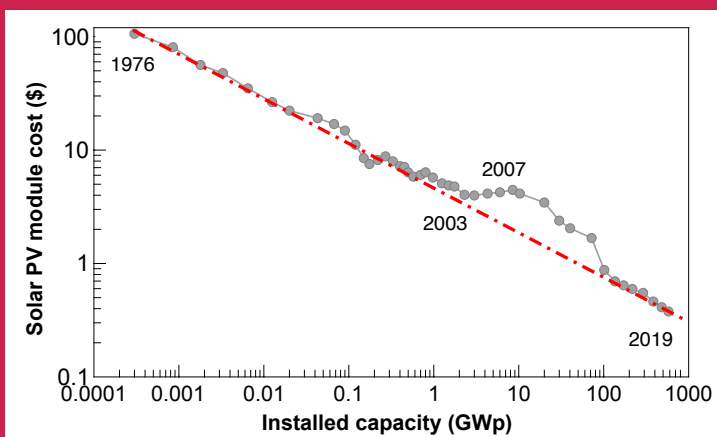


Fig. 6. Learning curve of solar power. Reproduced from the Fraunhofer Institute.

According to BP, costs of wind and solar could still decrease respectively by around 30% and 60% by 2050. This is especially important as it allows **renewable markets to shift from subsidy-driven to competitive pricing models**.

THE NEED FOR STRONGER POLITICAL SUPPORT

Notwithstanding those spectacular cost reductions, multiple challenges remain in accelerating the speed of the low-carbon energy transition. In particular, the long lifetime of existing carbon-emitting assets makes the shift difficult, as associated emissions would exceed our 1.5°C carbon budget without their early decommissioning⁵. This could have a massive economic impact, potentially creating \$541 billion worth of stranded power plant assets across the US, EU, China, and India alone, the latter two facing the highest share of the costs²⁸. This is an example of carbon lock-in²⁹. An interdisciplinary review has showed that carbon lock-in is due not only to economic factors, notably related to those past investments that have long lead-times and sunk costs, but also the result of existing norms, social and psychological processes, as well as technological and institutional factors that reinforces established technologies³⁰.



As a consequence, the transition will require complex negotiations between multiple objectives and constraints, including cost-effectiveness but also equity, social acceptance, changes in user practices, cultural discourses, political choices, resilience and flexibility^{17,31,32}. Further, the feasibility of the low-carbon transition varies across countries, according to their domestic energy resources, the size of their internal energy market and their trade relations³³.

The transition can therefore be accelerated by stronger political support and appropriately-designed policies tailored to national contexts. At first, innovation must be encouraged and adoption stimulated through public R&D, funding for demonstration and pilot projects, and demand-pull instruments such as deployment subsidies to attain scale and support market creation⁵. Stop-and-go policies must be avoided, so that political and regulatory frameworks become stable enough to ensure long-term visibility¹⁶. Policy planning, with explicit deadlines, is also essential to deal with the early retirement of fossil fuel-fired generator capacity³⁴.

Investments in infrastructure upgrades, modernisation, and expansion are also needed to build diversified and interconnected systems capable of accommodating high shares of variable renewable energy⁷. In addition, markets should be adapted to the characteristics of decentralised generation technologies, with no fuel or opportunity cost, which is not the case of current markets tailored to fossil fuel based, centralised energy production⁷.

Permitting remains another main bottleneck. Therefore, the time required to process authorisation requests and legal procedures for new projects must be reduced as much as possible. Changes in the regulatory framework may also give the possibility to build larger wind turbines or to increase potential installation areas. Grid connection and integration should also be made easier. The connection of wind and solar farms to the grid can be pooled, as is in Germany for example, and the implementation of solar power at local or individual scale (self-consumption) can be encouraged.

BOX 2. The feasibility of the deployment of solar and wind energy may face some land-use competition issues, especially with agriculture. In France for instance, 1 hectare of land is needed to install 1 MW of ground-based solar PV¹⁶, even if the soil under the panels remains in its natural state. For offshore wind, there can be a competition with fishing. On the contrary, onshore wind has a low land-use impact — despite its high landscape impact — because most of the area occupied is available for other uses, including agriculture. The number of masts can be limited by increasing the size of the turbines, but in this case the turbines will be larger and therefore potentially more visible. In France for instance, it is estimated that there will be enough land available to develop as many wind power facilities as planned in all energy transition scenarios. Wind power in France could reach 30,000 masts in 2050 at maximum, which corresponds to the current number of units in Germany whose territory is 35% smaller than France's. Finally, the IPCC recently recalled that the feasibility of solar and wind energy projects can increase when combined or integrated, such as using land for both agriculture and solar energy production⁵.



Finally, strong institutions will also be needed to orchestrate a just transition that includes climate-responsive social protection and promotes social acceptance. Indeed, low social acceptance causes delays or cancellation of planned projects — especially for wind power, which often raises local opposition due to its landscape impact. A lever may be the development of citizen participation in new projects through crowdfunding or by including them in the governance.

FUNDING THE TRANSITION

To make the transition happen, political support must come with financial support. In 2021, it is estimated that renewable energy attracted \$366 billion (+6.5% from 2020) among the global investment in the low-carbon energy transition of \$755 billion — a record³⁵. It has been shown that countries that deploy the most renewable capacities are those that invest the most, led by China and the USA¹⁷.

However, to limit global warming to 2°C or 1.5°C, **average annual investment requirements from 2020 to 2030 must be a factor of three to six greater than current levels**⁵. Again, decisions should be guided by long-term logic since the risks of stranded assets are high⁷. Sharing risks between public and private sectors is encouraged, as well as the development of new risk management solutions⁴.

While many initiatives around sustainable finance have been launched in the last years, financial flows have grown more rapidly than actual capital expenditures. As a consequence, there is a lack of high-quality clean energy projects to be fund. Adequate channels and intermediaries capable of guiding funds and of matching surplus capital with the sustainability needs of companies and consumers is required³⁶.

In developing economies, the policy drivers for stimulating the transition may be different, notably because energy demand is still rising²¹. The challenge is therefore for rapidly building infrastructures and markets, enabling people to get access to basic energy. In this context, the energy transition is an opportunity to avoid the risk of carbon lock-in and stranded assets⁴. The historical example of Latin American countries that leapfrogged the transition from coal to oil over the first half of the 20th century shows, for instance, that these countries may transition faster than leading nations³³.

The ability of developing countries to deploy low-carbon technologies would be enhanced with increased financial resources, capacity for innovation and technology transfer, notably from developed countries. The role of early adopters is indeed to accumulate knowledge, provide scaled market and set positive examples for followers⁵.

Finally, although this report is deliberately focused on the most mature technologies — solar and wind energy, investment must also go to other energy transition areas such as mobility, electrified heat, storage, and carbon capture and storage (CCS). To maintain our decarbonization effort up to 2050 and beyond, technologies available at demonstration or early commercial stages will require substantial maturation and face significant technical and cost hurdles to scale up. Innovation must therefore be strengthened through the combination of dedicated technology-push policies and investments, such as R&D, with tailored demand-pull policies to create incentives and market opportunities.




CONCLUSION

The development of renewable energy is among the best mitigation options available to limit global warming as close as 1.5°C above pre-industrial levels. Solar and wind energy are notably expected to play a major role in this decade, accounting for up to a third of emission reductions. Net zero by 2050 scenarios from the IEA, IRENA and BP all agree that installed solar and wind capacities must be close to 9000 GW in 2030 and to 22000 GW in 2050, while they currently are around 800 GW.

About 200 GW of new solar PV and onshore wind were commissioned in 2021, mainly helping to meet the ever-increasing total energy demand rather than actually replacing fossil fuels. Capacity additions will need to increase to 700 GW per year on average by 2030.

These figures show the scale of what remains to be done, even if renewables are rapidly gaining momentum. Deployment ambitions must be strengthened, as well as the implementation of climate pledges — especially as historical evidence suggests that transition rates are at reach. Indeed, examples from the past show that the fastest transitions occur when new technologies offer a better service at a lower cost. This process can be even more accelerated if demand is surging at the time of the uptake and if there are no major technological lock-ins. This is precisely what it is happening as renewables are becoming the cheapest option in most regions. Their prices are increasingly below those of conventional fossil fuel, making them more and more competitive.



Notwithstanding spectacular cost reductions, renewables still need stronger political support, guided by long-term logic and coherence. Policy-makers should help manage declining industries and anticipate that the intentional phase-out of fossil fuels will create stranded assets. They should encourage innovation, develop demand-pull instruments, accelerate procedures for new renewable energy projects, facilitate their connection and integration to the grid, include climate-responsive social protection and promotes social acceptance of low-carbon energy.



Finally, to make the transition happen, political support must come with financial support: average annual investment requirements from 2020 to 2030 must be a factor of three to six greater than current levels (\$755 billion in 2021) to limit global warming to 2°C or 1.5°C. Developed countries should also encourage technology transfers and funding to increase the ability of developing countries to deploy low-carbon technologies.



The development of offshore wind in the UK illustrates that, when all those conditions are fulfilled, the energy transition can be both at scale and in time. Beyond its abundant wind resource, the UK owes its success to a clear political support despite government changes, significant public funding, several calls for bids including successive corrections based on experience, large sustained bidding volumes enabling cost reductions, a proactive R&D policy focused on relatively short-term dynamics giving a prominent role to the private sector and public-private partnerships, as well as the fact that oil industries in the North Sea took advantage of their experience with offshore oil to find new growth opportunities³⁷⁻³⁹

In its report 'The Speed of the Energy Transition', the World Economic Forum sees three signposts to be passed by 2030 to achieve a rapid transition: solar electricity at \$20-30 per MWh, advanced lithium-ion batteries at \$50-100 per kWh and carbon taxes implemented on around half of emissions at \$20 per tonne. In parallel, three peaks of demand must take place before the end of this decade: demand for new internal combustion engine cars, demand for fossil fuels in electricity generation and demand for all fossil fuels⁸. The opportunity is before us.

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