Batteries

Figures current as of October 2026

The electrochemistry, the chemistries, the factories and the cost curve, electric cars and grid storage, the minerals, and the trade war over who makes the cells.

MODULE 1 — Foundations: How a Battery Actually Works

Goal: Give every later claim about 'better' a definition.

The four parts and the ion shuttle, why lithium, cell versus module versus pack with a car pack built two ways, and the metrics in a table of 2026 values.

MODULE 2 — The Electrochemistry Inside a Cell

Goal: Go one level deeper than the cartoon.

Where the voltage comes from, intercalation and capacity, a cell's energy worked from its chemistry, the SEI and why cells age, and the electrolyte and separator.

MODULE 3 — A Brief History: From Volta to the Gigafactory

Goal: Show how each chemistry won and why the last one changed everything.

Lead-acid and nickel, the three inventors of lithium-ion, Sony's 1991 cell, and the cost curve from about $1,200 per kWh in 2010 to $108 in 2025.

MODULE 4 — The Lithium-Ion Family

Goal: Decode the chemistries and their tradeoffs with numbers.

NMC, NCA, LFP, LMFP, LCO, and LTO compared; graphite and silicon anodes; why LFP won; and LFP's share by region in 2024 and 2025.

MODULE 5 — Making a Cell: From Powder to Pack

Goal: Follow the manufacturing chain and its economics.

The eleven steps, the three formats, a cell's cost, yield and the utilization trap worked, China's pause on new plants, the manufacturers ranked for 2026, and Northvolt's collapse.

MODULE 6 — The Cost Curve and Battery Economics

Goal: Work the numbers that decide which battery wins where.

From cell to installed system, the levelized cost of storage worked, price parity for a car worked, and what drives the curve now, including the 2026 rebound in cell prices and China's new taxes.

MODULE 7 — Batteries for Electric Cars

Goal: Assess the state of play for the largest application.

The 2025-26 market by region; range, charging, and price; chemistry by market and the new vehicles; hybrids and degradation; and the argument over purchase support.

MODULE 8 — Batteries for the Grid

Goal: Explain the fastest-growing power technology.

The revenue stack worked for Texas, the 2025 build-out by country, durations and the four-hour standard, Moss Landing and the codes, and the argument over local moratoriums.

MODULE 9 — Sodium-Ion

Goal: Give the chemistry that is arriving its own module.

How it works, the comparison with LFP and NMC, the 2026 case and cost, where it is used, why it arrived at the bottom of the market, and the bifurcation.

MODULE 10 — Solid-State and the Density Frontier

Goal: Separate the claims from the products.

Sulfide, oxide, halide, and polymer routes; China's new definitions; every major program's October 2026 status; the manufacturing obstacle; and lithium-sulfur, lithium-metal, and silicon.

MODULE 11 — Long-Duration Storage

Goal: Cover the gap lithium cannot fill.

Why duration matters, iron-air worked against lithium, flow, zinc, thermal, compressed air, pumped hydro, gravity, and hydrogen compared, and the honest state of deployment.

MODULE 12 — The Minerals

Goal: Trace each mineral from mine to cathode with the quantities.

The bill of materials by chemistry, lithium and its 2021-26 price cycle, the spike of 2021-22 and its echo, nickel, cobalt, manganese, graphite, and copper, and where processing sits.

MODULE 13 — The Global Supply Chain and Trade Wars

Goal: Map who makes what and the rules that shape it.

Shares by stage, the Western build-out and its stalls, the tariff and export-control table, the Ford-CATL license and the argument over licensing Chinese technology, and the trade flows.

MODULE 14 — Recycling and Second Life

Goal: Assess circularity with its economics.

Black mass and the two routes, the economics by chemistry, the recyclers and the rules, second life, and the arithmetic of 2040.

MODULE 15 — Safety, Degradation, and Standards

Goal: Explain what fails, how, and what the rules require.

Thermal runaway by chemistry, the battery management system, codes and tests including China's 2026 vehicle standard, warranties, and the EU's battery passport.

MODULE 16 — Other Markets: Devices, Trucks, Aviation, Marine, and Defense

Goal: Cover the applications beyond cars and the grid.

Consumer electronics, two- and three-wheelers, buses and heavy trucks, electric flight and its limits, ships, and military batteries.

MODULE 17 — Where Things Stand, and What to Watch

Goal: Close with the argument, the turning points, and a dated watch list.

The cost curve and its 2026 bump, the bifurcation, six turning points and one lesson, five contradictions, the dates from November 2026 on, and a last word.

A note on the ground. The battery industry is argued over as much as it is measured. Forecasts of cost come from companies with products to sell, a factory's capacity is announced years before it produces, and claims for the next chemistry run ahead of the cells. The course gives figures as the agencies, analysts, and price reporters publish them, attributes companies' claims to the companies, and marks disputed figures as disputed. Where the field argues, over purchase subsidies, local moratoriums on grid batteries, and licensing Chinese technology, each side makes its case as its advocates make it before the evidence. Figures are dated to October 2026, and the table before Module 1 names the source and release of each.

Key Numbers, as of October 2026

The production, prices, and shares the course relies on

Measure	Figure	Period	Source and release
Lithium-ion battery demand	1.59 terawatt-hours (TWh), up 29%; electric vehicles 75%, storage growing fastest (up about 51%)	2025	Benchmark Mineral Intelligence (January 15, 2026)
Electric-vehicle batteries deployed	1.2 TWh, up almost 30%; lithium iron phosphate (LFP) over 55%, from nearly 50% in 2024	2025	International Energy Agency (IEA), *Global EV Outlook 2026* (May 20, 2026)
Electric-vehicle battery installations by maker	844.2 gigawatt-hours (GWh), up 19.7%: Contemporary Amperex Technology (CATL) 39.4%, BYD 15.1%, LG Energy Solution 8.1%; the seven Chinese makers in the top ten 73.3%	January-August 2026	SNE Research, via CnEVPost (October 2, 2026)
Cell manufacturing	China more than 80% of production and of nameplate capacity; the EU and the US 6-7% each; global capacity above 4 TWh	2025	IEA, *Global EV Outlook 2026*
China's battery industry	Output of 1,755.6 GWh of power and storage batteries, up 60%; exports 305 GWh; car batteries installed 769.7 GWh, 81.2% LFP	2025	China Automotive Battery Innovation Alliance, via CnEVPost (January 2026)
Battery pack prices	$108 per kilowatt-hour (kWh) on average, down 8%: electric-car packs $99, stationary-storage packs $70, LFP $81, nickel-manganese-cobalt (NMC) $128, China $84	2025	BloombergNEF (BNEF), *Lithium-Ion Battery Price Survey* (December 9, 2025)
Storage-cell prices, China	314-amp-hour LFP cells about 0.36 yuan per watt-hour at home, value-added tax included, and $50 per kWh for export, free on board; 2025 low about 0.26 yuan; near 0.40 in March 2026	July 2026	InfoLink, reported by Down To Earth (August 25, 2026); Energy-Storage.news (March 2026)
Storage-system prices	Turnkey systems $117 per kWh worldwide, down 31%; four-hour systems $110; China $73, Europe $177, US $219	2025	BNEF, *Energy Storage Systems Cost Survey* (December 2025)
Grid storage added	112 gigawatts (GW) and 307 GWh, up 48%; China 66.43 GW and 189.48 GWh; US 18.9 GW and 51 GWh; 158 GW and 459 GWh expected in 2026	2025; 2026 forecast	BNEF, *Energy Storage Market Outlook 1H 2026* (May 2026); China Energy Storage Alliance (January 2026); Wood Mackenzie (March 2026)
Storage cells shipped	612 GWh, up 95%; about 800 GWh expected in 2026; CATL, Hithium, EVE, BYD lead	2025	InfoLink (February 2026)
Electric-car sales	More than 20 million, up 20%, about a quarter of new cars; China about 13 million (nearly 55% of its market); Europe 28%; US just under 10%; 23 million (28%) expected in 2026	2025	IEA, *Global EV Outlook 2026*
Lithium carbonate price	127,750 yuan a tonne ($19,025), battery grade, ex-works China, down 20.8% in the quarter; above 200,000 yuan on the Guangzhou futures exchange in May; 2025 average about $9,000	End of September 2026	Benchmark, *Q3 2026 Lithium Price Review* (October 2, 2026); US Geological Survey (USGS)
Cobalt and nickel	Cobalt hydroxide $17.25 a pound, down 31% in the quarter; London Metal Exchange (LME) nickel $15,700 a tonne	Third quarter 2026; October 9, 2026	Benchmark, *Q3 2026 Cobalt Price Review* (September 30, 2026); LME

Measure	Figure	Period	Source and release
Mining shares	Lithium: Australia 32%, China 21%; nickel: Indonesia 67%; cobalt: the Democratic Republic of the Congo 73%; natural graphite: China 1.4 of 1.8 million tonnes	2025	USGS, *Mineral Commodity Summaries 2026* (January 2026)
US tariffs on Chinese lithium-ion batteries	About 41%: 3.4% normal duty, 25% under Section 301 (car batteries since September 2024, others since January 1, 2026), and 12.5% under the Section 301 action of July 24, 2026	October 2026	Office of the US Trade Representative; InfoLink's baseline for storage systems
US production credits	$35 per kWh for cells and $10 for modules, denied above thresholds of content from prohibited foreign entities: battery components must be 60% free of it in 2026, rising to 85% after 2029	2026	The July 2025 budget law; Treasury Notice 2026-15 (February 2026)
China's export controls on batteries	Licensing of advanced cells, LFP cathode, artificial graphite anode, and equipment, announced October 2025 and suspended under the US-China truce, which was extended on September 24, 2026 from November 10 to January 10, 2027	October 2026	China's Ministry of Commerce (November 2025; statement of September 28, 2026)
Storage safety	Failures per deployed GWh down 98% worldwide	2018 to 2025	Electric Power Research Institute (EPRI) (October 5, 2026)
Sodium-ion	Cells up to 175 watt-hours per kilogram; manufacturing capacity just over 1% of lithium-ion's; the first mass-produced car (Changan's, with CATL cells) unveiled in February 2026	2026	IEA, *Global EV Outlook 2026*; CATL

Tonnes are metric; one tonne is 1.10 US short tons, and one pound is 0.4536 kilograms. Power (GW) measures how fast a battery can deliver energy; energy (GWh) measures how much it holds. Prices move daily; the third column gives the dates of the figures, not of this course. Yuan convert at 6.71 to the dollar, the September 2026 average (Federal Reserve), unless a source gives its own dollar figure. Counts differ by stage: output and shipments include cells still in stock or awaiting installation, so they run ahead of demand and of installations.

Module 1 — Foundations

How a Battery Actually Works

Recommended Reading / Reference

Book: Seth Fletcher, *Bottled Lightning: Superbatteries, Electric Cars, and the New Lithium Economy* (2011)

Reference: Battery University (batteryuniversity.com); the International Energy Agency (IEA), *Batteries and Secure Energy Transitions* (2024) and *Global EV Outlook 2026* (May 2026)

1a. Four Parts and One Idea

Every rechargeable battery is a controlled chemical reaction that would rather happen all at once, and it has four parts. The anode is the electrode that gives up electrons during discharge, and in a lithium-ion cell it is a layer of graphite with lithium atoms tucked between its carbon sheets. The cathode receives them: a metal oxide or phosphate crystal with spaces for lithium to move back into.

The electrolyte is a liquid, or in solid-state designs a solid, that lets lithium ions travel between the two electrodes but blocks electrons, and the separator is a thin porous plastic film that keeps anode and cathode from touching. The one idea is that when a load is connected, lithium atoms at the anode split into ions and electrons, and the ions swim through the electrolyte to the cathode.

The electrons, blocked by the electrolyte, are forced to take the long way, through a motor or a phone, to reach the same destination: that detour is the electricity, and charging pushes everything back.

Component	Material (typical lithium-ion)	Function	Share of cell cost	Share of cell mass
Cathode active material	Nickel-manganese-cobalt (NMC), nickel-cobalt-aluminum (NCA), lithium iron phosphate (LFP), or lithium manganese iron phosphate (LMFP) powder on aluminum foil	Hosts lithium on discharge; sets voltage, energy, safety, and which minerals the cell needs	35-45%	25-35%
Anode active material	Graphite (natural or synthetic), with or without silicon, on copper foil	Hosts lithium on charge	10-15%	15-20%
Electrolyte	A lithium salt, lithium hexafluorophosphate (LiPF6), in organic carbonate solvents	Conducts ions, blocks electrons	5-8%	10-15%
Separator	Microporous polyethylene or polypropylene film, often ceramic-coated	Prevents contact, lets ions pass	3-5%	2-4%
Current collectors	Aluminum foil (cathode), copper foil (anode)	Carry electrons to the terminals	5-10%	10-15%
Can, tabs, housing, safety devices	Steel or aluminum can, vents, a current-interrupt device (CID), and a positive-temperature-coefficient (PTC) device that limits current when hot	Contain, connect, protect	5-10%	10-20%

Component	Material (typical lithium-ion)	Function	Share of cell cost	Share of cell mass
Manufacturing (labor, energy, depreciation, yield loss)	—	—	20-30%	—

Approximate shares for a 2026 LFP or mid-nickel NMC cell; the cathode's share is higher for nickel-rich chemistries and lower for LFP.

1b. Why Lithium

Lithium is the lightest metal, with an atomic mass of 6.9 and a density of 0.53 grams per cubic centimeter. It sits at the far end of the electrochemical series, at −3.04 volts against the standard hydrogen electrode (SHE), which means it gives up its electron more eagerly than almost any other element.

A cell's voltage is the difference in eagerness between its two electrodes, and lithium's chemistry makes a cell of roughly 3.2-3.7 volts, against 1.2 for nickel-metal hydride and 2.0 for lead-acid. Higher voltage and lower weight together mean more energy per kilogram, which is why lithium-ion holds four to five times the energy of lead-acid by weight.

Sodium sits one row below lithium on the periodic table, behaves similarly, and is about a thousand times more abundant in the Earth's crust. It is heavier (atomic mass 23) and slightly less eager (−2.71 volts), which is why sodium cells have stored 20-30% less energy per kilogram than lithium iron phosphate cells, although the best of 2026 reach 175 watt-hours per kilogram, close to LFP (Module 9).

Element or chemistry	Standard potential (V vs SHE)	Atomic mass	Typical cell voltage	Practical energy density (cell, Wh/kg)
Lithium (metal anode, theoretical)	−3.04	6.9	3.6-4.2	400-500 (solid-state target)
Lithium-ion (graphite / NMC)	—	—	3.6-3.7	220-300
Lithium-ion (graphite / LFP)	—	—	3.2	150-205
Sodium-ion (hard carbon / layered oxide)	−2.71 (sodium)	23.0	3.0-3.2	120-175
Nickel-metal hydride	—	—	1.2	60-100
Lead-acid	—	—	2.0	30-50
Zinc-air (primary, not rechargeable at scale)	−0.76 (zinc)	65.4	1.4	300-400

Wh/kg is watt-hours of stored energy per kilogram of cell. Upper LFP and sodium figures are the IEA's for the best 2025-26 cells.

1c. Cell, Module, Pack

A cell is the sealed unit containing one set of electrodes, and it comes as a cylinder a little larger than an AA battery (the 18650 is 18 millimeters wide and 65 long, about 0.7 by 2.6 inches), a flat pouch, or a rigid prismatic can. A module is a group of cells wired in series and parallel with sensors and cooling: series raises voltage, so 96 cells of 3.7 volts in a string make a 355-volt pack, and parallel raises capacity.

A pack is the assembly of modules plus the battery management system (BMS), cooling loops, structural housing, contactors, and fuses that make it a usable product, the thing bolted under an electric car or stacked in a grid container. Roughly 20-30% of a pack's weight and cost is not cells at all, which is why the newest designs skip the module and build cells directly into the pack.

Worked example — A Car Pack Built Two Ways

A mid-size electric vehicle (EV) needs about 75 kilowatt-hours (kWh) at 400 volts, and with 21700 cylindrical NMC cells of 3.6 volts and 5 amp-hours (18 watt-hours each), the pack needs 111 cells in series (400 ÷ 3.6) and 38 strings in parallel (75,000 ÷ (111 × 18)). That is about 4,200 cells of 70 grams each, or 295 kilograms of cells, and adding 25% for module hardware, cooling, and housing gives a pack of about 370 kilograms (815 pounds) at about 200 Wh/kg.

Built instead from prismatic LFP cells of 3.2 volts and about 190 amp-hours (about 610 watt-hours each, 3.6 kilograms), the same pack needs 125 cells in series and none in parallel, about 450 kilograms of cells. A cell-to-pack design adds only about 10% of overhead, so the pack weighs about 495 kilograms (1,090 pounds), at about 155 Wh/kg.

The NMC pack is about a quarter lighter, worth some range or a smaller motor, while the LFP pack costs roughly a third less and lasts about twice as many cycles. That is the tradeoff every automaker makes, and the rest of this course is in large part the story of how the cheaper side of it won.

1d. The Metrics That Matter

Metric	Definition	Consumer cell	EV cell (NMC / LFP)	Grid cell (LFP)	Who cares most
Energy density (gravimetric)	Wh per kg	250-300	250-300 / 160-205	160-190	Cars, aviation, drones
Energy density (volumetric)	Wh per liter	700-750	600-700 / 350-450	350-450	Phones, laptops, cars
Power density	Watts per kg	500-1,500	800-1,500	200-500	Tools, hybrids, frequency response
C-rate (charge)	Fraction of capacity charged per hour (1C is a full charge in an hour)	0.5-1C	1-4C in volume cars; 10C claimed for BYD's 2025 platform	0.25-0.5C	Fast charging, grid services
Cycle life (to 80% capacity)	Full charge-discharge cycles	500-1,000	1,500-3,000 / 3,000-6,000	6,000-10,000	Grid, taxis, warranties
Calendar life	Years to 80% at rest	3-5	8-15	15-20	All
Round-trip efficiency	Energy out ÷ energy in	95%	92-95%	90-95% (system 85-90%)	Grid economics
Cell price	Dollars per kWh	$100-150	$70-110 / $45-70	$45-60	Everyone
Operating temperature	°C (°F)	0 to 45 (32 to 113)	−20 to 55 (−4 to 131), heated or cooled	−20 to 50 (−4 to 122)	Cold markets, deserts

Approximate 2026 values. Chinese 314-amp-hour LFP storage cells sold for about 0.36 yuan per watt-hour at home, tax included, and about $50 per kWh for export in July 2026, up from a 2025 low near 0.26 yuan (InfoLink).

Module 1 Key Points

Foundations

• A battery is anode, cathode, electrolyte, and separator: ions cross inside while electrons take the long way outside, and that detour is the electricity.

• The cathode is 35-45% of a cell's cost and sets its voltage, energy, safety, and minerals; manufacturing is another 20-30%.

• Lithium's −3.04-volt potential and light weight give 3.2-3.7-volt cells with four to five times lead-acid's energy per kilogram.

• A 75 kWh pack weighs about 370 kilograms in NMC cylinders and 495 in LFP cell-to-pack, which costs roughly a third less.

• Each application weights the metrics differently: cars and aircraft prize energy per kilogram, grids prize cost and cycle life.

Module 1 Quiz

Check Your Understanding

1. What is the 'one idea' behind how a battery produces electricity?

A) Ions cross inside the cell while electrons go around outside
B) Electrons flow through the electrolyte from the anode to the cathode
C) Chemical reactions release heat that is turned into power
D) The separator generates the current as ions pass it

2. Roughly what share of a lithium-ion cell's cost is the cathode active material?

A) About 80% of the total
B) About 35-45%
C) About 5%, less than the separator
D) About 20%, the same as the anode

3. Why has sodium-ion stored less energy per kilogram than lithium-ion?

A) Sodium cells run at a higher voltage and waste more of it
B) Sodium is rarer in the crust
C) Sodium cells cannot be recharged more than a few times
D) Sodium atoms are heavier and give up their electrons less eagerly

4. In the worked example, how do the two 75 kWh packs compare?

A) The LFP pack is twice as heavy and no cheaper
B) They weigh the same, because cell-to-pack removes all overhead
C) NMC is a quarter lighter; LFP costs a third less
D) The LFP pack is lighter, because iron weighs less than nickel

5. Which metrics matter most for grid storage and for aviation?

A) Grid: charge rate and power output; aviation: cost per kWh stored
B) Grid: cost and cycle life; aviation: energy per kilogram
C) Both put power density above everything else
D) Both put energy per liter above everything else

Module 2 — The Electrochemistry Inside a Cell

One Level Deeper Than the Cartoon

Recommended Reading / Reference

Book: Isidor Buchmann, *Batteries in a Portable World* (fourth edition, 2016)

Reference: Argonne National Laboratory's battery primers; the *Journal of the Electrochemical Society*'s reviews of the solid-electrolyte interphase

2a. Where the Voltage Comes From

A cell's voltage is the difference in the chemical potential of lithium between its two electrodes, which is to say how much more comfortable a lithium atom is inside the cathode crystal than between graphite sheets. Graphite holds lithium at about 0.1 volts above lithium metal and a nickel-manganese-cobalt (NMC) cathode at about 3.8 volts, so the cell delivers the difference, about 3.7 volts.

Lithium iron phosphate (LFP) holds lithium in an olivine crystal at 3.4 volts, so its cell runs at 3.2-3.3 volts, and since energy is voltage times charge, it stores less energy for the same lithium. Lithium cobalt oxide, the original 1991 cathode, can be pushed to 4.2 volts but becomes unstable once more than about half of its lithium is removed. That limited early cells to about half their theoretical capacity, and it is why cobalt-oxide cathodes gave way to NMC blends that stay stable to higher states of charge.

The whole art of cathode chemistry is finding a crystal that holds lithium at high voltage, gives most of it back reversibly, and does not fall apart or release oxygen when nearly empty.

2b. Intercalation and Capacity

Intercalation is the insertion of lithium ions into the gaps of a layered or framework crystal without changing its structure, a rocking chair in which lithium moves between two hosts and neither host is consumed. Capacity is set by how much lithium the host holds per gram, measured in milliamp-hours per gram (mAh/g), and graphite accepts one lithium for every six carbon atoms (LiC6), which works out to 372 mAh/g.

Silicon forms an alloy, Li15Si4, holding nearly four lithium atoms per silicon atom, or 3,580 mAh/g, almost ten times graphite. But it swells by about 300% as it does, cracking the electrode and consuming electrolyte, which is why it is blended into graphite at a few percent to about 20% rather than used alone.

Cathodes hold less: NMC 811, whose metals are eight parts nickel to one each of manganese and cobalt, delivers about 200 mAh/g in practice against a theoretical 275, and LFP about 160 of a theoretical 170. That is why the cathode is the larger, heavier, and costlier electrode and the one that limits a cell's energy.

Worked example — A Cell's Energy From Its Chemistry

Take an NMC 811 cathode at 200 mAh/g and a graphite anode at 360 mAh/g, sized so the anode carries 10% more capacity than the cathode. Each amp-hour of cell capacity then needs 5.0 grams of cathode powder and about 3.1 grams of anode powder. A 21700 cell of 5 amp-hours at 3.6 volts therefore holds about 25 grams of cathode and 15 grams of anode, and the foils, electrolyte, separator, binder, and can add about 30 grams more.

The cell stores 18 watt-hours in about 70 grams, or 257 watt-hours per kilogram (Wh/kg), while the two active powders alone would store about 450 Wh/kg. Everything that is not cathode or anode costs the cell more than 40% of its potential energy density. Cell-to-pack designs, thinner foils, silicon anodes, and higher-voltage cathodes are each an attack on one term of that arithmetic.

2c. The Solid-Electrolyte Interphase and Why Cells Degrade

On a cell's first charge the electrolyte reacts with the lithiated graphite surface and forms a thin film, the solid-electrolyte interphase (SEI), which lets lithium ions through but stops further reaction. Forming a good SEI is what the factory's slow first charge, called formation (Module 5), is for, and it permanently consumes 5-10% of the cell's lithium.

The SEI is also why cells die: over hundreds of cycles it thickens, consuming lithium and electrolyte and raising resistance, and it grows faster at high temperature and a high state of charge, which is calendar aging. With each charge the graphite expands and contracts, cracking the film and forcing it to re-form, which is cycle aging.

At very high charge rates or in the cold, lithium ions cannot enter the graphite fast enough and plate as metal on its surface instead. Lithium plating is irreversible and dangerous, because the metal can grow needle-like dendrites that pierce the separator, and it is why fast charging is limited in cold weather. On the cathode side, nickel-rich crystals crack, dissolve manganese, and release oxygen when overheated, while LFP's iron-phosphate framework does none of these things, which is its advantage in safety and longevity.

Degradation mechanism	Driver	Effect	Slowed by
SEI growth	Time, heat, high state of charge	Lithium loss, rising resistance	Storing at 30-60% charge; cool temperatures; electrolyte additives
Lithium plating	Fast charging, cold, high state of charge	Irreversible capacity loss; risk of dendrites and fire	Slower charging below 10°C (50°F); pre-heating; tapering the charge above 80%
Particle cracking	Repeated expansion (silicon, nickel-rich cathodes)	Active material loses contact	Single-crystal cathodes; silicon-carbon composites; better binders
Transition-metal dissolution	High voltage, heat (manganese, nickel)	Cathode loss; anode poisoning	Coatings; a lower upper voltage limit
Electrolyte decomposition	High voltage, heat	Gas, resistance, dry-out	Additives; solid electrolytes
Current-collector corrosion	Over-discharge (copper), high voltage (aluminum)	Cell failure	Voltage limits set by the battery management system

2d. The Electrolyte and the Separator

The electrolyte in a lithium-ion cell is a lithium salt, lithium hexafluorophosphate (LiPF6), dissolved in a mixture of organic carbonates such as ethylene carbonate and dimethyl carbonate, chosen because they survive the cell's 4-volt window, which water cannot. They are flammable, which is the root of lithium-ion's fire risk, and they degrade above about 60°C (140°F) and below about −20°C (−4°F), which sets the operating window.

A few percent of additives, such as vinylene carbonate and fluoroethylene carbonate, shape the SEI and add years of life, and each maker's recipe is among the industry's best-kept secrets. The separator, a

polyolefin film 10-25 microns thick (a human hair is about 70), is coated with ceramic to resist shrinking when hot.

A separator's failure, from a stray metal particle, a dendrite, or heat, is the most common trigger of a short circuit and of thermal runaway (Module 15). Solid-state designs (Module 10) replace the flammable liquid with a ceramic or polymer that also serves as the separator.

Module 2 Key Points

The Electrochemistry Inside a Cell

• Voltage is the gap in lithium's chemical potential between electrodes: graphite holds it at 0.1 volts, NMC at 3.8, LFP at 3.4.

• Graphite holds 372 mAh/g; silicon holds almost ten times as much but swells about 300%, so it is blended in small shares.

• A 21700 cell stores 18 watt-hours in 70 grams, 257 Wh/kg; its active powders alone would store about 450.

• The SEI film consumes 5-10% of a cell's lithium at formation; its growth and cracking, and lithium plating, are why cells age.

• The electrolyte is a flammable carbonate solution; a failed separator is the most common trigger of thermal runaway.

Module 2 Quiz

Check Your Understanding

1. Where does a lithium-ion cell's voltage come from?

A) The copper and aluminum of the current collectors
B) The lithium salt dissolved in the electrolyte
C) The electrodes' gap in lithium's potential
D) The polymer film of the separator between them

2. Why is silicon blended into graphite rather than replacing it?

A) It conducts electricity too poorly to carry current
B) It is banned from sealed cells in most markets
C) It costs more than any cathode material
D) It holds almost ten times the lithium but swells about 300%

3. In the worked example, why does the 21700 cell reach only 257 Wh/kg when its active powders could store about 450?

A) Inactive parts add 30 grams that store nothing
B) The cathode delivers only half its capacity on the first cycle
C) The SEI consumes half the cell's lithium at formation
D) Graphite holds less lithium than the cathode

4. What is lithium plating, and when is it most likely?

A) A protective coating applied to the cathode at the factory
B) Lithium metal coating the anode in fast or cold charging
C) A recycling step that recovers lithium as metal
D) The normal storage of lithium between graphite sheets

5. Why is the electrolyte the root of lithium-ion's fire risk?

A) Its solvents are flammable
B) It is stored under high pressure
C) It is a water solution that boils
D) It contains metallic lithium from the start

Module 3 — A Brief History

From Volta to the Gigafactory

Recommended Reading / Reference

Book: Henry Schlesinger, *The Battery: How Portable Power Sparked a Technological Revolution* (2010)

Reference: The Nobel committee's 2019 citation for Goodenough, Whittingham, and Yoshino; BloombergNEF's annual battery price surveys, the latest of December 9, 2025; Our World in Data's series of lithium-ion cell prices since 1991

3a. Lead, Nickel, and the Long Wait

Alessandro Volta's pile of 1800, zinc and copper discs separated by brine-soaked cloth, was the first battery, but it could not be recharged. Gaston Planté's lead-acid cell of 1859 could, and it has never gone away: cheap, robust, and able to deliver the surge a starter motor needs, it still starts nearly every combustion car on earth and backs up telephone exchanges and data centers.

Nickel-cadmium, invented in 1899, powered the first portable electronics until the European Union restricted it for cadmium's toxicity. Nickel-metal hydride, sold from about 1990, replaced it and powered the first mass-market hybrid, the 1997 Toyota Prius, for two decades.

All three share a limit: heavy, low-voltage chemistry that could never give a car a useful range. General Motors' EV1 of 1996, on lead-acid batteries, managed 60 to 100 miles (about 100 to 160 kilometers) on a charge.

3b. The Lithium Breakthrough

Lithium's promise was obvious for a century, and so was its problem: pure lithium metal is violently reactive, and when it is plated again and again during charging it grows needle-like dendrites that short the cell and start fires, as Moli Energy's lithium-metal cells did in phones before their recall in 1989.

The solution took three people and two decades, beginning with Stanley Whittingham, who showed at Exxon in the 1970s that lithium ions could be inserted into and removed from a layered titanium disulfide crystal, the intercalation of Module 2, without metallic lithium ever forming. John Goodenough, at Oxford in 1980, found that a cobalt-oxide cathode doubled the voltage to 4 volts.

Akira Yoshino, at Asahi Kasei in 1985, replaced the lithium-metal anode with a petroleum-coke carbon that lithium could also intercalate into, so that no lithium metal existed anywhere in the cell. Sony commercialized the result in 1991 for camcorders, at about 80 watt-hours per kilogram and, by Our World in Data's reckoning, about $9,200 per kilowatt-hour (kWh) in 2024 dollars.

The three shared the 2019 Nobel Prize in Chemistry, and Goodenough, at 97, became the oldest laureate in any field. His group had also invented the manganese spinel cathode in 1983 and lithium iron phosphate (LFP), published in 1997, the chemistry that would later win the volume market.

3c. The Cost Collapse

For twenty years lithium-ion was a chemistry for consumer electronics, priced above $1,000 per kWh and made in modest volumes for laptops and phones. Three things changed it: Tesla's Roadster of 2008, built from 6,831 laptop cells, showed that a lithium car could work, and the gigafactories of Panasonic and later CATL showed that the cost fell steeply with scale.

The third was China's decision, from about 2009, to make electric vehicles and their batteries a national industrial priority. Subsidies, public procurement, and a 2015 whitelist that kept foreign cell makers out of subsidized cars for four years created the demand that drove the learning curve. The learning rate, the fall in cost for each doubling of cumulative production, has averaged about 18-20%, comparable to solar panels.

Year	Average pack price ($/kWh)	Electric car sales worldwide	Milestone
1991	About 9,200 (cell)	—	Sony's first cell, about 80 Wh/kg
2010	About 1,200	Under 0.1 million	Nissan Leaf on sale; Tesla lists its shares
2013	About 780	0.2 million	Tesla's Model S in volume; the gigafactory plan follows in 2014
2017	About 209	1.2 million	Tesla's Model 3; China's subsidies near their peak
2019	156	2.1 million	The Nobel Prize; LFP begins its return
2020	137	3 million	BYD's Blade cell; cell-to-pack designs
2021	132	6.6 million	Lithium begins its spike
2022	151	10.5 million	The first rise in BNEF's survey, 7%, on lithium
2023	139	14 million	Prices fall again as lithium collapses
2024	115	17 million	A 20% fall, the steepest since 2017; first sodium-ion cars
2025	108 (stationary storage packs 70)	More than 20 million	LFP passes 55% of electric-car batteries
2026	BloombergNEF's survey due in December 2026	23 million (IEA forecast)	Lithium's rebound lifts cell prices in the first half

Pack prices are BloombergNEF's volume-weighted averages, each in the real dollars of its survey year; the 1991 figure is a cell price from Our World in Data, in 2024 dollars. BloombergNEF states each year's change in constant dollars, so the changes in the text (a 7% rise in 2022, falls of 20% in 2024 and 8% in 2025) differ from those between the table's figures. Car sales are the IEA's, including plug-in hybrids.

Pack prices fell from about $1,200 per kWh in 2010 to $108 in 2025, by BloombergNEF's (BNEF's) surveys, a decline of about 90% in fifteen years. The one interruption came in 2022, when a spike in lithium prices (Module 12) raised packs 7%.

That decline is the reason electric cars reached price parity in China, the reason grid storage went from a curiosity to the fastest-growing power technology on earth, and the reason almost every other module in this course exists.

Module 3 Key Points

A Brief History

• Lead-acid, nickel-cadmium, and nickel-metal hydride were too heavy and low-voltage for a useful car; the lead-acid EV1 managed 60-100 miles.

• Intercalation solved lithium's dendrite problem: Whittingham's crystal, Goodenough's 4-volt cathode, Yoshino's carbon anode, with no lithium metal in the cell.

• Sony sold the first lithium-ion cell in 1991, at about 80 Wh/kg and about $9,200 per kWh in 2024 dollars.

• Tesla's Roadster, gigafactory scale, and Chinese industrial policy drove a learning rate of about 18-20% per doubling of output.

• Pack prices fell about 90%, from about $1,200 per kWh in 2010 to $108 in 2025, with one rise, in 2022.

Module 3 Quiz

Check Your Understanding

1. Why could lead-acid, nickel-cadmium, and nickel-metal hydride never give a car a useful range?

A) They cost too much to build in large volume
B) They could not be recharged
C) They are heavy, low-voltage chemistries
D) They were banned from vehicles in every major market

2. How did Yoshino's 1985 anode solve lithium's dendrite problem?

A) It used pure lithium metal coated with ceramic
B) It replaced lithium with sodium, which grows no dendrites
C) It added a water-based electrolyte that dissolved dendrites
D) It used a carbon that lithium intercalates into, so no lithium metal was left in the cell

3. What did Sony's first lithium-ion cell of 1991 store and cost?

A) About 300 Wh/kg at about $1,000 per kWh in 2024 dollars
B) About 500 Wh/kg at $10 per kWh
C) About 50 Wh/kg at $50 per kWh
D) About 80 Wh/kg at about $9,200 per kWh in 2024 dollars

4. What is the battery industry's learning rate?

A) About 18-20% per doubling of cumulative production
B) About 2% per doubling of output
C) About 50% per doubling of output
D) About 5% a year, regardless of output

5. What interrupted the fall in pack prices between 2010 and 2025?

A) The 2008 financial crisis
B) The 2022 spike in lithium prices
C) A shortage of cobalt from 2015 to 2016
D) The pandemic's factory closures in 2020

Module 4 — The Lithium-Ion Family

The Chemistries and Their Tradeoffs, With Numbers

Recommended Reading / Reference

Reference: IEA, *Global EV Outlook 2026* (May 2026), the battery chapter; BloombergNEF, *Lithium-Ion Battery Price Survey* (December 2025); the China Automotive Battery Innovation Alliance's monthly installation data; Argonne National Laboratory's BatPaC cost model

4a. The Cathode Is the Battery

Almost every lithium-ion cell uses the same anode, graphite, the same family of electrolytes, and the same kind of separator. What differs is the cathode, the crystal the lithium ions move into on discharge, which decides energy density, cost, safety, lifespan, and which minerals the battery needs, and the chemistries are named for the metals in that crystal.

Chemistry	Cathode formula	Cell voltage	Energy (Wh/kg, cell)	Cycle life (to 80%)	Thermal runaway onset	Cathode cost ($/kWh, 2026)	Metals	Where used
NMC 811	LiNi0.8Mn0.1Co0.1O2	3.7	260-300	1,500-2,500	About 150°C; releases oxygen	$35-45	Nickel, cobalt, manganese, lithium	Long-range cars (Hyundai, BMW, some Teslas)
NMC 622 / 532	LiNi0.6Mn0.2Co0.2O2	3.7	220-250	2,000-3,000	About 170°C	$40-50	Nickel, cobalt, manganese, lithium	Western cars of 2018-24; power tools
Nickel-cobalt-aluminum (NCA)	LiNi0.8Co0.15Al0.05O2	3.7	260-300	1,500-2,500	About 150°C	$35-45	Nickel, cobalt, aluminum, lithium	Panasonic's cylindrical cells for Tesla
LFP	LiFePO4	3.2	150-205	3,000-10,000	About 270°C; no oxygen	$15-25	Iron, phosphorus, lithium	Standard-range cars, nearly all grid storage, buses
Lithium manganese iron phosphate (LMFP)	LiMn0.6Fe0.4PO4	3.6-3.8	190-220	2,500-5,000	About 250°C	$18-28	Manganese, iron, phosphorus, lithium	CATL's M3P cells in Chinese cars; blends with NMC
Lithium manganese oxide (LMO, spinel)	LiMn2O4	3.9	120-150	500-1,000	About 200°C	$15-20	Manganese, lithium	Early Nissan Leaf; blends
Lithium cobalt oxide (LCO)	LiCoO2	3.8	200-250	500-1,000	About 150°C	$60-80	Cobalt, lithium	Phones and laptops, for energy per liter
Lithium titanate (LTO), an anode	LFP or NMC with a Li4Ti5O12 anode	2.3	70-90	15,000-30,000	Very high	High	Titanium, lithium	Buses, frequency regulation, extreme fast charging

Approximate values for 2026 production cells; cathode costs move with metal prices. Temperatures in °F: 150°C is 302°F, 170°C is 338°F, 200°C is 392°F, 250°C is 482°F, 270°C is 518°F.

4b. The Tradeoff

Nickel-rich cathodes (NMC 811 and NCA) give the highest energy density, which makes them the choice for long-range and premium cars. They cost more than LFP and are the least thermally stable, releasing oxygen near 150°C (302°F), and they depend on nickel and cobalt, although single-crystal particles and coatings are extending their life.

Mid-nickel cathodes (NMC 622 and 532) were the compromise that dominated Western electric cars into the early 2020s. They are more stable than 811 but store less energy. Because they carry twice the cobalt, they cost as much per kWh or more at 2026 prices, and they are being squeezed from both sides.

LFP stores 150-205 Wh/kg in the cell, so a pack for the same range is heavier, but its packs averaged $81 per kWh in 2025 against $128 for NMC, by BloombergNEF's count, and it is far safer, because its phosphate framework releases no oxygen and runaway begins only near 270°C (518°F). It tolerates daily charging to 100%, lasts 3,000-10,000 cycles, and uses no cobalt or nickel at all. Its weaknesses are cold weather, where it keeps 70-75% of its capacity at −20°C (−4°F), and its lower voltage.

LMFP is LFP's fix for energy density: substituting manganese for part of the iron raises the voltage to 3.6-3.8 volts and the energy by 15-20%, to 190-220 Wh/kg, closing part of the gap with mid-nickel NMC while keeping LFP's cost and safety, although manganese dissolving out of the cathode is its engineering problem.

LTO replaces the graphite anode with a titanate, which stores little energy but offers extraordinary cycle life and charging speed with no risk of lithium plating, giving it a niche in buses and in grid frequency response.

4c. Anodes: Graphite and the Silicon Question

Graphite has been the anode since Yoshino, because its layered structure accepts lithium reliably for thousands of cycles at 372 mAh/g. Natural graphite is mined, mostly in China, which produced about 1.4 of the world's 1.8 million tonnes in 2025 by the US Geological Survey's (USGS's) estimate, and then in Mozambique and Madagascar, and it is purified, rounded into spheres, and coated.

Synthetic graphite is baked from petroleum or needle coke at about 3,000°C (5,400°F), overwhelmingly in China, and it now dominates electric-car cells for its consistency. China placed graphite exports under licensing in December 2023, and in October 2025 extended controls to artificial graphite anode material, a measure suspended under the US-China truce until January 10, 2027 (Module 13).

Silicon, with almost ten times graphite's capacity, is blended in: premium cells have carried 2-5% of silicon oxide since the late 2010s, and silicon-carbon composites at 10-20%, from Group14, Sila, and Chinese producers, entered high-end phones and car cells in 2025-26, raising cell energy by 10-15%. Anodes made entirely of silicon remain a demonstration.

4d. Why LFP Won the Volume Market

A decade ago LFP was the poor relation, a chemistry for Chinese buses and cheap cars with too little energy for a serious electric car, and its Western champion, A123 Systems, went bankrupt in 2012. Three things reversed that, beginning with Chinese engineers, who improved the cell and the pack, with BYD's Blade cell of 2020, a long thin prismatic that doubles as structure, and CATL's cell-to-pack designs, until the pack-level gap with NMC narrowed to a range most drivers do not notice.

Cobalt and nickel spikes in 2021-22 then made the mineral-light chemistry cheaper by a widening margin, and grid storage, which cares about cost and cycle life and not at all about weight, boomed and chose LFP almost exclusively. The key LFP patents expired in 2022, which is why the West could follow.

Region or segment	LFP share, 2024	LFP share, 2025	Note
China, electric-vehicle batteries installed	74.6%	81.2%	BYD's cars run entirely on LFP
World, electric-vehicle batteries deployed	Nearly 50%	Over 55%	The IEA's count, including trucks and buses
European Union, electric-vehicle batteries	Under 10%	Over 10%	Nearly all imported from China, directly (30%) or inside Chinese-made cars (nearly 70%)
United States, electric-vehicle batteries	Low	Almost halved from 2024	Tariffs and the 2025 rules on Chinese content penalize Chinese cells
Grid storage added worldwide	About 80-90%	About 90% (over 98% in China)	Near-exclusive

China Automotive Battery Innovation Alliance (China); IEA, *Global EV Outlook 2026* (world, EU, US); BloombergNEF and the China Energy Storage Alliance (grid).

Module 4 Key Points

The Lithium-Ion Family

• The cathode decides a cell's energy, cost, safety, life, and minerals; the table compares eight chemistries on each.

• Nickel-rich cathodes give 260-300 Wh/kg but release oxygen near 150°C (302°F); LFP gives 150-205 and runs away only near 270°C (518°F).

• LFP packs averaged $81 per kWh in 2025 against $128 for NMC, by BloombergNEF's survey.

• China mined about 1.4 of the world's 1.8 million tonnes of natural graphite in 2025; silicon blends add 10-15% energy.

• LFP won on engineering, cheap minerals, and grid storage: 81% of China's 2025 car batteries and over 55% worldwide.

Module 4 Quiz

Check Your Understanding

1. How do nickel-rich NMC and LFP differ when they overheat?

A) LFP runs away at about 100°C, NMC at about 300°C
B) Both run away at about 100°C, with no chemical difference
C) NMC near 150°C, with oxygen; LFP near 270°C
D) Neither runs away below 400°C, whatever its chemistry

2. What is LMFP?

A) A nickel-rich cathode for long range
B) A cathode for sodium-ion cells
C) Manganese-enriched LFP
D) A titanate anode for fast charging

3. What were average pack prices for LFP and NMC in 2025, by BloombergNEF's survey?

A) About $200 for each
B) About $128 for LFP and $81 for NMC, because iron is costly to refine
C) About $50 for LFP and $60 for NMC
D) About $81 per kWh for LFP and $128 for NMC

4. What was LFP's share of the electric-vehicle batteries installed in China in 2025?

A) About 10%, as in Europe
B) About 81%, up from about three-quarters in 2024
C) About 40%, behind nickel-rich chemistries
D) Exactly half, by government quota

5. What reversed LFP's status as the poor relation?

A) Chinese engineering, metal price spikes, and grid storage
B) Western subsidies tied to LFP, cobalt discoveries in Canada, and higher voltage
C) A ban on NMC in China
D) Higher energy density than nickel-rich NMC cells from 2020 on

Module 5 — Making a Cell

From Powder to Pack, and the Economics of the Factory

Recommended Reading / Reference

Reference: IEA, *Global EV Outlook 2026*, the battery manufacturing and trade sections; SNE Research's monthly rankings of battery installations; InfoLink's rankings of storage-cell shipments; Argonne National Laboratory's BatPaC model; the companies' reports (CATL, BYD, LG Energy Solution, Panasonic)

5a. The Chain, Step by Step

Step	What happens	Where value and difficulty lie	Chinese share
1. Refining	Lithium into battery-grade carbonate or hydroxide; nickel, cobalt, and manganese into sulfates; graphite purified	Chemistry and purity; China makes about two-thirds of lithium chemicals and refines about three-quarters of cobalt	65-95% by material
2. Precursor (precursor cathode active material, pCAM)	Metal sulfates co-precipitated into a nickel-manganese-cobalt hydroxide powder	Particle engineering; the recipe	About 80%
3. Cathode active material (CAM)	Precursor baked with lithium at 700-900°C (1,290-1,650°F) into the cathode crystal	Where most of the value and chemistry live	About 75-85%
4. Anode active material	Spherical natural or synthetic graphite, coated, with or without silicon	Energy-intensive graphitization	More than 90%
5. Electrode slurry and coating	Active material, binder, and conductive carbon mixed into a slurry, coated onto foil, and dried	The most capital-intensive and quality-critical step; drying ovens run 50-100 meters (165-330 feet)	—
6. Calendering and slitting	Electrodes pressed to density and cut to width	Precision	—
7. Cell assembly	Electrodes and separator wound (cylinders) or stacked (pouches, prismatic cans), inserted, and welded	Speed: more than 200 cylindrical cells a minute on one line	—
8. Electrolyte filling and sealing	Cell filled under vacuum and sealed	Dry rooms below 1% humidity	—
9. Formation	The slow first charge that forms the SEI, over days	Ties up floor space and capital; 10-15% of cell cost	—
10. Aging and testing	Weeks of rest, then capacity and leakage tests, and grading	Where yield is measured	—
11. Module and pack	Cells grouped, wired, cooled, housed, and given a battery management system	Mechanical and thermal engineering; 20-30% of pack cost	—

Chinese shares approximate, 2025-26 (IEA, Benchmark Mineral Intelligence, USGS).

5b. Formats

Format	Examples	Advantages	Disadvantages	Who uses it
Cylindrical	18650 (3 amp-hours), 21700 (5), 4680 (about 25)	Cheapest to make at speed; mechanically strong; proven; runaway contained cell by cell	Packs inefficiently, with space between cylinders; thousands of connections; the 4680 took years to reach yield	Panasonic and Tesla; BMW's 46-series cells; power tools, e-bikes
Prismatic	BYD's Blade (up to a meter long); storage cells of 280-314 amp-hours, now 500 and more	Packs densely; large cells mean fewer connections; suits cell-to-pack designs	Swelling stresses the can; runaway in a large cell is severe; slower assembly	Chinese cars, nearly all grid storage, Volkswagen, Toyota
Pouch	LG Energy Solution and SK On cells for General Motors, Ford, Hyundai	Lightest and most space-efficient; flexible shape	Needs external structure; prone to swelling and gas; harder to cool	Korean makers, Western automakers, phones

Cell-to-pack (CTP) and cell-to-chassis designs, pioneered by CATL and BYD from 2019-20, delete the module and build large prismatic cells straight into the pack structure. They recover the 20-30% of pack volume that modules consumed and let LFP packs match the range of older NMC packs built from modules.

Tesla's structural pack of 4680 cells is the cylindrical version, and its dry-electrode process, meant to eliminate the solvent and the drying ovens, took years longer than planned to reach production yields.

5c. What a Cell Costs

Cost element	LFP prismatic cell ($/kWh, China, 2026)	NMC 811 cylindrical cell ($/kWh, Korea or US, 2026)	Notes
Cathode active material	$14-20	$35-45	Lithium carbonate near $19 per kg in late September 2026, about twice its 2025 average; nickel and cobalt drive NMC
Anode active material	$4-6	$7-10	Synthetic graphite; silicon adds cost
Electrolyte	$2-4	$4-6	Sensitive to the price of LiPF6
Separator	$1-3	$3-4	Ceramic-coated
Foils (aluminum, copper)	$3-5	$5-7	Copper near record prices in 2026
Can and hardware	$2-4	$4-6	
Labor	$1-3	$6-10	US labor costs 3-5 times China's
Energy, depreciation, overhead	$6-10	$15-25	Plant utilization is the swing factor
Yield loss and scrap	$2-4	$5-10	New plants run at 60-80% yield for years
Margin	$2-6	$5-15	
Total cell	$45-60	$90-130	Chinese 314-amp-hour storage cells sold for about $50 per kWh, export price, in July 2026 (InfoLink)

Cost element	LFP prismatic cell ($/kWh, China, 2026)	NMC 811 cylindrical cell ($/kWh, Korea or US, 2026)	Notes
Pack (add 20-30%)	$60-80	$115-160	BloombergNEF's 2025 averages: LFP packs $81, NMC $128, China $84

Indicative cost stacks; actual figures vary with metal prices, plant age, and utilization.

5d. Scale, Yield, and the Utilization Trap

A gigafactory is measured in gigawatt-hours (GWh) of annual output, and each GWh makes enough cells for roughly 15,000-20,000 cars. The largest plants exceed 100 GWh, and CATL's campus at Ningde and BYD's clusters run to several hundred. The economics turn on yield: a line producing 95% good cells and one producing 85% have very different costs, and yield is learned over years of operation on a specific chemistry and format.

That is why the IEA attributes more than 40% of the cost gap between European and Chinese cells to manufacturing efficiency rather than labor or materials, and why it puts the yields needed to compete above 90%. A Western plant costs $50-100 million per GWh of capacity to build, and at 60% utilization its depreciation per kilowatt-hour (kWh) is half again as high as at 90%.

Worked example — The Utilization Trap

A 40 GWh American LFP plant costs $3 billion, or $75 million per GWh, and at 90% utilization it makes 36 GWh a year, so depreciating the plant over ten years costs $8.30 per kWh. At 40% utilization, the state of many Western plants in 2025-26 as electric-car demand stalled, it makes 16 GWh, and depreciation rises to $18.75 per kWh. Add labor and energy that do not fall with output, and a plant that would make cells for $70 per kWh at full utilization makes them for about $95 at 40%.

A Chinese storage cell sold for about $50 per kWh for export in July 2026, and the roughly 41% American tariff (Module 13) lifts it to about $71, so the full plant roughly ties and the idle one loses. The production credit of $35 per kWh changes the sum for plants that qualify under the rules on Chinese content (Module 13): $95 less $35 is $60.

Utilization and the credit, more than the tariff, therefore decide whether American cell plants run. That arithmetic, rather than chemistry, is why Korean-partnered plants that could not fill their lines paused, split, or turned to storage cells in 2025.

The trap is now global: nameplate capacity passed 4 terawatt-hours (TWh) at the end of 2025, by the IEA's count, against demand of about 1.6 TWh that year, by Benchmark Mineral Intelligence's. China, which made 1,755.6 GWh of power and storage batteries in 2025, planned about 2,600 GWh of new capacity for 2026 alone.

From mid-May 2026 the authorities paused approvals and construction of new power and storage battery projects pending a year-end review of capacity by the Ministry of Industry and Information Technology (MIIT), after meetings in January and April on what Beijing calls involution: price wars that leave whole industries unprofitable.

5e. The Manufacturers

Company	Base	Share of electric-vehicle batteries installed, January-August 2026	Rank in storage-cell shipments, 2025	Notes
CATL	China	39.4% (333.0 GWh)	1st	The largest by far; listed in Hong Kong in May 2025; opened a storage-testing platform of about 3 billion yuan ($450 million) in Xiamen in 2026; trial production in Hungary from September 22, 2026
BYD (FinDreams)	China	15.1%	4th	Vertically integrated; Blade cell; LFP only; third-largest storage integrator in 2025
LG Energy Solution	Korea	8.1%	Outside the top ten	General Motors, Hyundai; converted American lines to LFP storage cells in 2025
CALB	China	5.3%	5th	Chinese carmakers
Gotion	China	4.9%	—	Volkswagen its largest shareholder; a 2 GWh all-solid-state line designed in March 2026
Panasonic	Japan	3.5%	—	Tesla's cylindrical cells; its Kansas plant opened in July 2025; over 40% of the batteries in American-made electric cars
EVE Energy	China	3.5%	3rd	A storage leader; cylindrical cells for BMW
SK On	Korea	2.9%	—	Took the Tennessee plant when its venture with Ford split; losses
SVOLT, REPT	China	2.6%, 2.4%	REPT 6th	Chinese second tier; REPT's installations more than doubled
Hithium	China	—	2nd	A storage specialist
Samsung SDI	Korea	Below 2.4%	Outside the top ten	All-solid-state production planned for the second half of 2027

SNE Research via CnEVPost (October 2, 2026) for installations, which include plug-in and conventional hybrids; InfoLink (February 2026) for storage cells. The seven Chinese makers in the top ten held 73.3% of installations in January-August 2026.

5f. Northvolt: A Plant That Could Not Learn

Europe's flagship cell maker raised about $15 billion in equity and debt, won about $55 billion of orders from Volkswagen, BMW, Volvo, and Scania, and built a plant at Skellefteå in northern Sweden whose first phase was designed for 16 GWh. It produced a small fraction of that, at poor yield, while expanding into four countries at once.

BMW cancelled a €2 billion order in June 2024, and the company filed for Chapter 11 protection in the United States in November 2024 and for bankruptcy in Sweden in March 2025. Lyten, an American start-up, completed its purchase of the Swedish assets in February 2026 and said it would supply NMC cells from Skellefteå for storage systems from the second half of 2026.

The plant had Chinese equipment, Korean engineers, cheap hydropower, and customers waiting, and it still could not learn the process at speed. The lesson the industry drew is that manufacturing is learned, not bought, and that a gigafactory is a decade-long apprenticeship.

Module 5 Key Points

Making a Cell

• The chain runs eleven steps; China makes about 75-85% of cathode and more than 90% of anode material.

• Coating is the most capital-intensive step and formation takes 10-15% of cell cost; cell-to-pack recovers 20-30% of pack volume.

• A Chinese LFP cell cost about $45-60 per kWh in 2026, against $90-130 for a Korean or American NMC cell.

• A plant at 40% utilization makes $95 cells that it could make for $70 when full; China itself paused new projects in May 2026.

• CATL held 39.4% of installations in January-August 2026; Northvolt's collapse showed that manufacturing is learned, not bought.

Module 5 Quiz

Check Your Understanding

1. Which manufacturing step is the most capital-intensive and quality-critical?

A) Pack assembly and module welding
B) Filling with electrolyte and sealing
C) Formation cycling of finished cells
D) Electrode coating and drying

2. Why does formation account for 10-15% of cell cost although it adds no material?

A) The slow first charge ties up equipment for days
B) It is done by hand, one cell at a time, in clean rooms
C) It consumes costly gases
D) It requires platinum catalysts

3. In the worked example, why does a plant at 40% utilization make $95 cells instead of $70?

A) Its yield rises as volume falls
B) Tariffs are added at the factory gate
C) Its fixed costs, above all depreciation, are spread over far fewer kWh
D) Materials cost more when bought in small lots

4. What did China do in 2026 about its own battery overcapacity?

A) It banned exports of LFP cells
B) It paused approvals of new plants
C) It doubled subsidies for new plants
D) It set minimum prices for exported cells

5. What does Northvolt's collapse teach, as the module tells it?

A) That manufacturing is learned over years, not bought with capital
B) That European hydropower is too expensive for cell making
C) That Chinese equipment cannot work outside China
D) That NMC chemistry cannot be made at scale

Module 6 — The Cost Curve and Battery Economics

The Numbers That Decide Which Battery Wins Where

Recommended Reading / Reference

Reference: BloombergNEF, *Lithium-Ion Battery Price Survey* (December 9, 2025), *Energy Storage Systems Cost Survey* (December 2025), and *Levelized Cost of Electricity 2026* (February 2026); Ember, *How Cheap Is Battery Storage?* (December 2025); Lazard, *LCOE+* (July 2026, version 19); InfoLink's storage-cell price series

6a. From Cell to System

The cell price is the number in the headlines, but outside China it is a minority of what a buyer pays. A grid-storage system adds the pack and its cooling, the container, the inverter that converts direct to alternating current, the transformer and switchgear, the energy-management software, installation, the grid connection, and the developer's margin, while a car adds the pack structure, cooling, and the vehicle's own electronics.

The gap between cell and system is why cheaper cells take years to reach customers, why integrators rather than cell makers capture much of the margin, and why the same battery costs three times as much installed in the United States as in China.

Layer	Grid system, 4-hour LFP ($/kWh)	Electric car ($/kWh of pack)	Notes
Cells	$45-60	$50-110	Chemistry and origin; Chinese storage cells near $50 in July 2026
Pack, battery management system, cooling	$10-20	$10-30	Cell-to-pack designs shrink this layer
Container, racking, fire suppression	$10-20	—	Grid only
Inverter (power conversion system) and transformer	$10-20	In the vehicle's electronics	Falls with duration: a 4-hour system needs a quarter of the inverter per kWh that a 1-hour system does
Energy-management software and controls	$2-5	—	
Installation, civil works, grid connection	$30-100	—	The most variable layer: grid-connection fees differ several-fold between markets
Developer margin and financing	$10-30	—	
Total	Turnkey averages for 2025, all durations: China $73, Europe $177, US $219 (BNEF); about $125 all-in outside China and the US (Ember)	BNEF's 2025 averages: electric-car packs $99; LFP packs $81; NMC $128	

BloombergNEF's turnkey systems averaged $117 per kWh worldwide in 2025, down 31%, and $110 for four-hour systems. Layer ranges are indicative.

6b. Levelized Cost of Storage, Worked

The measure for comparing storage technologies is the levelized cost of storage (LCOS): the total lifetime cost of a system divided by the total energy it discharges over its life, in dollars per megawatt-hour (MWh). It depends on installed cost, cycle life, round-trip efficiency, the price of charging electricity, financing, and how often the system is used, which is why the same battery has a different LCOS in California and in Texas.

Worked example — The LCOS of a 4-Hour LFP System

A system of 100 megawatts (MW) and 400 MWh, built in the United States at $200 per kWh installed, costs $80 million and cycles once a day on about 330 days a year, allowing for maintenance and days of poor prices, for 15 years: about 5,000 cycles, within LFP's life. Each cycle takes in 360 MWh and, at 88% round-trip efficiency, returns about 317 MWh, so the system discharges about 1.58 million MWh over its life.

Its costs are the $80 million of capital, about $30 million of operations and augmentation at $2 million a year, $54 million for 1.8 million MWh of charging electricity at $30, and roughly $45 million of financing at 7% in present-value terms. The total, about $209 million, divided by 1.58 million MWh gives about $132 per MWh.

At $120 per kWh, near the all-in cost outside China and the United States, the LCOS falls to about $95-100, and charging electricity becomes the largest single cost. At China's $73, with operating costs scaled down in proportion, it falls to about $70, about half of it charging. Cycled twice a day, the American system's LCOS falls toward $90 if augmentation keeps it running, and BloombergNEF's benchmark for a four-hour battery project fell 27% in 2025 to $78 per MWh.

A gas peaking plant costs $144-276 per MWh by Lazard's July 2026 estimate, which is why storage cycled daily is displacing peakers. Cycled only once a week, as a reserve for long lulls, the same American battery's LCOS rises to about $650 per MWh, which is why lithium cannot do long-duration storage and why Module 11's technologies exist.

6c. Price Parity for Cars, Worked

Worked example — When an Electric Car Costs No More to Build

An electric compact drops the engine, transmission, exhaust and emissions system, and fuel system, about $6,500 of parts in an American or European car, and adds a motor, inverter, and charger, about $2,000. The pack must therefore cost no more than about $4,500 for the two to cost the same to build. With a 50 kWh pack, a typical size for a compact, that is a pack price of about $90 per kWh.

At $130 per kWh, near the average for nickel-rich packs, the pack costs $6,500 and the electric car about $2,000 more to build. At $70, near China's LFP packs, it costs $3,500 and the electric car is about $1,000 cheaper. That is the line China crossed first: the IEA found that 70% of the battery-electric cars sold in China in 2025 were already cheaper than the average conventional car.

Western buyers have not crossed it, because North American packs averaged about 44% more than Chinese ones in 2025 and European packs about 56% more, by BloombergNEF's count, and tariffs keep the cheapest Chinese cells out. Over a car's life, cheaper electricity and maintenance usually make the electric car the cheaper one to own, but the purchase price is what moves most buyers. A city car with a 30 kWh pack at $60-70 per kWh needs only about $2,000 of battery, which is the arithmetic behind China's electric cars at $8,000-10,000.

6d. What Drives the Curve Now

The 90% decline came from chemistry, as LFP spread, from cheaper materials, from the scale of the gigafactories, and from learning, as yields rose. By 2026 chemistry was nearly exhausted for LFP, whose cathode is already iron and phosphate, so further declines come from manufacturing scale and utilization, overwhelmingly Chinese, from cell-to-pack designs and larger cells (storage cells of 500 amp-hours and more shipped from 2026), from sodium-ion (Module 9), and from overcapacity.

The curve also bent the other way in 2026. Lithium carbonate rose from its 2025 lows to above 200,000 yuan a tonne on the Guangzhou futures exchange in May 2026 (Module 12). Chinese storage cells, about 0.26 yuan per watt-hour at their 2025 low, approached 0.40 yuan in March 2026 before easing to about 0.36 in July, still almost 40% above the low. BloombergNEF had expected pack prices to fall again in 2026; its December 2026 survey will show whether the year's average did.

Beijing added costs of its own: a 2% consumption tax on lithium-ion cells and packs took effect on September 1, 2026, rising to the statutory 4% a year later, with sodium-ion and solid-state cells exempt through 2028. The export rebate of value-added tax on batteries was cut from 9% to 6% in April 2026 and ends on January 1, 2027, which raises the price of Chinese cells abroad.

The curve's shape is now set less by chemistry than by manufacturing scale and by policy, and both are Chinese, which is why the cost curve of batteries is a Chinese curve.

Module 6 Key Points

The Cost Curve and Battery Economics

• Turnkey storage systems of all durations averaged $73 per kWh in China in 2025, $177 in Europe, and $219 in the US (BloombergNEF).

• A $200-per-kWh system cycled daily stores power for about $132 per MWh; at China's prices, about $70; cycled weekly, about $650.

• Daily-cycled storage undercuts gas peakers at $144-276 per MWh; BloombergNEF's four-hour benchmark fell to $78 in 2025.

• A compact's 50 kWh pack must cost about $90 per kWh for parity; 70% of China's 2025 battery-electric cars beat the average conventional car's price.

• Lithium's 2026 rebound lifted Chinese storage-cell prices almost 40% from 2025 lows; new Chinese taxes and lost rebates add more.

Module 6 Quiz

Check Your Understanding

1. Why does a cheaper cell take years to reach grid-storage customers?

A) Cells are stockpiled for years before use
B) The cell is a minority of installed cost
C) Integrators are barred from passing on savings
D) Tariffs absorb every saving

2. In the worked LCOS example, what happens if the battery is cycled once a week instead of daily?

A) The LCOS halves, because the battery lasts twice as long
B) The LCOS falls to about $50 per MWh, with less wear
C) The battery lasts five years instead of fifteen
D) The LCOS rises to about $650 per MWh

3. In the parity example, what pack price makes a 50 kWh electric compact cost no more to build than a combustion one?

A) About $250 per kWh
B) About $500 a kWh
C) About $90 per kilowatt-hour
D) No pack price, because motors cost more than engines

4. What did the IEA find about electric-car prices in China in 2025?

A) That Chinese electric cars still cost about 30% more than combustion cars
B) That 70% of battery-electric cars sold were already cheaper than the average conventional car
C) That prices were fixed by the state
D) That only imported electric cars were cheaper

5. What pushed Chinese storage-cell prices up in 2026?

A) A cobalt shortage
B) The end of LFP patents
C) A ban on exports of storage cells
D) Lithium carbonate's rebound

Module 7 — Batteries for Electric Cars

The State of Play for the Largest Application

Recommended Reading / Reference

Reference: IEA, *Global EV Outlook 2026* (May 20, 2026); BloombergNEF, *Electric Vehicle Outlook*; Geotab's and Recurrent's studies of battery health in used cars; Tesla's annual impact reports

7a. The Market in 2025-26

Market	2025 electric-car sales	Share of new cars	Change from 2024	Main chemistry	Policy in 2026
China	About 13 million	Nearly 55%	Growth slightly slower than in 2024	LFP (81% of batteries installed)	Purchase-tax exemption halved to a 5% tax; a pause in the trade-in scheme; exports doubled to more than 2.5 million
Europe	About 4 million	28%	Up more than 30%	NMC from Korean makers; LFP just over 10%, imported	Tighter carbon-dioxide standards; duties on Chinese electric cars, with minimum-price offers allowed from January 2026
United States	About 1.5 million	Just under 10%	Slightly down; fourth quarter 45% lower	NMC from Korean makers and Panasonic; LFP's small share almost halved	Federal credit ended September 30, 2025; virtually no federal purchase support
Southeast Asia	—	Nearly 20%	More than doubled	LFP, mostly in Chinese imports	Local incentives; Chinese brands' plants in Thailand and Indonesia
Latin America	—	Small	Up 75%	Chinese imports	Brazil's and Mexico's tariffs on Chinese cars
World	More than 20 million	About 25%	Up 20%	LFP over 55%	23 million (28%) expected in 2026

IEA, *Global EV Outlook 2026*; sales include plug-in hybrids. The American fourth-quarter fall is measured against the same quarter of 2024; buyers had pulled purchases into the third quarter of 2025, before the credit's September 30 end. Volumes for Europe and the US are approximate.

The market is three markets. China is the center: it bought about 60% of the world's electric cars, built nearly 75% of the 22 million produced, and sold a majority of its new cars electric. Europe grew fastest of the large markets, driven by tighter carbon-dioxide standards.

The United States went the other way: with the federal tax credit gone, sales slipped for the year and fell 45% in the fourth quarter from a year earlier, leaving the electric share just under 10%, and in Canada the share fell from nearly 17% to 11% when its rebate ended. Global sales fell 8% in the first quarter of 2026 after policy changes in China and the United States, although China's electric share set a record above 60% in April.

7b. Range, Charging, Price

Objection	2016	2020	2026, China	2026, US and Europe
Range of a mainstream model	150-250 km (90-155 miles)	350-450 km (220-280 miles)	500-700 km (310-435 miles) on LFP or LMFP; more than 800 km for premium cars	400-550 km (250-340 miles)
Charging from 10% to 80%	60 minutes or more	30-40 minutes	10-15 minutes on 800-volt cars; BYD claims about 400 km of range in five minutes at up to 1,000 kilowatts	20-30 minutes; 800-volt cars spreading (Hyundai, Porsche, General Motors)
Cheapest new electric car	Over $30,000	Over $20,000	About $8,000-10,000	About €17,000 in Europe; about $29,000-30,000 in the US

The three old objections have been answered in China and partly elsewhere, and on range, mainstream Chinese cars offer 500-700 kilometers on LFP or LMFP packs. On charging, 800-volt designs and cells rated for fast charging bring 10-80% charges under 15 minutes in the newest models, although in most countries the network of chargers, not the battery, is the constraint.

On price, the IEA found that 70% of the battery-electric cars sold in China in 2025 were cheaper than the average conventional car (Module 6). In Europe and the United States electric cars still cost more to buy, which, with tariffs that exclude the cheapest Chinese models, is why those markets lag, even though average battery prices fell 8% in 2025, by the IEA's and BloombergNEF's counts.

7c. Chemistry by Market and the New Vehicles

The chemistry split follows the price split: LFP made up 81% of the batteries installed in Chinese electric vehicles in 2025, and over 55% worldwide. In the European Union it was just over 10%, nearly all imported from China, either directly or inside Chinese-made cars.

In the United States LFP's share almost halved in 2025 from an already low base, as tariffs and the 2025 rules on Chinese content penalized Chinese cells, even as Ford and LG Energy Solution turned American capacity toward LFP for grid storage. Western automakers still mostly buy mid- and high-nickel NMC from Korean suppliers and Panasonic, which made over 40% of the batteries in American-built electric cars, and the trend, wherever the rules allow, is LFP for standard range and NMC for long range.

Two 2026 vehicles mark the frontier, the first being Tesla's Cybercab, a two-seat robotaxi with no steering wheel, which entered production at its Texas factory in April 2026 and was ramping slowly. The second is Changan's sodium-ion car, unveiled with CATL in February 2026 as the first mass-produced passenger car on sodium cells, with sales planned from mid-2026. Its 45 kWh pack gives up to about 400 kilometers (250 miles), CATL says the cells keep about 90% of their capacity at −40°C (−40°F), and CATL expected 10,000-20,000 sodium cars in 2026 (Module 9).

7d. Hybrids and Degradation

Plug-in hybrids and range-extender cars, which carry a small battery plus a combustion engine used as a generator, were the fastest-growing category in China in 2024-25 and are spreading to Europe, because they answer range anxiety with a smaller and cheaper pack, 20-40 kWh instead of 60-100. The fear that packs die early has largely been disproven by the data from used cars.

Source	Finding
Geotab (about 10,000 fleet vehicles, 2024)	Average capacity loss of 1.8% a year, with newer packs degrading more slowly
Recurrent (consumer cars)	Few packs replaced outside recalls; most replacements under warranty
Tesla's impact reports	Model 3 and Model Y packs keep about 85% of their capacity after 200,000 miles (320,000 km)
Typical warranty	8 years or 100,000 miles (160,000 km) at 70% capacity in the US; longer terms from many Chinese brands, some for life

The rules of Module 2 extend life further: keep nickel packs between 20% and 80% charge when possible, while LFP tolerates 100%, and avoid heat and constant fast charging. What holds adoption back outside China in 2026 is the charging network, the gap in purchase price, the policy reversal in North America, and, in the used market, buyers' doubts about battery health, which the EU's battery passport (Module 15) is meant to answer.

7e. Purchase Support: The Argument

The case for support. Environmental groups, many economists, and the automakers that invested in electric models argue that purchase incentives buy volume on a learning curve whose costs fall with every doubling (Module 3). The cars cut oil imports and emissions, and Western markets that withdraw support cede the industry to China, whose own subsidies built its lead. They point to Canada, where the share fell from nearly 17% to 11% when the rebate ended, and to the 45% fall in American sales in the quarter after the credit expired.

The case against. The administration and congressional majority that ended the credits in July 2025, together with free-market economists and taxpayer groups, argue that subsidies flow mostly to well-off buyers, many of whom would have bought anyway, at a high cost per tonne of carbon avoided. They add that consumers rather than governments should choose their cars, that credits subsidized supply chains running through China, and that cheaper batteries will make electric cars competitive on their own.

The evidence. Withdrawal hurt where electric cars still cost more: American and Canadian sales fell when support ended. Where batteries had pushed prices to parity, growth continued without it: China's electric share set a record above 60% in April 2026 after the purchase-tax exemption was halved, and Europe grew more than 30% in 2025, driven mainly by carbon-dioxide standards on automakers. Studies of earlier American credits found that a large share went to buyers who would have purchased anyway.

The course's reading. Purchase support matters most before parity and least after it, and the battery's price, not the subsidy, decides adoption over a decade. In markets where tariffs keep out the cheapest cells, ending support before parity arrives cuts sales, as 2025 showed.

Module 7 Key Points

Batteries for Electric Cars

• More than 20 million electric cars sold in 2025, a quarter of the market; China sold about 13 million, nearly 55% of its cars.

• American sales fell 45% in the fourth quarter of 2025 after the federal credit ended; Canada's share fell from nearly 17% to 11%.

• Chinese cars offer 500-700 km and 10-15-minute charging; Changan's sodium car, the first mass-produced, was due on sale from mid-2026.

• Used-car data show about 1.8% capacity loss a year; Tesla's Model 3 and Y packs keep about 85% after 200,000 miles.

• Advocates call purchase support a bridge to parity; critics call it costly and poorly targeted; after parity, price decides.

Module 7 Quiz

Check Your Understanding

1. What happened to American electric-car sales after the federal credit ended in September 2025?

A) They fell 45% in the fourth quarter, year on year
B) They doubled as cheaper models arrived in showrooms
C) They were unaffected, because buyers had already adjusted
D) They rose to about 30% of all new-car sales by December

2. What happened to Canada's electric-car share when its rebate ended?

A) It rose from 11% to nearly 17% in a year
B) It held near 17% as prices fell
C) It fell from nearly 17% to 11%
D) It fell to about 5%

3. Why do plug-in hybrids and range-extenders answer range anxiety cheaply?

A) They charge faster than battery-electric cars
B) They carry larger packs than battery-electric cars
C) They use sodium-ion cells for range
D) A small pack backed by a generator engine

4. What do the data from used cars show about battery degradation?

A) That packs fail within five years
B) That half the capacity is lost by 100,000 km
C) That capacity loss averages about 1.8% a year
D) That no data exist, because failing packs are replaced

5. What is the course's reading of the argument over purchase support?

A) Support matters most before parity, least after
B) Subsidies alone explain China's lead in electric cars
C) Support never changes sales, before or after parity
D) Every market should keep subsidies permanently, whatever the price

Module 8 — Batteries for the Grid

The Fastest-Growing Power Technology

Recommended Reading / Reference

Reference: BloombergNEF, *Energy Storage Market Outlook 1H 2026* (May 2026); IEA, *Global Energy Review 2026*, the battery storage section; the China Energy Storage Alliance (CNESA), 2025 annual data (January 2026); Wood Mackenzie, *US Energy Storage Monitor* (March 2026) and integrator rankings (July 2026); the Electric Power Research Institute's (EPRI's) report on storage failures (October 5, 2026); *CalMatters* on the Moss Landing flare-up (September 2026)

8a. The Revenue Stack, Worked

A grid battery generates nothing: it moves electricity in time, and it is paid for four things that stack. The first is energy arbitrage: buying midday solar power when wholesale prices are near zero and selling it at the evening peak, on the duck curve of solar-heavy grids, where net demand surges just as the sun sets.

The second is capacity: a battery that can reliably discharge for four hours at the peak substitutes for a gas peaking plant and is paid for being available, in markets that pay for capacity. The third is ancillary services, the frequency regulation and reserves that batteries provide faster and more precisely than any turbine, the first market they dominated and saturated. The fourth is deferral: a battery at a congested substation can postpone an upgrade of the wires.

Worked example — A 100 MW / 400 MWh Battery in Texas

In arbitrage, the battery takes in 360 MWh a day at an average $20 per MWh and sells about 317 MWh, after losses, at an average $70, for about $15,000 a day, or about $5.1 million over 340 days. Committing 20 MW to frequency regulation at $10 per megawatt for each hour on call, for all 8,760 hours of the year, earns about $1.75 million, a fraction of what the same service paid in 2022-23, before batteries saturated it, and a handful of scarcity days with prices of $2,000-5,000 per MWh add $2-6 million.

The Texas grid operator, the Electric Reliability Council of Texas (ERCOT), has no capacity market, so the battery earns about $9-13 million a year on an $80 million system, a gross yield of 11-16% before operations and financing. In California, where buyers pay $50-100 per kilowatt-year for resource adequacy, the same battery would add $5-10 million, which is why California built its fleet first and why returns everywhere compress as batteries multiply.

The fleet's effect shows on the evening peak: at 7 p.m. on March 29, 2026, California's batteries discharged a record 12,293 megawatts, 44% of the state's demand, from a fleet of more than 17 gigawatts (GW). In Australia, storage reached 18% of installed dispatchable capacity in 2025, by the IEA's count.

8b. The Scale of 2025-26

Market	2025 additions	Notes
World	112 GW and 307 GWh, up 48% (BNEF); 108 GW, 87 of it utility-scale (IEA)	Utility-scale about 80% of additions (IEA); LFP about 90% of lithium-ion storage; average duration about 3 hours; 158 GW and 459 GWh forecast for 2026 (BNEF)
China	66.43 GW and 189.48 GWh, up 52% and 73% (CNESA)	54% of the world's additions by BNEF's count, about 60% on CNESA's figures; LFP over 98%; 2025's additions averaged about 2.85 hours; about 145 GW of new-type storage installed by end-2025
United States	18.9 GW and 51 GWh, up 52% (Wood Mackenzie)	Utility-scale 16 GW; 43.6 GW of utility batteries installed at end-2025 and nearly 52 GW by June 2026 (EIA)
Australia	Nearly 8 GW, about nine times 2024 (IEA)	Utility-scale about 4.2 GW, homes and businesses about 3.4 GW; storage is 18% of dispatchable capacity
Europe	Over 10 GWh of large-scale storage, up 28% (Rho Motion)	Britain about 4 GWh; storage is about 4% of dispatchable capacity
Middle East	Large projects under way	BYD and Sungrow supplied 87% of the region's systems; Abu Dhabi's Masdar is building 19 GWh beside 5.2 GW of solar

BloombergNEF's 1H 2026 outlook (May 2026); IEA, *Global Energy Review 2026*; CNESA (January 2026); Wood Mackenzie (March 2026); EIA (August 2026); Rho Motion (January 2026). Sources count differently, so totals differ.

Batteries added in 2025 more power capacity than gas plants did in any year, by the IEA's comparison. Storage cells shipped worldwide nearly doubled in 2025 to 612 GWh, and InfoLink expects about 800 GWh in 2026. Shipments run ahead of installations, because cells wait in stock and in projects not yet connected.

Chinese integrators held 76% of the global market in 2025 and eight of the top ten places, by Wood Mackenzie's ranking. Tesla, with its Megapack, kept first place, Sungrow second, and BYD rose to third, while Fluence and other Western integrators trail. Data centers have become buyers too, from Redwood Materials' system of second-life car batteries for Crusoe in Nevada to the 30 GWh of iron-air storage planned for a Google-backed project (Module 11).

8c. Duration Economics and the Four-Hour Standard

The standard product is a container of LFP cells sized for about four hours of discharge, the duration that captures most of the evening peak's value and qualifies for capacity payments in most markets. Average durations are lengthening, from about two hours in 2023 to about three in 2025, by the IEA's count, because a grid with more solar needs to shift more energy further into the night, and the gap the industry cannot yet fill is the long-duration one.

Duration	Installed cost ($/kWh, 2025-26)	What it serves	Note
1 hour	$250-400	Frequency regulation, reserves	The first market batteries saturated
2 hours	$120-250	Peak shaving; arbitrage in tight markets	BNEF's 2025 turnkey average: $124
4 hours	$75-220	The evening peak; capacity credit	BNEF's 2025 turnkey average: $110; China $73, US $219 (all durations)
8 hours	$100-180 (lithium); flow batteries more	Grids with high solar shares (California, Australia)	Growing; cost per kWh falls as the inverter is shared over more energy
100 hours	About $20 targeted (iron-air)	Multi-day reserve	Form Energy's first system due in 2027 (Module 11)

8d. Moss Landing and the Codes

Grid batteries have burned, most notoriously on January 16, 2025, when fire broke out at Vistra's Moss Landing storage plant on California's central coast, then one of the largest in the world, in a 300 MW hall of older NMC batteries installed inside a converted gas-fired power plant. It burned for days, consumed an estimated 55-80% of about 100,000 battery modules, flared again in February, and forced the evacuation of more than a thousand residents.

Peer-reviewed research found a thin layer of heavy-metal dust in the nearby Elkhorn Slough, while testing by Vistra's consultant found no widespread contamination but elevated cobalt, lead, or manganese in a few samples. Cleanup began in September 2025, and by January 2026 more than 15,200 modules had been safely de-energized for recycling.

On September 18, 2026, about 1,200 modules that were still charged and could not be reached ignited against a wall of the burned building. The county ordered nearby residents to shelter in place until that afternoon, and air monitors found no unhealthy levels of particles. The cause of the original fire was still undetermined: the California Public Utilities Commission said a root-cause analysis by Vistra and an independent consultant was under way.

Earlier fires had already written the rules: an explosion at a site in Arizona in 2019 injured firefighters, and about two dozen fires in South Korea in 2017-19 halted its market. Out of them came the propagation test of Underwriters Laboratories (UL), UL 9540A, and the National Fire Protection Association's (NFPA's) installation standard, NFPA 855, revised in its 2026 edition.

The industry shifted to LFP and to small outdoor containers spaced apart rather than warehouse halls, and California's Senate Bill 283, enacted in the autumn of 2025, requires developers to meet local fire authorities before applying and to align their designs with NFPA 855. CATL opened a validation and testing platform worth about 3 billion yuan ($450 million) in Xiamen in 2026.

8e. Local Moratoriums: The Argument

The case for local limits. Residents, many local officials, and some firefighters argue that a battery fire is unlike other fires: it cannot be put out, only contained, it can burn for days and reignite, and its smoke carries toxic gases and metals. To them, Moss Landing showed all of it, with its evacuations, a flare-up twenty months later, and a cause still undetermined. Rural fire departments lack training and water, and sites are proposed near homes and wetlands, which is why dozens of towns adopted moratoriums in 2025-26.

The case against. Developers, grid operators, state energy agencies, and many fire-safety engineers argue that the risk is falling fast and that modern outdoor LFP containers are tested to stop propagation. Batteries now carry California's evening peak, and moratoriums delay the cheapest source of reliable capacity and raise bills, while gas plants and substations also burn.

The evidence. EPRI, the American utilities' research institute, found in October 2026 that failures per deployed GWh fell 98% worldwide from 2018 to 2025, while deployment passed 300 GWh in a single year. It found indoor facilities overrepresented among incidents and older systems failing more often, but could not isolate cell chemistry as a risk factor on its own. Moss Landing was an indoor hall of older NMC cells, the design the codes now discourage.

The course's reading. The risk is real but concentrated in older and indoor designs: siting rules, outdoor spacing, and planning with fire departments address most of it, while blanket moratoriums treat the newest designs like the oldest.

Module 8 Key Points

Batteries for the Grid

• A Texas battery earns about $9-13 million a year on $80 million from arbitrage, regulation, and scarcity; ERCOT pays no capacity.

• California's batteries met a record 44% of evening demand on March 29, 2026, from a fleet above 17 GW.

• The world added 112 GW and 307 GWh of storage in 2025, up 48% (BNEF); China added 189 GWh, the US 51.

• Chinese integrators held 76% of the 2025 market, though Tesla stayed first; average durations rose to about three hours.

• Moss Landing's 2025 fire was still unexplained when 1,200 stranded modules reignited on September 18, 2026.

• EPRI finds failures per deployed GWh down 98% from 2018 to 2025; indoor sites were overrepresented, older systems failed more often.

Module 8 Quiz

Check Your Understanding

1. What are the four revenue streams in a grid battery's stack?

A) Generation, transmission, distribution, and retail
B) Arbitrage, capacity, ancillary services, and deferral of wire upgrades
C) Subsidies, credits, grants, and loans
D) Arbitrage, capacity, renewable credits, and fuel savings

2. Why does the Texas battery in the worked example earn no capacity payment?

A) Its batteries are too small to qualify
B) ERCOT has no capacity market
C) Federal law forbids capacity payments to batteries
D) Texas pays for capacity only to gas plants

3. What share of California's demand did batteries meet at 7 p.m. on March 29, 2026?

A) About 44%
B) About 4%
C) Nearly 80%
D) About 18%, the same as Australia's share of dispatchable capacity

4. How much storage did the world add in 2025, by BloombergNEF's count?

A) About 30 GWh, mostly in Europe
B) About 1,000 GWh, mostly in the US
C) About 50 GW, the same as 2024
D) About 112 GW and 307 GWh, up 48% from 2024

5. What did EPRI find about battery-storage failures?

A) That failures rose with deployment
B) That LFP alone explains the decline
C) That failures per GWh fell 98% from 2018 to 2025
D) That no failures at all occurred after 2020, anywhere

Module 9 — Sodium-Ion

The Chemistry That Is Arriving

Recommended Reading / Reference

Reference: IEA, *Global EV Outlook 2026*, on sodium-ion cells and capacity; CATL's Naxtra disclosures (April 2025, February and June 2026); China's Ministry of Finance on the 2026 consumption tax and its exemptions; Benchmark Mineral Intelligence's sodium-ion tracker

9a. How It Works

Sodium-ion works like lithium-ion, with sodium ions shuttling instead. CATL's cathode is a layered metal oxide, akin to NMC but built from iron, manganese, and some nickel, with no cobalt or lithium. Other makers use Prussian-blue analogues such as Prussian white, or polyanions such as sodium iron phosphate, a route akin to LFP. The anode is hard carbon, a disordered carbon made from biomass, coconut shells, or petroleum pitch, whose pores accept the larger sodium ion that graphite's tight layers cannot.

The electrolyte is a sodium salt in carbonate solvents, and because sodium does not alloy with aluminum as lithium does, the anode's current collector can be aluminum instead of copper, which saves cost and weight and lets the cell be shipped at zero volts, a safety and logistics advantage lithium cells lack.

Property	Sodium-ion (2026)	LFP (2026)	NMC 811 (2026)
Cell voltage	3.0-3.2 V	3.2 V	3.7 V
Energy density (cell)	120-175 Wh/kg (CATL's Naxtra 175)	150-205 Wh/kg	260-300 Wh/kg
Cycle life (to 80%)	3,000-8,000	3,000-10,000	1,500-2,500
Cold performance	About 90% of capacity at −40°C (−40°F), by CATL's and the IEA's accounts of the latest cells	70-75% at −20°C (−4°F)	80-85% at −20°C (−4°F)
Raw materials	Sodium, iron, manganese, some nickel, hard carbon, aluminum on both sides	Lithium, iron, phosphate, graphite, copper	Lithium, nickel, cobalt, manganese, graphite, copper
Manufacturing capacity	Just over 1% of lithium-ion's (IEA)	The bulk of more than 4 TWh of lithium-ion capacity	—
China's 2026 consumption tax	Exempt through 2028	2%, rising to 4% in September 2027	2%, rising to 4%

IEA, *Global EV Outlook 2026*; CATL; China's Ministry of Finance. Cycle-life ranges are typical claims for production cells.

9b. The Case and the Cost

The case for sodium is abundance and safety: sodium is available anywhere there is salt, and the chemistry needs no lithium, cobalt, or graphite, and little or no nickel, which detaches it from the price spikes and export controls of Modules 12 and 13, and it tolerates cold, charges fast, and fails gently.

Its costs have been energy density and, so far, price: CATL's Naxtra cell, announced in April 2025, reaches 175 Wh/kg, on a par with mainstream LFP, but sodium cells have cost more than LFP because their volumes are small and their supply chains for hard carbon and cathode precursors are immature, not because their materials are dearer.

The lithium rebound changed the arithmetic: Chinese lithium carbonate rose nearly 190% between June 2025 and April 2026, and CATL now forecasts that sodium-ion cells will match lithium-ion's cost by the end of 2026. Beijing tilted the field as well: the consumption tax on lithium-ion batteries that took effect on September 1, 2026 exempts sodium-ion cells through 2028.

9c. Where It Is Used

Application	Status (October 2026)	Why sodium
Passenger cars	Changan's car with CATL's Naxtra cells, unveiled in February 2026 as the first mass-produced sodium car, with sales planned from mid-2026; a 45 kWh pack gives up to about 400 km; CATL expected 10,000-20,000 sodium cars in 2026	Cost, cold tolerance, safety
Small and cheap cars	Small volumes since JAC's Yiwei model of 2024	The cheapest new cars in China
Two- and three-wheelers	Growing, from Yadea and others	Cost, safety, cold
Grid storage	China's first 100 MWh-class sodium plant (Datang, Hubei, 2024); CATL said in June 2026 that its Tener Sodium systems would ship in China from September, reaching 1 GWh by year-end, and abroad from June 2027; a July 2026 memorandum covers 5 GWh for Alfen in the Netherlands and Western Europe	Cost per kWh, cycle life, safety, no exposure to lithium
Truck starter batteries	CATL's 24-volt sodium starter, launched in 2025	Starting power in the cold; replaces lead-acid
Mixed packs	CATL's Freevoy packs combine sodium and lithium cells	Sodium for cold and cost, lithium for range
Long-range cars	Not competitive	Energy density too low

9d. Why Sodium Arrived at the Bottom of the Market

CATL showed its first-generation sodium cell in 2021, at 160 Wh/kg, when the lithium spike of 2021-22 was turning cheap lithium into an expensive bottleneck. The first products followed in the cheapest segments: two- and three-wheelers, small Chinese city cars, starter batteries, and pilot storage plants, where buyers cared about price, cold weather, and safety more than range.

When lithium collapsed in 2023-25, sodium's case weakened and many plans slowed, and the 2026 rebound revived them. The pattern is the opposite of the headlines: the first new chemistry in a generation arrived in the cheapest vehicles and the plainest grid cabinets, not in premium cars.

9e. The Bifurcation

The industry expects a split: sodium for grid storage, cheap short-range cars, and cold markets, and lithium for everything that needs range. Sodium's spread would do to lithium demand what LFP did to cobalt demand, flatten it, and it is one reason lithium forecasts are hedged.

Its constraints are the supply chains for hard carbon and precursors, which do not yet exist at scale, and the same learning curve that LFP took a decade to climb. Announced projects for 2030 amount to only about 7% of committed lithium-ion capacity, by the IEA's count. And its cells are made mostly by the same Chinese companies that dominate lithium, so sodium diversifies the chemistry, not the geography.

Outside China the base is thin: Natron Energy, the leading American developer, shut down in September 2025; Faradion in Britain belongs to India's Reliance; and in June 2026 General Motors said it would develop sodium-ion cells for grid storage with Peak Energy, an American start-up.

Module 9 Key Points

Sodium-Ion

• Sodium-ion uses hard-carbon anodes and aluminum on both sides, so cells can ship at zero volts; it needs no lithium, cobalt, or graphite.

• CATL's Naxtra cell reaches 175 Wh/kg, near mainstream LFP, and keeps about 90% of capacity at −40°C (−40°F).

• Lithium's 2025-26 rebound and China's tax exemption through 2028 revived sodium; CATL expects cost parity by end-2026.

• Changan's sodium car was due on sale from mid-2026; CATL planned sodium storage deliveries from September 2026, and 5 GWh for Europe.

• Sodium capacity is just over 1% of lithium-ion's and mostly Chinese: it diversifies the chemistry, not the geography.

Module 9 Quiz

Check Your Understanding

1. Why does sodium-ion use hard carbon rather than graphite for the anode?

A) Hard carbon is cheaper to make, and cost is the only reason
B) The larger sodium ion cannot fit between graphite's layers
C) Graphite is banned from sodium cells
D) Hard carbon conducts electricity better than graphite

2. What advantage does an aluminum anode collector give sodium cells?

A) Shipping at zero volts
B) Faster charging in cold weather
C) A higher voltage in each cell
D) No need for a liquid electrolyte

3. What revived sodium-ion's prospects in 2026?

A) An American subsidy for sodium-ion cell plants
B) A European ban on lithium imports
C) Lithium's rebound and a Chinese tax break
D) The discovery that sodium cells store more energy than NMC

4. Where is sodium-ion competitive in 2026, and where is it not?

A) Only in phones and laptops
B) In every segment, including long-range cars
C) Nowhere yet, at any price
D) In grid storage, cheap cars, two-wheelers, and starter batteries, but not in long-range cars

5. Why does sodium-ion diversify the chemistry but not the geography?

A) It works well only in cold climates
B) Its cathodes still need cobalt refined in China
C) The same Chinese firms make it
D) Sodium itself is mined mainly in China

Module 10 — Solid-State and the Density Frontier

Separating the Claims From the Products

Recommended Reading / Reference

Reference: The companies' disclosures (CATL, Gotion, Samsung SDI, Toyota, QuantumScape, Solid Power, Factorial); China's draft national standard on solid-state batteries for electric vehicles (December 2025); the Faraday Institution's solid-state roadmap

10a. What a Solid-State Battery Is

A solid-state battery replaces the flammable liquid electrolyte with a solid, which also serves as the separator. The candidates are sulfides, such as Li6PS5Cl, which conduct well but react with moisture; oxides, such as the garnet LLZO (lithium lanthanum zirconium oxide), which are stable but brittle and hard to make thin; halides; and polymers, which conduct only when warm.

The prize is not the electrolyte but what it permits: a solid that resists dendrites could allow a lithium-metal anode, which stores about ten times graphite's lithium per gram and could roughly double cell energy to 400-500 Wh/kg while removing the fuel for fires. The claims have run a decade ahead of the products for a decade.

Definitions matter, because much of what was sold as solid-state contains liquid, and China's draft national standard of December 2025 drops the term semi-solid altogether. It sorts cells into liquid, hybrid solid-liquid, and solid-state, and a solid-state cell must lose no more than 0.5% of its weight under a specified vacuum-drying test, and China's 2026 consumption tax exempts solid-state cells through 2028 while semi-solid cells do not qualify.

Company or route	Electrolyte	Status (October 2026)	Stated timeline	Assessment
CATL	Hybrid solid-liquid ('condensed') now; sulfide all-solid in development	Hybrid cells in mass production from 2026; a 500 Wh/kg condensed cell claimed for aircraft	All-solid in small-scale production from 2027; large-scale before 2030	A density step now; the all-solid plan is the industry's benchmark
WeLion with NIO; SAIC's MG	Hybrid solid-liquid	150 kWh packs in NIO cars since 2024; an MG4 version priced at 99,800 yuan (about $15,000), delivered in China from December 2025	On the road	The first such cars in volume
Gotion ('Jinshi')	Sulfide, all-solid	0.2 GWh pilot line since 2025; cells of 350 Wh/kg road-tested; a 2 GWh line designed in March 2026; target raised to 400 Wh/kg	Earlier plans: small-scale 2027, mass production 2030, since advanced	The most visible Chinese all-solid program
Samsung SDI	Sulfide, all-solid	Prototype cells with customers; pilot line validated	Mass production at Ulsan in the second half of 2027; above 900 Wh per liter	Credible; first in Korea if on time
Toyota, with Idemitsu	Sulfide, all-solid, lithium-metal anode	Pilot production; Idemitsu building the electrolyte supply	2027-28, in small volumes	The long-promised leader, delayed repeatedly since 2020

Company or route	Electrolyte	Status (October 2026)	Stated timeline	Assessment
QuantumScape, with Volkswagen's PowerCo	Ceramic oxide separator, anode-free lithium metal	Eagle pilot line shipping sample cells; in July 2026 it aimed to double output in the second half; a Honda partnership; PowerCo's deal revised to milestone payments	PowerCo's start of production targeted for 2029	The longest-running Western program; no volume yet
Solid Power	Sulfide electrolyte supplier	Supplies electrolyte to BMW and SK On	2027 and after	A materials business
Factorial, SES, Blue Solutions	Quasi-solid, lithium-metal, polymer	Samples; Mercedes road tests of Factorial cells in 2025	2027-29	Second tier
Chinese carmakers (BYD, Chery, Geely, Changan, GAC)	Sulfide, all-solid	Validation and demonstration vehicles	Small batches from 2027	Racing to be first

Companies' statements; timelines are the companies' own claims, not independent forecasts.

10b. The Manufacturing Obstacle

The realistic reading is that true all-solid-state cells will reach premium cars in small volumes from 2027-28 and will not challenge LFP's cost for a decade. Gotion's own long-term goal of about one yuan per watt-hour, roughly $150 per kWh, is three times the price of a Chinese LFP cell, and the obstacles are in manufacturing, not chemistry.

Solid electrolytes crack as a lithium-metal anode expands and shrinks, and cells need heavy stack pressure, measured in megapascals, from fixtures that eat the weight saved. Sulfides release hydrogen sulfide on contact with moisture and need drier rooms than lithium-ion uses, while oxides must be sintered at high temperature and are brittle when thin.

None of it runs on the coating lines the industry already owns, hundreds of billions of dollars of sunk capital that favor a hybrid retrofit over an all-solid rebuild. Hybrid solid-liquid cells, with a modest gain in density on conventional lines, are the pragmatic bridge, and they are what most 2026 claims of solid-state actually describe.

10c. Lithium-Sulfur, Lithium-Metal, and Silicon

Technology	Energy (Wh/kg)	Cycle life	Status (2026)	Niche
Silicon-carbon composite anodes (10-20% silicon)	Cells 10-15% higher, about 330-350	Near graphite's, with new binders	In premium phones (Honor, Xiaomi); entering car cells (Group14, Sila, Chinese producers)	The nearest gain in density
Silicon-dominant anodes	400 and more	500-1,000	Amprius cells in drones and aircraft	Where weight is critical
Lithium-metal with liquid electrolyte	400-450	300-800	SES and others; samples for aircraft	A halfway house to solid-state
Lithium-sulfur	400-500, with a cheap cathode	100-500, limited by the polysulfide shuttle	Lyten (which also bought Northvolt's Swedish plants) and Zeta, for drones and satellites	Aviation, defense
All-solid lithium-metal	400-500	1,000 and more targeted	Pilot cells (10a)	Premium cars from 2027-28
Lithium-air	1,000 and more, in theory	—	Laboratories	None yet

None of these threatens LFP or sodium on cost, because all of them target the applications where energy per kilogram is worth paying for: aircraft, drones, premium devices, and long-range premium cars. The density frontier that matters commercially in 2026 is silicon-carbon anodes, already in phones and arriving in cars, not the solid-state cells in the headlines.

Module 10 Key Points

Solid-State and the Density Frontier

• Solid electrolytes could allow lithium-metal anodes and 400-500 Wh/kg cells without the flammable liquid; claims have led products for a decade.

• China's draft 2025 standard drops 'semi-solid': cells are liquid, hybrid solid-liquid, or solid-state, which must lose under 0.5% weight.

• CATL plans small-scale all-solid production in 2027; Samsung SDI in the second half of 2027; Toyota in 2027-28.

• Cracking, stack pressure, moisture, and new production lines are the obstacles; all-solid cells will not match LFP's cost for a decade.

• Silicon-carbon anodes, adding 10-15% energy and already in phones, are the density gain that matters commercially in 2026.

Module 10 Quiz

Check Your Understanding

1. What is the real prize of a solid electrolyte?

A) Faster manufacturing at lower temperatures and cost
B) A lithium-metal anode without dendrites or fire
C) A lower cost per kWh than LFP
D) Compatibility with sodium cells

2. How does China's draft standard of December 2025 classify cells?

A) As liquid, hybrid, or solid-state
B) As semi-solid or solid, with no other class
C) By energy density alone
D) By the country where the cells were made

3. Why is manufacturing, rather than chemistry, the main obstacle to all-solid cells?

A) The chemistry is unknown
B) Lithium foil cannot be made
C) Regulators forbid the cells in cars
D) Solid electrolytes crack, need heavy stack pressure, and cannot run on existing coating lines

4. When does Samsung SDI plan to mass-produce all-solid-state batteries?

A) In 2025, at its plant in Hungary
B) Never; it abandoned the program
C) In 2035, after a decade of pilots
D) In the second half of 2027

5. Which density technology matters most commercially in 2026?

A) Lithium-air
B) Silicon-carbon anodes, adding 10-15% energy
C) Oxide solid-state in trucks
D) Lithium-sulfur cells in mass-market cars and vans

Module 11 — Long-Duration Storage

The Gap Lithium Cannot Fill

Recommended Reading / Reference

> **Reference:** Form Energy's project and financing announcements (2024-26); *MIT Technology Review*'s profile of Form Energy (October 6, 2026); the Long Duration Energy Storage Council's annual reports; the Department of Energy's long-duration storage reports; BloombergNEF, *Energy Storage Market Outlook 1H 2026*

11a. Why Duration Matters

A grid with 20% solar power needs about four hours of storage to move the midday surplus into the evening. A grid with 60-80% solar and wind needs storage that can carry it through a windless, cloudy week in winter, 50 to 200 hours, and Module 6's arithmetic showed why lithium cannot do that: a lithium battery used rarely spreads its high cost per kWh over too few discharges.

Long-duration storage therefore makes a different trade: it needs a very low cost per kWh of capacity, under about $50 against lithium's $110-220 installed, and it can accept lower efficiency, 40-70% against lithium's 85-90%, lower power density, and slower response. The candidates store energy in cheap bulk materials: iron, water, air, rock, and salt.

11b. Iron-Air, Worked

Form Energy's iron-air battery, the most closely watched candidate, discharges by rusting iron: iron pellets in a water-based electrolyte react with oxygen from the air to form iron oxide, releasing electrons, and charging runs current through the cell to turn the rust back into iron. It uses iron, water, and air, its cells sit in enclosures the size of shipping containers, and a 100-hour system is a field of them, needing roughly an acre (0.4 hectares) for every 2-3 MW.

Its first commercial system, 150 MWh for Great River Energy in Minnesota, is scheduled to come online in 2027. In 2026 Form said its backlog had grown from about 20 GWh to 80 GWh, including 30 GWh for an Xcel Energy project powering a Google data center in phases from 2028 to 2031. In August 2026 it raised a $750 million Series G, taking its funding past $2 billion, to expand a factory in Weirton, West Virginia, that can make about 2 GWh a year.

Worked example — Iron-Air Against Lithium for a Four-Day Reserve

A utility wants 100 MW available for 100 hours, 10,000 MWh, to cover winter wind lulls, and expects to use it for the equivalent of about 20 full discharges a year. In lithium at $150 per kWh installed, the reserve costs $1.5 billion; financed at 7% over 20 years and operated for about $15 million a year, it costs about $157 million a year, or about $790 per MWh discharged.

In iron-air at Form's target of about $20 per kWh, the same 10,000 MWh costs about $200 million, or about $24 million a year with operations and charging. That is about $120 per MWh, even though at roughly 45% efficiency it wastes more than half the energy it stores, because that energy is surplus wind that would otherwise be curtailed at nearly no cost.

Used only ten times a year, the figures double, to about $230 for iron-air and $1,570 for lithium. The case for iron-air is not that it is a better battery but that it is a cheaper reservoir, competitive with a gas plant kept idle for the same purpose. The case against it is that no system has yet run commercially, Form has not disclosed its current costs, and its backlog is forty times its factory's annual output.

11c. The Field

Technology	How it stores	Duration	Efficiency	Capital cost ($/kWh)	Status (2026)	Leaders
Iron-air	Rusting and un-rusting iron	About 100 hours	40-50%	About $20 targeted	First commercial system due in 2027; 80 GWh backlog	Form Energy
Vanadium flow	Vanadium ions in two tanks pumped through a stack; tank size sets duration	4-12 hours	65-75%	$300-500, falling with duration	Mature; China's largest systems run to hundreds of MWh	Rongke Power, Sumitomo, Invinity
Iron flow	Iron chloride electrolyte	8-12 hours	65-70%	$200-300	Small commercial projects	ESS Inc.
Zinc batteries	Zinc plated and dissolved	4-12 hours	65-80%	$150-300	Small commercial; Eos expanding in Pennsylvania with a federal loan	Eos; Redflow went insolvent in 2024
Thermal (bricks, sand, salt)	Electricity to heat, stored and returned as heat or power	8 to more than 100 hours	40-60% as power; over 90% as heat	$20-60	Commercial for industrial heat; power pilots	Rondo, Antora, Malta
Compressed air (adiabatic, A-CAES)	Air compressed into caverns or tanks	8-24 hours	55-65%	$100-200	China runs plants of 300 MW; Hydrostor plans one in California	Hydrostor, Chinese state companies
Pumped hydro	Water pumped uphill	8-24 hours	70-85%	$50-150, depending on the site	Over 90% of the world's stored energy; China builds tens of GW	State utilities
Gravity	Blocks or rail cars raised and lowered	4-12 hours	80% and more	Unproven	Pilots; skepticism	Energy Vault, which pivoted to batteries
Hydrogen	Electrolysis, storage in caverns, then turbines or fuel cells	Seasonal	30-40%	Low per kWh, high per kW	Pilots (Utah's salt caverns)	Utilities, oil companies

11d. The Honest State

None of the new technologies has reached the volumes of lithium, and the honest status is early commercial, with multi-GWh pipelines, real doubts, and a graveyard of failed predecessors: Redflow's insolvency, Ambri's receivership, ESS's struggles, and Energy Vault's pivot. BloombergNEF expects storage of six hours and longer to quadruple in 2026, but only to about 2 GW.

Pumped hydro remains more than 90% of the world's stored energy, and China is building it at tens of gigawatts, but it needs mountains and water. The IEA notes that battery durations are lengthening gradually rather than leaping, from about two hours in 2023 to about three in 2025.

Until iron-air or flow batteries reach scale in the 2030s, the long-duration gap is filled by gas plants running less often. It is the most consequential unsolved problem in the field, and the one where an American company holds the lead.

Module 11 Key Points

Long-Duration Storage

• Grids with 60-80% wind and solar need 50-200 hours of storage; lithium used rarely costs far too much per MWh.

• Long-duration storage needs capacity under about $50 per kWh and accepts 40-70% efficiency, using iron, water, air, rock, or salt.

• At 20 uses a year, a 100-hour reserve costs about $790 per MWh in lithium and about $120 in iron-air at Form's target.

• Form's first system is due in 2027; its backlog is 80 GWh, its factory makes about 2 GWh a year.

• Pumped hydro still holds over 90% of stored energy; gas fills the long-duration gap until the new storage scales.

Module 11 Quiz

Check Your Understanding

1. Why can lithium not serve long-duration storage economically?

A) It is banned from grid use
B) Its cells lose their charge within hours
C) Its cost is spread over too few uses
D) It cannot discharge for more than an hour

2. What is the case for iron-air, according to the worked example?

A) It is a cheaper reservoir, at about $120 per MWh against about $790 for lithium at 20 uses a year
B) It is more efficient than lithium
C) It charges faster than lithium
D) It is a better battery in every respect

3. What sets a flow battery's duration?

A) The operating temperature of the stack
B) The size of its tanks
C) The cell voltage
D) The type of membrane in the stack

4. What was the status of Form Energy in October 2026?

A) Hundreds of systems in operation
B) Bankrupt after its first project failed
C) Its first system due in 2027
D) Running a 1 GWh system in Minnesota

5. What holds more than 90% of the world's stored energy?

A) Pumped hydroelectric storage
B) Lithium-ion batteries
C) Hydrogen in caverns
D) Vanadium flow batteries

Module 12 — The Minerals

From Mine to Cathode, With the Quantities

Recommended Reading / Reference

Reference: US Geological Survey, *Mineral Commodity Summaries 2026* (January 2026); IEA, *Global Critical Minerals Outlook 2026* (July 16, 2026); Benchmark Mineral Intelligence's third-quarter 2026 lithium and cobalt price reviews; the London Metal Exchange (LME)

12a. The Bill of Materials

Mineral (kg per 60 kWh pack)	NMC 811	NMC 622	LFP	Sodium-ion	Where mined (2025)	Where refined to battery grade
Lithium (metal content)	6-7	7-8	5-6	0	Australia 32%, China 21%, Chile 19%, Zimbabwe 10%, Argentina 8%	China about two-thirds of chemicals; Chile, Argentina (carbonate)
Nickel	40-45	30-35	0	0-5 (some cathodes)	Indonesia 67%, Philippines, Russia, Canada	Indonesia, in mostly Chinese-owned plants; China second
Cobalt	5-6	10-12	0	0	The Democratic Republic of the Congo (DRC) 73%, Indonesia 14%	China about three-quarters
Manganese	5-6	10-12	0 (LMFP 10-15)	5-15	South Africa, Gabon, Australia	China about 95% of battery-grade sulfate
Iron	0	0	40-45	5-15	Everywhere	—
Phosphorus (in phosphate)	0	0	20-25	0-10 (polyanion)	Morocco, China, US	China (purified phosphoric acid)
Graphite (anode)	50-70	50-70	50-70	0 (hard carbon 40-60)	China about four-fifths of natural graphite; Mozambique, Madagascar; synthetic almost all Chinese	China more than 90% of anode material
Copper (foil, wiring)	20-30	20-30	20-30	10-15 (aluminum anode foil)	Chile 23%, the DRC, Peru, China	China 48% of refining
Aluminum (foil, can, housing)	30-50	30-50	30-50	40-60	Guinea and Australia lead in bauxite	China 61% of smelting

Quantities approximate, varying with cell design; shares from the USGS for 2025 and the IEA. The Congo's cobalt share is of the USGS's unrounded world total. Chemistry is mineral policy: LFP's rise has cut projected cobalt demand and flattened nickel's, and sodium's would do the same to lithium and graphite.

12b. Lithium

Lithium comes from two sources, the first being brine, salt-flat groundwater in the lithium triangle of Chile, Argentina, and Bolivia, which is pumped into ponds and evaporated for twelve to eighteen months, then converted to lithium carbonate. It is cheap to produce, slow to expand, and entangled in disputes over water and indigenous land, and Bolivia's large resource is still barely developed.

Hard rock, mostly spodumene from Australia, the largest producer, and from Zimbabwe, Brazil, and China, is crushed and concentrated to about 6% lithium oxide, then converted, overwhelmingly in China, into

carbonate or hydroxide. It is faster to build and costlier to run, and it is the marginal supply that sets the price. Direct lithium extraction (DLE), which pulls lithium chemically from brine in hours without ponds, reached its first commercial scale in Argentina in 2024-25 and is being developed in Arkansas's Smackover formation.

The world mined about 290,000 tonnes of lithium in 2025, roughly 1.5 million tonnes of lithium carbonate equivalent (LCE), by the USGS's estimate, excluding the United States. China mines a growing share, including lepidolite, a low-grade ore it processes anyway, and makes about two-thirds of the world's lithium chemicals.

Date	Lithium carbonate, battery grade, per tonne	Context
2021	$11,700 (average)	The first electric-car wave
November 2022	About $80,000 in China (the peak)	Demand outran supply
2022	$63,700 (average)	The bubble year; battery packs rose 7%
2023	$39,000 (average), falling all year	New supply, Chinese destocking
2024	$11,800 (average)	The bust: mines idled, projects cancelled
2025	$9,000 (average); a low near $8,000 in mid-year	CATL's Jianxiawo mine halted; storage demand rising
Mid-May 2026	Above 200,000 yuan a tonne on the Guangzhou futures exchange	The spike: storage demand, Zimbabwe's export suspension, costlier acid
End of September 2026	127,750 yuan a tonne ($19,025), down 20.8% in the quarter	Australian mines restarting; China pausing new battery plants

Annual averages are the USGS's; 2026 prices are ex-works China from Benchmark Mineral Intelligence and the Guangzhou Futures Exchange.

12c. The Spike of 2021-22 and Its Echo

The decisive episode for battery chemistry was a price spike: electric-car sales doubled in 2021 while new mines take five to seven years to build, so lithium carbonate rose from about $6,000 a tonne in 2020 to about $80,000 in November 2022, more than thirteenfold. Cobalt doubled, and in March 2022 a short squeeze drove nickel on the LME past $100,000 a tonne, the exchange suspended trading, and it cancelled about $3.9 billion of trades.

Battery packs rose 7% in 2022, the first increase in BloombergNEF's survey, and LFP's cost advantage widened, sodium-ion was funded, and automakers signed offtake contracts and took stakes in mines, as General Motors did in Lithium Americas. The lesson the industry drew is that volatility rather than scarcity is the risk, and that volatility drives substitution of one chemistry for another.

The echo came in 2026, when grid storage pushed demand up just as Zimbabwe suspended concentrate exports and costlier sulfuric acid raised refining costs, and Guangzhou futures rose above 200,000 yuan a tonne in May before falling back, lifting cell prices (Module 6) and reviving sodium's case (Module 9).

12d. Nickel, Cobalt, and Manganese

Nickel: Indonesia banned exports of raw ore in 2020 to force smelting onshore, and Chinese-financed plants, including high-pressure acid leaching (HPAL) plants for battery-grade nickel, made it the source of 67% of the world's mined nickel in 2025. The glut cut LME prices from their 2022 highs to an average of

$15,000 a tonne in 2025, closing Australian and other high-cost mines; nickel stood at $15,700 on October 9, 2026, after Jakarta cut its 2026 ore quota to 260-270 million wet tonnes.

Most Indonesian nickel goes into stainless steel, and LFP's rise means the battery market for nickel is smaller than the forecasts of 2021 assumed. Indonesia plans a national mineral exchange by January 1, 2027, meant to make it a price setter.

Cobalt: The Congo mined about 73% of the world's cobalt in 2025, much of it as a byproduct of copper at mines run by Glencore and China's CMOC, and some by informal miners, children among them, and China refines about three-quarters of it. After cobalt metal fell to about $10 a pound (about $22,000 a tonne) in February 2025, the Congo suspended exports that month and replaced the suspension in October with quotas of 96,600 tonnes a year for 2026 and 2027. The metal price more than doubled, holding above $25 a pound through August 2026.

Cobalt hydroxide, the Congo's export, then fell 31% in the third quarter of 2026 to $17.25 a pound, by Benchmark's count, in a standoff between buyers and the quota, and every rise advertises the cobalt-free LFP and sodium cells that shrink the market.

Manganese: The ore is abundant and cheap, mined in South Africa, Gabon, and Australia, but battery-grade high-purity manganese sulfate is, again, a Chinese specialty, about 95% of supply, and LMFP's rise will raise its importance.

12e. Graphite, Copper, and the Processing Bottleneck

Graphite is the heaviest mineral in a lithium-ion cell, 50-70 kilograms in a 60 kWh pack, and the most concentrated in supply. China mined about four-fifths of the world's natural graphite in 2025, makes nearly all synthetic graphite on cheap coal power, and makes more than 90% of finished anode material.

China put graphite exports under licensing in December 2023 and extended controls to artificial graphite anode material in October 2025, then suspended the extension under the truce, now until January 10, 2027 (Module 13). American producers sought duties on Chinese anode material, and the Commerce Department set final rates of about 160% combined in February 2026, but the International Trade Commission (ITC) found no injury on March 12, 2026, so no duties took effect.

Copper is not specific to batteries, but an electric car uses about 60-80 kilograms, two to four times a combustion car's, and the grid build-out uses far more. Chile, the Congo, and Peru mine most of it, China refines 48%, and LME copper set a record of $14,875 a tonne on September 10, 2026.

Stage	Lithium	Nickel (battery grade)	Cobalt	Graphite and anode	Cathode material	Cells
Leading miner	Australia 32%	Indonesia 67%	The DRC 73%	China, about four-fifths of natural graphite	—	—
China's share of mining	21%	Small, but Chinese firms own most Indonesian plants	Small, but Chinese firms own major Congolese mines	About four-fifths	—	—
China's share of processing	About two-thirds	Second to Indonesia	About three-quarters	More than 90%	About 75-85%	More than 80%

Stage	Lithium	Nickel (battery grade)	Cobalt	Graphite and anode	Cathode material	Cells
Processing elsewhere	Chile, Argentina, Australia (new), Tesla's Texas refinery	Indonesia (Chinese-owned), Finland, Canada	Finland, Canada, the DRC	Japan, Korea; Syrah in Louisiana	Korea, Japan	Korea, Japan, the US, Europe

USGS, IEA, Benchmark; shares for 2025. The pattern: mining is spread across many countries, while the chemical processing that makes battery-grade material is mostly Chinese, and that step, not the mine, is the bottleneck industrial policy is trying to break.

Module 12 Key Points

The Minerals

• A 60 kWh NMC 811 pack holds about 6-7 kg of lithium, 40-45 of nickel, and 5-6 of cobalt; LFP drops the nickel and cobalt.

• Lithium carbonate rose about thirteenfold to about $80,000 in 2022, averaged $9,000 in 2025, and ended September 2026 near $19,000.

• The 2021-22 spike raised packs 7%, widened LFP's lead, and funded sodium: volatility, not scarcity, drives substitution.

• Indonesia mines 67% of nickel and the Congo 73% of cobalt, under 96,600-tonne quotas for 2026-27; China refines about three-quarters of cobalt.

• China makes more than 90% of anode material; its October 2025 anode controls are suspended until January 10, 2027, but 2023's licensing stands.

Module 12 Quiz

Check Your Understanding

1. How does switching a 60 kWh pack from NMC 811 to LFP change its minerals?

A) It adds cobalt to the cathode
B) It removes the graphite from the anode
C) It doubles the lithium
D) It removes all the nickel and cobalt

2. What did lithium carbonate do between 2020 and 2025?

A) It held near $10,000 throughout
B) It rose about thirteenfold to about $80,000 in 2022, then fell to a $9,000 average in 2025
C) It rose tenfold and never fell back
D) It fell to nearly zero on oversupply

3. What lesson did the industry draw from the spike of 2021-22?

A) That volatility, not scarcity, is the risk
B) That lithium is running out
C) That price controls work
D) That NMC would win the volume market for good

4. What did the Congo do to cobalt in 2025?

A) It nationalized Glencore's mines
B) It raised royalties but left exports unlimited
C) It lifted all its limits on cobalt exports
D) It halted exports, then imposed quotas

5. What happened to the American case for duties on Chinese anode material?

A) Duties of 160% took effect in February 2026
B) China agreed to stop exporting anode material
C) The ITC found no injury
D) The case was never filed

Module 13 — The Global Supply Chain and Trade Wars

Who Makes What, and the Rules That Shape It

Recommended Reading / Reference

Reference: IEA, *Global EV Outlook 2026*, the supply-chain and trade sections; the July 2025 budget law's rules on prohibited foreign entities and the Treasury's Notice 2026-15 (February 2026); the Office of the US Trade Representative's tariff notices; China's Ministry of Commerce (MOFCOM) export-control announcements; the House Select Committee on China's letter to Ford (January 2026)

13a. The Shape of the Chain

Stage	China	Korea and Japan	United States	Europe	Note
Refined battery minerals	65-95% by material	Small	Small	Small	Indonesia's nickel plants are mostly Chinese-owned
Cathode active material	About 75-85%	Most of the rest	Little	Little	Korea is the main alternative
Anode active material	More than 90%	Small	Little	Little	Syrah's Louisiana plant is the first integrated one outside China
Cells (nameplate capacity)	More than 80%	Korean and Japanese firms also own plants in the US and Europe	6-7%	6-7% (EU)	Global capacity passed 4 TWh at the end of 2025
Electric cars produced	Nearly 75%	Some	Some	Some	Chinese brands made 60% of the electric cars sold worldwide
Grid-storage systems (integrators)	76%	Small	Tesla first, Fluence	Small	Eight of the top ten integrators are Chinese

IEA, *Global EV Outlook 2026*; Wood Mackenzie (July 2026); Benchmark. Shares are approximate, for 2025.

The battery supply chain is the most geographically concentrated of any large industry, and China's cell industry runs on the world's largest markets for electric cars and storage and on exports, which reached about 305 GWh in 2025, about 17% of its output, by its industry alliance's count, along with more than 2.5 million electric cars.

Korea and Japan are the second tier, supplying most Western automakers from plants at home, in the United States, and in Europe, and depending on Chinese materials to do it. Europe and the United States assemble packs and, increasingly, cells, but their factories import most of their components, by the IEA's account.

13b. The Western Build-Out and Its Stalls

The United States and the European Union both tried to build their own chains, and both have stalled. America's 2022 Inflation Reduction Act offered production credits under section 45X of the tax code, $35 per kWh for cells and $10 for modules, plus consumer credits tied to North American content, which together triggered more than $100 billion of announced plants.

The July 2025 budget law ended the consumer credits on September 30, 2025. It kept the production credits but denied them to products with too much content from prohibited foreign entities, Chinese companies among them: battery components must source at least 60% of their direct costs outside such entities in 2026, rising to 85% after 2029. Storage projects claiming the investment credit face a threshold of 55% for those starting construction in 2026, rising to 75%.

Licensing deals signed or modified after July 4, 2025 that give such an entity effective control also disqualify a plant. With demand stalling, automakers and their Korean partners paused or reshaped projects, and more than $22 billion of clean-energy factories and projects were cancelled or scaled back in the first half of 2025 alone, led by battery plants, by the count of E2, a business group.

Ford and SK On dissolved their BlueOval SK venture in December 2025, Ford keeping the Kentucky plants and SK On the Tennessee one, and Ford said it would turn its Kentucky capacity into a 20 GWh business making LFP storage systems from 2027. Capacity moved to grid storage, where demand is strong: LG Energy Solution began making LFP storage cells in Michigan in 2025, and Tesla's LFP cell plant in Nevada, about 10 GWh a year for its Megapacks, began ramping in April 2026.

Europe's flagship, Northvolt, went bankrupt in March 2025 (Module 5), and the EU's duties on Chinese electric cars have not produced a competitive European cell industry. In practice both regions import Chinese know-how through licenses and Chinese-owned plants rather than replacing it. CATL began trial production at its Hungarian plant, planned for 100 GWh, on September 22, 2026, and CATL and Gotion are building in Spain, Morocco, and elsewhere to serve markets that tax Chinese-made goods.

13c. Tariffs, Rules, and Export Controls

Measure	Who	What	Status, October 2026
Section 301 tariffs on Chinese lithium-ion batteries	US	25% on electric-vehicle batteries since September 2024 and on other lithium-ion batteries since January 1, 2026	In force
Emergency (IEEPA) tariffs on China	US	Reciprocal and fentanyl tariffs of 2025	Struck down by the Supreme Court on February 20, 2026; replaced by a 10% Section 122 tariff until July 24, 2026, then a new Section 301 tariff of 12.5% on Chinese goods; with the 3.4% normal duty, Chinese batteries pay about 41%
Section 232 critical-minerals action	US	Proclamation of January 14, 2026, covering lithium, cobalt, nickel, graphite, and products such as batteries	No tariffs yet; negotiations, with tariffs, minimum prices, or quotas possible
Tariffs on Chinese electric cars	US	100% under Section 301, plus other duties	In force; effectively excludes Chinese cars
Rules on prohibited foreign entities	US	No production or storage credits above the thresholds of Chinese-linked content; limits on licensing	In force; Treasury guidance of February 2026
Defense procurement ban	US	No Pentagon purchases of batteries from CATL, BYD, Envision, EVE, Gotion, or Hithium	From October 2027
Countervailing duties on Chinese battery-electric cars	EU	7.8-35.3% on top of the 10% base duty, since October 2024	In force; minimum-price offers allowed from January 2026; no duties on cells or storage
Battery Regulation	EU	Battery passport (February 18, 2027); due diligence (postponed to August 18, 2027); recycled content (2031)	Phasing in

Measure	Who	What	Status, October 2026
Graphite export licensing	China	Natural and synthetic graphite (December 2023); stricter checks on graphite bound for the US	The stricter US checks suspended until November 27, 2026, a date the truce's extension did not mention
Technology-export restrictions	China	LFP and LMFP cathode technology and lithium extraction and refining technology (July 2025)	In force
Controls on advanced batteries, materials, and equipment	China	Licensing of cells of 300 Wh/kg or more, LFP cathode, precursors, artificial graphite anode, and their equipment (October 2025)	Suspended on November 7, 2025; the truce behind the suspension was extended on September 24, 2026 from November 10 to January 10, 2027
Taxes and rebates	China	A 2% consumption tax on lithium-ion batteries from September 1, 2026; export rebate of value-added tax cut from 9% to 6% in April 2026	The tax rises to 4% in September 2027; the rebate ends January 1, 2027

IEEPA is the International Emergency Economic Powers Act. Tariff rates on specific products should be checked against the US tariff schedule.

China's export controls are the decisive lever: after the trade truce of October 30, 2025, Beijing suspended its October licensing of advanced batteries, cathode and anode materials, and equipment until November 10, 2026, and eased graphite checks for the United States until November 27. In September 2026 the two governments extended the truce to January 10, 2027, and the announcements did not mention the graphite date. The controls are paused, not gone, and the July 2025 restrictions on cathode and lithium-processing technology remain.

The expiry of the suspension is the largest scheduled risk in the battery trade, because if the controls return, Western cell plants that depend on Chinese cathode and anode material, and on Chinese coating and winding equipment, would need a license for every input.

13d. The Ford-CATL License

In February 2023 Ford announced a $3.5 billion LFP plant at Marshall, Michigan, BlueOval Battery Park, using CATL's technology under license, with Ford owning and running the plant and CATL supplying the process, equipment, and training. Ford paused construction in September 2023 amid political criticism and in November cut the plan by 43%, to 20 GWh.

The plant began pilot production in 2026, with CATL technicians training its workers, and Ford expects launch-ready cells before the end of 2026 for a midsize electric pickup in 2027, and its new Kentucky storage business also uses CATL's licensed technology. In January 2025 the Pentagon added CATL to its list of Chinese military companies, and in January 2026 the chairman of the House Select Committee on China, John Moolenaar, asked Ford whether its licensing terms had changed since the 2025 law.

13e. Licensing Chinese Technology: The Argument

The case for licensing. Ford, Michigan's officials, and many industry analysts argue that licensing is the fastest route to cost-competitive LFP cells made in America, since no Western company owned a competitive LFP process after A123's bankruptcy in 2012. The plant is American-owned, employs American workers, more than 500 in mid-2026 with 1,700 planned, and teaches them the process, while the alternatives are imported cells or Chinese-owned plants.

The case against. Moolenaar, other members of Congress, and many security analysts argue that licensing pays royalties and lends legitimacy to a company the Pentagon lists as a Chinese military company. They say it keeps American plants dependent on Chinese know-how, equipment, technicians, and materials, and that taxpayers' credits should not fund it, which is why the 2025 law restricts licensing deals signed or modified after its enactment.

The evidence. The license produced a plant, smaller and later than planned, that reached pilot production in 2026 with CATL's help, while most Western attempts to develop LFP independently have yet to reach scale. The 2025 law spared existing licenses unless modified, and the Pentagon's 2027 ban covers purchases, not licensed production. Alternatives now exist in grid storage, from LG Energy Solution's Michigan lines to Tesla's Nevada plant, though at small scale.

The course's reading. Licensing buys factories and time, not independence: it becomes a path to independence only if a plant learns the process well enough to improve it without its licensor, and Marshall's first years will show which it is.

13f. Where the Batteries Actually Flow

Cells and storage systems flow from China to Europe, the United States, Australia, and the Middle East, and electric cars from China to Europe, Southeast Asia, Latin America, and the Gulf. Materials flow from China to Korea, Japan, the United States, and Europe, while ore flows into China: lithium from Australia, Chile, and Argentina, nickel from Indonesia, cobalt from the Congo, and graphite from Mozambique and Madagascar.

Korean cells flow from Korean-owned plants in the United States and Hungary to Western automakers. The one large flow in the other direction is technology and capital: Western licensing of Chinese processes, and Chinese plants in Hungary, Spain, Morocco, Indonesia, Thailand, and Brazil built to serve markets that tax Chinese-made goods, so the map of factories has moved more than the map of ownership.

Module 13 Key Points

The Global Supply Chain and Trade Wars

• China holds more than 80% of cell capacity and more than 90% of anode material; the EU and US have 6-7% of cell capacity each.

• The 2025 law ended American consumer credits and limits production credits to products below rising thresholds of Chinese-linked content.

• Chinese lithium-ion batteries pay about 41% in American tariffs since July 24, 2026; Chinese electric cars pay over 100%.

• China's October 2025 controls on advanced batteries, materials, and equipment are suspended only until January 10, 2027.

• Ford licensed CATL's LFP process; supporters call it the fastest route, critics a dependence, and Marshall's first years will tell.

Module 13 Quiz

Check Your Understanding

1. What share of the world's battery-cell capacity did China hold at the end of 2025, by the IEA's count?

A) About half
B) Over 80%
C) About 20%
D) About two-thirds

2. What did the July 2025 budget law do to American battery incentives?

A) It doubled the production credit and extended it through 2035
B) It banned Chinese cells outright from all American projects
C) It left the 2022 law unchanged
D) It ended consumer credits and limited production credits

3. What is the total American tariff on Chinese lithium-ion batteries since July 24, 2026, by the module's count?

A) About 100%, as for cars
B) Zero, after the Supreme Court ruling
C) About 41%: 3.4% normal duty, 25% under Section 301, and 12.5% under the new Section 301 action
D) About 7.5%

4. What is the status of China's October 2025 controls on advanced batteries, materials, and equipment?

A) Suspended until January 10, 2027
B) In full force since early November 2025
C) Repealed permanently
D) Replaced by tariffs

5. What is the course's reading of the Ford-CATL license?

A) It buys factories and time, not independence
B) It already gave the United States independence in LFP
C) It should be banned outright as a security risk
D) It has no real bearing on the American supply chain

Module 14 — Recycling and Second Life

Circularity, With Its Economics

Recommended Reading / Reference

Reference: IEA, *Recycling of Critical Minerals* (2024); the EU Battery Regulation (2023/1542) on collection, recovery, and recycled content; Fastmarkets on China's rules for imports of black mass (2025); the companies' disclosures (Redwood Materials, Brunp, GEM, Glencore)

14a. Black Mass and the Two Routes

A spent battery is discharged, dismantled, and shredded, and the pack housing, the copper and aluminum foils, and the plastics are separated mechanically, leaving black mass, a powder of cathode and anode material that holds the lithium, nickel, cobalt, manganese, and graphite, from which two routes recover the metals.

Pyrometallurgy smelts the black mass at about 1,400°C (2,550°F) and recovers nickel, cobalt, and copper as an alloy, but it sends the lithium into slag and burns the graphite. It is robust and handles any chemistry, but it wastes the cheapest materials, which in an LFP battery are the only valuable ones.

Hydrometallurgy dissolves the black mass in sulfuric acid and precipitates the metals one by one: copper, then iron and aluminum, then cobalt, nickel, and manganese as sulfates, and finally lithium carbonate. It recovers more than 95% of the lithium, nickel, and cobalt at battery grade, and it is the route the industry is converging on, led, like everything upstream, by China, which processes most of the world's black mass. Direct recycling, which repairs cathode crystals without dissolving them, is the research frontier.

Route	Recovers	Loses	Recovery	Cost	Chemistry fit	Leaders
Pyrometallurgy	Nickel, cobalt, copper (as an alloy)	Lithium, graphite, manganese, aluminum, electrolyte	50-70% of value	Lower capital cost, more energy	NMC; any feed	Umicore, Glencore
Hydrometallurgy	Lithium, nickel, cobalt, manganese, copper (battery grade)	Most graphite, electrolyte	More than 95% of metals	More capital, chemicals, wastewater	NMC and LFP	Brunp (CATL), GEM, Redwood Materials
Direct (research)	The cathode crystal, intact	—	More than 90% targeted	Unknown	LFP especially	Laboratories, pilots

14b. The Economics by Chemistry

Chemistry	Recoverable value per tonne of black mass	Processing cost per tonne	Net	Implication
NMC 811	About $5,000-7,000 (nickel, cobalt, lithium)	$2,000-3,000	Profitable	Recyclers pay for the feed
NMC 622	About $6,000-8,000 (more cobalt)	$2,000-3,000	Profitable	The most valuable feed
LFP	About $1,000-2,000 (lithium only; iron and phosphate nearly worthless)	$2,000-3,000	Loss-making at 2024-25 lithium prices; closer to break-even after the 2026 rebound	Recyclers charge to take it; mandates required
Sodium-ion	About $300-500 (aluminum, some nickel and manganese)	$1,500-2,500	Loss-making	Compliance only

Indicative values at 2026 metal prices; they move with those prices.

Recycling pays when the recovered metals are worth more than the process, and an NMC battery yields nickel and cobalt worth recovering at almost any price, which is why recyclers have historically paid for NMC black mass. An LFP battery yields iron and phosphate worth almost nothing and lithium worth recovering only when lithium is dear, so at the prices of 2024-25 recyclers charged to take it.

That is the industry's central problem: the chemistry winning the market is the one that pays least to recycle, and the feedstock that makes recycling profitable is shrinking.

14c. The Industry and the Rules

China's Brunp, a CATL subsidiary, and GEM lead the world, each with capacity above a million tonnes a year. In the West, Redwood Materials, founded by Tesla's former chief technology officer, built the largest American operation in Nevada and South Carolina, and in June 2025 it turned toward reusing batteries for storage, starting with a 63 MWh system of second-life car batteries for Crusoe's data center in Nevada.

Li-Cycle, once the West's flagship, went bankrupt in 2025, and Glencore bought its assets in August, while Ascend Elements, Cirba Solutions, Umicore, and others operate, and Korean cell makers recycle their own scrap.

The trade in black mass now runs on rules: China began allowing imports of black mass that meets its standards on August 1, 2025. The EU went the other way, classifying black mass as hazardous waste in a March 2025 decision that becomes mandatory on November 9, 2026, which bars its export to countries outside the Organisation for Economic Co-operation and Development. Manufacturing scrap, 5-10% of a gigafactory's output, rather than retired batteries, is still most of the feedstock, and the first large wave of electric-car batteries reaches the end of its life around 2030-35.

Rule	Jurisdiction	Requirement	Date
Collection targets	EU	63% of portable batteries by the end of 2027 and 73% by 2030; 51% of light-transport batteries by 2028	2027-30
Recycling efficiency	EU	65% of lithium-ion battery mass recycled by 2025, 70% by 2030	2025-30
Material recovery	EU	Lithium 50% by 2027 and 80% by 2031; cobalt, copper, and nickel 90% by 2027 and 95% by 2031	2027-31

Rule	Jurisdiction	Requirement	Date
Recycled-content minimums	EU	Cobalt 16%, lithium 6%, nickel 6% in new batteries from 2031; 26%, 12%, and 15% from 2036	2031-36
Battery passport	EU	A digital record of origin, carbon footprint, recycled content, and health for electric-vehicle and industrial batteries	February 18, 2027
Federal rules	US	None comprehensive; state laws (California, New Jersey) on collection	—
Producer responsibility	China	Producers responsible for take-back; a tracing platform since 2018	In force

EU Battery Regulation (2023/1542).

14d. Second Life and the Circularity Arithmetic

A retired car pack with 70-80% of its capacity is no longer good enough for a car but adequate for stationary storage, and repurposing such packs is a real if small market, of which Redwood's systems for data centers are the largest example. Its limits are logistics, since packs are heavy and varied, warranty, since someone must be liable, testing, since each pack must be graded, and the falling price of new LFP systems, which makes a used NMC pack a hard sell.

The arithmetic of circularity is sobering: the IEA estimates that recycling could supply 10-20% of battery mineral demand by 2040 in an accelerated scenario, meaningful but far from replacing mining, because a fleet growing 20% or more a year retires only a few percent of its stock each year. Recycling is a supply-security and waste policy first and a source of minerals second.

Module 14 Key Points

Recycling and Second Life

• Hydrometallurgy recovers more than 95% of lithium, nickel, and cobalt at battery grade; pyrometallurgy loses the lithium.

• NMC black mass is worth $5,000-8,000 a tonne and recyclers pay for it; LFP's is worth $1,000-2,000, near or below processing cost.

• Brunp and GEM lead; Li-Cycle's assets went to Glencore in 2025, and Redwood turned toward second-life storage for data centers.

• The EU requires 80% lithium recovery by 2031, minimum recycled content from 2031, and a battery passport from February 2027.

• Recycling could meet 10-20% of mineral demand by 2040, because a fast-growing fleet retires only a few percent a year.

Module 14 Quiz

Check Your Understanding

1. Why is hydrometallurgy the route the industry is converging on?

A) It is the cheapest route by a wide margin
B) It handles only NMC
C) It recovers over 95% at battery grade
D) It needs no chemicals or wastewater handling

2. Why have recyclers charged to take LFP black mass?

A) It contains cobalt that must be removed
B) LFP is too toxic to process
C) EU rules forbid recycling it within the Union
D) Its value is below the cost of processing

3. What is most of today's recycling feedstock?

A) Consumer electronics
B) Scrap from battery factories
C) Retired grid batteries
D) Retired car packs

4. What recycled content will the EU require in new batteries from 2031?

A) Lithium 50%
B) Cobalt 26%, lithium 12%, nickel 15%
C) Cobalt 16%, lithium 6%, and nickel 6%
D) Half of each metal

5. Why can recycling supply only 10-20% of mineral demand by 2040, by the IEA's estimate?

A) Recycling does not yet work at industrial scale
B) The EU forbids it
C) Lithium cannot be recovered from black mass
D) The fleet grows far faster than it retires

Module 15 — Safety, Degradation, and Standards

What Fails, How, and What the Rules Require

Recommended Reading / Reference

Reference: NFPA 855 (2026 edition) and UL 9540A; EPRI's database and October 2026 report on storage failures; China's national standard (GB) 38031-2025 on traction-battery safety; the Swedish Civil Contingencies Agency's data on vehicle fires; the EU's delegated acts on the battery passport

15a. Thermal Runaway, by Chemistry

A lithium-ion cell fails by thermal runaway, when a defect, an overcharge, physical damage, or outside heat pushes a cell past a threshold: the SEI breaks down at about 90-120°C (195-250°F), then the electrolyte and the cathode decompose, and the reactions release heat faster than it can escape. The cell vents flammable gas, hydrogen, carbon monoxide, and methane, plus oxygen from nickel cathodes, and it can ignite or explode.

The danger is propagation, one cell's heat tipping its neighbors, which is why packs are built with barriers, spacing, and cooling to keep a single failure single, and chemistry sets the size of the risk.

Chemistry	Runaway onset	Peak temperature	Oxygen release	Gas volume	Severity	Notes
NMC 811 / NCA	About 150°C	800-1,000°C	Yes, large	High	Highest	Cathode oxygen feeds the fire; fastest propagation
NMC 622	About 170°C	700-900°C	Yes	High	High	
LCO	About 150°C	800°C and more	Yes	High	High	Phones, laptops
LFP	About 270°C	400-500°C	No	Moderate, but rich in hydrogen	Low to moderate	Fails by venting more than by flame; slower propagation
LMFP	About 250°C	About 500°C	No	Moderate	Low to moderate	
Sodium-ion (polyanion)	About 280°C	About 400°C	No	Low	Low	Shippable at zero volts
Solid-state (sulfide)	Higher	—	No liquid to burn	Hydrogen sulfide if wet	Lower, unproven at scale	

Approximate values from testing literature. In °F: 150°C is 302°F, 170°C 338°F, 250°C 482°F, 270°C 518°F, 280°C 536°F, 400°C 752°F, 500°C 932°F, 700°C 1,292°F, 800°C 1,472°F, 900°C 1,652°F, and 1,000°C 1,832°F.

Most fires trace to manufacturing defects such as metal particles or flawed separators, to physical damage, to charging faults, or, in grid systems, to water getting in and integration errors. Electric cars catch fire less often than combustion cars: in Sweden in 2022 the Civil Contingencies Agency counted 23 fires among 611,000 electric cars, about 0.004%, against about 3,400 among 4.4 million petrol and diesel cars, about 0.08%.

But battery fires are harder to extinguish, can reignite hours later, and produce toxic gas. For grid storage, EPRI found in October 2026 that failures per deployed GWh fell 98% worldwide from 2018 to 2025, as

codes, outdoor containers, and newer designs spread, though it could not isolate cell chemistry as a factor on its own.

15b. The Battery Management System

Every pack has a battery management system (BMS), the electronics that measure each cell's voltage, temperature, and current. It balances cells so that none is overcharged, either by bleeding charge from the fullest (passive balancing) or by moving it (active balancing). It estimates the state of charge and state of health from voltage and from counting the charge in and out, controls the cooling, logs faults, and disconnects the pack through contactors if anything drifts out of bounds.

The BMS is why a pack of thousands of cells behaves like one, it is where most of a pack's intellectual property lives, and it is the difference between a well-managed pack lasting fifteen years and a badly managed one failing in five. Software updates to its settings are how manufacturers have changed charging speed, range, and degradation after cars were sold, and, in recalls, how they have limited packs to 80% until cells could be replaced.

15c. Codes and Tests

Standard	Scope	What it requires	Adopted
UL 9540A	Stationary storage: the test method	Forces a cell, then a module, then a unit into thermal runaway and measures propagation, gas, and flame; the results set allowed spacing and size	US, and referenced worldwide
UL 9540	Stationary storage: system certification	A safety listing for the whole system	US
NFPA 855	Stationary storage: installation	Separation distances (3 feet, about 0.9 meters, between units and 10 feet, about 3 meters, from buildings unless testing shows less is safe), size limits, fire suppression, ventilation, explosion control, emergency plans	Most US building codes; the 2026 edition tightens the rules
California's Senate Bill 283 (2025)	Stationary storage in California	Developers must meet local fire authorities before applying, consult them after installation, and align designs with NFPA 855	In force
International Electrotechnical Commission (IEC) 62619 and 62933	Industrial and grid batteries	Cell and system safety	Europe, Asia
UN 38.3	Transport	Altitude, heat, vibration, shock, short-circuit, and overcharge tests before shipping, under United Nations rules	Worldwide
The UN's Global Technical Regulation (GTR) 20; the US Federal Motor Vehicle Safety Standard (FMVSS) 305	Vehicles	Crash, thermal, and electrical safety	Global; US
GB 38031-2025	Vehicles, China	No fire or explosion after a single cell's thermal runaway, and smoke that cannot harm occupants; a test of impacts to the pack's underside; no fire after 300 fast-charge cycles and a short circuit	Mandatory from July 1, 2026; the strictest in the world

Standard	Scope	What it requires	Adopted
EU Battery Regulation	All batteries	Carbon-footprint rules, due diligence (from August 2027), recycled content, the passport (February 18, 2027), removability	EU

The trend after Moss Landing (Module 8) is toward outdoor, isolated containers, LFP chemistry, wider separation, and explosion venting, with local moratoriums the main obstacle to siting. China's vehicle standard, in force from July 2026, sets the highest bar in the world: no fire or explosion at all after a single cell runs away. It is driving pack designs with barriers between cells, directed venting, and immersion cooling that Western standards do not yet require.

15d. Degradation, Warranties, and the Battery Passport

Batteries age in two ways, as Module 2 explained: calendar aging is the SEI thickening whether or not the battery is used, faster when it is hot or held at a high charge, and cycle aging is the expansion that cracks electrodes and traps lithium. The practical rules follow: keep nickel packs between 20% and 80% charge when possible, while LFP tolerates 100%, and avoid heat and constant fast charging.

Warranties are the industry's commitment: typically eight years or 100,000 miles (160,000 km) at 70% capacity for American cars, longer terms from many Chinese brands, and ten to fifteen years or a cycle count, often 6,000-8,000, for grid systems, with contracts to add cells as capacity fades.

The EU's battery passport, mandatory from February 18, 2027 for electric-vehicle and industrial batteries, is a digital record reached by a code on the battery. It holds the maker, the carbon footprint, the origin of the materials and the due diligence on them, the recycled content, and the state of health over the battery's life. It is meant to give the used market a reason to trust, to enforce the recycling rules, and, once carbon limits are set, to favor cells made with low-carbon electricity.

Module 15 Key Points

Safety, Degradation, and Standards

• Thermal runaway begins near 150°C (302°F) in nickel-rich cells, which release oxygen, and near 270°C (518°F) in LFP, which releases none.

• In Sweden in 2022, 0.004% of electric cars caught fire against 0.08% of petrol and diesel cars; battery fires are harder to fight.

• EPRI found storage failures per deployed GWh down 98% from 2018 to 2025 as codes and outdoor designs spread.

• China's GB 38031-2025, mandatory from July 1, 2026, forbids fire or explosion after a single cell runs away.

• The EU's battery passport, from February 18, 2027, records each battery's origin, carbon footprint, recycled content, and health.

Module 15 Quiz

Check Your Understanding

1. Why does nickel-rich NMC fail more violently than LFP?

A) It holds more lithium per cell
B) Its cathode releases oxygen
C) It has a thicker, hotter separator
D) It runs at a lower voltage than LFP

2. How did fire rates of electric and combustion cars compare in Sweden in 2022?

A) About 0.004% of electric cars, 0.08% of the rest
B) Electric cars burned about ten times as often per car
C) The rates were equal
D) No electric car caught fire

3. What does China's GB 38031-2025 require from July 1, 2026?

A) LFP in every new car
B) No fire after one cell runs away
C) A five-year warranty on every pack
D) Air cooling in every new pack made in China

4. What does a battery management system do?

A) It monitors and balances the cells
B) It forms the SEI during the factory's first charge
C) It stops thermal runaway once it has begun
D) It certifies the pack under UL 9540A

5. What is the EU battery passport?

A) A shipping document for dangerous goods
B) A tariff exemption for European cells
C) A warranty card guaranteeing 70% of capacity
D) A digital record of each battery's origin

Module 16 — Other Markets

Devices, Two-Wheelers, Trucks, Aviation, Marine, and Defense

Recommended Reading / Reference

Reference: Benchmark Mineral Intelligence on 2025 battery demand by segment (January 2026); IEA, *Global EV Outlook 2026*, on electric trucks; the National Defense Authorization Act for fiscal 2024 on the Pentagon's battery purchases; the companies' disclosures (Tesla, CATL, Amprius)

16a. The Segments

Segment	Share of 2025 lithium-ion demand	Main chemistry	What matters	2026 trend
Electric vehicles: cars, buses, trucks, two-wheelers	About 75% (about 1.2 TWh)	LFP in China and for standard range; NMC in the West and for long range	Cost, range, charging	Electric trucks reached 9% of the world's truck sales in 2025; Tesla's Semi entered volume production
Stationary storage	About a fifth, and growing fastest (up about 51% in 2025)	LFP	Cost per kWh, cycle life, safety	The fastest growth of any segment
Consumer electronics	About 5%	LCO and NMC pouches; silicon-carbon anodes	Energy per liter, safety	Flat; bigger phone batteries
Power tools, drones, aircraft	Small	NMC cylinders; silicon-dominant and lithium-metal cells	Power, energy per kilogram	Drones surging with war and delivery; air taxis delayed
Marine and defense	Small	LFP, NMC, lithium titanate, primary lithium	Safety, reliability, supply security	Ferries electrifying; Pentagon purchases from six Chinese firms banned from October 2027

Benchmark Mineral Intelligence put 2025 demand at 1.59 TWh, up 29%, with electric vehicles 75% and portables 5%; the IEA counted 1.2 TWh of electric-vehicle batteries.

16b. Consumer Electronics

The market that created lithium-ion is now a small share of it, dominated by pouch cells of lithium cobalt oxide or high-nickel NMC chosen for energy per liter, because a phone cares about millimeters, not grams. The innovation of 2025-26 is the silicon-carbon anode, which let Chinese phone makers such as Honor and Xiaomi fit batteries of 6,000-7,000 milliamp-hours in the space that once held 4,500.

The segment's safety record, from Samsung's Galaxy Note 7 recall in 2016 to the e-bike fires in New York, is why the UN's transport tests exist and why airlines restrict lithium batteries in checked bags.

16c. Two-Wheelers, Buses, and Trucks

Electric two- and three-wheelers, hundreds of millions of them, most in China and the rest of Asia, are the largest electric fleet on earth by count. They run on lead-acid, LFP, and now sodium, and battery swapping, from Gogoro in Taiwan to dozens of Chinese and Indian networks, solves charging for riders without

garages. Electric buses were LFP's first success, from BYD and Yutong, and Shenzhen's fleet of about 16,000 buses was fully electric by 2017.

Heavy trucks are the frontier: electric trucks were 9% of the world's truck sales in 2025, more than double 2024's share, and one in four trucks sold in China was electric, on cheap LFP, megawatt charging, and battery swapping, including CATL's network for heavy trucks. They still cost two to three times as much as diesel trucks to buy, by the IEA's count. Tesla's first Semi came off its high-volume line in Nevada on April 29, 2026, rated for up to about 500 miles (about 800 km).

The economics turn on the pack: a long-haul truck needs 600-900 kWh, which at $100 per kWh is $60,000-90,000 of battery and a payload penalty of 2-4 tonnes, and it needs chargers of a megawatt or more. Hydrogen trucks, the alternative, have stalled on the cost of fuel, and Nikola, their best-known American maker, went bankrupt in February 2025.

16d. Aviation, Marine, and Defense

Aviation is where energy per kilogram is worth almost anything, and a kilogram of jet fuel holds about 12,000 watt-hours while a kilogram of the best battery holds about 400, a ratio of about thirty to one, narrowed to about ten by the electric motor's higher efficiency. Electric flight is therefore limited to drones, trainers, and short hops.

Drones, military and commercial, are the fastest-growing battery market by count, using silicon-dominant and lithium-metal cells from Amprius and others. Electric air taxis have slipped repeatedly on certification and range, and Lilium of Germany went insolvent in 2024-25, and CATL claims a 500 Wh/kg cell for regional aircraft.

Ships electrify on LFP and NMC, in ferries such as Norway's fleet, harbor craft, and hybrid vessels, under safety rules from classification societies such as DNV, the Norwegian firm, which are stricter than those on land after several vessel fires. Defense, from soldiers' packs to Japan's lithium-ion submarines, demands reliability from −40°C to 60°C (−40°F to 140°F) and, above all, secure supply.

The defense bill for fiscal 2024 bars the Pentagon from buying batteries from CATL, BYD, Envision, EVE, Gotion, and Hithium from October 2027, making defense the one segment where a Western supply chain is being built regardless of cost.

Module 16 Key Points

Other Markets

• Electric vehicles took about 75% of 2025's 1.59 TWh of lithium-ion demand; storage grew fastest, up about 51%.

• Silicon-carbon anodes let Chinese phones carry 6,000-7,000 mAh batteries in the space that held 4,500.

• Electric trucks were 9% of world truck sales in 2025 and a quarter in China, though they cost two to three times diesel.

• Jet fuel holds about thirty times a battery's energy per kilogram, so electric flight is drones, trainers, and short hops.

• From October 2027 the Pentagon may not buy batteries from six Chinese makers, including CATL and BYD.

Module 16 Quiz

Check Your Understanding

1. Why do phones use lithium cobalt oxide or high-nickel pouch cells rather than LFP?

A) LFP costs more
B) LFP is banned in phones
C) Phones need the most energy per liter
D) Regulations require cobalt

2. What share of the world's truck sales were electric in 2025, by the IEA's count?

A) About 50%
B) Under 1%
C) About 30% in Europe and none in China
D) About 9%, and about a quarter in China

3. What is the main battery problem of a long-haul electric truck?

A) Trucks cannot use LFP
B) Truck motors cannot run on batteries at highway loads
C) A costly 600-900 kWh pack that cuts payload
D) Trucks need sodium cells

4. Why is electric flight limited to drones, trainers, and short hops?

A) Jet fuel holds 30 times the energy per kg
B) Batteries fail in the cold at high altitude
C) Electric motors are too heavy for aircraft
D) Regulators forbid any longer electric flights

5. In which segment is a Western supply chain being built regardless of cost?

A) Consumer electronics
B) Defense, under the Pentagon's ban
C) Two- and three-wheelers across Asia
D) Grid storage for the American utilities

Module 17 — Where Things Stand, and What to Watch

The Argument, the Turning Points, and the Dates

Recommended Reading / Reference

Reference: IEA, *Global EV Outlook 2026* and *Global Energy Review 2026*; BloombergNEF's December 2025 price surveys and 1H 2026 storage outlook; China's Ministry of Commerce and Ministry of Finance announcements; the companies' published schedules

17a. The Argument

A battery is a controlled chemical reaction, and the industry built on it is a controlled cost curve. Pack prices fell about 90% between 2010 and 2025, to $108 per kWh, because LFP spread, factories grew, and yields rose, and that decline made electric cars cheaper than combustion cars in China and made batteries the fastest-growing technology on the world's grids.

The curve is now steered less by chemistry than by manufacturing scale and policy, and both are Chinese. China holds more than 80% of cell capacity and more than 90% of anode material, and in 2025-26 it showed it could bend the curve both ways. It announced export licensing and then suspended it, under a truce now extended to January 10, 2027, and it taxed its own batteries, cut an export rebate that ends on January 1, 2027, and paused approvals of new plants. The United States answers with tariffs of about 41% on Chinese cells and rules on Chinese content, Europe with duties on Chinese cars but none on cells, and both with licenses for Chinese processes.

Measure	2025	What 2026 is expected to bring	Source
Average battery pack price	$108 per kWh, down 8%	BloombergNEF's December 2026 survey; Chinese storage-cell prices rose almost 40% from their 2025 low by July	BloombergNEF; InfoLink
Electric-car sales	More than 20 million, about a quarter of the market	23 million, 28%	IEA
Grid storage added	112 GW and 307 GWh, up 48%	158 GW and 459 GWh	BloombergNEF
Storage cells shipped	612 GWh, up 95%	About 800 GWh	InfoLink
Lithium-ion demand	1.59 TWh, up 29%	Further growth, led by storage	Benchmark Mineral Intelligence

17b. The Bifurcation

The industry is splitting into two tiers: the high tier, nickel-rich NMC, then silicon-carbon anodes, then hybrid and all-solid cells, serves the applications where energy per kilogram is worth paying for, such as long-range and premium cars, aircraft, drones, and devices. The volume tier, LFP and LMFP now and sodium-ion increasingly, serves everything else: standard-range cars, buses, trucks, two-wheelers, and nearly the entire grid.

The volume tier is where the gigawatt-hours are, where China's lead is widest, and where the West depends most on Chinese licenses. The frontier that matters commercially is not the one in the headlines, solid-state, but the ones already in cheap cars and storage cabinets, sodium, and in phones, silicon.

17c. Six Turning Points, One Lesson

Six turning points, each taught in its home module, carry one lesson, and the first, the lithium spike of 2021-22 (Module 12), raised pack prices for the first time and drove the industry toward LFP and sodium, showing that volatility rather than scarcity drives substitution. Northvolt's collapse (Module 5) showed that manufacturing is learned, not bought.

The Moss Landing fire (Module 8) showed that the oldest designs shape public trust in the newest, the Ford-CATL license (Module 13) revealed that the West depends on Chinese processes as well as Chinese cells, and China's export controls of 2023-25 (Module 13) showed that the processing bottleneck is a weapon. Sodium's arrival at the bottom of the market (Module 9) showed that the next chemistry comes in the cheapest products, not the most expensive.

None of the six was a breakthrough in chemistry: Yoshino's carbon anode dates from 1985 and LFP was published in 1997, so the chemistry of 2026 is mostly the chemistry of the 1980s and 1990s. What changed is who can make it, at what yield, from what inputs, and who controls those.

17d. Five Contradictions

- **The winner and the recyclers:** LFP is winning the market because it is cheap, and for the same reason it is the chemistry that pays least to recycle.
- **The tariff and the license:** the United States taxes Chinese cells at about 41% while its automakers license Chinese processes to make the same cells at home.
- **The glut and the price rise:** more than 4 TWh of capacity faced about 1.6 TWh of demand in 2025, yet Chinese storage-cell prices rose almost 40% from their 2025 low by July 2026, because lithium did.
- **Safety and siting:** storage failures per deployed GWh fell 98% from 2018 to 2025 while local moratoriums multiplied.
- **Escape and dependence:** nearly every Western plant built to escape Chinese supply runs on Chinese cathode, anode, or equipment that Beijing can license, and that it has agreed not to license only until January 10, 2027.

17e. The Watch List

What	When	Why it matters
The US midterm elections	November 3, 2026	The future of the remaining credits, the tariffs, and the rules on Chinese content
The EU's classification of black mass as hazardous waste becomes mandatory	November 9, 2026	Recycling flows within and out of Europe
China's suspension of stricter graphite checks for the US reaches its end date, which the truce's extension did not mention	November 27, 2026	The anode supply of American cell plants
BloombergNEF's 2026 battery price survey	December 2026	Whether pack prices fell in a year when cell prices rose
China's year-end review of battery capacity	End of 2026	Whether approvals of new plants resume
Ford's first launch-ready LFP cells from Marshall; CATL's promised sodium cost parity	End of 2026	Licensing's first test; sodium's case
China ends its export rebate on batteries	January 1, 2027	Higher prices for Chinese cells abroad

What	When	Why it matters
The extended truce ends, and with it China's suspension of its October 2025 controls on advanced batteries, materials, and equipment	January 10, 2027	Another extension, selective renewal, or reimposition: the largest scheduled risk in the trade
The EU battery passport becomes mandatory	February 18, 2027	Traceability and the used-car market
Form Energy's first commercial iron-air system; Ford's storage systems from Kentucky	2027	Long-duration storage and American LFP
The first all-solid-state production: CATL's at small scale, Samsung SDI's in the second half of the year; Toyota's to follow	2027; Toyota 2027-28	Whether solid-state claims become products
The EU's due-diligence rules for batteries apply	August 18, 2027	Supply-chain audits
China's consumption tax on lithium-ion batteries rises to 4%	September 1, 2027	Domestic battery prices
The Pentagon's ban on batteries from six Chinese makers	October 2027	The defense supply chain
China's tax exemption for sodium-ion and solid-state cells ends	End of 2028	Sodium's head start
The root cause of the Moss Landing fire, from the analysis by Vistra and an independent consultant that the California Public Utilities Commission reports under way	Not yet scheduled	Siting rules and local moratoriums

17f. The Last Word

The throughline of these seventeen modules is a cost curve that fell 90% in fifteen years, that is now steered by manufacturing scale and policy rather than chemistry, and that is, for the volume of cells that matter, Chinese. The technology has done what was asked of it: electric cars cost less than combustion cars in the largest market, and batteries carry the evening peak on the grids that have built them.

What it has not done is spread evenly: the West lags on cost, has reversed course on policy, licenses processes it could not learn, and depends on a chain it is trying to escape, and no one has yet solved the long-duration storage that a grid run mostly on wind and sun will need. The next chemistry that matters is already in cheap cars and storage cabinets, the one in the headlines is years from mattering, and the mineral question has become a question of processing, with a deadline on January 10, 2027, when the extended truce ends.

Module 17 Key Points

Where Things Stand, and What to Watch

• Pack prices fell about 90% to $108 per kWh in 2025; the curve is now steered by Chinese scale and by policy.

• The industry is splitting: a high tier for energy per kilogram and a volume tier, LFP and sodium, for everything else.

• Six turning points from 2021 to 2026 carry one lesson: manufacturing and materials, not chemistry breakthroughs, decide the industry.

• The United States taxes Chinese cells at about 41% while licensing Chinese processes to make them at home.

• Watch January 10, 2027, when China's extended battery-control suspension expires, then the EU passport on February 18, 2027.

Module 17 Quiz

Check Your Understanding

1. What steers the battery cost curve in 2026, according to the closing module?

A) New chemistry alone, as in the 1990s
B) Scale and policy, mostly Chinese
C) Cobalt supply from the Congo's big mines
D) American subsidies

2. What is the bifurcation the module describes?

A) A split between cylindrical and pouch cells
B) A split between Korean and Japanese makers
C) A split between cars and phones
D) A high tier for energy per kilogram and a volume tier, LFP and sodium, for everything else

3. What lesson do the six turning points share?

A) That breakthroughs in chemistry decide the industry
B) That regulation decides everything in it
C) That manufacturing and materials decide
D) That Western firms still lead the industry

4. Why does the module call the American tariff and the Ford-CATL license a contradiction?

A) Because it taxes Chinese cells while licensing their processes
B) Because the license was cancelled after the 2025 budget law passed
C) Because the tariff was struck down
D) Because China banned the license

5. What happens on January 10, 2027?

A) China's control suspension ends
B) The EU battery passport becomes mandatory
C) The Pentagon's ban on six Chinese makers begins
D) China's consumption tax on batteries rises to 4%

Answer Sheet

Answers to every module's Check Your Understanding quiz.

Module	Answers
Module 1 Quiz	1. A 2. B 3. D 4. C 5. B
Module 2 Quiz	1. C 2. D 3. A 4. B 5. A
Module 3 Quiz	1. C 2. D 3. D 4. A 5. B
Module 4 Quiz	1. C 2. C 3. D 4. B 5. A
Module 5 Quiz	1. D 2. A 3. C 4. B 5. A
Module 6 Quiz	1. B 2. D 3. C 4. B 5. D
Module 7 Quiz	1. A 2. C 3. D 4. C 5. A
Module 8 Quiz	1. B 2. B 3. A 4. D 5. C
Module 9 Quiz	1. B 2. A 3. C 4. D 5. C
Module 10 Quiz	1. B 2. A 3. D 4. D 5. B
Module 11 Quiz	1. C 2. A 3. B 4. C 5. A
Module 12 Quiz	1. D 2. B 3. A 4. D 5. C
Module 13 Quiz	1. B 2. D 3. C 4. A 5. A
Module 14 Quiz	1. C 2. D 3. B 4. C 5. D
Module 15 Quiz	1. B 2. A 3. B 4. A 5. D
Module 16 Quiz	1. C 2. D 3. C 4. A 5. B
Module 17 Quiz	1. B 2. D 3. C 4. A 5. A