Market Briefing

The cost of renewables will continue to fall, this is why

Long-term cost drivers for solar, wind and energy storage

March 31, 2023

Key implications

– The cost of generating and storing renewable power has fallen almost without interruption for the past several decades. Although recent turmoil in supply and logistics chains has resulted in increased costs of all renewable technologies, we expect that cost reductions for photovoltaics (PV), onshore and offshore wind, and energy storage will resume sooner rather than later, driving the ongoing transformation of the power sector.

– Economics of mass production combined with technology-enabled improvements in efficiency are expected to drive another 55–60% drop in capex for PV between now and 2050. An increase in local manufacturing driven by aggressive policies could slow the pace of these reduction, but ultimately result in a more resilient supply chain.

– A mix of capex reductions and higher capacity factors continue to determine the future cost of wind—both onshore and offshore—which is expected to fall by about 45–50% between now and 2050. Although offshore wind mostly relies on ever larger turbines, with floating foundations in some regions, onshore wind will require a modular mix of options that make the most out of a very diverse set of siting conditions.

– Cost declines will continue in battery manufacturing as the industry will still benefit from major economies of scale. But supply chain complexity and aggressively increasing demand dictated by the automotive industry may bake in higher material costs. This uncertainty results in a wide range of potential cost declines of 35–65%. Promising technologies that would enable a step change in costs are unlikely to achieve scale in sufficient time.

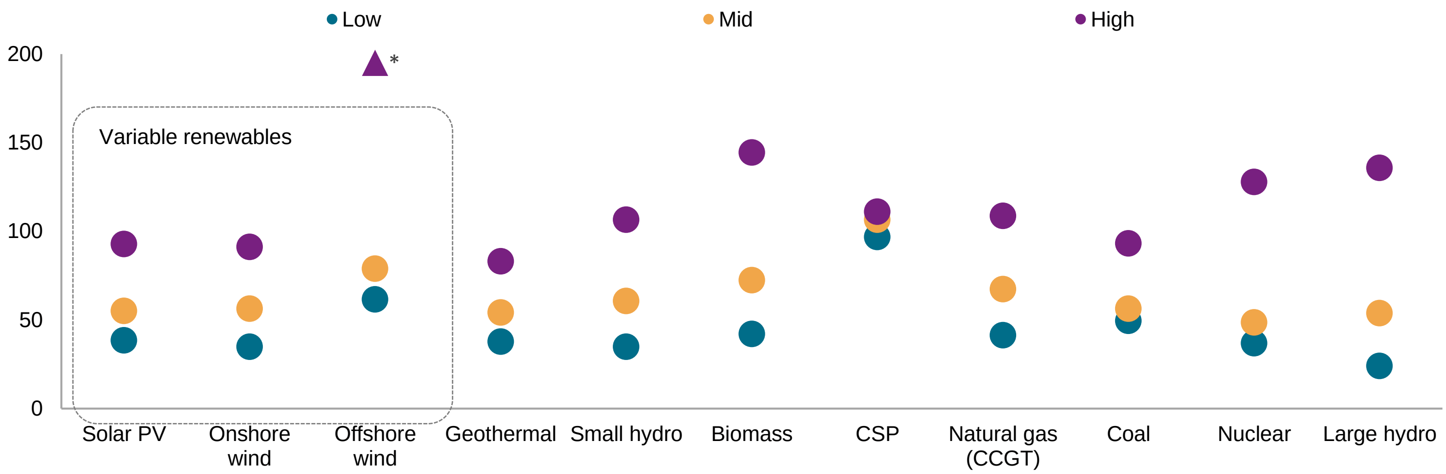
S&P Global
Commodity Insights

A combination of demand and supply shocks—turmoil in commodity markets; crisis in shipping and logistics; raw material shortages; a serious polysilicon bottleneck, triggered by disparate post-pandemic economic recoveries; economic consequences of mainland China's "zero-COVID" policy; Russia's war in Ukraine, compounded by policy shocks such as RePowerEU and IRA—have led to predictions that the spectacular fall renewables cost over the past few decades could now finally be coming to an end.

Blended average selling prices for photovoltaic (PV) modules were in the fourth quarter of 2023 as high as they were toward the end of 2018, up nearly 30% compared with the same period two years ago. Major western wind turbine manufacturers have raised prices for wind turbines by nearly 30% in 2022 to compensate for skyrocketing costs of raw materials. Prices for lithium, nickel, and cobalt all rose sharply during the past two years, resulting in battery cell prices increasing by 20-30%.

Yet, the recent increases are almost anecdotal compared with historical cost declines for these technologies. Capex for PV projects was nearly 300% higher 10 years ago, and that for onshore wind at least 150%. The cost of batteries has dropped by 95% since 2012.[1] Today, solar and wind are among the cheapest options to generate power, both for new and existing plants.

LCOE of different renewable and conventional power generation technologies, 2020 (US$/MWh)



Data compiled November 2022.

LCOE = levelized cost of electricity; CSP = concentrated solar power; CCGT = combined-cycle gas turbine.

High, mid, and low correpond to the 80th percentile, the weighted average, and the 20th percentile of tracked data. LCOEs are shown in real 2021 US dollars.
*High value for offshore wind is more than $250/MWh.

Sources: S&P Global Commodity Insights; International Renewable Energy Agency (IRENA).

Over the coming decades, renewables will represent more than 90% of capacity additions in the power sector, implying that electricity generated from these technologies will surpass that from fossil fuels by the early 2030s.[2] Annual installations of energy storage, mainly in the form of Li-ion batteries, are expected to grow by 280% by 2030. Policy and shifting attitudes toward climate change are an important driver of this transformation, but the underlying enabler is cost: solar and wind technologies keep getting cheaper on a per MWh basis, driven by scale and marginal technological improvements.

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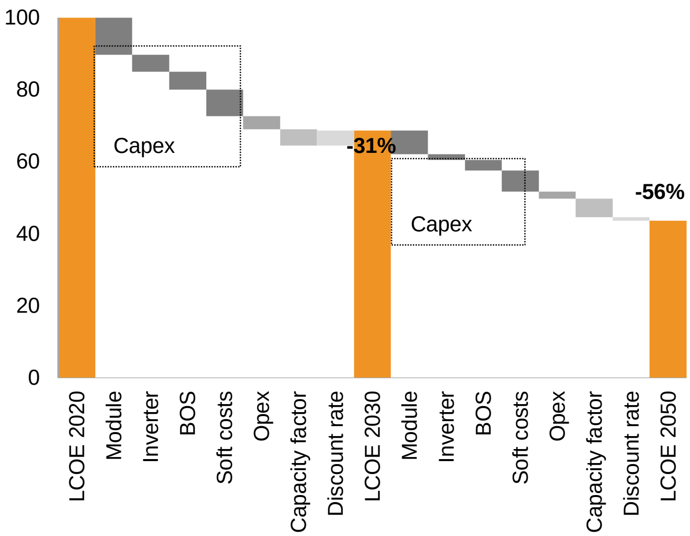
[1] Based on average cost ($/kWh) of a lithium-ion (Li-ion) energy storage module blended across all technologies.

[2] Non-hydro renewables will produce more power than fossil fuels by 2034, according to the S&P Global Commodity Insights Inflections Scenario, and become the dominant source of power by 2042.

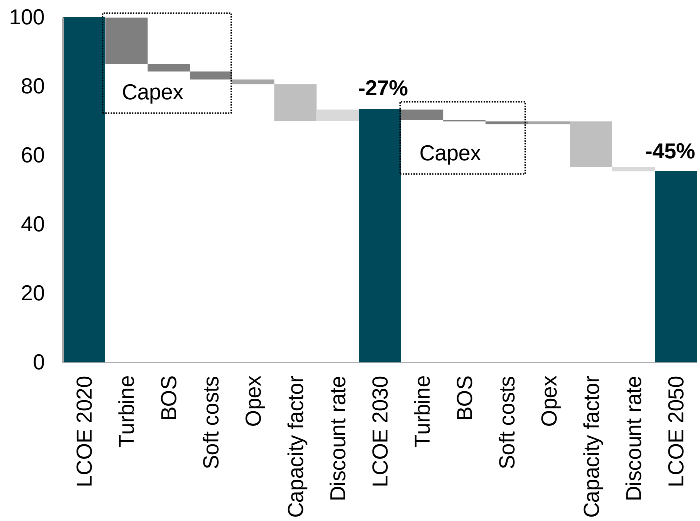
The long-term outlook for the cost of renewable power and energy storage: Onward and downward

Power generation costs differ a lot across markets due to a variety of reasons, but on average, we expect the LCOE from PV, onshore wind, and offshore wind to fall by 45–60% between 2020 and 2050. Having very low operating costs, the key levers for cost reduction are capex, the capacity factor, and the cost of capital.

Solar PV



Onshore wind



Data compiled November 2022.
BOS = balance of system; soft cost = installation and development.
Index values correspond to weighted global averages.
Source: S&P Global Commodity Insights.

The weight of these inputs varies depending on the technology. In the case of PV, costs will continue to be driven primarily through reductions in capex. While non-module costs do play a role in lowering LCOEs, module technology improvements will play the key part. For wind, it is a combination of capacity factor gains coupled with a fall in capex, both enabled by an evolution in the size and type of turbines. To meet modern power systems' needs, a variety of attributes are required beyond just cheap energy—energy storage is becoming a necessary complement for variable generation from wind and solar. The cost of storage, measured in $/kWh, is expected to drop by 35–65% by 2050, driven by manufacturing scale, but with a wide range because of supply chain uncertainty.[3]

Solar PV: The benefits of mass production

Economics of mass production combined with technology-enabled improvements in efficiency are expected to drive another 55–60% drop in capex for PV between now and 2050. An increase in local manufacturing driven by aggressive policies could slow the pace of these reductions but ultimately result in more resilient supply chains.

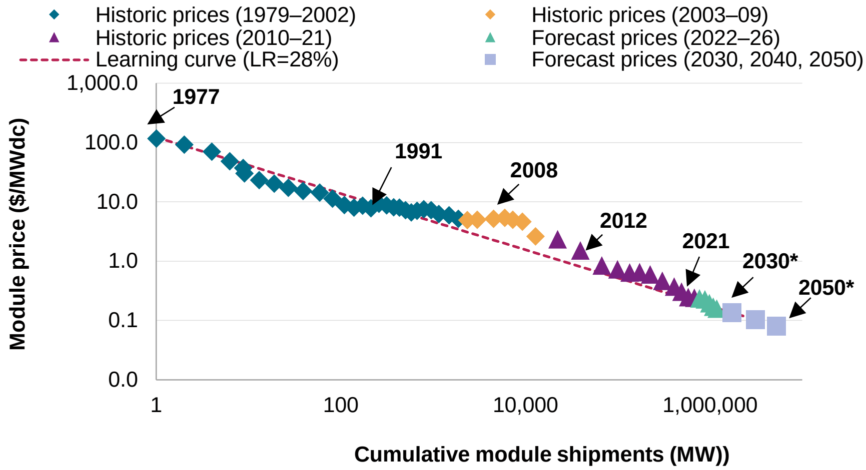
Cost reductions for PV modules can be described using an experience curve, a fixed ratio between the cost of a manufactured good, and the amount of that good that has been made. Historically, each doubling of cumulative installed solar

[3] Note that the impact of the recent rise in interest rates has a direct impact on the cost of financing for capital intensive renewable power projects, offsetting some of the technology-driven gains in costs. For more analysis on this, see the S&P Global Commodity Insights Market Briefing *Fear the Fed: Rising rates add to squeeze on margins – Cleantech Edge*.

PV capacity corresponds to a drop of about 26–28% of the module cost. Between 2000 and 2008, module prices rose owing to supply bottlenecks and overly generous support schemes, but the underlying downward cost trend continued, as evidenced by the return of module prices to the long-term trend by 2012. We expect that this relationship will continue to hold, driven by more efficient use of materials, increases in module efficiency, and competition.

PV manufacturers continue to optimize the quantity of expensive materials that they use. For instance, the polysilicon conversion rate (grams of polysilicon per Watt) improved from about 6 g/W in 2010 to about 2.5 g/W today and it is expected to continue falling over the next 10 years thanks to the use of thinner, larger wafers and improved ways that ingots are cut into wafers. Similar trends apply to the use of silver in cells and copper in modules, or replacement of silver printing by copper plating. Another example of substitution of an expensive material would be a switch from aluminum to steel frames with anticorrosive coating for modules. Steel frames are heavier but also much less energy intensive to manufacture.

Historical crystalline silicon PV module prices and the experience



Data compiled November 2022.
LR = learning rate.
A 28% learning rate implies that with each doubling of cumulative manufacturing capacity, costs fall by
Source: S&P Global Commodity Insights.

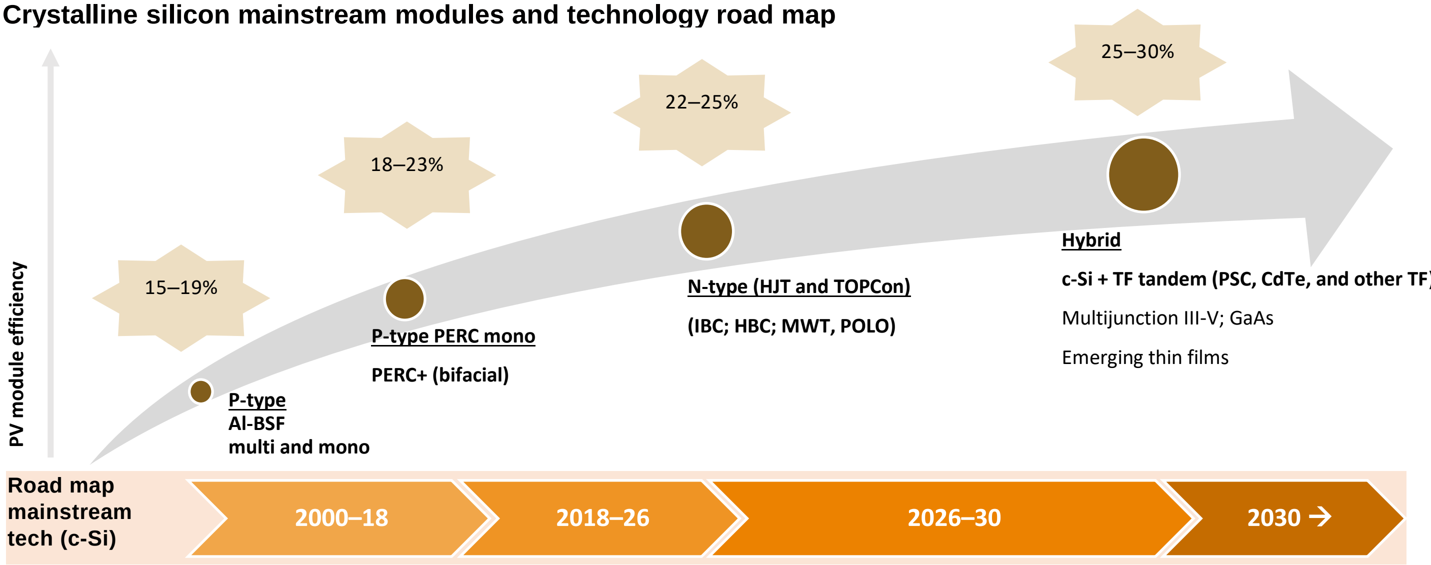
More generally, PV manufacturing benefits from adapting processes that are also used in other industries such as semiconductors, from wet chemical processes to metallization.

Average PV cell efficiency has increased from about 16–17% in 2010 to 20% in 2020 and is expected to grow to 25% in 2030, or surpass 28% using new cell concepts. Higher efficiency reduces the number of modules required for a given capacity, leading to lower land use, BOS cost, opex, and ultimately LCOEs.[4] This explains why manufacturers keep investing in new manufacturing technology to sustain this trend. In the near term, efficiency increases will come from the diffusion of already-existing products and processes: these include larger wafers, half-cut cells, and a multitude of small improvements to manufacturing processes that marginally improve efficiency but taken together add up to significant gains. Longer term, improvements will come from new cell architectures that combine different types of semiconductors to broaden the spectrum of light that can be absorbed.[5] These new cell architectures also have the potential of better temperature coefficients and lower degradation rates, which would translate in higher lifetime capacity factors, further reducing LCOEs.

[4] Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. It measures the portion of energy in the form of sunlight per square meter that can be converted via photovoltaics into electricity, under standard test conditions. Modules account today for about one-third of the capex of a typical utility-scale project, but since a large share of the remaining cost depends on the size of the installation, a 10% increase in efficiency leads to proportional decrease in these area-related costs.

[5] See the S&P Global Commodity Insights Strategic Report *High efficiency n-type cell technologies—HJT and TOPCon*.

Crystalline silicon mainstream modules and technology road map



Data compiled November 2022.

Al-BSF = Aluminum back surface field (forms a local electric field and prevents free electrons from flowing to recombine on the rear); PERC = Passivated emitter rear cells, additional passivated layer on rear side (improved prevention of electrons recombination); HJT = Amorphous/crystalline silicon heterojunction (SHJ) cell with a thin intrinsic layer. It passivates the surface and enables a very low defect density at the junction; TOPCon = Tunnel oxide passivated contacts formed by ultra-thin tunnel oxide and an amorphous (a-Si) or poly-crystalline silicon (poly-Si) layer to improve passivation and junction properties; IBC = Interdigitated back contact, placing both positive polarity and negative polarity on the rear, to remove the loss from the shadow from reflection on the front side; POLO = Poly-silicon on oxide; MWT = Metal wrapped through; HBC = Heterojunction back contact.

Includes all applicable bifacial technologies, as well as various types of technology mix (provided there is technical compatibility).

Source: S&P Global Commodity Insights.

Wind: Size and modularity

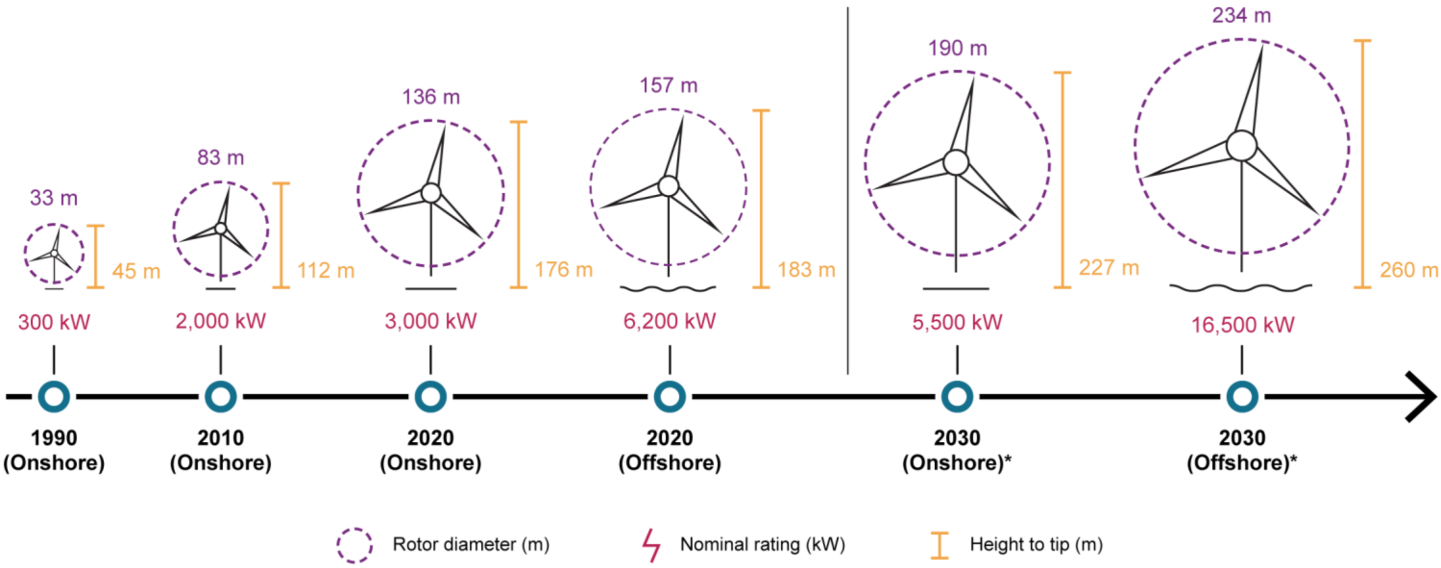
A mix of capex reductions and higher capacity factors continue to determine the future cost of wind—both onshore and offshore—which is expected to fall by about 45–50% between now and 2050. Although offshore wind mostly relies on ever larger turbines, with floating foundations in some regions, onshore wind will require a modular mix of options that make the most out of a very diverse set of siting conditions.

Historically, the size of wind turbines has been growing, as this was the only way to make wind energy cheaper. A large turbine is more expensive per unit because it requires more materials and the logistics are costlier, but cheaper on a per MW basis, because the turbine represents only a part of the total installed cost: more capacity per unit means costs are spread over a larger base. Larger turbines also enable higher capacity factors. Put simply, the capacity factor of a wind turbine is the result of an optimization of three variables: the amount of wind, how long the blades are, and the size of the generator. Larger turbines can extract more power from faster winds. Although size is the key variable for offshore wind, modularity is much more important for onshore wind.

Offshore wind requires ever bigger turbines to lower the per MW cost of its massive foundations. Size is particularly important for offshore wind. First, the turbine only represents about 40% of the total cost of an offshore wind project, versus up to 70% for an onshore wind farm. The rest goes to foundations, transition pieces, cables, and installation expenses, among others. The additional cost of installing larger turbines is quickly covered by bigger per unit capacity. Second, because offshore wind projects tend to be far away from where people live, there are fewer non-technical constraints limiting turbine size. Moreover, the wind resource dramatically improves with distance from shore, creating a stronger case for bigger turbines. Together, these factors have resulted in a research and development boom for offshore wind where announced turbine sizes have grown by nearly 60% in 2022, to 16 MW, compared with four years ago. Turbine technology will be a key driver behind capacity factors for European offshore wind projects increasing from 45% to 55% on average over the next 30 years. Similar improvements are expected in other major offshore wind markets. One important limitation to capacity factors in markets with strong growth and limited space will be the wake effect—the influence on energy production caused by the impact of the turbines on each other.[6]

Floating platforms will be deployed in areas where water depth, seabed, and market conditions do not allow for more bottom-fixed solutions. They also provide access to better and steadier wind resources and while they are starting at a cost premium, we expect their costs to follow a similar trend to bottom-fixed.[7]

Evolution of installed wind turbine sizes, 1990–2030



As of Dec. 6, 2022.
*Weighted average configurations of wind turbines to be installed in 2030 have been estimated.
Turbine sizes shown in the exhibit denote the global weighted average.
Source: S&P Global Commodity Insights.

Onshore wind relies more on a large range of turbine options to adapt to a wide range of siting conditions. Siting parameters for onshore wind are much more diverse than for offshore wind. Optimizing the cost of energy over more than 100 different markets with a variety of wind speeds, terrains, local regulations, population density, and supply chain issues requires a broad yet customizable portfolio of turbine options. In other words, unlike offshore, bigger is not always better. This has led original equipment manufacturers (OEMs) to invest in platforms that allow for some degree of customization to respond to onshore wind developers' need to adapt to very specific site conditions while allowing manufacturers to control costs through the standardization of subcomponents.

This expensive technology race to develop new turbines together with increased raw material prices, logistic issues, rapid demand growth, and fierce competition has taken a heavy toll on European OEMs.[8] In response, these players have adopted a multipronged strategy to further optimize product portfolios by rationalizing turbine models, focus on new and more profitable modular platforms, and explore technological and manufacturing synergies between onshore and offshore divisions. This also implies a reshuffling of supply chains, as standardized subcomponents benefit from manufacturing economies of scale and can be outsourced to low-cost location, while nacelles, blades, or towers can be manufactured closer

6 Wake effect–related losses are already forcing developers in key markets to recalculate their original generation and revenue estimates.

7 See the S&P Global Commodity Insights Market Briefing *Floating Offshore Wind Market Overview*.

8 See the S&P Global Commodity Insights Insight *Weathering the storm: A wind turbine manufacturer perspective*.

to end-markets. What will determine future cost reductions is how successful OEMs will be at combining the cost savings from one platform with the ability to constantly develop new ones.[9]

Turbine size is not the only avenue of cost improvements. Logistics and key commodities are also major factors.[10] As turbines are getting bigger, controlling these costs becomes increasingly important: segmented blades, on-site assembly, and self-hoisting cranes all significantly reduce logistic costs for ever larger turbines. Hybrid materials, innovative tower designs, or new material options such as wood would help to minimize their use. Finally, while not directly related to capex savings, further digitalization will boost capacity factors and lower operation and maintenance cost by making sure turbines are always optimally positioned through improved predictive and scheduled maintenance.

Energy storage: Materials and manufacturing in the shade of the automotive industry

Cost declines will continue in battery manufacturing as the industry is still to benefit from major economies of scale. But supply chain complexity and aggressively increasing demand dictated by the automotive industry may bake in higher material costs. This uncertainty results in a wide range of potential cost declines from 35-65%. Promising technologies which would enable a step change in costs are unlikely to achieve scale in sufficient time.

Manufacturing Li-ion cells is a highly complex and energy intensive process that is ripe for continual improvement. It is one that requires the use of expensive solvents, heated drying equipment, and cell assembly processing. It has progressed from a largely manual operation including multiple separate steps to one more closely resembling a printing press, where cells are produced on a continual basis at ever increasing volumes. In this way, battery manufacturing is not unlike PV. Similar to PV, this efficiency drive in manufacturing has enabled the industry to produce in the order of 1 billion cells per year. Clearly, this level of scale has already led to significant cost reductions, and the pipeline of future cell production plans continues to expand, charting the path further down the learning curve.

The complexity of cell manufacturing leaves the door open for future cost declines through multiple avenues. Economies of scale for the manufacturing machinery will continue to provide strong downward pressure on costs as factories increase in size—with a broader development of so-called “giga-factories.” Equally, there remains significant scope for cost reductions in efficient use of solvents throughout the process and more effective recycling of scrap materials. More widely, there are likely to be countless improvements across each component and process leading to greatly improved overall plant efficiency as the industry progresses toward maturity in the coming years.

Material costs account for 65–70% of the overall cell cost with an unclear route to cost reduction. Unlike the material requirements for solar, and to some extent wind, batteries require a complex mix of raw materials that are sourced from all over the world. The predominant cost driver of these materials is currently derived from supply-demand balances.[11] As battery material manufacturing is the leading source of demand for some of the most critical materials (lithium and cobalt in particular), mining capacity needs to expand at a similar pace to cell manufacturing. Rapidly accelerating demand expectations for electric vehicle have led to shortages and price rises for many materials, with no end in sight (energy storage currently accounts for only 7% of global battery demand). The extent to which supply shortages will continue to elevate material prices above the inherent cost of extraction in the longer term remains unclear.

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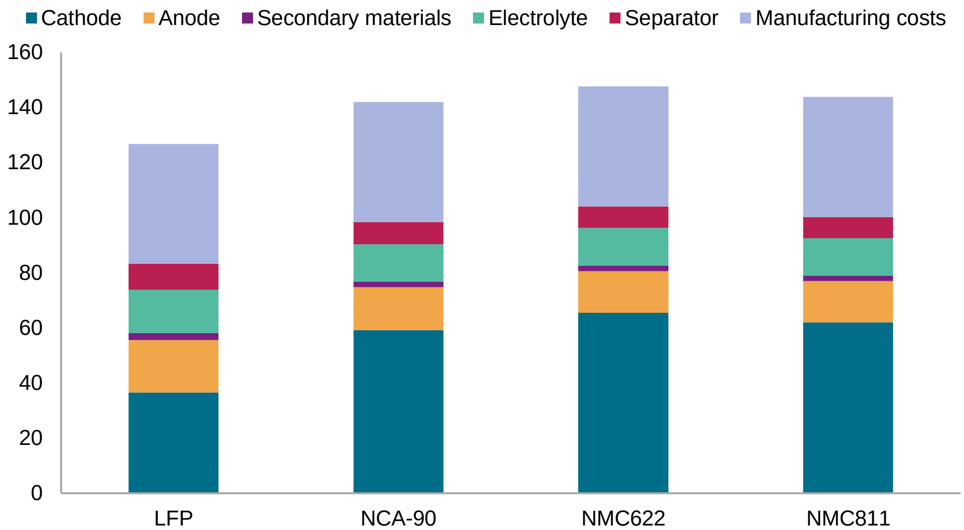
[9] The Boston Consulting Group, who originally developed the concept of the Experience Curve, refers to this as experience *fulfilling* demand versus experience in *shaping* demand: https://www.bcg.com/publications/2013/growth-business-unit-strategy-experience-curve-bcg-classics-revisited.

[10] See the S&P Global Commodity Insights Market Briefing *Impact of raw materials on the cost of onshore wind*.

[11] For wider analysis of the raw material supply dynamics, see the S&P Global Commodity Insights Strategic Report *Big shovels: Can battery raw material supply keep pace with demand?* and Market Briefing *The reasons behind the 1,000% increase in lithium prices*.

However, the scale of investment in the space is providing some clues to the potential for material cost reductions in the space. Mining operations in many countries are likely to grow substantially as multinational conglomerates begin to invest. But this is likely to be countered by a more fragmented supply chain with increasing trade barriers leading to nonoptimal resource extraction (e.g., by potentially favoring raw material extraction in specific countries that are geopolitically favorable, despite higher extraction costs).[12] It is clear, though, that these dynamics of supply and demand will be driven by the automotive industry with energy storage remaining a price and technology taker for li-ion for the foreseeable future.

Li-ion cell cost by component and cell type in 2022 ($/kWh)



Data compiled November 2022.
Cathode and anode includes current collectors.
Source: S&P Global Commodity Insights.

There may be a step change in costs following a shift to a different technology, but there are few clear contenders today. The increasing share of variable renewables in the energy mix shifts the focus from cost to value of energy, and as a consequence the role of energy storage changes. Instead of a technology well suited to niche ancillary services, energy storage will be called upon to provide flexibility and reliability at increasing scale. Li-ion may not be the most suitable technology for this role as power will need to be provided over increasing durations, but its sheer scale in production may mean that it is used anyway. However, there is potential for a step change in the technology of choice and subsequently the costs of energy storage.

Any successor technology to Li-ion would need to be available at huge scale and have very low marginal costs of additional capacity. This means any realistic contender almost certainly already exists, with embedded scale from other industries, and is configurated in such a way that energy capacity can be added very cheaply (i.e., through additional low-cost items such as tanks). Applying these simple filters dramatically reduces the list of available options. And so, although the potential for a step change in technology exists, it remains unlikely that it will be fulfilled before the need for longer-duration storage at significant scale develops.[13]

[12] See the S&P Global Commodity Insights Insight *Inflation Reduction Act sparks huge optimism in solar and energy storage industry but persistent supply chain challenges act as a drag on installations*.

[13] See the S&P Global Commodity Insights Insight *Long-duration energy storage: Can alternatives to Li-ion claim a piece of the action?*

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