In focus

The green energy transition

Examining the supply side

October 2023

Our energy systems are the foundation of modern human life. Every aspect of the global economy, from transportation and manufacturing to technological development and food production rely on these energy systems. It's hard to overstate their importance.

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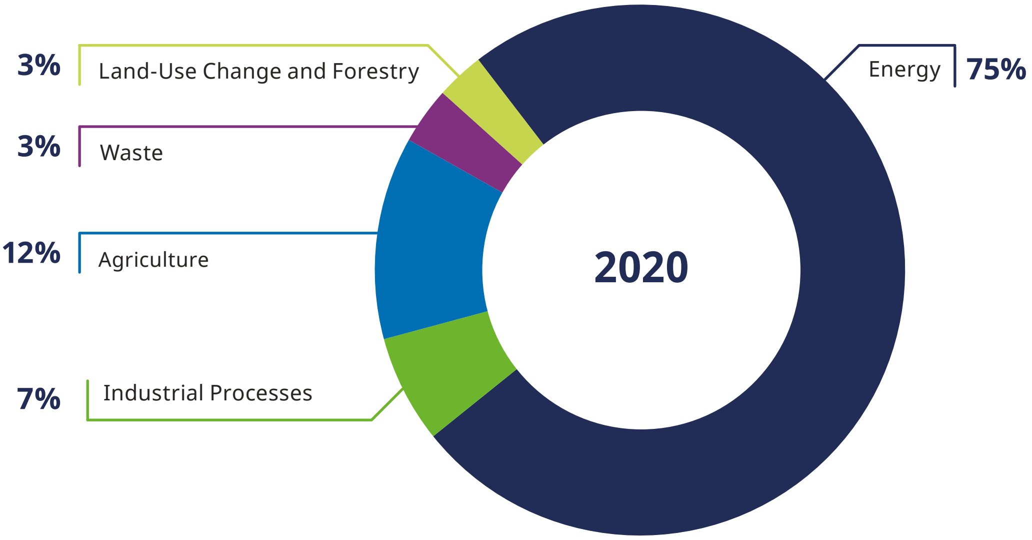
Around 80% of the current global energy supply is provided by high-emission fossil fuels[1], primarily from oil (contributing 30%), followed by coal (27%) and natural gas (24%). So, it comes as no surprise that the energy sector is responsible for around 75% of global greenhouse gas emissions.[2] Decarbonising our energy systems takes centre stage in our collective action to reach net-zero by 2050. However, transitioning away from fossil fuels is a complex and challenging endeavour. It requires us to not only transform how we produce, transmit and use energy, but to carry out this change in a manner which ensures that economies continue to function properly. It is a technical, financial, and social challenge which will fundamentally change how our economies operate.

Expensive, unaffordable, unfeasible

Three words which have come to describe the decarbonisation of energy systems over the past few decades. Building a clean, low-carbon energy system places significant upfront costs on economies. The fact that these costs need to be incurred over a short period of time makes the proposition more tenuous. The list of disincentives grows if one considers the high cost of collateral damage (ie stranded assets) left in the wake of this structural shift. The consensus steeped in pessimism has been, to some extent, understandable.

However, the changing energy landscape – particularly as it relates to improving competitiveness of renewable energy and the geopolitical/national security risks from relying on fossil fuels – prompts us to revisit this hitherto held narrative centred on the unaffordability and unattractiveness of a green energy transition. But before I discuss the remarkable progress made in the field of renewable energy, it would first be useful to understand what we really mean by decarbonising energy systems.

Figure 1: Global greenhouse gas emissions by sector in 2020



Source: Climate Watch

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[1] IEA 2022

[2] ClimateWatch

Section 1: The energy system flows

An energy system is a complex network of interconnected components that produce, transmit, distribute and consume energy. Once the energy is produced, it is refined to make it usable. For example, crude oil is refined into gasoline or diesel, coal is often pulverised, and natural gas is filtered for impurities. These non-renewable sources of energy can either be used to generate electricity or can be consumed directly by transportation, industrial, residential, or commercial sectors (we refer to them as end-use sectors).

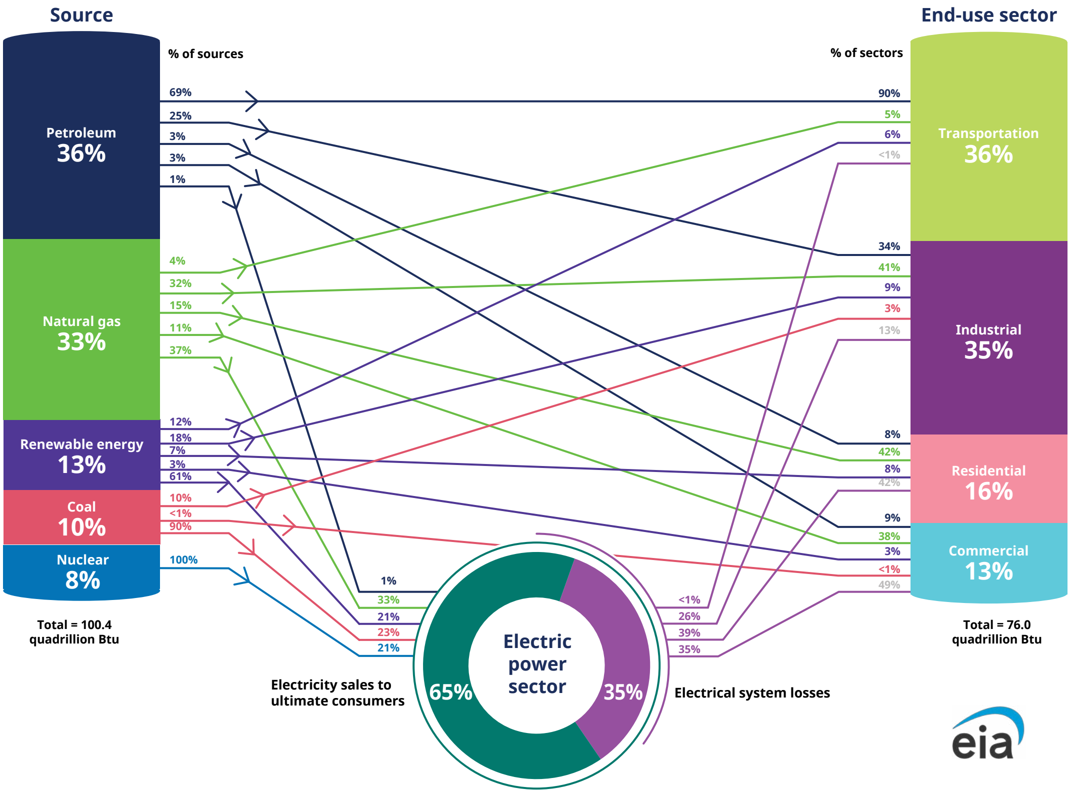
Figure 2 is a simple schematic by the Energy Information Administration (EIA) which captures the major components of the energy system and enables us to understand how the green energy transition will play out.

There are a few key points worth noting:

- **Energy supply:** Fossil fuels are used in both electricity generation and for direct consumption by end-use sectors. Oil is primarily used by the transportation sector and industrial sector (petrochemical production). Natural gas is used in heating and feedstock in industries such as manufacturing and chemicals. And coal is used as a heat source in industrials and buildings. These fossil fuels are also used in electricity generation and accounted for 62% of total global electricity generation in 2022[3]. (Renewables stand at 28% and nuclear around 10%).
- **The energy sector itself consumes energy:** From extracting these resources to refining, processing, transmitting, or transporting, and electricity generation – the energy sector also consumes a notable amount of energy. The energy sector's own energy consumption is around 8% to 9% of global energy consumption and around 2% is lost in transformation, distribution, and supply[4]. The energy conversion loss from burning fossil fuels to produce electricity is notable at around 60%[5]. Renewable electricity generation have much better energy conversion efficiencies, so shifting energy sources to renewables leads to a reduction in final energy demand[6].
- **Final energy consumption:** Decarbonising energy consumption can include i) transitioning away from fossil fuels to low-carbon energy sources ii) improving energy efficiency iii) behavioural shifts and iv) increased electrification[7]. Shifting to electric vehicles, installing heat pumps and LED lighting, improving insulation, car pooling are all examples of these. However, there are some hard-to-abate sectors which will face challenges in decarbonising due to the nature of their processing or the lack of low-carbon alternatives. Heavy industries (such as manufacturing, chemicals and cement production which utilise high temperature processes), long-distance transportation (such as aviation, maritime transportation), extractive industries (such as mining) are some of these hard-to-abate sectors. Green hydrogen as a clean energy source might be used for these sectors in the future if they are cost-effective, readily scalable, and available.
- **Energy is not just about electricity generation:** The discourse on energy transition usually focuses on decarbonising electricity. This makes sense as electricity is expected to account for 50% of total energy consumption by 2050 (with around 90% of electricity generation provided from renewable sources, especially wind and solar PV[8]). But focusing purely on power generation misses out on the larger picture of fossil fuels used as a direct source of consumption and hard-to-abate sector.

Figure 2: Overview of the energy system

US energy consumption by source and sector, 2022



Source: EIA Monthly energy review, Aug 2023

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3 IEA World Energy Outlook 2022 (Pg 279).

4 IEA Key world energy statistics 2021 (Pg 47).

5 EIA (2020)

6 So does electrification.

7 While transitioning to clean energy sources focuses on changing the source for energy generation, electrification involves changing the way energy is used.

8 IEA: Net zero by 2050 – A roadmap for the Global Energy Sector (2021) (Pg 9).

Section 2: Decarbonising the supply side

The energy landscape is rapidly changing. Renewable energy, particularly solar photovoltaics (PV) and wind energy have experienced an exponential decline in costs and a rapid increase in deployment rates. In this section, we discuss whether renewable energy costs have declined to a point where transitioning to a clean, low-carbon energy system is now financially viable, without accounting for climate change or national energy security concerns?

The changing energy landscape

A recent working paper by the University of Oxford examines the supply-side dynamics of energy services to shed light on the question stated above. By examining historical long-term cost trends of different energy sources, they build probabilistic cost forecasts for the major energy sources and then sum these up to estimate total system costs in various energy scenarios. They conclude that, “compared to continuing with a fossil-fuel-based system, a rapid green energy transition will likely result in overall net savings of at least $12tn by 2050 – even without accounting for climate damages or co-benefits of climate policy.”[9]

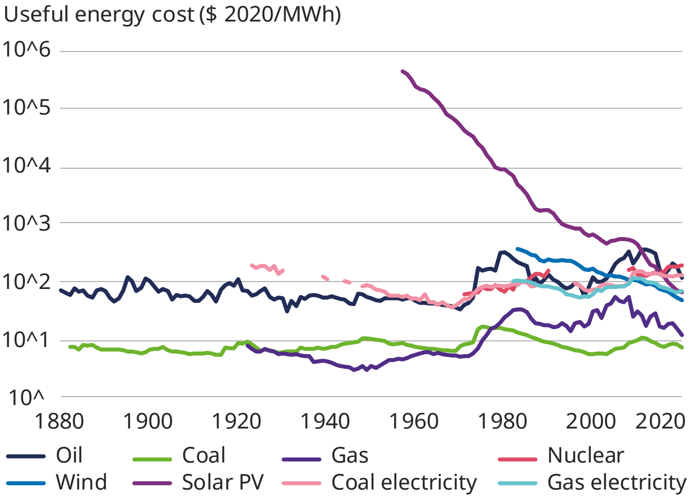
The authors of the paper believe that they can estimate costs of future energy systems more accurately by developing probabilistic models based on past data[10 11]. Their approach made reliable predictions when they were empirically tested on more than 50 technologies. By focusing on the supply-side equation of the energy transition (and assuming end-demand sectors grow at the same pace as they have done for the past few decades), the paper builds a simple and transparent way to forecast future energy systems.

Historical data provides important clues

The authors of the paper study the cost trajectories of different energy sources over the past 140 years and note that conventional fossil fuels and renewable energy technologies are qualitatively distinct and should be calibrated differently when projecting future cost trajectories. Figure 3 and Figure 4 capture the cost trajectory and rates of deployment for key energy sources over the long term.

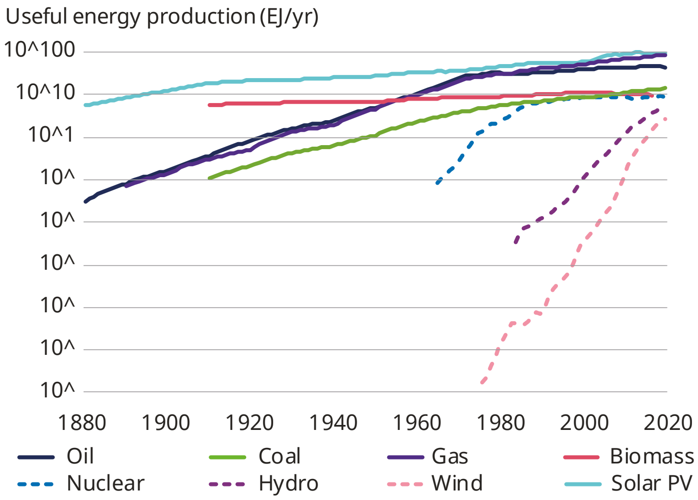
- **Fossil fuel prices show no long-term trend:** Prices of fossil fuels are volatile over the short term but have remained more or less constant over the past 140 years (after adjusting for inflation). This long-term trend in prices is not well understood, but they note that the empirical findings hold strong. Indeed, oil and gas sector did experience a somewhat exponential increase in production in the early 1900s as it replaced coal and traditional biomass and witnessed its fair share of technological progress and efficiency improvements in production, but resource extraction also became more difficult. In this case, the authors use autoregressive [AR(1)] time series model to forecast costs. This applies to direct-use oil, coal and gas, as well as coal-fired and gas-fired electricity (Both coal-fired and gas-fired electricity experienced declining costs initially, but their long-run costs are ‘increasingly dominated by fuel costs’)[12]
- **Renewable energy[13] transformation dominated by solar PV and wind:** The cost of solar PV and wind has declined exponentially at the rate of roughly 10% per year, and their production has increased by 44% and 23% per year respectively, over the past 30 years. These developments bear a striking resemblance to the technological revolutions of the past. The advent of electricity, the rise of automobiles, the proliferation of the internet are a few examples where technologies experienced a sharp decline in costs and a rapid expansion of deployment. They use a probabilistic cost model based on these exponential trajectories to forecast future cost trajectories (more on this later).

Figure 3: The cost of renewables (especially wind and solar PV) has experienced an exponential decline



Source: Rupert Way et al. (2021) Note: 1. Data is as of 2020. 2. Chart is in logarithmic form i.e. a straight line in a log-scale chart shows exponential growth. 3. Useful energy refers to the energy that is used to effectively perform a particular task. Useful energy takes energy conversion into account. Electricity is a secondary energy source that is produced when primary energy sources are converted into electric power[14]. When we burn fossil fuels for electricity generation, around 60% to 67% of energy is wasted, primarily in the form of heat[15]. Electricity generation from renewables have a much higher energy conversion rates of around 80%. 4. The chart shows useful energy costs, after adjusting for inflation, but in some cases prices are used as a proxy due to lack of data, especially for earlier time periods. 5. Electricity generation costs (from wind, solar PV, coal, and gas) are shown as Levelised Cost of Electricity (LCOE) and coal, oil, gas are shown as primary energy costs.

Figure 4: Deployment rates for different energy sources through time



Source: Rupert Way et al. (2021) Note: 1) Data is as of 2020 2) Chart is in logarithmic form i.e. a straight line in a log-scale chart shows exponential growth.

9,10 Decarbonising the energy system by 2050 could save trillions

[11] The exponential reduction in costs in renewables is better captured by the stochastic generalisation of Wrights law and the fairly stationary fossil fuel costs are better captured by an autoregressive time series model.

[12] Rupert Way, et al. (Supplemental information).

[13] Interestingly, nuclear, biopower and hydropower (not shown in the chart) don’t show these strong historic trends witnessed in solar PV and wind. Nuclear energy saw a rapid rollout and declining costs early on in its journey, but recently their trajectories flattened. The authors still apply a stochastic generalisation of Wright’s law to all renewable energy technologies but note that nuclear, biopower and hydropower have a less significant role to pay in the energy transition.

[14] EIA (2020)

[15] Our world in data

Levelised Cost of Electricity (LCOE)

The levelized cost of electricity is a popular metric to compare the competitiveness of different sources for electricity generation. LCOE is the discounted lifetime cost of generating electricity from a particular source over the lifetime of a power plant. It's expressed a cost per unit of electricity generated.

$$\text{LCOE\^{}} = \frac{\text{Net present value of total costs}}{\text{Net present value of electricity generation}}$$

LCOE estimates typically include:

Capital costs:
upfront costs in building the power generation infrastructure including land, equipment, construction, and capital costs

Operating and maintenance costs:
to ensure the plant is operating efficiently

Financing costs

Fuel costs (if applicable)

Capacity factor:
which measures the efficiency of power plants i.e., how much electrical power is produced by a plant relative to how much could possibly be produced at peak capacity

Discount rates:
to calculate the net present value of total costs and electricity generation

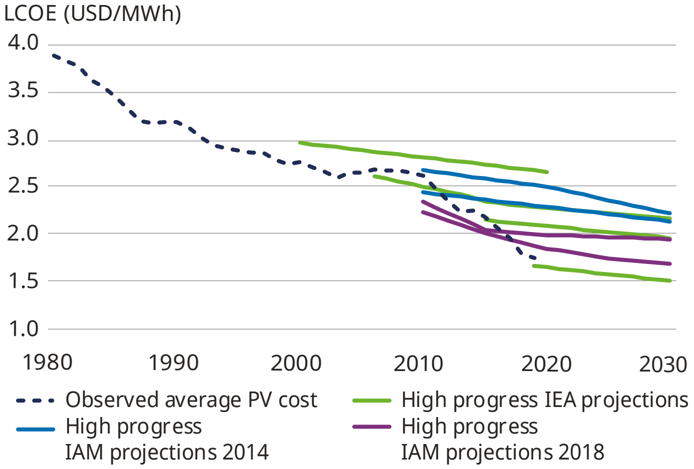
LCOE is technology agnostic (which means it can be applied to any electricity generation technology such as coal, gas, wind, solar, nuclear) and can standardise costs for comparison and decision making. It is a comprehensive measure which captures all the long-term costs that are expected over the plant's anticipated lifetime as well as shorter term considerations of changing capacity factors and energy production, which are important for intermittent energy sources such as solar and wind. Lastly, it is transparent and simple to understand, making it a powerful tool for communicating changes widely.

However, like any metric, it has some limitations which are worth highlighting. LCOE is sensitive to changes in discount rates. In addition, it does not take into account energy value chain considerations such as upgrading electricity grid infrastructure to integrate intermittent renewables, improving energy storage or any technological innovations that might occur in the future. Nevertheless, it is an important tool to assess the economic viability of different energy sources.

Popular energy-economy models have missed the mark

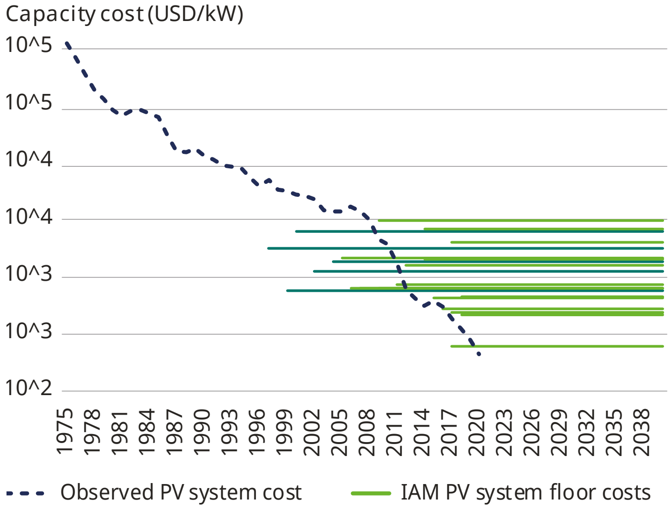
The study also noted how popular energy-economy models failed to capture the remarkable progress delivered by renewables over the past two decades. The study analysed more than 3,000 energy system scenarios between 2010 and 2020 – scenarios they consider to be optimistic and aggressive decarbonisation pathways – and found that they consistently underestimated deployment rates, overestimated costs (Figure 5), and imposed floor costs – which are fixed levels below which costs can't fall. Floor costs, which are not only empirically unfounded, but have also been continuously breached. Figure 6 shows floor cost estimates for solar PV from optimistic scenarios compared to what has transpired. The study finds that, the mean value of projected cost reduction of solar PVs under these optimistic scenarios was 2.6% per year, with none of the models forecasting more than a 6% decline per year. In contrast, solar PV costs fell by 15% per year. This is a startling mis-estimation with far ranging implications for policymakers and economists alike, and risks locking in high capital cost, high emission projects and under investing in clean, green technologies[16]. Even though many energy-economy models have updated their cost and deployment trajectories to reflect ongoing improvements, they still apply floor costs. The International Energy Agency, in its latest World Energy Outlook, has recognised the exponential, rather than the linear nature of growth in renewables.

Figure 5: Energy-economy model forecasts of solar PV compared to actual costs



Source: Rupert Way et al. (2021).

Figure 6: Floor costs of solar PV assumed by energy-economy models have been continuously breached



Source: Rupert Way et al. (2021).

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[16] Concerns around battery storage costs and low capacity factors in wind, solar PV are addressed in section 3.

There are three possible explanations for these models falling short. The first is a more obvious one – that these models are the victims of their own complexity. Energy-economy are Integrated Assessment Models, which examine linkages between economy, energy systems and earth systems to provide policymakers pathways for energy transition under different criteria (for example, limiting temperature increases to 1.5C). From forecasting policy pathways, resource availability, energy prices and technological advancements to geopolitical factors, demographic changes, financing costs and behavioural change – one can see how the many moving parts and errors compound as they are integrated. The second reason is apparent and simultaneously inconspicuous– the influence of fossil industry incumbents on the modellers.

And the final justification is around shifting our perspective on renewable energy – to view it as a technology, not as a commodity. Kingsmill Bond, a leading energy strategist from the Rocky Mountain Institute[17], shows that the cost and deployment rates of renewable energy follow similar trajectories to those experienced in other technological developments. These cost and deployment trajectories are akin to S-curves or learning curves – where rising production leads to improved experience, expertise, and efficiency, causing costs to decline, which in turn improves economies of scale and production. These learning curves embody Wright's law. Learning curves are a powerful tool for cost prediction and technological change. The associated innovations in battery technology, conversion efficiencies, further strengthen these positive dynamics. Fossil fuels – a commodity – display no learning curves, as evidenced by the constant prices of fuels over the past 140 years. Viewing renewables as a technology and not as a commodity is a subtle but powerful shift in perspective.

Figure 7: Learning rates[18] for renewables from 2010 to 2020

	Total installed costs	LCOE
Utility-scale solar PV	34%	39%
Concentrated Solar Power (CSP)	22%	36%
Onshore wind	17%	32%
Offshore wind	9%	15%

Source: IRENA power generation costs in 2020 (Pg 11) Note: 1. Total installed costs are upfront costs in building the infrastructure for a renewable energy plant. These costs form a part of Levelised Cost of Electricity (LCOE), which captures the lifetime cost of a power plant. 2. These learning rates are corroborated by other studies like Bolinger et al. (2022), Rubin et al. (2015) and Lafond et al (2017).

Figure 8: Differences between energy as a commodity and as a technology

Fossil fuels	Renewables
Commodity-based system	Technology-based system
No learning curve	Learning curve
Finite and geographically concentrated	Abundant and available everywhere
Continuous material flow required	Low marginal cost
Low conversion efficiency	High conversion efficiency
Pervasive negative externalities	Much lower impact on nature

Source: Table adapted from a graph presented by the Rocky Mountain Institute

Rapidly transitioning to green energy by 2050 will save trillions

The study forecasts that rapidly transitioning to low-carbon, green energy by 2050 will save the global system trillions compared to taking no action. Scaling up key renewable technologies will continue to drive down their costs. And the faster we go, the more we will be able to save. It's worth recognising that building any energy transition scenario still requires a substantial amount of judgements of simplifications (you can dive deeper into this here). The study deliberately adopts fairly conservative estimates for renewable energy to highlight the feasibility of a fast transition. This conclusion holds true across a range of reasonably acceptable discount rates.

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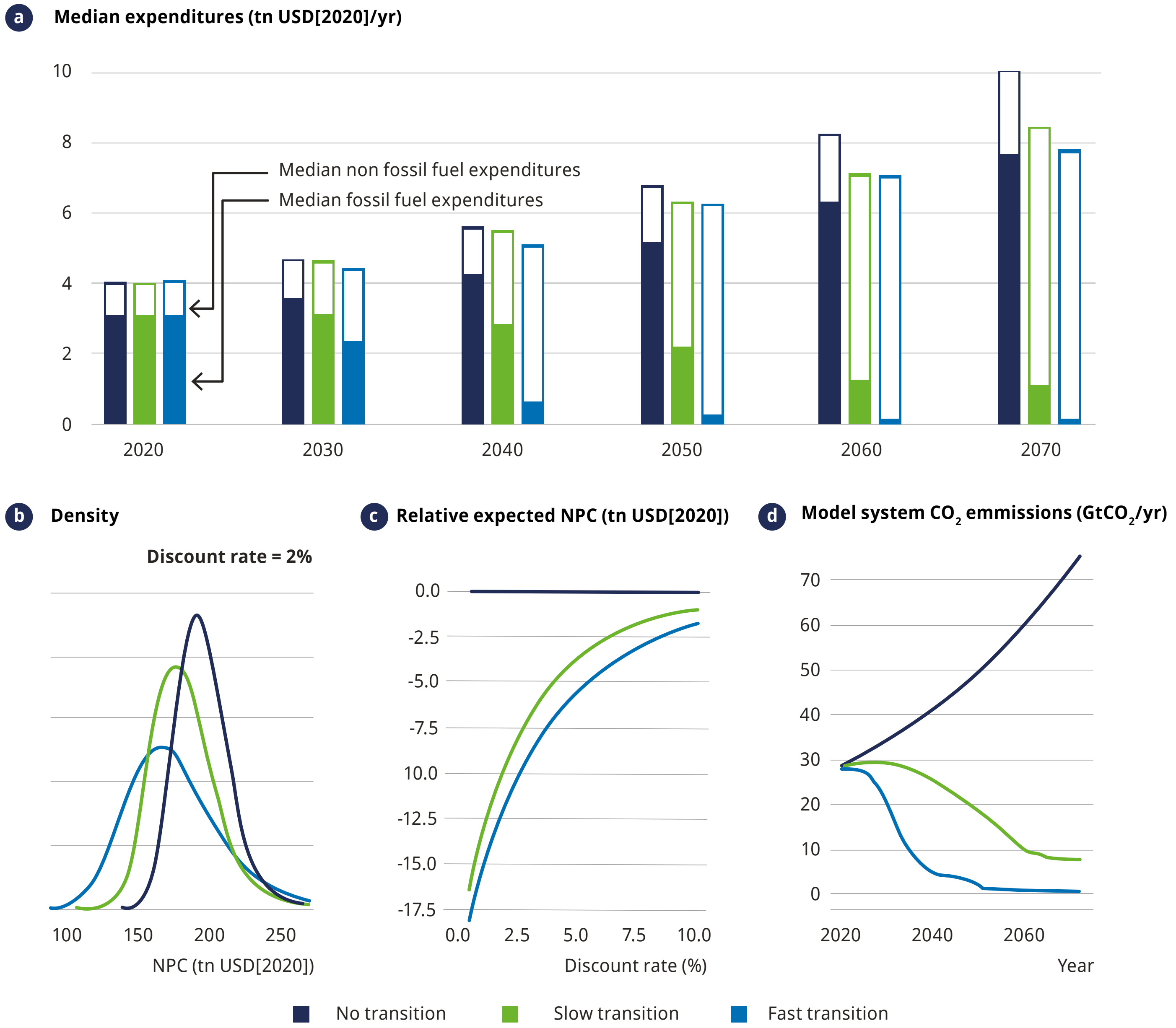
[17] https://rmi.org/the-energy-transition-in-five-charts-and-not-too-many-numbers/

[18] Learning rate is the percent reduction in cost for every doubling of cumulative installed capacity.

Figure 9: A faster transition to clean, green energy will lead to the most savings



Source: Reproduced from Rupert Way et al. (2021). Note: Fast transition: Maintain current renewable energy deployment rates with almost complete electrification, replacing fossil fuels in two decades. Slow transition: Renewable energy deployment rates slow immediately, fossil fuels continue to dominate till 2050. No transition: Fossil fuel growth follows historical trends. Energy system remains similar to current form.

Other economists have used similar approaches to understand the exponential decline in solar PV costs and forecast future trajectories. A paper by Lafond et al. (2017) uses learning (experience) curves to produce distributional forecasts over different horizons and found that if solar PV exponential trends in diffusion continues, they are likely to become very inexpensive in the near future. Pioneering work by De La Tour (2013), Farmer et al. (2016) and Kavlak et al. (2018) have all examined learning curves and technological progress in the past, and concluded the exponential decline in solar PV costs.

By analysing historical cost trends, their research shows that renewable energy will become cheaper than fossil fuels across almost all applications in the years to come. The evidence from a purely financial perspective is clear. If one considers the positive externalities from this transition – such as mitigating the worst impacts of climate change, safeguarding domestic energy security, and providing equal distribution of power – the case for transitioning to renewable energy becomes more obvious.

Zooming in on recent trends in renewable energy production

Yogi Berra rightly quipped “It’s tough to make predictions, especially about the future.” One might argue that it is easier to forecast long-term trends with confidence because you won’t be around when they actually materialise. Additionally, one model can’t change the long-held view of the unattractiveness of the green transition. These are valid challenges. Can the conclusions drawn from the above study be corroborated with current trends in renewable energy?

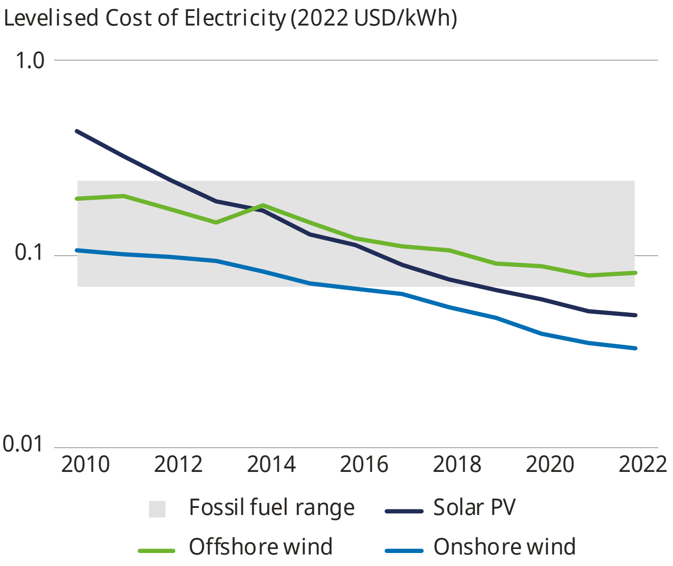
To answer this, we need to examine two underlying drivers. Firstly, how the demand for new energy is currently being met. Secondly, what we say about replacing fossil fuel plants with renewable energy? The answer is looking increasingly promising in both these considerations.

New capacity generation

A policy-maker deciding between installing a renewable energy plant or a fossil fuel plant will compare the lifetime costs of generating electricity (LCOE) from each source. If the LCOE of newly commissioned renewable energy plants is lower than the LCOE of fossil-fuel fired plants, then they will favour the former over the latter.

The data shown by IRENA in Figure 10, captures the improvement in competitiveness of renewables. The global weighted average LCOE of newly commissioned utility-scale solar PV projects declined by 89% between 2010 and 2022, whilst onshore and offshore wind fell by 69% and 59% respectively.

Figure 10: Global LCOE from newly commissioned utility-scale solar PV, onshore and offshore wind technologies from 2010 to 2022

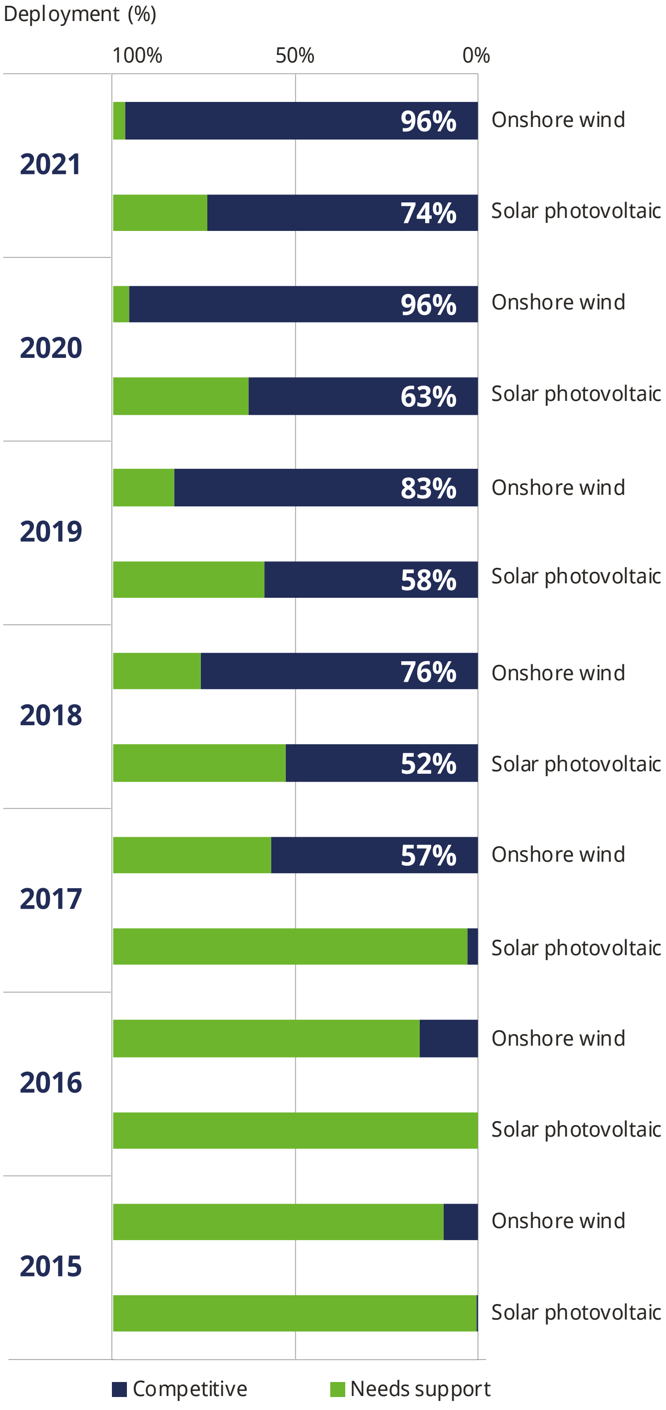


Source: [IRENA (2023), Renewable Power Generation Costs in 2022, International Renewable Energy Agency, Abu Dhabi](). Note: Chart is in log-scale.

Solar PV's global-weighted LCOE was 710% more expensive than the cheapest fossil fuel-fired option in 2010. By 2022, the figure was 29% lower than the cheapest fossil fuel-fired option. Onshore wind is now 52% lower than the cheapest fossil fuel-fired option[19].

According to IRENA, around 73% of newly commissioned, utility-scale renewable power generation capacity in 2021 had costs of electricity lower than the cheapest fossil fuel-fired option in the G20 (Figure 11). This figure rose to 86% in 2022[20]. **Renewable power generation is becoming the default economic choice for new capacity.**

Figure 11: Annual total new renewable power generation capacity added at a lower cost than the cheapest fossil fuel-fired option, 2010 – 2021



Source: IRENA (2022), Renewable Power Generation Costs in 2021, International Renewable Energy Agency, Abu Dhabi

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[19] IRENA Renewable Power Generation Costs in 2022

[20] IRENA Renewable Power Generation Costs in 2022

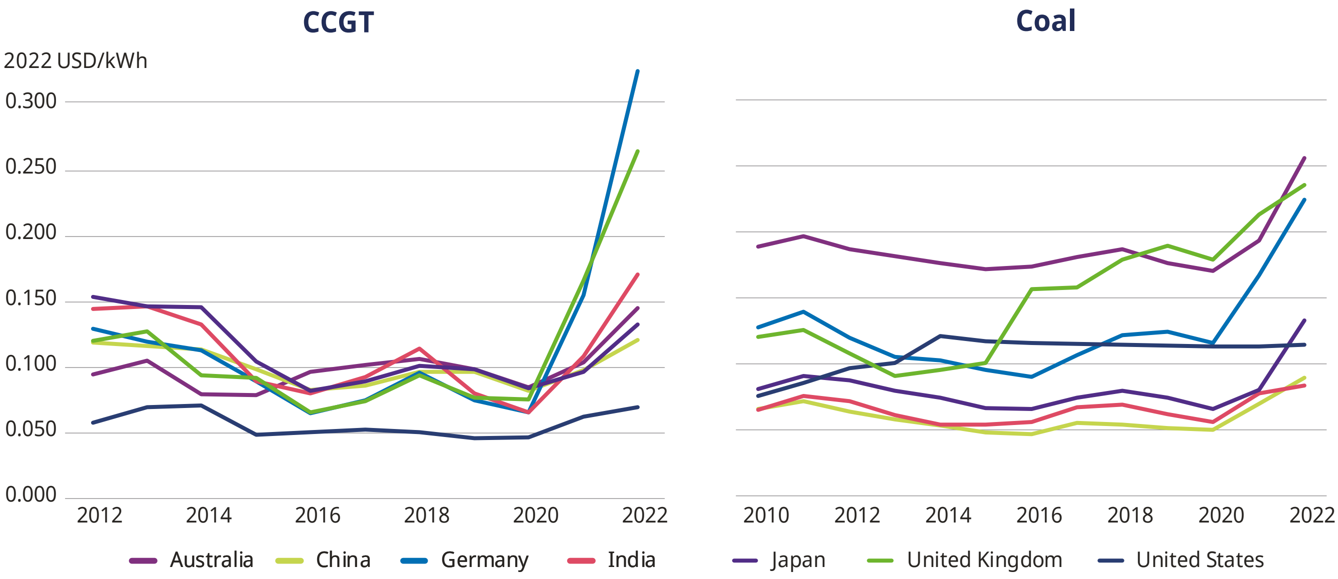
It's worth acknowledging that the comparison with 2021/2022 fossil fuel prices is a tad unfair, given these were at elevated levels. Nevertheless, there is something to be said about how fossil fuel prices are being driven by geopolitical meanderings – exposing energy importing nations to volatility and economic pain – the recent cuts in oil production by OPEC to shore up prices and growing regional conflicts reflect this ongoing trend. In comparison, the cost trajectories for renewables (especially solar PV and wind) are firmly established, are declining, and are insulating nations from elevated fossil fuel prices. According to IRENA[21], renewable power deployed globally since 2000 saved around $521bn in fuel costs during the fossil fuel price spike in 2022 in the electricity sector alone.

It's also important to note that renewable energy i) was becoming increasingly competitive even prior to the oil price crisis and ii) have also faced rising equipment and material costs from the oil price shock[22]. The recent escalation in fossil fuel prices have simply brought forward the positive tipping points experienced by renewables.

Replacing existing fossil fuel infrastructure

Turning our attention to the financial viability of replacing existing fossil fuel plants, the analysis changes. In this case, it would only make sense to shut down a fossil fuel fired plant if its operating (fuel-only) costs are higher than the average full lifecycle costs (LCOE) of renewables. The hurdle is understandably higher. In this case, the viability of oil and gas is looking questionable, even more so for coal power plants. Figure 13 from IRENA cost database shows that "As costs for solar PV and onshore wind have fallen, new renewable capacity is not only increasingly cheaper than new fossil fuel-fired capacity, but increasingly undercuts the operating costs alone of existing coal-fired power plants." Fuel costs have come to dominate the total LCOE of gas and coal-fired plants. The average fuel cost as a percentage of total LCOE was around 64% for combined-cycle gas turbine and around 40% of LCOE for coal-fired power plants in 2022[23].

Figure 12: Fossil-fuel fired LCOE of combined cycle gas turbine (CCGT) and Coal, 2010 – 2022



Source: IRENA (2023), Renewable Power Generation Costs in 2022, International Renewable Energy Agency, Abu Dhabi

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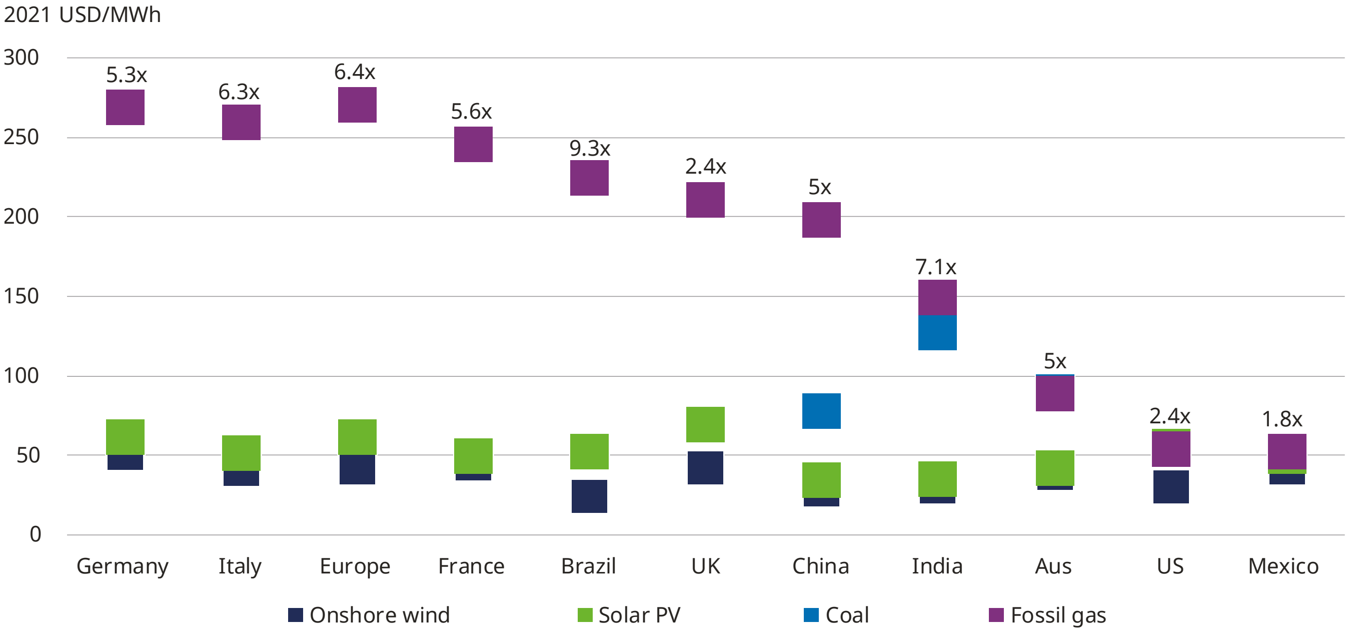
[21] IRENA Renewable power generation costs in 2022

[22] As is also noted by IRENA Renewable power generation costs in 2022

[23] IRENA Renewable power generation costs in 2022. Capital costs for coal-fired power plants are higher than gas plants.

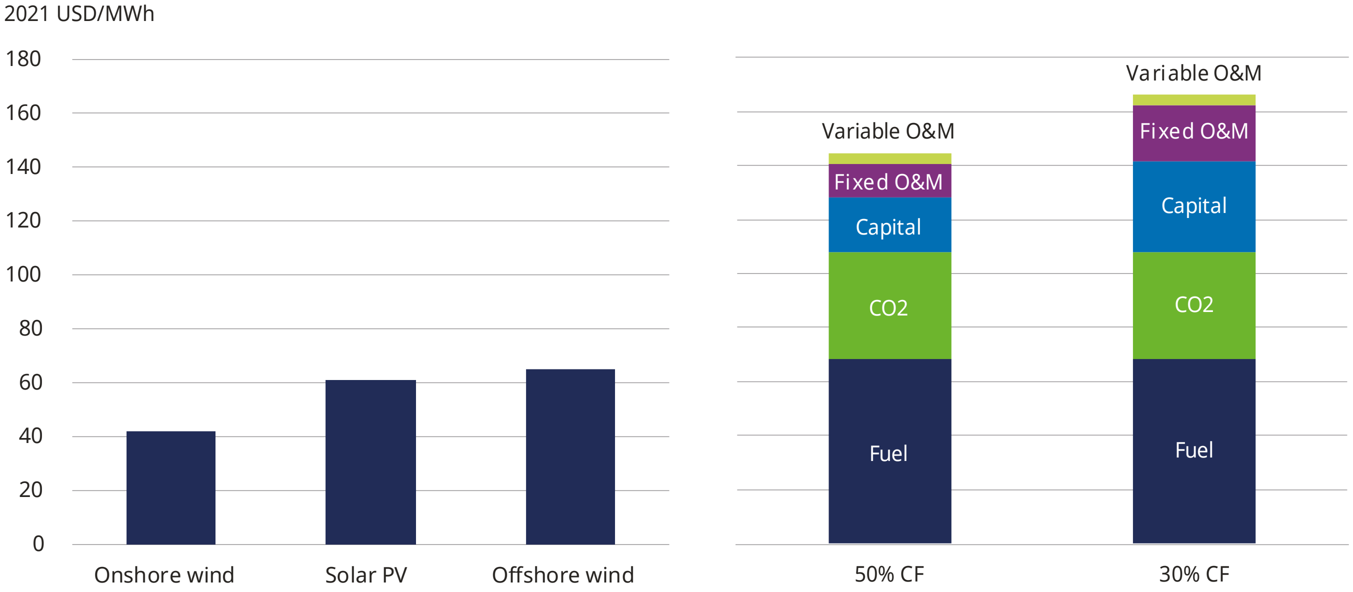
Figure 13: Fuel-only generation costs for coal and fossil gas for 2022 relative to LCOE of new solar PV, onshore wind projects commissioned in 2021, by country



Source: IRENA (2022), Renewable Power Generation Costs in 2021, International Renewable Energy Agency, Abu Dhabi. Note: The data labels show ratio of gas-fired power plant's fuel-only operating costs to onshore wind. The low cost of fossil gas in the US stands out and can be explained by the sharp rise in shale production over the past decade. India and China still use coal for electricity generation.

To further elucidate this point, we focus in on Europe's changing energy landscape. The data emerging from IRENA shows that new fossil gas-fired power generation does not look economic over its lifetime in the near future. Figure 14 shows that the cost of electricity for a new combined-cycle gas turbine (CCGT)[24] in Europe today (with a 50% capacity factor and without assuming carbon capture and storage costs) would be 75% higher than the weighted average full lifetime cost of new solar PV commissioned in 2021 and 155% higher than the cost of newly commissioned onshore wind power.

Figure 14: LCOE of new solar, onshore, and offshore wind in Europe compared to fossil gas-fired plants (2021)



Source: IRENA (2022), Renewable Power Generation Costs in 2021, International Renewable Energy Agency, Abu Dhabi. Note: Required real return on capital assumed at 7%,. CF stands for Capacity factor (more detail below). Consider price of carbon at EUR 90/tonne under EU Emissions Trading Scheme. Consider fuel plus carbon-only costs for operation. We don't assume any Carbon Capture and Storage here.

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[24] CCGT combines a gas and steam turbine to more efficiently produce electricity compared to traditional gas-fired plants.

Section 3: Further considerations

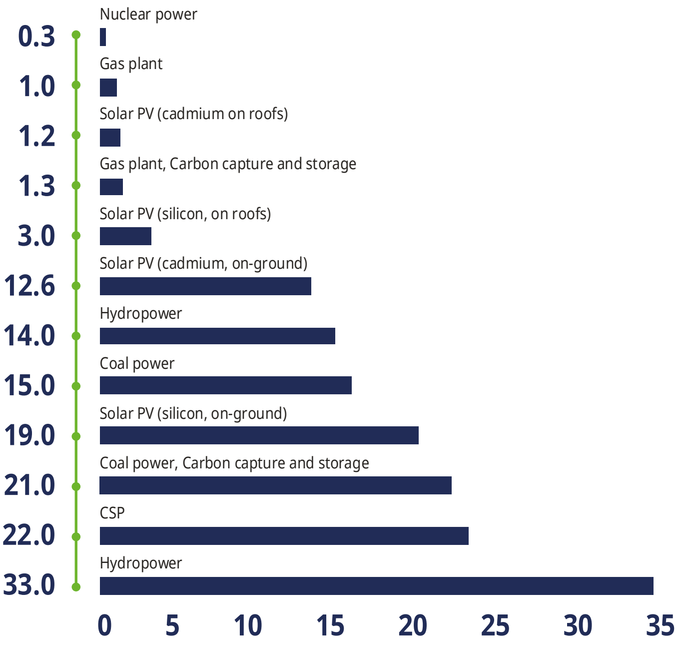
Would building renewable energy capacity take up too much land?

Land costs are an important consideration when it comes to installing any electricity generating plant. Life-cycle assessments are typically used to estimate land use needed to i) mine metals, minerals, and energy sources ii) operate the plant to convert it into usable energy iii) connect it to an electricity grid and iv) dispose of any waste[25]. Figure 15 shows the land use of energy sources per unit of electricity. We find that nuclear energy is the most land-efficient source and hydropower is the least efficient. Land-use estimates of solar PV rooftops are lower than their on-ground counterparts but are still notable as they incorporate land used for mining and extraction. Within solar PV, cadmium is more efficient than silicon and uses less land per unit.

In any case, estimates of land-use costs are already factored into LCOE calculations, which we know have experienced significant declines. As the renewable energy technology revolution continues and becomes more efficient, the land use to supply a unit of energy will decline.

Figure 15: Median land use per megawatt-hour of electricity

(m2-annum per MWh)



Source: Our world in data and UNECE's Lifecycle Assessment of Electricity Generation Options Note: CSP is Concentrated Solar Power.

Where do battery storage costs fit into all of this?

Battery technology is essential for unlocking the full potential of renewable energy. Given the inherent variability in renewable energy power generation, batteries store excess energy generated by renewables in order to be used during periods of high demand or low energy generation, thereby enhancing grid stability[26].

Energy storage solutions can be grouped into three broad categories[27]:

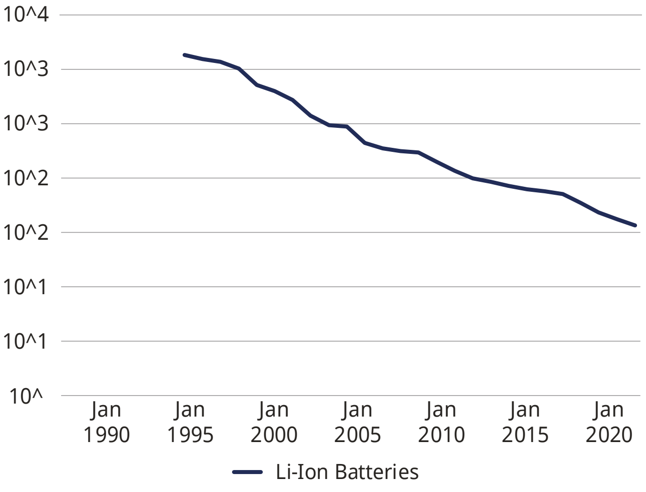
- Short-term (Minutes to hours): such as lithium-Ion batteries, which are designed to provide quick and immediate energy supply and absorption. Lithium-Ion battery technologies are a fairly recent innovation (around 20 years old), but even here we find that it has followed a cost deflation and deployment trajectory similar to that of solar PV and wind (and akin to technological advancements of the past)
- Medium-term (days to weeks): such as flow batteries, advanced compressed air energy storage, pumped thermal storage, pumped hydro storage
- Long-term (months to years): such as synthetic fuels, ammonia, hydrogen – where renewable electricity can be used to generate hydrogen through electrolysis

Medium and long-term storage technologies are critical to ensure consistent energy supply over different seasons. While cost estimates for this depend upon what technology is used, geographical location, existing grid infrastructure, we note higher upfront costs compared to short-term storage options. According to IRENA[28], total installed costs for battery electricity storage systems could fall by between 50% to 60% over this decade, driven by optimisation of manufacturing facilities, more research and development, improving battery lifetimes, and the growing cost competitiveness of renewable energy. Indeed, the levelised costs have been steadily declining for many long-term storage options.

A study by Blanco and Faaij (2018)[29], shows how long-term storage solutions can i) lower fuel costs – more storage saves electricity for peak demand and increase higher operational efficiency due to a higher load ii) lower curtailment – which is intentionally reducing electricity generation to manage supply-demand balance, iii) lower generation investment – storage provides balancing function, so backup and balancing capacities needed are lower, and iv) lower network investment – as storage eases congestion on network lines during peak hours. These savings potentially offset some of the investment and operational costs for storage.

Figure 16: Batteries have become a proven technology with cost trajectories similar to previous technological revolutions

Useful energy cost ($ 2020/MWh)



Source: Rupert Way et al. (2021) Note: Chart is in log-scale.

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[25] How does the land use of different electricity sources compare?

[26] Rupert Way et al. (2021)

[27] Large-scale energy storage by the Royal Society.

[28] Electricity storage and renewables: Costs and markets by 2030

[29] A review at the role of storage in energy systems with a focus on Power to Gas and long-term storage: Blanco, Faaij (2018)

What about stranded assets?

'Stranded assets' are assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities[30]. Assets becoming financially unviable before the end of their anticipated life could be due to a number of regulatory, behavioural, market or technology-related reasons.

One study estimates of net present value of future impairments or losses are between $5tn to $17tn[31]. The large range speaks to the challenges faced by models in estimating this value. The values are dependent on the pace of transition, risk of abrupt policy shifts, asset impairments in upstream activities (fossil fuel left in the ground), write-downs in downstream assets (fossil fuel refineries), impacts on end-sector use (buildings, transport, power generation), the discount rate used – to name a few.

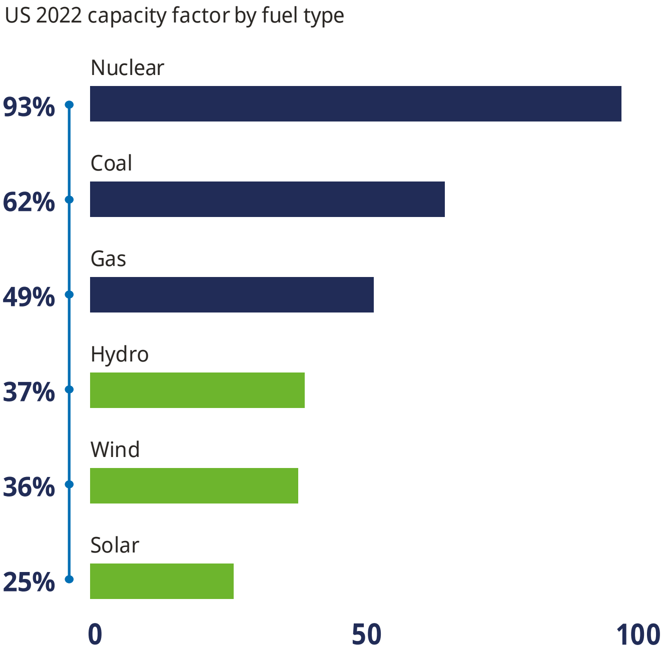
However, given the growing competitiveness of renewable energy technologies, we can invoke Schumpeter's theory of creative destruction – where constant innovation means the 'old' is replaced with the cheaper and more efficient 'new.' Stranded assets due to technological obsolescence are different from that brought on by regulation. Every technological revolution, from horses to cars and from cassettes to digital steaming, have seen assets being 'replaced by superior alternatives before their engineering lifetimes'. This renewable energy revolution is no different. As LCOE of renewable projects fall below the operating costs of fossil fuel plants, the latter will increasingly be underutilised before being replaced. The Oxford study[32] notes – "Lifetimes of large energy infrastructure projects typically range from 25 to 50 years, meaning that on average about 2-4% of capacity needs replacing in any given year. In addition, useful energy demand grows at 2% per year. These two factors make it possible for renewables to replace most of the existing energy system in 20 years and replace the remaining 5% within a few decades without necessarily stranding assets beyond their economic lifetime".

A similar argument is true for light passenger vehicles, which usually don't have a life of more than a couple of decades. The actual value of stranded assets is likely to be much lower than estimates.

What's the big deal about capacity factors?

Capacity Factor (CF) is the ratio of the actual energy output of a power plant to the maximum potential output if it were operating at full capacity continuously[33]. Renewable energy technologies, such as wind and solar, have lower capacity factors as changing whether and daylight conditions lead to intermittent power generation. On the other hand, fossil fuel-fired electricity generation has a higher and more stable capacity factor as they operate continuously[34]. This high-capacity factor has until recently tipped the debate in favour of fossil fuels as it translates into a lower LCOE. According to the EIA, CF for solar and wind power in the US in 2022 was 25% and 36% respectively, which is lower than the average CF for fossil fuel-fired power plants as seen in the Figure 17.

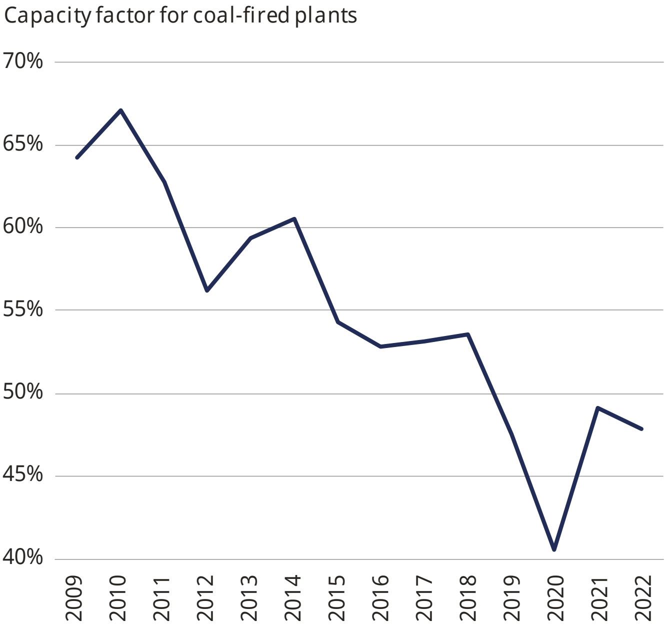
Figure 17: Capacity factor of energy sources is an important determinant of competitiveness, and is captured in LCOE estimates



Source: US Energy Information Administration, Electric Power Monthly.

However, improving capacity factors of renewables is increasing their competitiveness. According to IRENA, the global weighted-average capacity factor of newly commissioned utility-scale solar PV plants increased from 13.8% in 2010 to 16.1% in 2020[35]. At the same time, fossil fuel-fired power plants are increasingly being out-competed by renewables, which is leading to their underutilisation and then shutting down. Because fossil-fuel fired plants have much higher fixed operating and maintenance costs compared to renewables, the drop in utilisation rates increases the LCOE by a larger factor.

Figure 18: Trend of underutilisation of coal-fired plants in the US



Source: US Energy Information Administration, Electric Power Monthly

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[30] https://www.smithschool.ox.ac.uk/sites/default/files/2022-04/Stranded-Assets-and-Scenarios-Discussion-Paper.pdf

[31] https://pubmed.ncbi.nlm.nih.gov/31261374/

[32] https://www.cell.com/joule/fulltext/S2542-4351(22)00410-X

[33] https://www.pnas.org/doi/10.1073/pnas.220542911932

[34] Note the difference between conversion efficiency (how effectively a power plant converts fuel source energy into useful energy) and capacity factor (Ratio of electrical output of power plant to its maximum potential output).

[35] IRENA (2022), Renewable technology innovation indicators

Metals supply and the role of China

The clean energy transition is driving up the demand for several critical minerals. According to the IEA, this transition will need 40 times the amount of lithium, 25 times graphite, 20 times Nickel and 20 times Cobalt by 2040[36]. We need to consider three factors when we examine the supply of metals and minerals critical for the renewable energy transition. The first has to do with reserves of minerals and metals – we find that these are abundant and not concentrated in a particular region. The second and third factors are that of extraction and processing. China dominates these two.

As we can see from Figure 18, decades of strategic development in the mining and refining of critical metals has meant that China currently control the supply chains of metals and minerals crucial for the green energy transition. The worsening of trade relationships between nations (such as the US recently restricting investments in Chinese semiconductor and AI technologies, and China restricting the supply of gallium), makes the risk of supply bottlenecks notable. Other nations are actively looking to diversify their metal supply chains[37], are forging new partnerships with mining countries[38], and are investing in the development of new technologies[39] to secure the supply of minerals and metals. But building new extraction and processing pipelines is time consuming and complex and the risk of supply bottlenecks derailing the energy transition is material till 2030. The ongoing 'metals protectionism' deserves its own analysis, one which I'll cover in another paper.

Figure 19: Many mineral supply chains lack diversity

Share of China in processing of selected minerals, 2022

Copper	42%	Nickel	17%
Cobalt	74%	Lithium	65%
Graphite	100%	Rare earths	90%

Source: IEA, the role of critical minerals in clean energy transitions (2021)

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36 IEA, The Role of Critical Minerals in Clean Energy Transitions

37 like the European Critical Raw Minerals Act

38 UK's Critical Minerals Strategy

39 Like advancements in sodium-ion battery technology

Conclusion

Viewing renewable energy as a technological revolution not only helps us understand the impressive cost and deployment trajectories we have witnessed over the past few years but enables us to make more accurate assessments of what the future energy landscape might look like. Renewable energy is not only dominating new power generation but is increasingly undercutting fossil-fuel fired plants as its costs continue to decline exponentially.

What does this mean for investors and policymakers?

1. Underestimating the exponential rise of renewables increases the risk of capital misallocation: either in the form of underinvestment in the green energy technological revolution (losing out on potential returns) or because of over investment/locking-in capital in expensive, high-carbon emitting projects (increasing the risk of stranded assets)
2. Stranded assets due to technological obsolescence are different from those brought on by regulation: The improving cost competitiveness of renewables implies that it will continue to undercut fossil fuel-fired power generation – in line with the theory of creative destruction – continuous innovation replaces the efficient 'new' with the costly 'old' before their anticipated lifetimes. Consider the example of the shift from vinyl records to cassettes, CDs, and eventually digital streaming. Investors should reflect on whether they choose to hold onto cassettes when the world is moving onto digital streaming. In addition, as fossil fuel infrastructure depreciates over its lifetime, it can be replaced with cheaper and more efficient renewables – which means that the current estimates of stranded assets are likely too high
3. Decarbonising energy demand represents a huge opportunity: From the exponential rise in sales of electric vehicles to technological advancements in energy efficiency and new fuels, the way we consume energy is undergoing a fundamental change. Building investment strategies which are aligned to the new, zero-emissions economy will not only allow investors to better manage transition risks but will make them better positioned to gain from 'positive' tipping points in technological revolutions

What is good for the planet, can be good for profits too.

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