WHEN TRUST MATTERS

2022 BATTERY SCORECARD

CONTENTS

1 INTRODUCTION

1 INTRODUCTION

Energy storage is a key technology enabling the energy transition. Over the past ten years we've seen significant growth of utility-scale and behind-the-meter stationary storage along with electric vehicle adoption. These markets are built primarily upon a single technology: the lithium-ion battery.

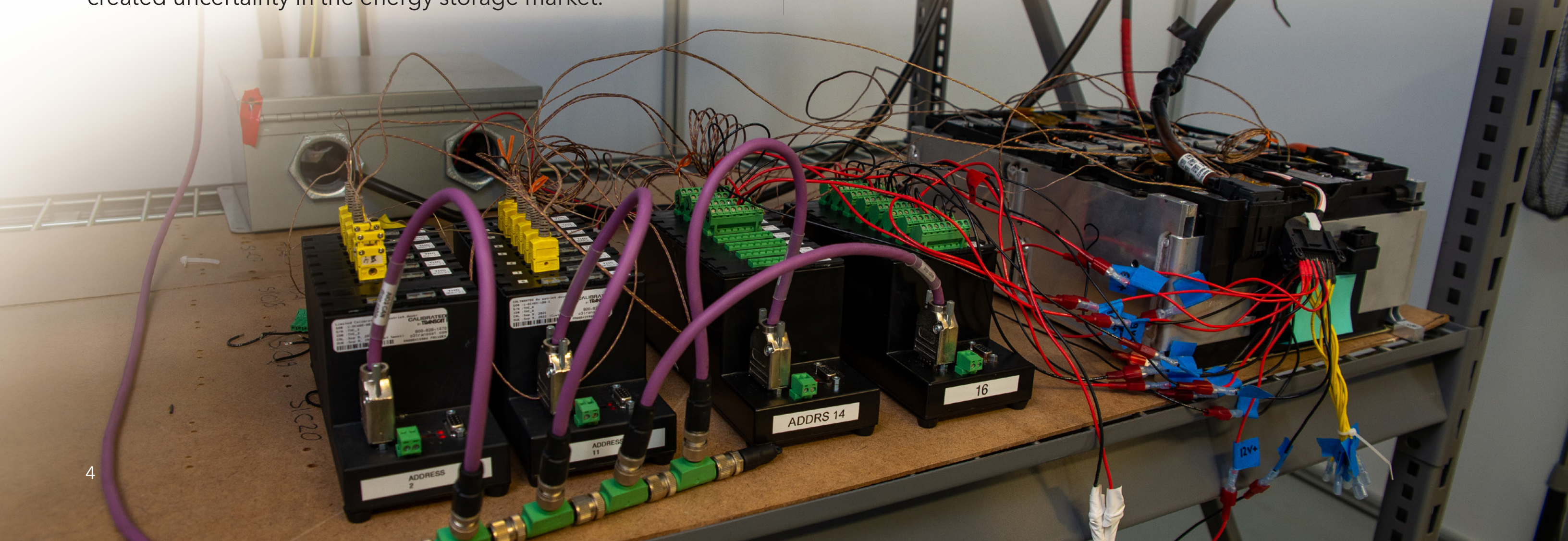
While increases in battery costs have slowed growth this year, we believe the market will quickly recover and eventually achieve over 4,500 cumulative GWh of stationary energy deployments by 2050 (DNV's Energy Transition Outlook). Energy storage—due to its versatility, novelty, and complexity—make it a very interesting and exciting market, which will continue to grow in the coming years as it enables us to cost effectively decarbonize the grid and automotive sectors.

Battery storage has proven valuable across multiple global markets, taking a similar trajectory in each. It typically is first introduced to reduce peak demand for commercial and industrial applications and to provide ancillary services to balance the grid due to its fast-responding and flexible nature. As markets evolve, we see energy storage systems providing clean sources of capacity to the electric grid and shifting renewable energy from periods of high supply to times of high demand.

Battery energy storage systems are adopted when their value exceeds costs, which is becoming common in many areas. Energy storage system costs are typically dominated by the battery, which has seen a recent uptick in price due to lithium and other raw material shortages. This price volatility has created uncertainty in the energy storage market.

For over a decade, DNV has been helping energy storage partners identify these types of uncertainty to help manage and reduce risk. Every release of our Battery Scorecard shares new insights from the data gathered during testing, analysis, and forecasting to help characterize asset performance. This 4th edition of DNV's Battery Scorecard incorporates an interactive component through an online dashboard that provides deep insights into battery testing conducted at the Battery and Energy Storage Technology (BEST) Test & Commercialization Center (BEST Test Center) in Rochester, New York, and free limited access to our Battery AI forecasting tool.

Battery storage—in both stationary energy storage systems and electric vehicles—has an important role in accelerating the uptake of renewable generation and decreasing greenhouse gases. We at DNV look forward to helping lead the energy transition and would love to hear from you on how we can help achieve this together.



2 WHAT IS THE BATTERY SCORECARD?

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DNV's Battery Scorecard is a free, publicly available report and online dashboard that illuminates on some of the most pressing questions around batteries:

- Who are the major battery suppliers, and have they been vetted?
- How do batteries degrade?
- What is a battery's useful life?
- Are some batteries safer than others?

These are complex questions that require a comprehensive understanding of battery technology, system integration and control, testing strategies, manufacturing, and the energy storage market. The Battery Scorecard and online dashboard address these questions head-on and are discussed in detail in the following sections.

There are many current events that raise questions about the energy storage market, including COVID-19, the Russian invasion of Ukraine, and mineral supply. We address these uncertainties and how they affect the market in Section 4.

DNV'S NEW BATTERY SCORECARD ONLINE DASHBOARD

Are you wondering why the Battery Scorecard now incorporates an online dashboard? Our insights are based on considerable amounts of data and DNV has incorporated advanced computational methods to process and convert this data into meaningful insights. We couldn't share everything in a static report, so the online dashboard now gives you the ability to dynamically filter and focus on what you care about most. The dashboard also links to some of the most advanced online modeling tools on the market, including DNV's predictive degradation tool Battery AI. DNV plans to share updates more often and will be updating the online dashboard with key insights throughout the year, so please check back regularly.

3 HOW TO INTERPRET THE BATTERY SCORECARD

3 HOW TO INTERPET THE BATTERY SCORECARD

The Battery Scorecard provides insights into technology readiness, degradation, useful life, and safety. DNV's approach to assessing these topics is detailed below.

Technology readiness/bankability

Selecting suitable technology suppliers can be one of the most important and challenging endeavors for product designers, system integrators, and project developers. While batteries have been commercially available for decades, most stationary energy storage products are less than five years old.

Many battery suppliers have limited global exposure or are new to stationary energy storage, so it can be challenging to make informed purchasing decisions.

Here is our recommended approach when evaluating vendors within the energy storage market:

1 START WITH THE CELL

Battery energy storage systems all have battery cells as their core component, which dictate performance, safety, and cost. Find out who manufactures the cell (if different from the system integrator), and how long that cell has been in production. DNV shares information about cell manufacturers of various battery energy storage systems in the online dashboard to help you better understand these products. This information can be found in the Bankability section of the dashboard.

2 EVALUATE TOTAL DEPLOYMENTS OF CELLS AND SYSTEMS

Total deployments of the underlying battery cell and the integrated system are both good indicators of how reliable the product will be. There are often many bugs to work through after product launch. More experience in the field often leads to improved products. DNV shares the top battery cell providers globally below in Section 5.1.1 and in the online dashboard. This information can be found in the Battery Cell Market Overview section of the dashboard.

3 REQUEST THE 'BANKABILITY REPORT'

Independent vetting of the integrated system is critical to make an informed decision. Battery manufacturers should have Bankability Reports on their products and should be excited to share these with potential customers to prove they have been independently vetted. DNV has reviewed many products on the market spanning battery cells, residential and utility scale battery energy storage systems, controls, integrated dc-coupled solar + storage systems, and non-lithium storage systems, with the summary list shared in the online dashboard. This information can be found in the Bankability section of the dashboard.

4 REQUEST INDEPENDENT TEST DATA TO VALIDATE PERFORMANCE, WARRANTY CLAIMS, AND SAFETY

Testing provides validation of each product's design, operation, and safety. Independent testing verifies that the product will operate as specified without manufacturer intervention. DNV recommends requesting independent test data from all battery suppliers before making a purchasing decision to better understand the product and its impact on your project.

DNV provides a list of battery cells that have been independently performance tested and details use-case specific results in Sections 5.1.2 - 5.1.5 and in the online dashboard. This information can be found on the Battery Performance section of the dashboard. The results suggest early degradation trends and preferred operating parameters for each product. Third party safety testing is also required and should be provided by manufacturers for battery cells, integrated modules, and full systems. Burn testing is also required to understand the fire and explosion risk associated with battery products. These safety risks are discussed below and further in the online dashboard. This information can be found on the Battery Safety section of the dashboard.

After completing initial vetting of battery suppliers discussed in steps 1-4, you can now progress to vendor selection and more accurately predict degradation, augmentation needs, useful life, and battery safety.

Battery degradation

Battery degradation can only be determined through cell testing, which DNV conducts at the BEST Test Center in Rochester, New York. DNV also collects data through onsite witness testing conducted in the labs of cell manufacturers around the globe. While battery manufacturers also conduct their own testing, these test results are not currently incorporated into the Battery Scorecard because the test methods and results have not been independently verified. DNV categorizes test data as follows:

- **DNV testing:** testing conducted at the BEST Test Center by DNV employees using the Battery Scorecard Test Plan.
- **Witness testing:** testing overseen by DNV at a battery manufacturer's site and using Battery Scorecard Test Plan.
- **Manufacturer testing:** not included in the Battery Scorecard since test methods and results have not been independently verified.

All testing follows DNV's standard testing protocol known as the Battery Scorecard Test Plan, which evaluates battery cells across four primary stress factors: charge and discharge rate (C-rate/P-rate); state of charge (SOC) swing (0 >100 > 0 =100, 25 > 75 > 25 = 50, etc.); average SOC; and ambient operating temperature. The Battery Scorecard Test Plan includes nearly 40 separate tests that cover typical operating windows and stress cases for stationary and mobile battery operation. While most testing is conducted for 6 to 12 months, early failure modes and degradation trends can be identified in the first month or two of testing, especially in stress cases. Many are also pushing for longer testing to better understand when a battery cell fails, entering a period of accelerated, non-linear degradation and ultimately losing all capacity to hold a charge. DNV shares Battery Scorecard Test results from the BEST Test Center and from Witness testing in the section below and in the online dashboard These results highlight initial trends in performance across key categories.

Additionally, there is a separate form of degradation that occurs independent of use, often called "calendar fade". This phenomenon may be accelerated at elevated temperatures and SOC, depending on the cell, and should be a prime focus of project developers when calculating long-term degradation, planning augmentation, and scheduling battery delivery and commissioning. Multi-month delays could have serious impacts on initial energy capacity of your storage system and may or may not be covered in the product warranty. DNV shares Battery Scorecard Test results from the BEST Test Center and from witness testing below and in the online dashboard in the Calendar Fade section.

Finally, to encourage even more independent testing, DNV will publish a Recommended Practice that standardizes battery cell performance testing. The goal is to help guide the industry towards a standard best practice for battery cell testing so that data across chemistries, form factors, manufacturers, and from different labs can better be used interchangeably.

Useful life

Useful life is the period of operation when a battery energy storage system (BESS) can predictably charge, store, and return energy for a useful application. When a battery operates beyond its useful life, it degrades unpredictably and loses its capacity to store energy at an accelerated rate until it is unable to hold a charge. The useful life of a BESS is dependent upon the underlying useful life of each battery cell, with the combined performance being dependent on how the cells are integrated, operated, maintained, and balanced within the BESS. If individual cells degrade differently, it can severely limit the system's energy capacity, or worse, it could cause accelerated heating and eventual failure of the cell.

The transition from predictable (generally linear) to accelerated degradation is often referred to as the "knee" or "shoulder" in the degradation curve and should be avoided. Predicting the knee in a BESS degradation curve is very difficult, given the multiple factors involved in integrating and controlling the batteries to achieve project-specific requirements. DNV has developed an advanced software modeling tool called Battery AI to predict project-specific degradation and prevent BESS operators from hitting the knee. Battery AI imports data from Battery Scorecard testing and implements battery-specific degradation algorithms to create a "digital twin" of a battery cell that can predict cell and system performance over a range of user-defined cases.

To demonstrate how useful life modeling in Battery AI is conducted, we selected four representative use cases to analyze BESS performance, including:

- **Firm frequency response in the United Kingdom:** A one-hour battery participating in the Firm Frequency Response market in the United Kingdom in 2018;
- **Merchant storage in Texas, U.S. (ERCOT):** A two-hour commercial battery providing energy and ancillary services products in the ERCOT market;
- **Solar firming in a moderate climate (25°C):** A four-hour battery co-located with a solar farm to shift production to peak price hours under a moderate temperature;
- **Solar firming in a hot climate (40°C):** A four-hour battery co-located with a solar farm to shift production to peak price hours operating in an elevated temperature environment.

These sample use cases help demonstrate the expected degradation of each BESS and can be used by project developers and lenders to compare against warranties being provided by battery manufacturers and integrators.

A battery's useful life is highly dependent on use case, as discussed above, so manufacturers and integrators typically limit daily and/or annual usage (known as "throughput") so that the useful life can be converted into years, which is needed when developing a maintenance and replacement schedule for a project. While stationary BESS typically have warranties ranging from 10 to 25 years, these warranty periods are typically achieved by adding batteries to, or "augmenting", the system during operations. There are very few (if any) stationary batteries on the market today that have been operating for 15+ years, even though many new storage projects have warranty periods that exceed this. The useful life of an individual battery may be much less than the warrantied period, depending on application. DNV considers the useful life of individual batteries to be 10 to 20 years or when the batteries have degraded to 60-65% of initial energy capacity, whichever comes first.

Vehicle battery warranties are typically based on distance traveled (i.e., 200,000 km) and duration (i.e., 10 years), which is one step removed from the factors that cause degradation (such as throughput and calendar fade). Typical automotive use cases differ widely, with passenger vehicles having much more variability than an electric bus fleet with more predictable routes and charging profiles. DNV considers 6- to 12-year warranties for vehicle batteries to be standard, with energy capacity limits set at 80% of initial capacity (rather than 60-65% in stationary applications).

Marine electrification includes additional risk factors that can accelerate battery degradation, such as water and salt infiltration, and has rigorous safety standards given the risk to life and property if failures occur at sea. Emerging aviation applications demand even more reliability and safety.

The Battery Scorecard's online dashboard links to the Battery AI service and provides a demonstration of the tool's useful life prediction capabilities. All registered users can sample Battery AI's functionality. Customers can also purchase detailed cell modeling in Battery AI to pre-screen different cells and see which are best for specific applications. DNV expects this tool to get increased focus from developers and lenders as useful life, and in turn project cashflow, receive increased scrutiny as the market expands.

> “Battery systems aren't worth installing if they can't be run safely”

Battery safety

Arguably the most important aspects of the design are safety features, and, like performance, safety features need to be vetted thoroughly. There are many required safety certifications for battery cells, modules, energy storage systems, and electric vehicles across regions, including IEC, UL, and SAE Standards, to name a few. Safety of an energy storage system builds up from the battery cell and is relevant to every stage of a product’s lifecycle, based upon both code requirements and best practices. Battery safety has quickly become one of the most central focuses in evaluating battery products and projects due to some high-profile battery fires that have made news globally.

DNV includes anonymized, aggregated UL 9540A burn testing results in this year's Battery Scorecard to draw focus to some of the most important questions being asked related to battery storage safety. In the section below and within the online dashboard, we address key themes to consider when evaluating battery cells and BESS for safety considerations.

4 TRENDS IN ENERGY STORAGE

4 ENERGY STORAGE MARKET OVERVIEW

Many factors affect the energy storage market, with some underlying drivers providing predictable growth trends. The ability of an energy storage system to stabilize the electricity grid and shift daytime solar energy into morning and evening hours has been a consistent driver of growth.

In general, early markets form in new global regions around ancillary services, which balance the electricity grid when consumption (load) is not perfectly aligned with generation. Ancillary services require fast-responding resources to perform “grid support” such as frequency and voltage control and add power capacity, for which BESS are particularly well suited. Other early battery energy storage success stories are found in commercial-and-industrial (C&I) behind-the-meter applications, such as demand charge reduction, where batteries provide energy during periods of high pricing. This behind-the-meter application reduces peak power costs, thus saving money for the C&I facility owners. These types of systems can also provide resilience, such as temporary backup power during a grid outage.

Other factors affecting the energy storage market are less predictable, where reliable information is hard to come by and reporting seems to change daily. Government mandates and incentives, commodity mineral pricing, battery supply shortages, new disruptive technologies, and both regional and global politics create uncertainty in the market. Trends across these less-predictable categories are discussed next.

Li-ion chemistries dominate

After over a decade of investments into electric vehicles, consumer electronics, and more recently stationary energy storage, Li-ion batteries have become the dominant battery on the market. Within the broad category of Li-ion batteries, nickel manganese cobalt oxide (NMC) chemistry has roughly 50% of the market, with lithium iron phosphate (LFP) and nickel cobalt aluminum oxide (NCA) chemistries gaining quickly. There has been regional focus across battery chemistries, with many leading NMC manufacturers based in Korea and LFP manufacturers based in China, though some notable manufacturing development in Europe and the U.S. is expected to compete in the coming years. The big story is that LFP battery manufacturer CATL has become the global leader in Li-ion battery supply, overtaking the long-standing NMC manufacturer LG ES, which now holds the second spot (see Scorecard Results below for a list of top 10 manufacturers). Stationary storage is also trending toward LFP, while electric vehicles still primarily employ NMC and NCA due to their higher energy densities. For the near term, Li-ion in both transportation and stationary energy storage should remain dominant for at least the next three to seven years.

Next-generation technologies, such as silicon, sodium, and lithium metal anodes, solid-state electrolytes, new cathode material and cell manufacturing processes, flow batteries, and other non-lithium technologies, could play an important role in enabling these price reductions, which is discussed further in Section 6.

Current price volatility

In 2010, average Li-ion battery pack prices, across different battery end uses, were above $1,200 per kilowatt-hour. These prices have fallen 89% to $132/kWh in 2021, according to Bloomberg New Energy Finance (BloombergNEF Annual Battery Price Survey 2021), and this is a 6% drop from $140/kWh in 2020.

But the end of 2021 and first half of 2022 has seen a sharp uptick in costs, driven primarily by the rising cost of lithium and other raw materials, global supply constraints, broader inflation, and production curbs in China. While the coveted $100/kWh battery is still attainable in the longer-term, battery costs are significantly higher than this in many regions, with project developers in North America getting quotes from battery manufacturers up to nearly $500/kWh in mid-2022. Average battery costs in 2021 were lower, though they saw an imbalance across regions, with the lowest costs in China, at $111/kWh. Packs in the U.S. and Europe cost 40% and 60% higher, respectively, according to BNEF. Prices have fallen as the adoption of LFP has increased and as the use of expensive cobalt in nickel-base cathodes has lessened. On average, LFP cells were nearly 30% cheaper than NMC cells.

This volatility has impacted project financials, and the market is already responding. In the U.S., which is a leading market for grid energy storage, the market is being driven by new state-level storage mandates and supportive federal policy such as Federal Energy Regulatory Commission Order 2222. The U.S. energy storage market is expected to expand from an annual deployment of 5 GW/14 GWh in 2022 to 14 GW/50 GWh in 2026, according to Wood Mackenzie projections. Off-takers are renegotiating (and paying more for) purchase agreements to better reflect the cost of procuring energy when they need it.

COVID-19 challenged storage sector growth in some countries, but deployment in the U.S. has been strong, with new hybrid solar + storage driving growth in sunnier regions. China will compete with the U.S. for greatest volume of deployment of lithium batteries in the coming years—and Chinese suppliers of lithium batteries are poised to provide the lowest-cost products. China is set to be the world leader in storage capacity by 2024.

Battery safety testing: critical yet complicated

With European, North American, and Asian energy storage markets quickly growing and tenders being a race to bottom on price, it is more important than ever that owners and operators consider battery safety. Relatively rare but high-profile battery fires such as the Victoria (Australia) Big Battery fire in July 2021 and London Buses in May 2022 bring increased scrutiny to the deployment of future EVs and stationary systems. The industry needs to learn—and is learning—from these events, with public release of root cause analyses becoming more common. But with wider deployment the industry must continue to reduce failures to avoid widespread loss of equipment, environmental impact, or worse, and in turn lose confidence from consumers and regulators.

For stationary storage applications, results from industry standard test methods such as UL 9540A (Test Method for Evaluating Thermal Runaway Propagation in Battery Energy Storage Systems) are critical to obtaining approval from permitting authorities. UL 9540A is a test method, not a standard by which a battery passes or fails the test. Instead, test results provide key information to inform system design, spacing, siting decisions, and emergency response plans. The method includes a progression of testing from individual cells to modules, units, and installations, shown in Figure 4-1.

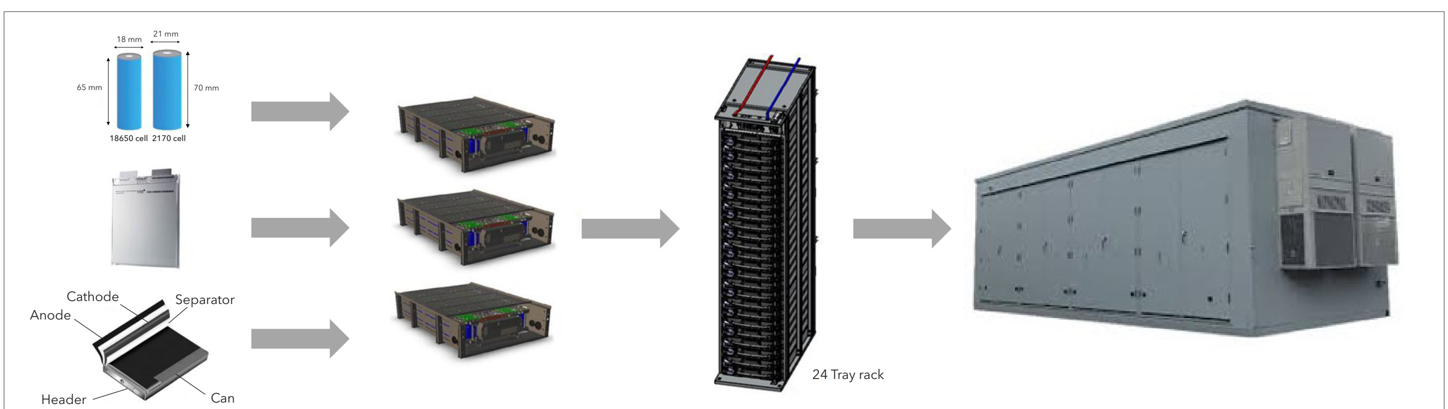


Figure 4-1 UL9540A testing is conducted at the cell, module, unit (racks), and installation (system) level

Figure 4-2 Cell-level testing helps understand failure modes and thresholds of each battery cell

Cell-level testing evaluates fault conditions and failure modes at the smallest divisible level of a battery system—the cell. The photos in Figure 4-2 show an example UL 9540A prismatic cell test setup, with the cell sandwiched within pressure plates and thermocouples applied to measure temperature (at left), and an example of a cell's response to nail penetration (at right). Note that actual 9540A cell-level tests occur within an enclosed environment.

The plot in Figure 4-3 is from an example cell-level 9540A overheating test, showing temperatures from the start of the test through about 60 minutes, when thermal runaway occurs, and the onset of subsequent cooling. The thin grey line represents the atmosphere within the test chamber. The three colored lines represent different measurement points on the battery surface, including front center (red), side center (blue), and top (green), with only the front and side being in direct contact with the heater. During the test, heat is applied by an external film heater wrapped around the cell to raise the cell's temperature by 5°C per minute. At about 40 minutes into the test, liquid within the cell's electrolyte boils and the gases vent, leading to short-term cooling of the battery (dips in blue and green lines) and an increase in the chamber's ambient temperature (grey line blip). Continued heating leads to thermal runaway of the cell at about 60 minutes—when the temperature increase from reactions within the cell exceed the temperature increase from the external heater. During thermal runaway, all temperatures increase rapidly.

Note the variation in temperatures at different measurement points on the cell—up to roughly 90°C difference at venting, and 110°C difference at thermal runaway. The test method is not always clear which temperature measurement points should be used in reporting the results, causing confusion when being used to inform downstream design and safety decisions. DNV recommends conferring with a battery testing expert when interpreting UL 9540A test results.

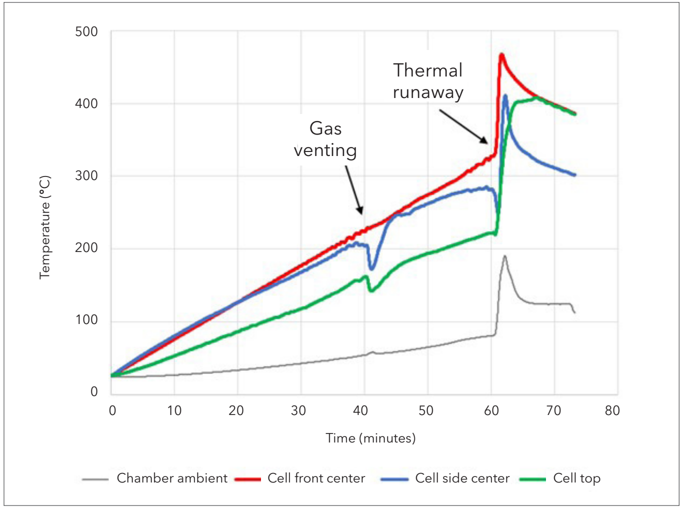


Figure 4-3 Cell-level UL 9540A test results show temperatures rising steadily, dipping, rising again, and then spiking during thermal runaway

5 SCORECARD RESULTS

5 SCORECARD RESULTS

DNV recently tested 19 battery cells through the Battery Scorecard Testing program and includes findings from these tests below. In some cases, the cell manufacturer has agreed to share its name, though many of the manufacturers chose to remain anonymous.

In the categories where the manufacturers chose to remain anonymous, DNV provides general insights to guide downstream partners in evaluating and selecting batteries for their application. DNV plans to release additional results as they become available. We also hope to share additional names of currently anonymized manufacturers as these manufacturers see the value in transparency.

Beyond performance testing results, DNV is also sharing publicly available information on battery cell manufacturing and system deployments, where the cell manufacturers and system integrators have released this information publicly online.

For battery safety results, all manufacturers have remained anonymous; therefore, we have focused on presenting general trends and comparisons between chemistries rather than highlighting specific manufacturers or products.

DNV evaluates cells and systems across the following categories:

- Cell manufacturing volume
- Cell performance: <2-hour grid support services
  - LFP category
  - NMC category
- Cell performance: 4-hour solar shifting
  - LFP category
  - NMC category
- Cell performance: high-power vehicle application
  - NMC category
- Calendar fade
- Battery management system optimization
- Safety: offgas and thermal runaway temperature thresholds
- Safety: offgas composition

The results for each category are summarized next.

5.1 Battery cells

5.1.1 CELL MANUFACTURING VOLUME

The top 10 battery cell manufacturers by volume for 2022 are projected in Table 5-1. These results include all battery cells produced across EV and stationary energy storage systems (ESS). With only a few notable exceptions, most battery cell manufacturers have >90% of their cells going to EVs. Other battery cell manufacturers not listed in the top 10 are grouped together in the "Other (cumulative)" category, totaling 235.1 GWh of projected cells produced in 2022.

MANUFACTURER	TOTAL 2022 CELL PRODUCTION (GWh)
1. Contemporary Amperex Technology Co Ltd (CATL)	132.0
2. LG Energy Solution	93.9
3. Panasonic Corp	60.1
4. BYD Co Ltd	58.6
5. Samsung SDI	47.1
6. SK Innovation	32.0
7. TianJin Lishen Battery Joint-Stock Co Ltd	21.9
8. Gotion High Tech Co Ltd	21.5
9. EVE Energy	18.5
10. Amperex Technology Ltd (ATL)	17.5
Other (Cumulative)	235.1

Table 5-1 Leading cell manufacturers by 2022 projected volume
Data from Benchmark Mineral Intelligence

5.1.2 CELL PERFORMANCE: <2-HOUR GRID SUPPORT

Out of 19 cells included in this year's Battery Scorecard, the top 3 performing LFP and NMC battery cells within the <2-hour grid support category are presented here. Battery Scorecard Testing that evaluated 0.5C-1C performance across various temperatures were included in these results.

TOP PERFORMERS (LFP)

CATL | Narada | OEM-6

TOP PERFORMERS (NMC)

OEM-2 | OEM-3

The graphs in Figure 5-1 show cell testing results across a range of test parameters for each chemistry, including low, high, and room temperature conditions, a range of SOCs, and C-rates of 0.5 and 1. Generally, capacity degradation happens more quickly in the first year (assuming 365 equivalent full cycles per year), falling 3% to 5% in the first year before leveling out to an annual degradation rate between 1% and 3% per year, depending on use case, cell type, SOC, and temperature. Cell operation at the upper and/or lower regions of each category, even within specified windows, such as hot or cold temperatures, high C-rates, or high SOC thresholds, can result in capacity degradation at 8-10% per year.

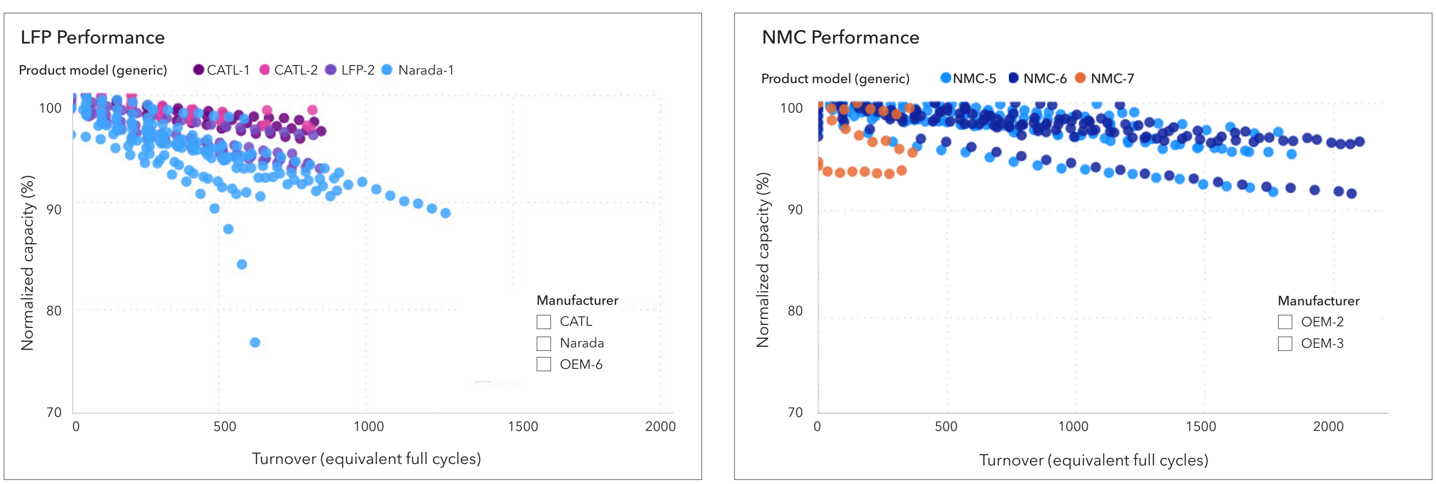
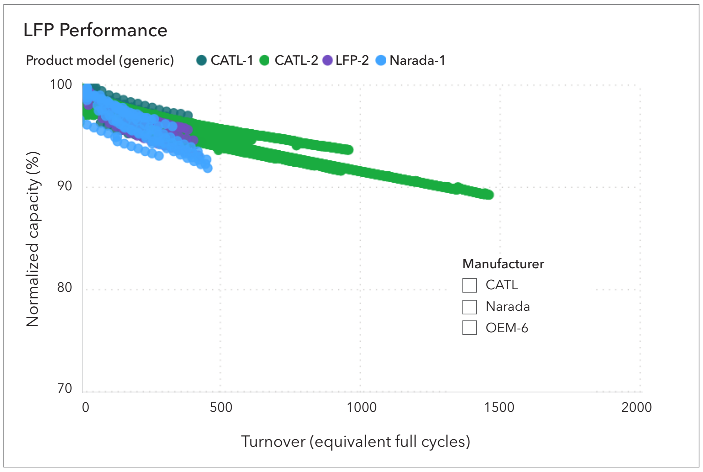


Figure 5-1 Top 3 performing cells in the <2 hour grid support category



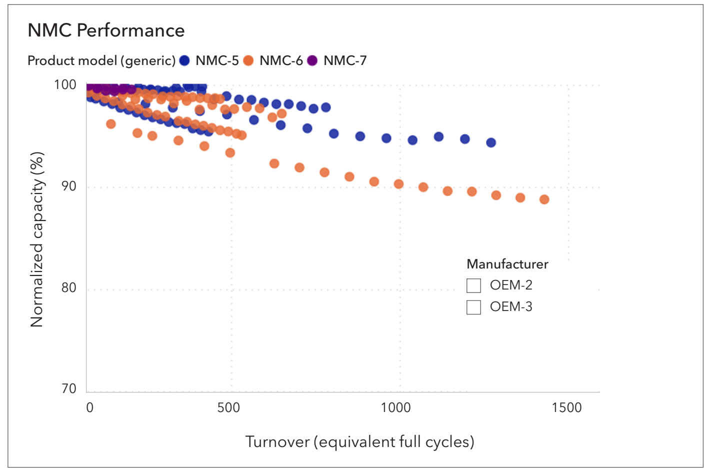


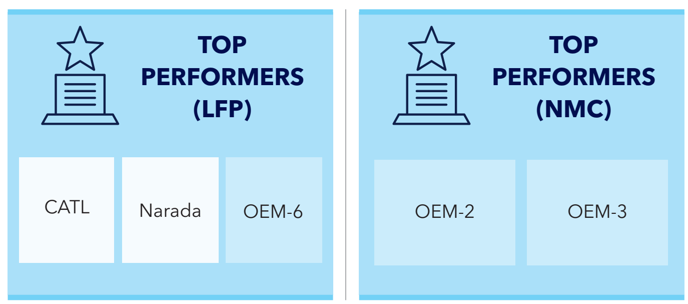
Figure 5-2 Top 3 performing cells in the 4-hour solar shifting category

As discussed above, each cell eventually falls over a knee and begins to degrade rapidly, after which the cell has exceeded its useful life. This is demonstrated in Figure 5-1 by the lower light blue curve for LFP cells. These two cells performed admirably compared to their peers for use cases that aligned with their design specifications but demonstrated early and rapid degradation when stressed under a higher than designed C-rate and exposure to temperature extremes. Ideally, all cells would be tested to the end of their useful life, or when they reach the knee; however, gentler cycling conditions and improved cell performance has extended the testing timeline to reach this point.

Shorter duration applications that require <2 hours of energy storage capacity are typical for grid support, with example markets being Firm Frequency Response in the United Kingdom and ancillary services in Texas, U.S. These applications often require the system to charge and discharge, which means that the system is held near the middle of the SOC range so that it can perform both functions.

5.1.3 CELL PERFORMANCE: 4-HOUR SOLAR SHIFTING

Out of 19 cells included in this year's Battery Scorecard, the top 3 performing LFP and NMC battery cells within the 4-hour solar shifting category are presented here. Battery Scorecard Testing that evaluated 0.25C performance across various temperatures were included in these results.



In contrast to the grid support use case above, none of the cells in the 4-hour solar shifting use case shown in Figure 5-2 reached the knee of the degradation curve in which the capacity degradation accelerates asymptotically towards an end-of-life. There appears to be only minor differences between LFP and NMC performance, with a more pronounced differentiation at higher cycles. While only one LFP cell and two NMC cells made it to four years of simulated daily cycling (~1,500 equivalent full cycles), all three maintained nearly 90% of their initial capacity. For the cells that have not been tested through as many cycles at this condition, some were trending higher (with lower degradation) and others trending lower (with higher degradation). Generally, the 4-hour use case is less impactful on cell degradation. Lower C-rates tend to produce less heat at the cell level, requiring less heat rejection in the thermal management system and allowing for more optimal temperatures.

The 4-hour use case is common in U.S. markets, with capacity products such as resource adequacy in California requiring four-hour durations. Four-hour applications also favor coupling with solar since peak generation (midday) can be shifted to peak demand times later in the day.

5.1.4 CELL PERFORMANCE: VEHICLE APPLICATION

Out of 19 cells included in this year's Battery Scorecard, the top performing NMC battery cell in the EV category is presented here. Battery Scorecard Testing that evaluated 1C to 5C performance across various temperatures were included in these results.

TOP PERFORMER (NMC)

OEM-1

Higher C-rate testing allows for more equivalent full cycles to be examined in a shorter calendar period because each cycle takes less time to simulate (0.25C takes at least eight hours for a full equivalent cycle while 2C takes only one hour).
As shown in Figure 5-3, NMC-1 demonstrates ~90% capacity retention over 4,000 equivalent full cycles of testing, representing about 11 years of daily use. It should be noted that other than commercial vehicles (e.g., ride sharing or buses), most passenger vehicles do not experience use cases represented by a daily full equivalent cycle as the majority of vehicle usage in the U.S. is below 40 miles/day. Under more aggressive test conditions, cell capacity dropped to 65% after ~3,200 equivalent full cycles, which shows the sensitivity of these cells to key operational parameters.

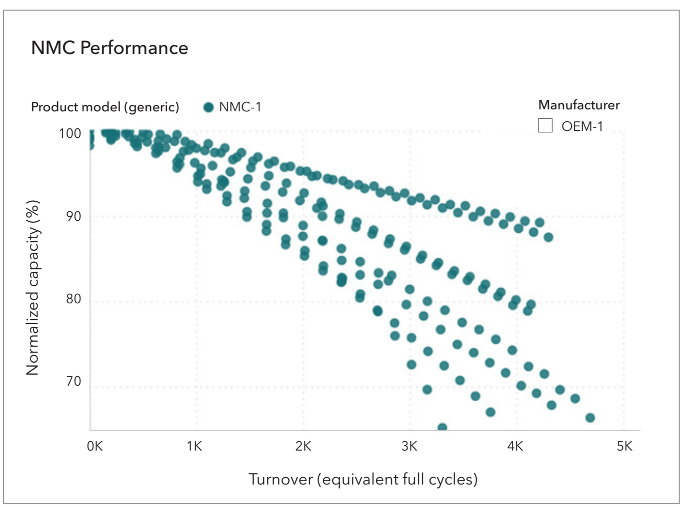


Figure 5-3 Top performing cells in the EV/high C-rate category

5.1.5 CALENDAR FADE

Of the 19 cells included in this year's Battery Scorecard, nearly all cells showed degradation due to calendar fade. Battery Scorecard Testing evaluated these cells by charging them to specified SOCs, and then held them at target temperatures without cycling. These tests are intended to evaluate the impact of SOC and temperature on calendar fade degradation. The cells were periodically recharged and then fully discharged to determine their remaining capacity, with room temperature results presented in Figure 5-4.

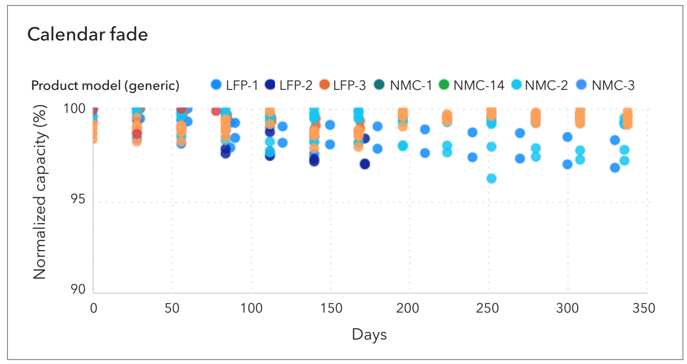


Figure 5-4 Calendar fade degradation at room temperature across various cells and at 30% and 100% SOC

Calendar fade ranged from 1%-4% per year across the cells tested at room temperature and various SOCs.

Temperature had a clear impact on calendar fade, with nearly all cells having increased degradation at elevated temperatures and decreased degradation at lower temperatures. Temperature impact on calendar fade degradation is shown in Figure 5-5.

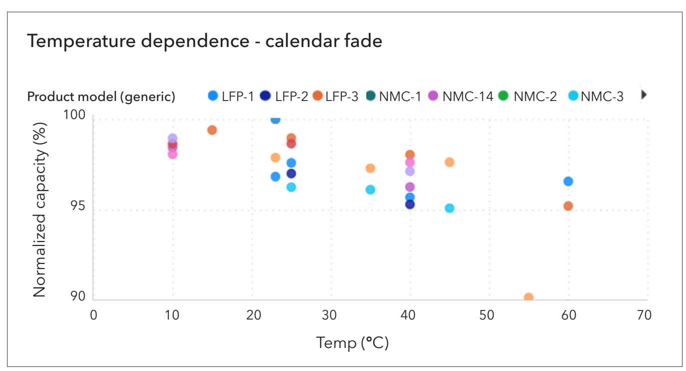


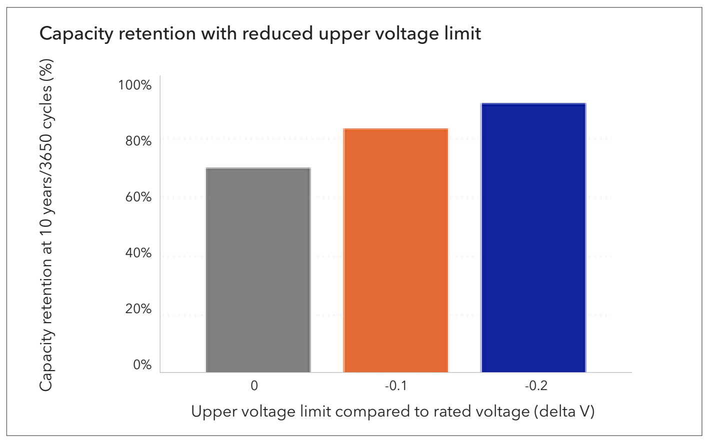
Figure 5-5 Temperature dependence of calendar fade degradation across various cells

5.2 Battery Management System (BMS)

A well-tuned BMS can save the day (or year)
Battery cells are typically assembled into modules or racks with an integrated battery management system (BMS). The BMS controls upper and lower voltage limits of the cells as they charge and discharge, among other things. Manufacturers can tune their BMS to allow for wider voltage limits (more aggressive) to capture more energy per charge/discharge cycle. They can also set narrower voltage limits (more conservative) to avoid upper and/or lower charge states with the goal of prolonging battery life. All cells degrade rapidly if operated outside of their preferred voltage range, so BMS tuning is critical to optimize the tradeoff of maximizing short-term capacity while not unduly sacrificing long-term performance.

In Figure 5-6, multiple cells were tested at 100% rated capacity, getting charged (up) to the rated upper voltage limit and discharged (down) to the rated lower voltage limit. Simultaneous tests used the same cell types with reduced upper voltage limits, by charging to (a) rated voltage, (b) 0.1 volts below rated, and (c) 0.2 volts below rated.

DNV plans to incorporate BMS rankings in future iterations of the scorecard.



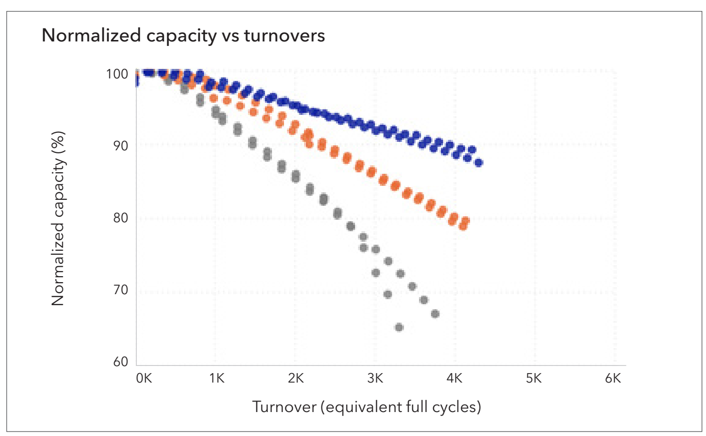


Figure 5-6 Degradation rates can be significantly affected by adjusting the upper voltage limit in the BMS

5.3 Safety

Batteries subjected to overheating, short circuits, or internal faults can vent gases and, in some cases, reach thermal runaway. Understanding the temperatures at which venting and thermal runaway occur, and the composition of the vent gases, are important to safe design and operation.

5.3.1 THERMAL RUNAWAY TEMPERATURE THRESHOLD AND DIFFERENTIAL BETWEEN VENTING AND THERMAL RUNAWAY TEMPERATURES

Two temperatures are most important when considering thermal runaway. The first is the cell venting temperature, or the temperature at which the buildup of gases within the cell are released through the cell's pressure release vent to avoid rupturing the cell's casing. The second temperature is the onset temperature at which thermal runaway occurs. This is the "point of no return" for the cell, where uncontrollable self-propagating reactions involved in thermal runaway begin. While cells may ultimately reach temperatures as high as 1000 °C, the temperature at which these reactions begin helps determine monitoring and control mechanisms needed to avoid thermal runaway altogether. While venting and thermal runaway of an isolated cell is concerning by itself, a key design and control mechanism within battery systems lies in preventing cascading effects of one cell's thermal runaway causing other cells to also reach thermal runaway.

As is evident in Figure 5-7, cells from different manufacturers and chemistries have vastly different venting and thermal runaway onset temperatures. This data from UL 9540A cell-level tests had thermal runaway initiated using a standard repeatable methodology. It is generally considered favorable to have a higher degree of separation between the gas venting and thermal runaway onset temperatures, especially if gas detection is available within the energy storage system. If gas is detected early, there is more time to catch an overheating cell and prevent thermal runaway from occurring altogether. If the venting and runaway temperatures are closer together, there is less time available to prevent thermal runaway using gas detection. In addition, higher thermal runaway temperatures are better: this means relatively more energy is needed for the cell to reach that temperature and go into runaway.

5.3.2 OFF-GAS FLAMMABILITY

Prior to and during thermal runaway, reactions within the cell produce gases which get vented. These gases are considered the off-gas, which is measured during cell-level UL 9540A testing to determine flammability and other characteristics.

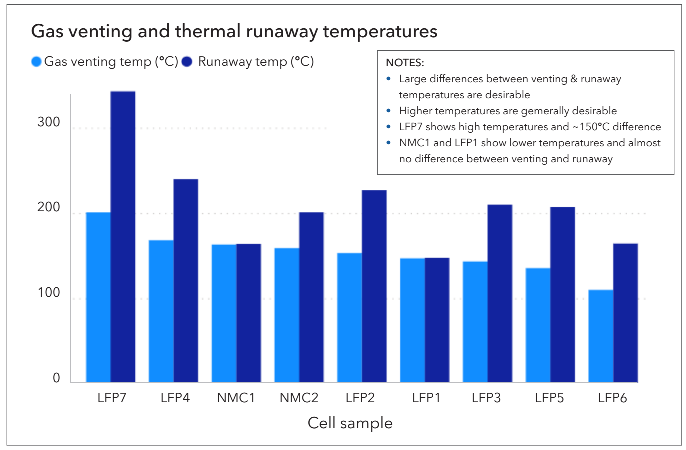


Figure 5-7 Venting and thermal runaway onset temperatures for various cells across chemistries

Typical off-gas compositions include: hydrogen (H_2), carbon dioxide (CO_2), carbon monoxide (CO), and a variety of hydrocarbons (HxCy). Hydrogen, carbon monoxide, and hydrocarbons are flammable gases that can contribute as a fuel source for a fire. If not burned as it is emitted, hydrogen contributes to the explosivity of the off-gas; the more hydrogen present, the more energetic the explosion can be. Other hazard considerations for the gas composition include carbon monoxide as a toxic gas and carbon dioxide as an asphyxiant.

The volume and ratio of gases is largely dependent on the materials used inside the cell such as the cathode, electrolyte, and anode. A cell of the same chemistry and size might have a different composition ratio due to the other components within the cell. The average off-gas composition from UL 9540A data collected for a number of different cells across chemistries and manufacturers is shown in Figure 5-8.

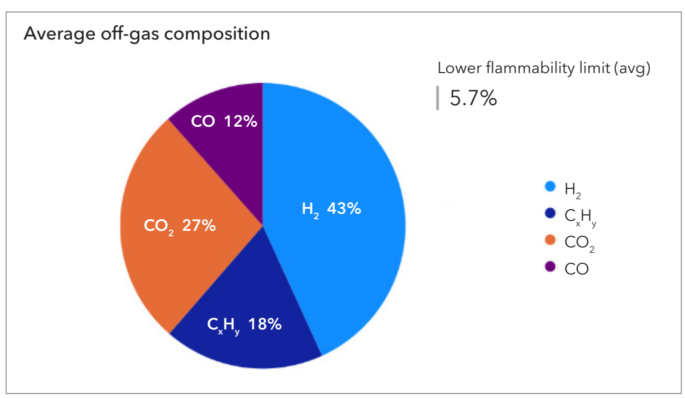


Figure 5-8 Off-gas composition of gas released during thermal runaway

6 2023 AND BEYOND

Driven primarily by the growth in electric vehicle (EV) demand, the lithium batteries we have today will continue to see advances that benefit the EV sector and, to a lesser degree, the stationary energy storage sector. In the short- and mid-term, lithium batteries will dominate the stationary storage market due to their versatility, durability, and general downward trend in cost. We can also expect improvements across energy density, durability, performance, and safety. Below we discuss some of the expected improvements.

As background, Li-ion batteries are made of several components, including an anode, a cathode, electrolyte, separator, and the cell casing. The anode and cathode are the electrochemically active components that store (intercalate) lithium ions when charging and discharging. Development efforts have focused on reducing the cost of the cells by increasing energy density, improving reliability and safety of the anode and cathode, increasing ability to charge quickly, and reducing inactive materials.

Li-ion battery improvements

CATHODE

With regards to the cathode, most EV batteries incorporate some combination of lithium with cobalt, magnesium, aluminum, and nickel to form the NMC or NCA chemistry, as discussed above. Many of these metals, particularly cobalt and lithium, have increased in cost over the last 12 months due to demand growth, supply constraints, or both. Lower range EVs and stationary storage applications also use lithium combined with iron to form the LFP battery chemistry. While LFP is cheaper and generally has a higher temperature threshold to entering thermal runaway than NMC and NCA, it sacrifices energy density, so it takes up more space in the vehicle or project site for the same amount of storage capacity. It is unclear which battery chemistry will prevail as rapid growth and material supply constraints will change the relative costs of these commodities. Sulfur, as a replacement for the layered oxide class used by NMC and NCA, is also being considered for battery cathodes because of its very high energy density, though no commercial products are on the market.

ELECTROLYTE

Advancements are also expected in electrolytes, which facilitate the flow of ions from anode to cathode and back again. An example of liquid electrolyte is the acid in a conventional automotive lead-acid starter battery. In lithium batteries, the electrolyte is typically an organic-based compound or solvent that interfaces with the cathode and anode and permeates a separator. While most Li-ion battery electrolytes are liquid, polymer electrolytes are also commercially employed, and solid electrolytes are in development. The solid electrolyte material is an exciting prospect because it has a significant safety advantage over organic polymer and liquid electrolytes due to its non-flammable nature. Other potential advantages of solid-electrolyte batteries include higher energy density, longevity, and stability, though these claims need to be proven before commercialization.

ANODE

Today's anodes are typically made of graphite, a form of carbon that has a structure which allows lithium ions to be reversibly inserted (intercalated) between the carbon layers. While graphite works quite well as an anode material, silicon is being considered as a replacement since it can hold 10 times more lithium than graphite. The problem with silicon is that it swells in size with the insertion of the lithium ions much more than graphite, which can damage the cell. A proposed solution is to use a mixture of graphite and silicon, which has been seen to reduce swelling at the cost of lesser gains in density.

Non-lithium technology

A variety of non-lithium technologies are primed to step into the stationary sector, or in the case of pumped hydro, already have a dominant market share. According to the China Energy Storage Alliance (CNESA), of the 209.4 GW of electrical energy storage deployed globally at the end of 2021, pumped hydro had 86.2% of the installed capacity, followed by Li-ion at 11.0%, and then a variety of other non-lithium technologies making up the remaining 2.8% (CNESA Energy Storage Industry White Paper 2022). They can broadly be classified as electrochemical storage (other battery chemistries including flow batteries), mechanical storage (compressed/liquid air, gravity storage, pumped hydro), and thermal storage that converts energy into heat and either directly or indirectly uses that heat to replace electricity. There is also significant focus on hydrogen, which can be classified as chemical energy storage, and how it can play a role in long-duration storage applications and industrial use in other markets like fertilizer production and steel processing. DNV is actively working with various technology providers to independently assess their products, though this year's Battery Scorecard focuses on Li-ion. We hope that future reports will include a wider range of technologies.

Many non-lithium energy storage technologies are classified as 'long duration', which the U.S. Department of Energy (DOE) defines as 10+ hours of storage capacity at rated power. Typically, Li-ion technologies operate for 6 hours or less at rated power. Long-duration energy storage is an emerging focus area that many believe is required to fully decarbonize the electricity grid. To become viable, the long-duration storage market must meet the following criteria:

- capital costs of long-duration storage equipment must be significantly cheaper than Li-ion on an average $/kWh basis (targeting $20/kWh or less), with operation and maintenance costs and useful life being comparable;
- off-takers (like utilities and commercial & industrial partners) must value the service of long-duration storage so that they pay project owners enough to cover the cost of operating these assets;
- long-duration storage equipment must be as safe or safer the Li-ion technology; and
- performance and safety of long duration storage equipment must be tested and vetted by third parties to build broader confidence in this technology.

Many long-duration storage technologies 'decouple' power and energy, which means they increase duration (MWh) at relatively lower costs without having to increase the power (MW). This is different than conventional batteries that require proportional increases in power and duration because all DC energy storage components are contained within one cell.

Another advantage of many long-duration technologies is their reduced fire safety risk and low degradation potential. There are also various disadvantages with long-duration energy storage technologies compared to Li-ion batteries, including:

- the round-trip efficiency is limited to approximately 50%-70%, depending on the technology, compared to Li-ion which often exceeds 90%;
- ramp rate for some long-duration energy storage technologies can be limited, meaning they are not well suited for shorter durations under 4 hours;
- they can have moderately to significantly lower energy density compared to Li-ion, meaning they are almost always larger and heavier and not well suited for mobile applications; and
- with a notable exception of hydropower which has been around for centuries, long-duration energy storage technologies are less proven in many cases, though this is starting to change as investment has been flowing into this sector.

DNV expects non-lithium and long-duration energy storage technologies to gradually expand into niche markets over the next 3-5 years, with increased growth as renewable penetration increases above 50%. Local and federal mandates and incentives will also drive the long-duration energy storage market to broader adoption.

In conclusion, there is a lot to be excited about across the energy storage sector in the coming years: strong growth, technology advancements, policy drivers, improved safety, and increased motivation to support the energy transition away from carbon-based fuels to name a few. We at DNV look forward to helping lead the energy transition and would love to hear from you on how we can help achieve this together.
Want to learn more? Schedule a meeting with our team to discuss the findings and learn more about what the Scorecard means for your business.

ABOUT DNV

DNV is an independent assurance and risk management provider, operating in more than 100 countries, with the purpose of safeguarding life, property, and the environment. As a trusted voice for many of the world's most successful organizations, we help seize opportunities and tackle the risks arising from global transformations. We use our broad experience and deep expertise to advance safety and sustainable performance, set industry standards, and inspire and invent solutions.

In the energy industry

We provide assurance to the entire energy value chain through our advisory, monitoring, verification, and certification services. As the world's leading resource of independent energy experts and technical advisors, we help industries and governments to navigate the many complex, interrelated transitions taking place globally and regionally, in the energy industry. We are committed to realizing the goals of the Paris Agreement, and support our customers to transition faster to a deeply decarbonized energy system.

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