Future of batteries

Winner takes all?

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Content

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Executive summary

Battery technologies are central to delivering significant advances in a wide range of industries, from electric vehicles to renewable power. This has catapulted battery technology to the top of the priority list for many players, leading to a huge boom in investment, as companies try to build key positions in the market.

However, this investment frenzy threatens to lead companies to rush forward without asking themselves key questions. What will the landscape look like when the dust settles? Which technology will dominate the battery space in the future, and what are the potential scenarios for future growth? How do I (as a chemical company, utility, investor, battery manufacturer, automotive manufacturer, mobility provider or government / regulator) prepare for the future and position myself to benefit?

There is no simple answer to these questions, as they depend on a range of factors, from the speed of new innovation to the ability to reduce costs of existing technologies.

Achieving market dominance in a wide range of electrifying industries, from automotive to electronic devices, will require companies to build and defend successful battery technology positions together with hosts of larger and smaller partners. If they lose that battle, they may lose the war. Risks are high, and not all players will be successful in terms of technology choices, their positions in the value chain and partnering strategies.

This study aims to provide a guide to the current state of the market and future scenarios, analyzing the various battery technologies and mapping them to the unmet needs of specific applications. The findings and conclusions mentioned in this report are the result of Arthur D. Little analyses on a wide range of sources which we have not all listed separately for the sake of readability, unless indicated otherwise.

From this study we outline the three most likely potential scenarios and outcomes in terms of the winning technology of the future, and explain the implications for industries and players either dependent on battery technology or looking to benefit from its evolution. In particular, we believe the ultimate winners of this game will be companies that orchestrate the best innovation ecosystems in battery technology.

Key insights

1. Despite uncertainty, demand for battery storage will continue to grow across a wide variety of markets and applications. Each of these has different unmet needs that offer enormous potential to innovative players. *(See Chapter 2.)*
2. While a vast number of next-generation technologies are in development, with large potential markets, it is easy to bet on the wrong horse. Ultimately, many of today's new entrants and investors will be disappointed. *(See Chapter 3.)*
3. Entrants to the battery space face considerable risks, which vary dependent on their positions in the value chain. It is therefore vital to understand how these challenges impact your business. *(See Chapter 4.)*
4. Arthur D. Little believes that no single company will be able to come out on top without the support of an intricate and dynamic innovation ecosystem made up of partners, start-ups, institutes, etc. These bring complementary technologies, application know-how, and access to captive markets. Master the critical parts of your ecosystem – or lose. *(See Chapter 4.)*
5. Whatever their positioning or strategies, companies will need to carefully understand and monitor the technology and ecosystem landscapes as they evolve to navigate effectively and capture their shares of battery technology's enormous potential. *(See Chapter 4.)*

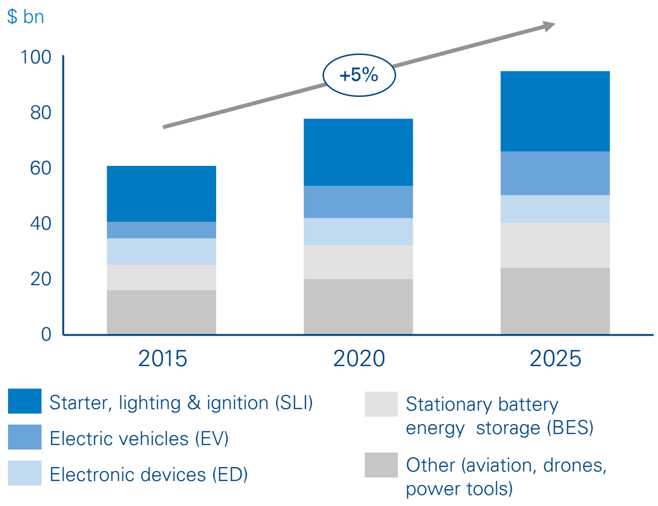
1. Understanding the fast-evolving battery market

Battery technologies are an essential catalyst to unlock growth and new advances in sectors such as electric vehicles (EVs), electronic devices and battery energy storage (BES) for renewable energy. The increasing reliance on battery storage is driving enormous demand – overall, battery applications are expected to become a $90 billion-plus market by 2025, up from $60 billion in 2015.

This is driving unprecedented growth in battery supply, from a wide range of existing – and new – players.

However, current technologies are not enough to unleash the full potential of applications such as power, renewable energy, consumer electronics, and mobility. Innovation is required to drive a step-change in performance and price for subsidy-free, mass-market adoption of products such as EVs. For example, Arthur D. Little estimates based on industry expert assessments, that to make EVs price-competitive with vehicles with internal combustion engines (ICEs) on an unsubsidized basis, EV battery packs need to fall to a cost of $100/kWh. Currently, lowest-cost estimates are in the range of $190–$250/kWh. The same is true for energy grids – for regions with high renewable penetration, such as Texas (where wind covers roughly 25 percent of demand), battery prices need to drop by 50 percent in order to switch back-up from gas-fired units to battery storage.

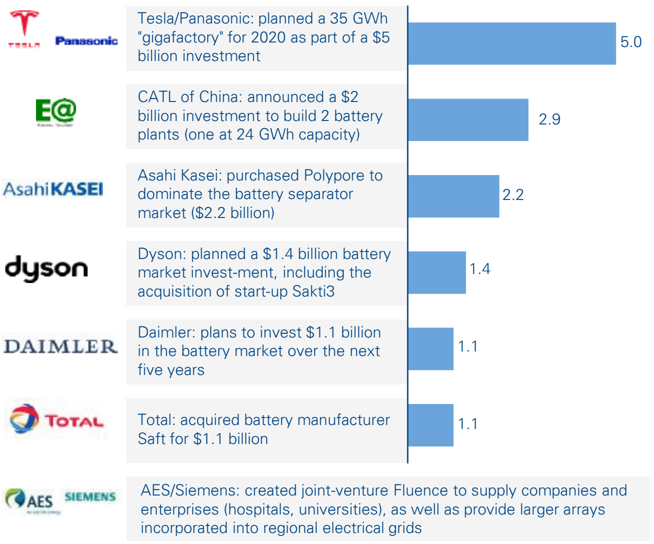
Figure 1: Battery application growth forecast



Comment: Selected companies
Source: Arthur D. Little analysis

The future size of markets and their importance to overall trends such as mobility, renewable energy and digitalization are shown by the multi-billion-dollar investments that have been announced across the ecosystem. These come from existing battery manufacturers, vehicle makers, chemicals companies, energy suppliers and others, with many businesses moving outside their traditional comfort zones.

Figure 2: Battery related investments (selection)



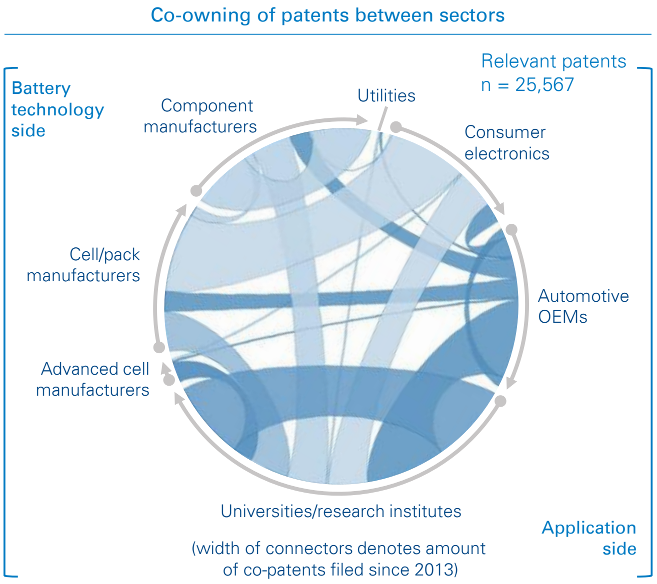
Tesla/Panasonic: planned a 35 GWh "gigafactory" for 2020 as part of a $5 billion investment	5.0
CATL of China: announced a $2 billion investment to build 2 battery plants (one at 24 GWh capacity)	2.9
Asahi Kasei: purchased Polypore to dominate the battery separator market ($2.2 billion)	2.2
Dyson: planned a $1.4 billion battery market invest-ment, including the acquisition of start-up Sakti3	1.4
Daimler: plans to invest $1.1 billion in the battery market over the next five years	1.1
Total: acquired battery manufacturer Saft for $1.1 billion	1.1
AES/Siemens: created joint-venture Fluence to supply companies and enterprises (hospitals, universities), as well as provide larger arrays incorporated into regional electrical grids	

Comment: Investments that are done or planned, 2016 and 2017, USD Bn
Source: reported news – various secondary sources, Arthur D. Little Analyses

The last two years have seen over $13.7 billion of battery-related investments and acquisitions. This frenzy of spending has seen many organizations move beyond their traditional specialisms. For example, Total acquired battery manufacturer Saft, home appliance company Dyson bought disruptive technology start-up Sakti3 as part of its planned $1.4 billion battery investment, and Tesla announced a "gigafactory" to produce batteries for EVs and energy storage in conjunction with Panasonic.

Due to these investments the world is seeing a rapid build-up of vast and intricate ecosystems of existing and new players. Patent filings have increased threefold since 2010 – particularly in the area of joint filings, often between organizations in very different sectors. Examples include research institutions, companies developing battery technology, and businesses using battery technology within applications, such as automotive, electronic devices and utilities. Players in the market therefore need to manage their way through these complex ecosystems if they are to thrive in the market.

Figure 3: Patent ownership map



Source: European Patent Office, Arthur D. Little analysis

There is no "God Battery"

We believe that no single technology will dominate the industry at large. Each of the five key battery storage markets (described in detail in Chapter 2) has very different requirements on factors such as power density, capacity, cycle lifetime, energy density, capital cost, charging time, reliability and safety.

Winning solutions remain unclear, and success will require a combination of next-generation innovation and improvements to current technologies to meet evolving needs.

Each technology has intrinsic limitations to their technical and economic windows of operations, whereby extending one performance feature (energy density, say) quickly goes at the expense of others (such as safety or costs).

Existing technologies, such as lithium-ion (Li-ion) batteries, have seen rapid improvements in performance and cost due to a combination of greater economies of scale and research and development. However, there are still burning unmet needs to be solved. Next-generation technologies are required to deliver a step-change in performance of key battery characteristics. Much of the development in this area is being led by ambitious start-ups, working in both the Li-ion market (such as on silica anodes, solid-state electrolytes and advanced cathodes) and in alternative technologies, such as flow and zinc-air batteries.

Table 1: Relative performance requirements of major battery applications

	Applications	Capital cost	Safety	Cycle lifetime	Energy density	Power density	Charging time	Reliability[1]
SLI	① Start-stop	●	○	◐	○	●	○	●
EV	② HEV/PHEV	◐	◐	●	○	●	●	◐
	③ BEV[2]	●	●	◐	●	◐	◐	●
	④ Commercial vehicles[3] (E-Bus)	●	●	●	◐	●	●	●
ED	⑤ Electronic devices	○	●	○	●	○	◐	○
BES[4]	⑥ Low frequency	●	●	○	◐	◐	○	○
	⑦ High frequency, short discharge	●	●	●	◐	●	●	○
	⑧ High frequency, long discharge	●	●	●	◐	◐	◐	○

1 Measured as low-temperature performance;
2 Battery Electric Vehicles include 100% battery powertrain and long-range PHEV;
3 Exclusively e-buses due to their dominance in the electric commercial vehicle segment;
4 BES low frequency includes back-up/uninterrupted power supply, high frequency short discharge is mainly frequency regulation & renewables stabilization, high frequency short discharge is mainly residential and grid peak shaving and load shifting;
Source: Arthur D. Little analysis

Not since the first rechargeable battery was invented back in 1859 has there been so much focus on battery technology. Yet, so far, return on this investment has been slight, demonstrating that caution is required from both incumbents and newcomers. Many new technologies are still in their infancy, and there is likely to be a significant time overlap between technologies entering the mainstream and their final replacement of incumbents. For example, Li-ion batteries currently dominate the automotive battery market. Despite this, production of NiMH batteries (the previous leader) is predicted to continue for five to 10 years. We expect that a similar time frame will drive the introduction of next-generation solid-state batteries. Players in the market must therefore take a long-term view and, at the same time, ensure they are focusing on the right technologies and business models for their organizational success.

Although the large influx of investments signals an attractive and growing market, new entrants should beware, as there are considerable risks. These differ dependent on their positions within the value chain:

- For component suppliers reliant on scarce metals such as cobalt, there are considerable risks in securing these raw materials. Additionally, the race for an ever-more powerful battery is continuously raising component performance, resulting in innovative new chemistry which could make current technology obsolete. But despite these risks, the component space offers attractive financial returns, generally yielding 10–30 percent EBIT margins.
- Due to overcapacity among battery cell manufacturers and their desire to lock in automotive OEMs on long-term contracts, margins have been squeezed. Not only has significant additional capacity been announced and built, but battery plants are of much greater scale, depressing prices ever further. Together with the need for "big battery" manufacturers to form early, strong partnerships with automotive companies, this pushes gross margins down to zero and below in the hope that greater rewards can be reaped later on. Bosch's recent decision to abandon electric-vehicle battery manufacturing (while maintaining its position in other parts of the value chain) underscores the challenges facing players in an increasingly crowded battery-manufacturing market.
- Besides value chain-specific risks, an overarching hurdle is that the battery industry is extremely conservative. There are long development cycles across every step of the value chain. This implies long payback periods and slow scale-up for those interested in entering the market.

So, amid all the announcements and investments, which technologies will triumph, and which players will prosper? This study aims to inform those within the battery technology ecosystem, and help them set their strategies and unlock value moving forward. It focuses on battery components and cells, rather than battery packs, which will be covered in Arthur D. Little's next report.

The analysis and insight in this study leverage Arthur D. Little's extensive engagements and one-on-one discussions with leading industry players, academia and start-ups.

2. Battery applications – different needs, different solutions

The global battery market is made up of multiple applications of battery technologies with slightly different needs and requirements, which leads to each being best served by specific technologies. Next-generation innovation will impact each of these applications in different ways, serving currently unmet needs and helping improve performance. The five major battery applications that comprise the bulk of the battery market are:

- Starter, lighting & ignition (SLI) batteries for internal combustion engine (ICE) vehicles
- Electric vehicles (xEV)
- Electronic devices (ED)
- Stationary battery energy storage (BES)
- Other (aviation, drones, power tools, etc.)

By analyzing the specifics of these applications we can understand the drivers of battery R&D and outline predictions on future trends.

1. Starter, lighting & ignition (SLI)

This is the oldest (and still largest) application area. An SLI battery is used in every conventional vehicle with an internal combustion engine (ICE), and serves to start and ignite the engine, as well as to provide electricity to the rest of the car when the engine is not running. Starting an engine requires very large currents for a short period – up to 300 amperes for only a few seconds. In comparison, a washing machine only requires 10 amperes. This makes power density a key requirement for such batteries. Additionally, it needs to be able to operate reliably across a wide range of temperatures and environments, while recent advances in "start-and-stop" systems, in which the engine shuts off automatically when waiting for a traffic light, are also placing an increasing burden on the cycle lifetime of SLI batteries.

2. Electric vehicles (xEVs)

The fast-growing xEV market is made up of major groups of EVs, each with a distinct set of requirements: hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), full electric vehicles (EVs) and commercial electric vehicles (CEVs).

HEVs are conventional ICE vehicles for which the propulsion systems are combined with smaller electromotors driven by batteries, which are commonly charged by regenerative braking. The smaller relative capacity of the batteries makes energy density and capital cost less relevant. However, as the battery is charged and discharged frequently and powerfully through braking, it has to have a high power density, extremely short charging time, and long cycle lifetime, which requires thousands of cycles.

Compared to HEVs, a PHEV has a battery that can also be charged by plugging into an external electricity source. These batteries typically have much larger capacity, enabling the vehicle to drive fully electric for short distances. This leads to requirements for lower capital cost and better energy density, while power density and cycle lifetime are of less concern.

"Full" EVs no longer have ICEs, and thus require much larger batteries to deliver sufficient range for drivers, which makes capital cost and energy density their most important needs. EVs also require batteries with high reliability (as the vehicle can no longer fall back on the ICE) and good cycle lifetimes of around 1,000 cycles, which enable them to last for the same mileage as the rest of the car components.

Commercial EVs such as e-buses typically have increased safety needs as the battery systems are large and the impact of a thermal runaway (battery meltdown) can be severe. Cycle lifetime is also of more importance than in PHEVs and EVs, as the buses are charged at least daily. In the case of buses for which fast charging is required, they can be fully charged multiple times a day, which makes cycle lifetime even more important.

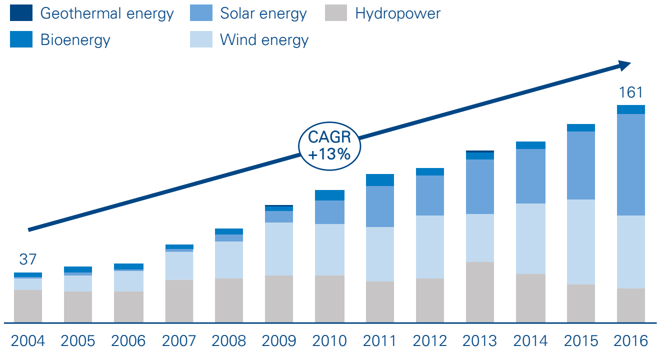
3. Electronic devices

Batteries for electronic devices are used mainly within laptops and mobile phones, as well as for tablets, e-readers and other devices. All these applications have similar requirements, with volumetric energy density by far the most important. They need to provide the largest-possible amount of energy in the most compact form. As most applications have low drain, power density is typically not an issue. Battery costs are relatively small in comparison to the end product, and as the willingness to pay for high-performance batteries is generally high, cost is of secondary importance.

4. Stationary battery energy storage (BES)

Stationary battery energy storage (BES) is a vital part of smoothing the supply and demand around power generated from wind and solar sources. Essentially, it ensures that electricity from renewables can be stored for use when the wind isn't blowing or the sun shining. Also, it ensures that peaks in consumption can be absorbed and backup is provided without having to temporarily rely on fossil fuel power plants (such as diesel generators).

Figure 4: Global annually installed capacity of renewable energy sources

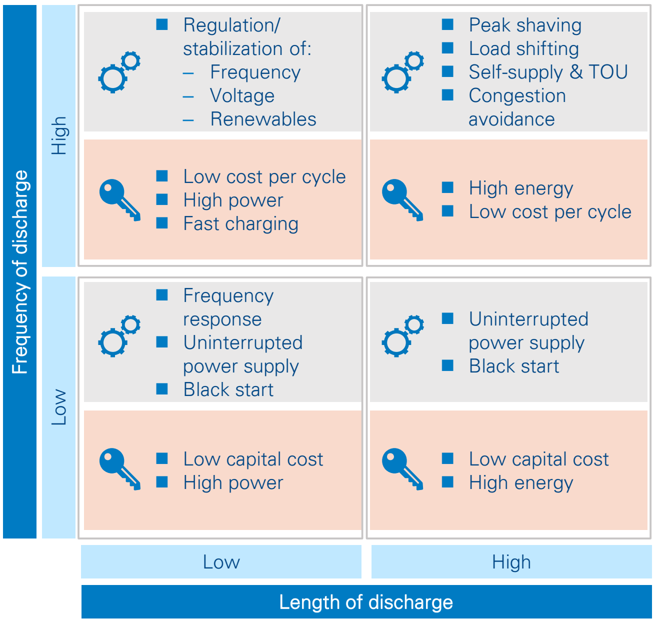


Source: BP. (2017). Statistical Review of World Energy

Arthur D. Little extensively covered BES in its previous report, "Battery storage: Still too early?", which identified multiple types of operating models for batteries in energy-storage applications, including at grid scale and for residential storage, in which it can be linked to wind turbines and rooftop solar panels. Based on their needs from batteries, these operating models can be divided across two axes: 1) frequency of discharge and 2) length of discharge. The applications and key needs of each quadrant are shown in Table 2.

One interesting example of this is Italian electricity transmission operator Terna, which is combining multiple technologies for different applications: high-energy (long-discharge) technologies for congestion avoidance in its mainland grid, and high-power, lower-frequency technologies to secure uninterrupted power supply on the islands of Sicily and Sardinia.

Table 2: Summary of key needs per application in battery energy storage



Frequency of discharge	High	■ Regulation/ stabilization of: – Frequency – Voltage – Renewables	■ Peak shaving ■ Load shifting ■ Self-supply & TOU ■ Congestion avoidance
		■ Low cost per cycle ■ High power ■ Fast charging	■ High energy ■ Low cost per cycle
	Low	■ Frequency response ■ Uninterrupted power supply ■ Black start	■ Uninterrupted power supply ■ Black start
		■ Low capital cost ■ High power	■ Low capital cost ■ High energy
		Low	High
		Length of discharge	

Source: Arthur D. Little analysis

Application

Key needs

5. Others

Many other applications exist, with their own sets of needs, e.g., drones, power tools, electric scooters, electric bikes, aviation, fork lifts. As they have a minor market share, they are not considered in this overview.

Next-generation technologies on the horizon

Li-ion batteries have improved dramatically over the past 25 years, enabling improved performance in consumer electronics and the introduction of new applications such as drones and EVs. However, to accelerate these and other applications, new innovation is vital – a step-change in performance is required.

As table 3 below demonstrates, there are still major unmet needs in each application – such as:

- Cost, reliability and charging time for EVs
- Cycle lifetime and cost for high-frequency stationary battery energy storage
- Safety across multiple applications

Table 3: Battery applications and unmet requirements

🟩 Key need that is met   🟧 Key need that is partially met   🟥 Key need that is significantly unmet inhibiting full adoption of technology   ⬜ Not of primary concern

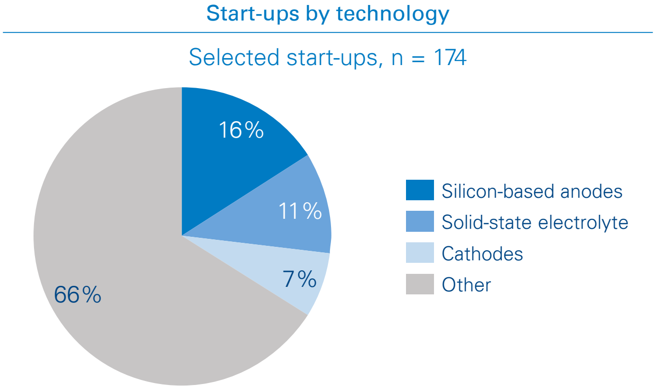
Application		Capital cost	Safety	Cycle lifetime	Energy density	Power density	Charging time	Reliability	Most suitable battery technology
	SLI (start-stop)	🟩	🟩	🟧	(N/A)	🟩	(N/A)	🟩	Currently lead acid, possible future shift to LFP
Electric vehicles	Hybrid	🟧	🟩	🟩	(N/A)	🟩	🟧	(N/A)	Shift from NiMH to LFP-C and NCM-C. NCM-LTO will be suitable if capital cost decreases
	Plug-in hybrid	🟥	🟧	🟩	🟧	🟩	(N/A)	(N/A)	LFP-C for small capacity PHEVs, NCM-C or NCA-C for larger capacity PHEVs
	Full	🟥	🟧	🟩	🟧	🟩	🟥	🟥	NCM-C or NCA-C
	Commercial	🟥	🟩	🟩	🟧	🟩	🟩	🟧	LFP-C or NCM-C mainstream, NCM-LTO if fast charging is required
	Electronic devices	(N/A)	🟩	🟩	🟩	(N/A)	(N/A)	(N/A)	LCO-C
Grid	Low frequency	🟩	🟩	(N/A)	(N/A)	(N/A)	(N/A)	🟥	Lead acid due to low capital cost
	High frequency Short discharge	🟥	🟩	🟥	(N/A)	🟩	🟩	(N/A)	LFP-C and NCM-LTO most likely if their capital cost drops and cycle life increases
	High frequency Long discharge	🟥	🟩	🟥	(N/A)	(N/A)	(N/A)	(N/A)	LFP-C and Flow most likely if their cycle life and/or capital costs improve

Needs

Source: Arthur D. Little analysis

A lot is happening in next-generation technologies. A host of battery technologies using alternative materials are being developed by ambitious start-ups, while there is increasing innovation within the Li-ion space primarily focusing on three areas: silica anodes, advanced cathodes and solid-state electrolytes.

Figure 5: Focus areas in the lithium-ion battery space from a representative sample of 180 start-ups



Source: Arthur D. Little analysis

Silica has higher energy capacity than graphite, the normal material for anodes. This is leading to it being blended through graphite anodes, with the aim of eventually moving towards full silica anodes. These can offer theoretical increases in energy density of up to 40 percent. However, for this to happen, issues in cycle lifetime have to be overcome, in which the anode pulverizes itself upon its 300 percent volume expansion while charging. Ongoing innovations use only minor silica concentrations, limiting potential density increases to 10–20 percent.

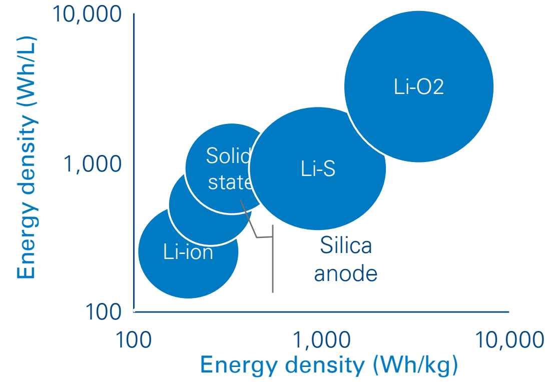
Many **advanced-cathode chemistries** exist that have higher energy capacities and voltages, such as lithium nickel manganese oxide (LNMO). These high-voltage cathode materials are currently facing issues with the liquid electrolyte used in common battery systems, which breaks down at voltages above 4.5 V.

The third and strongest contender for innovation is a **solid-state electrolyte**. This replaces the current electrolyte system that is made of organic solvents, dissolved lithium salts and polyolefin separators by one thin, ion-conducting membrane. It is often seen as one of the technologies with the most disruptive potential inside li-ion, unlocking the use of new cell components and delivering four benefits:

1. A solid-state electrolyte makes the safe use of pure lithium anodes possible, readily increasing the energy density of a cell by 40 percent.
2. It unlocks new types of cathodes. The oxide-based solid-state electrolyte no longer breaks down at 4.5 V, allowing the use of 5 V cathodes and further increasing the energy density by 10 percent.
3. It enables a new class of conversion cathodes such as sulfur and oxygen, enabling even larger potential increases in energy density. Lithium-sulfur systems have long been produced by companies such as Sion power; however, they suffer from cycling issues due to polysulfides shuttling through the separator to the anode. This is one of the many possible problems that solid-state electrolytes may solve.
4. Improved battery safety – perhaps the largest benefit. Using a solid material instead of a flammable liquid electrolyte prevents the formation of dendrites (lithium slivers living in the electrolyte that can cause internal battery short circuits, which lead to meltdowns) and makes electrolyte leakage impossible (avoiding potential self-ignition). Increased cell simplicity might potentially also lead to decreased costs. Given that safety is one of the primary priorities of virtually all big players, even a slightly higher initial cost of this new technology might be worth their investment.

Figure 6: Theoretical energy densities of various lithium-ion technologies

Energy density by volume and weight

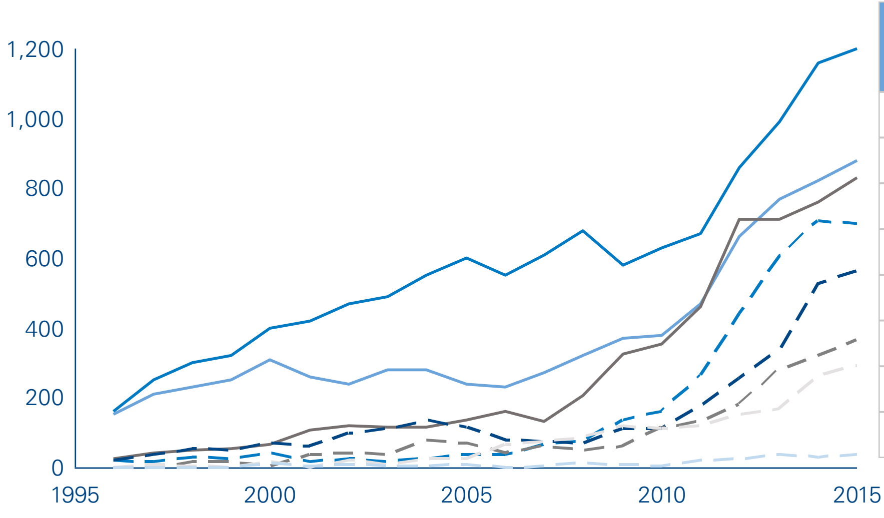


Comment: Selected major technologies
Source: Arthur D. Little analysis

Given these factors, it is no surprise that the perceived benefits of solid-state electrolytes are of large interest to battery manufacturers as well as users. This is demonstrated by the large amount of well-funded start-ups, investment activity, M&As, and research work/patent filings. Examples include:

- Recent ~$100m acquisitions of the start-ups Seeo and Sakti3 by Bosch and Dyson, respectively
- News from companies including Samsung, Toyota and Bosch, which claim they will be able to produce solid-state batteries before 2020
- Several ~$100m start-ups active in solid-state, with prominent VC and CVC investors including Khosla Ventures (into QuantumScape, Sakti3, Seeo), Kleiner, Perkins, Caufield & Byers (into QuantumScape, Ionic Materials), General Motors and Volkswagen
- Increased research activity and patent filing by large corporates (880 filings in 2015 alone)

Figure 7: Patent filings per technology



Technology	Patents filed (2015)
Liquid electrolyte	1,200
Solid-state electrolyte	880
Metal-oxide cathode	830
Lithium-air	700
Lithium-sulfur	565
Separator	365
Silicon-based anode	290
Recycling	35

Source: Arthur D. Little analysis

3. Which companies will be the winners in next-generation battery technology?

While there is extremely high potential demand for battery technologies in emerging markets such as EV and BES, the over-riding driver for success is cost. This has led to a concentrated focus on bringing down the costs of Li-ion batteries, such as by scaling up manufacturing, which has brought down prices further than many analysts expected.

Lowering Li-ion prices is a double-edged sword. It helps meet existing demand, but lengthens the commercialization time of new technologies, as they have to reduce costs further in order to cross the "valley of death" (the time between the R&D stage and becoming commercially cost-competitive with current technologies). In turn, this potentially holds back the longer-term innovation that battery-driven markets require.

Based on its analysis, Arthur D. Little predicts that one of three possible scenarios will dominate the mid-term battery technology industry:

1. The current generation of Li-ion prevails

Likelihood: medium probability

This scenario assumes a situation similar to that which happened in solar panels – the prevalence of one single technology. As with solar, massive investments in huge manufacturing facilities will further lower the costs of current-generation Li-ion technologies. At these price levels, other existing technologies will not be able to compete, while new innovations will not be able to cross the technological valley of death. Therefore, current Li-ion will become the technology of choice for the majority of manufacturers due to its good balance of technical properties and price.

However, even despite the huge increase in production capacity of the current Li-ion technology, we do not see this scenario as very likely, for two reasons:

- Batteries have very diverse applications: certain niche applications for which the willingness to pay is high (such as electronic devices) will drive new technological innovations, and these could later spread to mass-market applications.
- Further cost reduction will require performance improvements: the recent massive manufacturing scale-up has significantly reduced production costs. To further reduce costs, the focus needs to shift to improving the performance of batteries to make them cheaper on a cost/kWh basis. This cannot come from incremental development, but requires a step-change.

2. A new Li-ion generation emerges

Likelihood: highest probability

Essentially, the current generation of lithium-ion technology will keep its dominant position, but eventually, next-generation Li-ion technology will attract sufficient investment to make it a viable alternative.

We believe this scenario is most likely for three reasons:

- The current generation of Li-ion technology is hitting its theoretical limits.
- The development of EVs and consumer electronics are creating further "pull" for better solutions that could be potentially addressed by technologies early in the development pipeline.
- Applications such as high-end consumer electronics provide attractive markets with their willingness to pay for higher performance, enabling next-generation Li-ion to establish itself before targeting mass-market applications.

The hottest candidate, the solid-state electrolyte Li-ion battery, will need to surpass multiple challenges besides finding a safe pathway through the cost valley of death. Even when solid-state batteries enter the market in niche applications, current lithium-ion batteries will most likely be produced to cater for the bulk of applications for another 10–15 years.

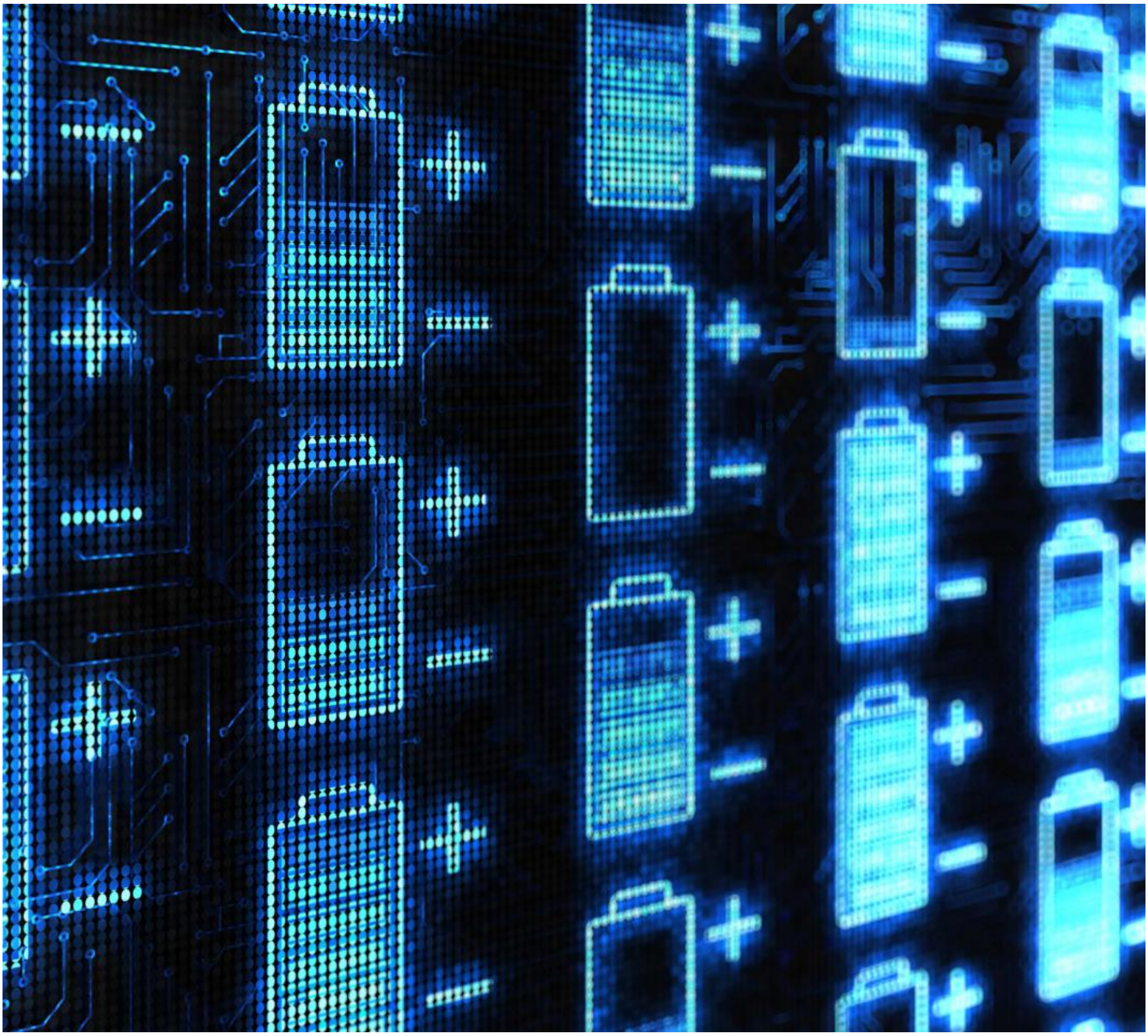
We expect solid-state electrolyte batteries to start in high-end consumer electronics, in which the willingness to pay for increased energy density is relatively high and development cycles relatively short. Thereafter, the technology will gradually spread to the majority of other applications, such as EV and grid storage, for which development cycles are typically much longer due to stricter requirements around cycle and shelf lifetime. Alternative technologies, such as flow and zinc-air batteries, will only occupy certain niche applications with very specific requirements. In the energy sector, a range of other technologies will coexist, depending on the application and driven by the less strict requirements on size and space for stationary systems.

3. Unforeseen technology steals the show

Likelihood: low probability

This scenario sees a completely new technology developed (outside lithium-based batteries) that will have such promising potential that it will attract sufficient capital and become a dominant alternative to existing Li-ion technologies.

As of now, there is no truly viable battery technology with sufficient potential to replace currently dominant Li-ion batteries across all applications. Lithium is the lightest metal around, with the lowest electrochemical reduction potential, making it clearly the most suitable charge carrier for high-performance batteries. Only in grid-storage applications do low-performance and low-cost technologies have potential applications. In EVs, no other battery type stands a chance, which makes only hydrogen fuel cells the only long term threat.



4. The impact for current and future battery players

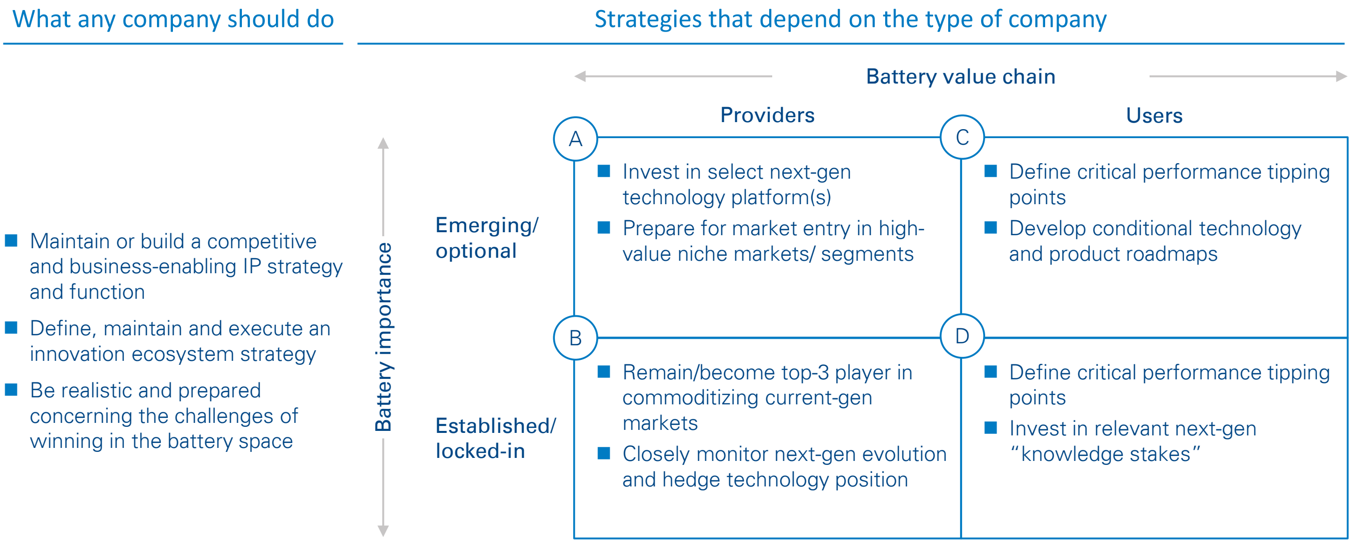
As our report shows, the battery technology market will remain highly dynamic, delivering both major rewards and large-scale risks over the coming years:

- Tomorrow’s winning innovators should benefit from continued, ongoing growth and have the potential to create tremendous value. However, high entry barriers in current-generation Li-ion markets will prove almost insurmountable to new entrants, while some consolidation among established players seems likely.
- Next-generation technologies show major promise. Despite some industry skepticism, we believe that over time they will eventually replace some, if not all, current-generation Li-ion batteries.
- Improved battery technology performance, especially in areas such as cost and energy density, will make batteries suitable for mainstream applications (such as in cars, cordless devices and grid storage) and in new, high-end uses (e.g., in aviation and military).
- However, some of the much-touted (and heavily invested-in) next-generation technologies will fail to live up to expectations.

Every part of the ecosystem and value chain faces different risks and opportunities. The ecosystem can be broadly broken down into companies that are providers of materials and technology (e.g., chemicals companies, cell and pack manufacturers) and those that are users of battery energy storage (such as automotive OEMs, electronics firms and utilities). And while there are already many established players in both categories, the enormous growth promise of the battery market will remain a strong magnet to new entrants – which will generally have more options but also a longer road ahead than current players.

Where does it leave each one of these groups? Figure 8 below provides an overview of our recommended high-level strategies:

Figure 8: Strategies for battery stakeholders



What any company should do

- Maintain or build a competitive and business-enabling IP strategy and function
- Define, maintain and execute an innovation ecosystem strategy
- Be realistic and prepared concerning the challenges of winning in the battery space

Strategies that depend on the type of company

	Providers	Users
Emerging/ optional	A Invest in select next-gen technology platform(s) Prepare for market entry in high-value niche markets/ segments	C Define critical performance tipping points Develop conditional technology and product roadmaps
Established/ locked-in	B Remain/become top-3 player in commoditizing current-gen markets Closely monitor next-gen evolution and hedge technology position	D Define critical performance tipping points Invest in relevant next-gen “knowledge stakes”

Source: Arthur D. Little analysis

For all companies in the battery space, three generic high-level strategies are of key importance:

- Managing IP is becoming more important than ever, and not just in protecting licenses to operate. Cross-licensing and co-patent ownership are on the rise, and industry convergence is bringing together companies with very different IP maturity and capacity, such as traditional chemical companies, automotive OEMs and connectivity players. (See Arthur D. Little's Prism article, "IP management 4.0".)
- Success relies on defining an innovation ecosystem strategy with key research partners, keeping it updated and pursuing it decisively.
- As with any other breakthrough technology, there is always a distinct chance that companies bet on the wrong horse. There is no easy way out on this one but creating a portfolio of options along strategic "competence platforms" is usually a good idea. And last but not least, companies need to ensure that they have the stamina and appetite for risk to continue to do what it takes to win.
- In addition, there are strategic requirements that depend on the strategic importance of batteries for the business, and of the position in the value chain. We distinguish four company situations:

A. Providers with emerging or optional interests

Given the innate conservatism of the battery market, it is futile to enter by offering current-generation technology. Companies are unlikely to switch suppliers unless there is a really good reason to do so (e.g., a price or performance impact of +10 percent). Instead, these new entrants should focus on investing in next-generation technologies. As these are expected to be costly at first, building a strong position will generally start in a niche in which the relative willingness to pay is high for high-performance products. Good examples include Bosch and Dyson, which are directly stepping into advanced solid-state batteries expected to be used in high-end applications. Other options are skipping Li-ion technology completely and launching into other promising technologies such as flow batteries, as witnessed in the cases of Foxconn and Jabil.

B. Providers with established or locked-in interests

Those already active in the battery field should focus on two main themes – relentlessly reducing costs in current-generation technology while innovating by looking for disruptive technology.

Many in the industry believe that current-generation lithium-ion battery is the only feasible technology and no challengers will emerge soon. This feeling has grown thanks to the failure of other battery chemistries (e.g., the sodium-ion battery Aquion) and insufficient breakthroughs in the area of solid-state technology, despite years of focus and investment. While we agree that most other battery chemistries have limited full-scope market impact, we do believe that next-generation solid-state lithium-ion batteries are closer than many industry experts believe. This should be of concern to any established player in the battery field – they should understand strategic scenarios that would allow them to extract maximum value from these new technology trends.

C. Users with emerging or optional interests

Battery performance is continually improving, while costs are becoming ever lower, on both a capital-cost and a levelized-cost basis. This unlocks many new opportunities in a wide variety of applications. Obvious examples include grid storage and EVs, which are gradually becoming cost-competitive with alternatives. However, less obvious examples also exist, such as garden tools shifting from traditional petrol engines to batteries and drones suddenly becoming feasible. Companies should be aware of how a "perfect battery" can impact their businesses and monitor battery price and performance characteristics to see when the tipping point has been reached. Active monitoring is vital, as battery price developments continue to exceed industry expectations year after year.

D. Users with established or locked-in interests

For current users, closely monitoring the evolution of battery characteristics is also of concern. Evolution in current lithium-ion technology is already supplanting other technologies, as it is happening to sodium-sulfur batteries in grid storage. To remain competitive, these users should keep abreast of current battery evolution, and actively invest in next-generation knowledge stakes (know-how, patents, etc.). When the time comes, they should be prepared for next-generation activity, ensuring that they have strong bargaining power when the time comes to secure the best partnerships and supplier contracts.

To maximize their chances of success, we believe that organizations need to start their strategic thinking by focusing on these five questions:

1. Where is the greatest future value creation for my company, and how can I access it?
2. What is the battle that my company needs to win – and what do I leave to others?
3. How do I then stitch together a fitting ecosystem of customers, partners, etc.?
4. Which part of my company will I need to build or transform to make this happen?
5. What, then, are the major uncertainties and risks, and how do I mitigate these?

5. Reference section – battery technology in detail

Following the invention of the first rechargeable battery over 150 years ago, research has led to the wide range of technologies that are now used today. However, each technology has its own strengths and weaknesses – product/technology designers therefore need to choose wisely for their particular applications.

Before discussing each technology, it is important to understand key terms:

- A battery pack consists of battery cells (as you would find in your TV remote control) and a battery management system, which regulates.
- A battery cell consists of multiple components, such as electrolyte fluids and electrodes, which can differ in chemistry, yielding different battery characteristics. This report focuses on battery components and cells.

Table 4: Battery performance indicators

Property	Metric	Description
Capital cost	EUR/kWh	Upfront cost to buy a battery (excluding O&M)
Safety	-	Resistivity against thermal runaway
Cycle lifetime	# of cycles	Amount of cycles a battery can be discharged from 100% to 20%, until capacity fades to 80% of its original capacity
Energy density	Wh/kg or Wh/L	Amount of energy which a battery can hold, measured by weight or volume
Power density	C-rate	Rate at which a battery is discharged relative to its maximum capacity
Charging time	C-rate	Rate at which a battery is charged relative to its maximum capacity
Reliability	-	Ability to operate in low temperatures or in extreme conditions
Others	-	Others properties, such as maintenance costs, shelf lifetime, self-discharge, or charging efficiency

Source: Arthur D. Little

To shed more light upon the complex battery space, Arthur D. Little has developed a framework consisting of seven key performance indicators (Table 4). Arthur D. Little uses this framework to assess the different technologies that currently exist, and to show where the burning unmet needs lie from the application perspective.

1. Lead-acid batteries

The grandfather of rechargeable batteries, lead-acid batteries, was the first rechargeable batteries ever made. While their technology is outdated, they have stood the test of time and are still one of the most widely used types today. Their popularity is due to their low capital cost and ability to operate efficiently even at low temperatures, which often trumps their low energy densities and low cycle lifetimes.

There are two main families of lead-acid batteries. The flooded type has optimal capital cost, dropping as low as $60/kWh for large systems, which is less than one-third of the current capital cost of the lithium batteries used in most EVs. However, its downsides are its low cycle life, low charging rate and maintenance requirements, in which the battery has to be topped up with water to remain "flooded". The second family, sealed batteries, applies a slightly more advanced design that does not require topping up with water. This eliminates maintenance costs and increases cycle lifetime, but doubles capital costs.

2. Lithium-ion

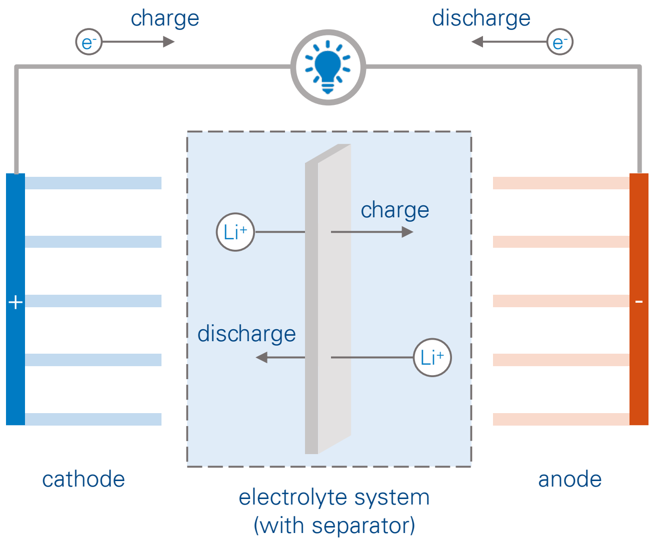
Lithium-ion (Li-ion) batteries have gained enormous attention in the past decade. While already commercialized in 1991, constant marginal improvements in cost and performance over the past 25 years have unlocked a host of new applications, making breaking news related to batteries a common sight.

The rapid decline in costs is mainly the result of two underlying drivers:

1. Massive increase in scale across all steps of the manufacturing value chain
2. Increase in performance of cells, making new cells cheaper on a cost/kWh basis

The constant search for more powerful battery components has now led to a wide breed of Li-ion battery compositions. While a perfect battery still remains a work in progress, different variants of the battery's three main components (anode, cathode, and electrolyte system, Figure 9) lead to specific strengths and weaknesses. In current systems, the cathode limits the power, while the charging is limited by the anode.

Figure 9: Simple schematic of a Lithium-ion battery. On discharge, lithium ions move from the anode to the cathode through the electrolyte system (and the separator), while electrons flow out from the anode through the electric circuit. On charge, the flows reverse.



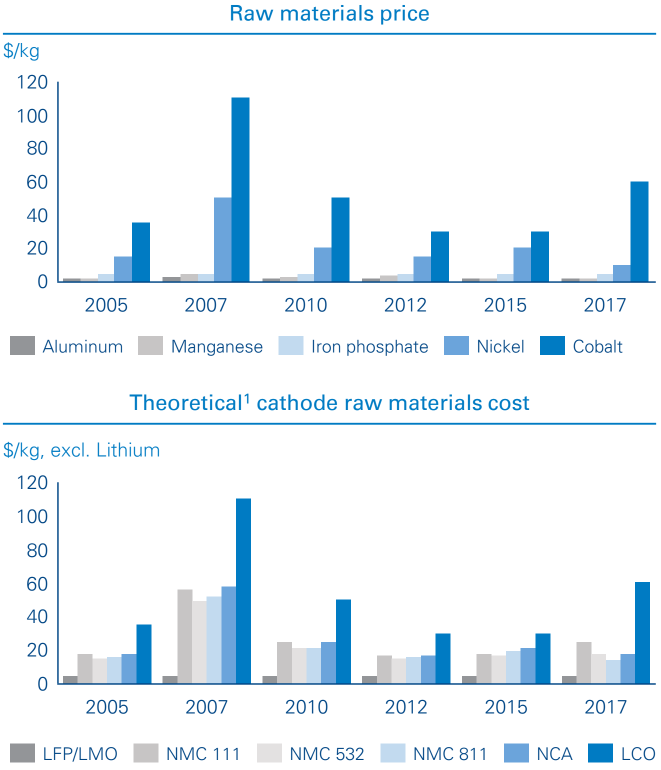
Source: Arthur D. Little

Cathode chemistry

Current Li-ion batteries are commonly classified by their cathode chemistry. Five solutions are currently available:

- **LCO** (lithium cobalt oxide) is the most mature cathode chemistry, which made the commercialization of Li-ion possible. It produces cells with the highest volumetric energy density, but with a downside of low power density and low cycling ability. Cost is proving to be an ever larger issue, as the cathode is entirely made of cobalt. Current innovation efforts are focused on squeezing the last drops out of the battery's performance by increasing the voltage and energy capacity of the material. Arthur D. Little believes that unless a better alternative comes around (such as solid-state batteries with new cathode types, see below), this technology will remain the cathode of choice in consumer electronics for two reasons: it has the highest volumetric energy density, and willingness to pay is generally higher in these applications.

Figure 10: Spot market costs of raw cathode materials (excluding lithium). Nickel and cobalt especially are expensive and volatile. Having a well-hedged materials procurement strategy is necessary to avoid cathode costs being volatile as well.



1Theoretical, as not all cathode material types were produced in 2005

Source: Infomine, Prayon, Arthur D. Little analysis

Securing a steady cobalt supply is paramount

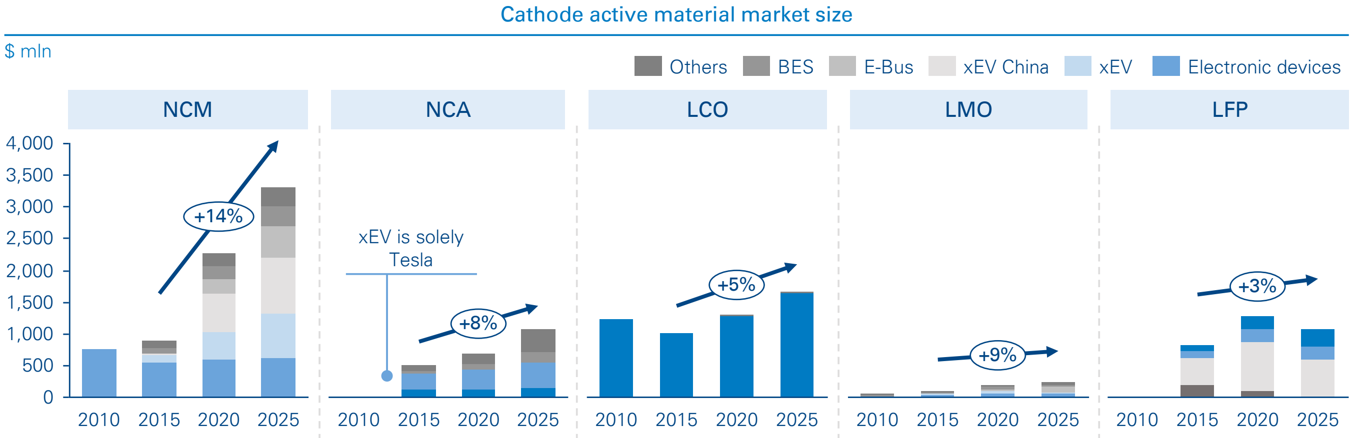
Cobalt, a scarce metal produced as a small-scale by-product of copper mining, is giving headaches to battery manufacturers. Its production nature makes its price-demand relationship highly inelastic, and on top of that, more than half of global supply lies in the Democratic Republic of Congo – a country with infamous for political instability and a long history of violent domestic disputes.

- **LFP** (lithium-iron phosphate) batteries take a different approach. The cathode is made out of more abundant iron and phosphate, leading to a lower raw material cost. However, cells produced with LFP have low energy density due to LFP's inherent low voltage and low energy capacity, eventually making it a more expensive cell when measured on a cost/kWh basis. The cathode material is still favored for its rigid olivine structure, which gives the material its extremely high power and high cycle lifetime. This technology is already very near its maximal theoretical performance, giving little room for further improvements besides cost cutting. The cheap LFP production path of using rotary kilns has dramatically grown the Chinese battery industry. Now that other technologies are evolving, higher-performance materials are gradually replacing LFP in applications such as EVs, leaving the market flooded with an overcapacity of cheap LFP. In contrast, high-performance LFP, commonly produced by hydrothermal methods, will maintain a strong position in applications requiring high power (e.g., HEVs and power tools) or high cycle life (CEVs, grid storage).

- **NCA** (lithium nickel cobalt aluminum oxide) is a high-energy cathode material. The current focus is to increase the nickel content further, resulting in higher energy density and simultaneously reducing cobalt usage, effectively bringing down the cost/kWh in two ways. NCA is primarily used by Tesla, while all other EV makers use NCM. (See next bullet point.) That dates back to when Tesla produced its first Roadster (2005). It needed a cheap, high-energy-density cell, and at the time, NCA was the only option, as NCM would not be commercialized until 2009. Tesla is most likely to keep using NCA in its current development cycle, as it is accustomed to using it in a supplied cylindrical cell format provided by Panasonic. However, Tesla has already switched to NCM for energy-storage applications, hinting that a future switch for EVs could soon take place.
- **NCM** (lithium nickel cobalt manganese oxide) is a diverse material dependent on the stoichiometric balance between the nickel, cobalt and manganese. An even ratio (called NCM 1-1-1) is suitable for high-power applications, while higher nickel contents (5-3-2 or 6-2-2) provide higher energy density and simultaneously reduce dependence on cobalt. These are two important reasons the industry is trying to commercialize the nickel-rich NCM 8-1-1 – major producers were expecting to have the first solutions to market early 2018. NCM will remain the cathode material of choice for nearly all EV manufacturers (besides Tesla) until superior 5V cathode materials can be used. Even then, NCM will continue to be used for another five to seven years due to the automotive industry's long and conservative development cycles. NCM will also be the occasional choice in other applications, such as energy storage, HEVs and e-buses.
- **LMO** (lithium manganese oxide) is similar to LFP, as it can deliver high power and lacks energy density, but is two to three times cheaper. The main issue that prevents its mass adoption is its low stability, as demonstrated by Nissan's recent shift away from using the technology due to continued battery malfunctions.

This short overview is not exhaustive. Besides the technologies mentioned above, different manufacturers are testing and pushing other solutions, such as pure nickel LNO (lithium nickel oxide) cathodes, manganese-rich NCMs and a host of 5V

Figure 11: Material market projections



- Large growth in market size due to growth in xEVs in China and rest of world

- High growth mainly due to Tesla/Panasonic
- Small market size if Tesla/Panasonic is to be excluded

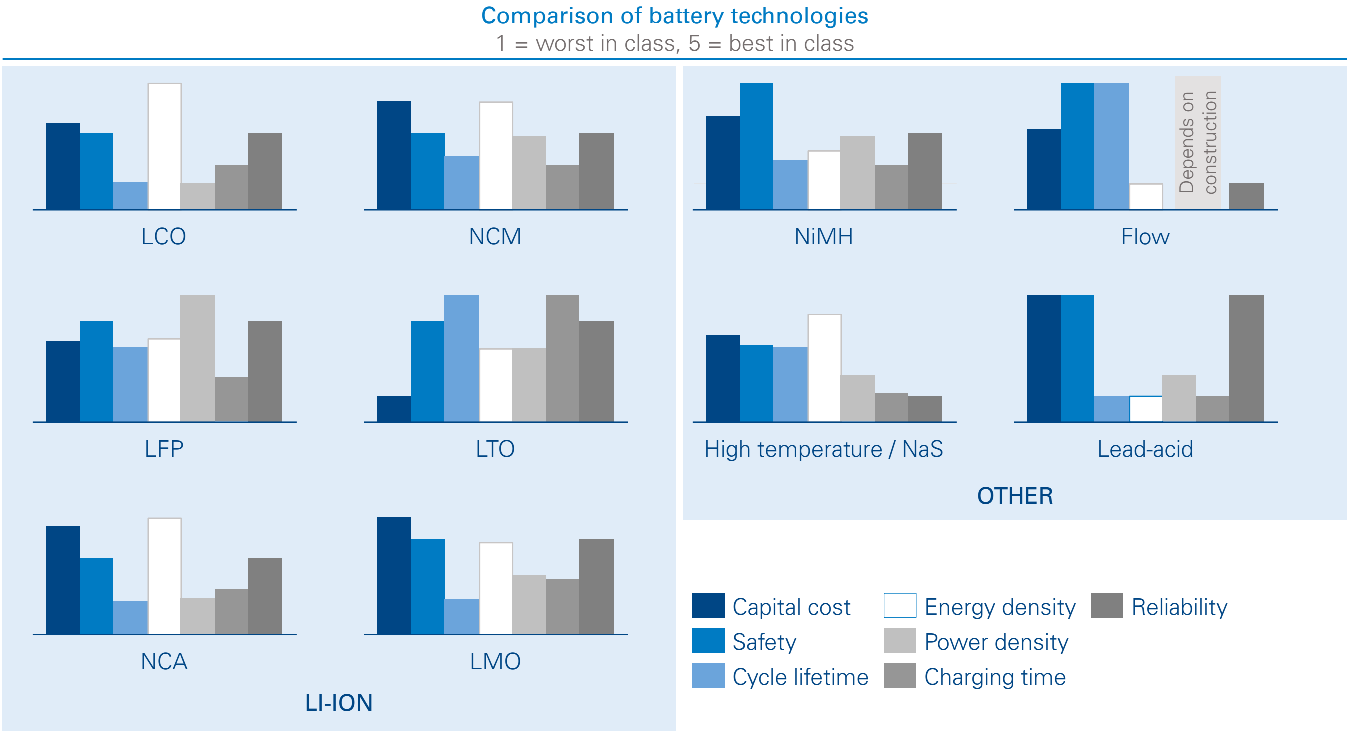
- Average growth sustained by growth in demand for consumer electronics
- Dip in 2015 only due to lower cobalt price

- Reasonable growth but low market value

- Market size has low growth due to decreasing manufacturing costs and China switching to NCM for xEV

Source: Avicenne (2017), Arthur D. Little analysis

Figure 12: Comparison of battery technologies on performance indicators



Source: Arthur D. Little analysis

cathode materials including LNMO (spinel type lithium nickel manganese oxide).

Anode chemistry

- **Carbon-based** anodes have been favored since the first commercialization of Li-ion batteries, as they are cheap and have high energy capacity and low voltage versus lithium ions. Multiple subcategories of carbon-based cathodes bring different trade-offs: amorphous carbon has slightly lower energy density but higher charging power when compared to graphite, while silica composites have higher energy but suffer from lower cycle lifetime due to the large volume expansion of silica upon charging. Currently, carbon-based anodes are the mainstream technology, and we do not expect them to be replaced in the near future, until disruptive technologies such as pure lithium and pure silica anodes are commercialized. The current major focus and challenge of carbon-anodes R&D is increasing the silica content while maintaining cycle life.
- **LTO** (lithium titanate oxide) anodes can charge extremely fast, enabling a battery cell to reach full charge in five minutes. On the downside, the anode is expensive and has low energy capacity and high voltage versus lithium ions, resulting in a low voltage cell with low energy density and extremely high capital costs on a $/kWh basis. Its high cycle lifetime, however, can partly compensate for this on a cost-per-cycle basis.

Electrolyte chemistry

The last part of the battery is the electrolyte system. This facilitates the transport of lithium ions from the anode to the cathode. Typically, the transport medium is made of organic solvents with dissolved lithium salts, with a polyolefin membrane between the electrodes (the separator). The separator is a critical element defining the safety of the battery, as it prevents dendrites (metal slivers) from growing from the anode to the cathode. When the separator breaks down, these dendrites form an internal bridge between the electrodes, which shorts the circuit, followed by a thermal runaway (an irreversible meltdown).

This makes the separator the Achilles' heel of every battery – one that led, for example, to the $5bn recall of millions of Samsung Note smartphones in 2016.

3. Others

Besides the major lead-acid and Li-ion battery types, other technologies are either currently used on a large scale or expected to take significant market share in the future.

Flow batteries are an emerging technology that provides an exceptional lifetime of up to 100,000 cycles. This is more than adequate for their typical application of bulk storage systems, which are designed for an average of two charging cycles per day over a lifetime of 20 years, totaling ~15,000 required cycles.

Flow batteries have two distinct categories – pure flow batteries with all active components stored separately from the cell, and hybrid flow batteries, in which one of the active materials is stored inside the cell. There are further differences based on the types of flow or materials used. Currently, the most mature technologies within pure flow batteries is the vanadium-redox flow battery (VRFB) and the zinc-bromine flow battery (ZBFB) within the hybrid flow category.

While similar in cost, VRFB has a longer cycle life and higher relative energy efficiency. ZBFB technology has higher cell voltage and energy density, but at the cost of high self-discharge rates (up to 33 percent per day) and the risk of dendrite formation.

In general, as flow batteries mechanically pump around highly acidic anode and cathode solutions, they have two drawbacks:

1. Decreased round-trip efficiency
2. Increased need for maintenance

Due to the extremely low energy density (lower than lead-acid), the systems can only be used for stationary purposes. The technology is still in its early stages of maturity, and large manufacturing companies such as Foxconn, Flextronics, and Jabil have only very recently entered the market through partnerships with innovative pioneers. The manufacturing scale-up provided by these players could bring costs down fast enough to unlock a competitive position in the battery energy storage (BES) market.

Sodium sulfur technology's high power and energy density, combined with high cycle life, made it one of the most popular large-scale battery storage systems in the past. These characteristics often forgave the operating costs of ~10–20 percent of initial capex p.a. required to keep the system at its 300–350°C operating temperatures. Today it is rapidly losing market share to Lithium-ion, as it struggles to keep up with the massive decreases currently being seen in Li-ion costs.

Nickel-based batteries, once favored for their safety, power and energy, have been replaced by Li-ion batteries in most applications. Originally both Toyota and Boeing invested heavily in using nickel-based batteries for the Prius and older version of the 787, but both companies have now switched to Li-ion-based technologies.

Many other battery technologies exist, which are based on other charge carriers such as sodium-ion, magnesium-ion, zinc, and aluminum. All of these materials are abundant and cheap, but in order to become a viable market option, the technologies need to be able to cross the treacherously deep valley of death – scaling these technologies to competitive levels as currently found in Li-ion requires investments of hundreds of millions of dollars.

These low-cost chemistries generally only appeal to the bulk energy storage market, in which cost is the one and only driver (as opposed to the expensive, high-performance chemistries that can occupy niche areas in the market). This makes manufacturing scale a necessity, a risk fewer and fewer investors are ready to make after a history of bankruptcies in this area.

A recent example is Aquion, a sodium-ion-based battery start-up, which went bankrupt after receiving $190m of funding. With proven technological capabilities and first large-scale orders delivered to its customers, it pulled the plug due to the massive cost reductions in Li-ion.

One possible candidate with sufficient potential to give Li-ion a run for its money is zinc-air technology. Multiple start-ups such as EoS and ZAF Energy Systems are raising millions from venture capitalists, starting pilots with larger utilities such as Con Ed and Engie, and claim to be able to reduce the cost down to $95/kWh by 2020.

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Arthur D. Little has been at the forefront of innovation since 1886. We are an acknowledged thought leader in linking strategy, innovation and transformation in technology-intensive and converging industries. We navigate our clients through changing business ecosystems to uncover new growth opportunities. We enable our clients to build innovation capabilities and transform their organizations.

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