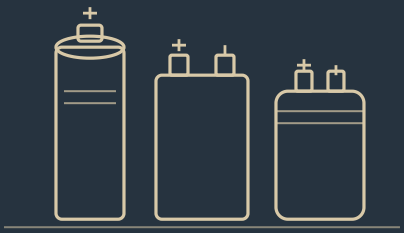
INDUSTRIES OF INDIA

THE LITHIUM-ION BATTERY

Ion, Cell, Charge



KETINENI RAMARAO

The Lithium-ion Battery

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Industries of India

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First edition, November 2026.
Industries of India — a research effort to map all industries in India, approached through study and theory.
industriesofindia.com

In the industry map: filed under GICS 20104010 (Industrials → Capital Goods → Electrical Equipment), with cross-links into the automobile, semiconductor, mining, chemical, utility and consumer-electronics branches of the library. Classification is an editorial framework, not a claim about any market.

Every reference number in this book resolves in its source companion, *The Lithium-ion Battery: Source Companion*, which records what each source is, how fully it was read, and its limits.

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PART ONE

The Element

Before the battery there was the metal: light, reactive, and for a century and a half almost useless. This is where the story has to start - with a stone, a flame, and an element that waited for its century.

CHAPTER 1

A Stone That Burns Crimson

On the island of Utö, in the Stockholm archipelago, there is an iron mine that Swedes have worked since the twelfth century. It is an unglamorous hole in the Baltic rock, but twice it has handed the world a new element. From Utö’s ore came the mineral ytterbite, which gave chemistry the whole family of rare earths. And around 1800, a Brazilian mineralogist serving the Portuguese crown, José Bonifácio de Andrada e Silva, picked out of the same workings a pale, glassy stone that behaved

strangely: tossed onto a fire, it flared an intense crimson. He named it petalite, for its leaf-like cleavage, and thought little more of it. [1.1]

Seventeen years later the stone reached the laboratory of Jöns Jacob Berzelius in Stockholm, then the most exacting chemical workshop in Europe. Berzelius set his young assistant, Johan August Arfvedson, to analyse it. The arithmetic would not close. Arfvedson accounted for silica, alumina, and the known alkalis, and still a few percent of the stone's weight belonged to nothing anyone had seen. In 1817 he announced a new alkali metal, lighter than sodium, hidden in the stone's crimson flame. Berzelius named it from the Greek *lithos*, stone: lithium — the metal from a rock, to stand beside sodium from soda and potassium from potash, which Humphry Davy had torn out of their compounds with his voltaic battery only a decade earlier. [1.1]

Arfvedson could never hold his element. It clung too tightly to its compounds. William Brande coaxed out a few grains by electrolysis in 1821, too little to weigh, and only in 1855 did Robert Bunsen and Augustus Matthiessen run a strong current through molten lithium chloride and collect the metal in quantity — a silvery something so light it floated on the oil it had to be stored under, so eager to react that it tarnished in air within seconds and hissed on water. [1.1]

The character of the metal

Everything the lithium-ion battery became is written in that paragraph. Lithium is the lightest metal in creation, with a density of about half that of water. It is the third element of the periodic table, three protons and three electrons, and it holds its outermost electron so loosely that it is among the most electropositive substances known: measured against the standard hydrogen electrode, the lithium couple sits at −3.04 volts, near the very top

of the electrochemical series. [1.2] A metal that wants, almost desperately, to give away an electron is a metal that wants to be a battery. The same eagerness makes it useless as a material in the ordinary sense. You cannot build a bridge out of lithium; the rain would dissolve it in flame. Its only structural use is to be consumed — to react, to give up that electron, to become a compound again. For a century and a half after Arfvedson, chemistry had no idea what to do with such a creature.

The twentieth century found it odd jobs, and the odd jobs are a history of industrial chemistry in miniature. Lithium carbonate, added to glass and glazes, lowers the melting point and the thermal expansion; the great heat-proof kitchen glass of the mid-century owed its composure to spodumene from the same mineral family as Arfvedson's stone. Lithium stearate, a soap of lithium and fat, made a grease that stayed put from arctic cold to engine heat, and the Allied air forces of the Second World War ran their aircraft on it; lithium grease has never really been displaced since. In the electrolysis of aluminium, a dash of lithium fluoride in the cryolite bath cuts the power bill of every smelter. And in 1948 an Australian psychiatrist, John Cade, working in a repatriation hospital outside Melbourne with guinea pigs, urine, and a hunch about what caused mania, noticed that lithium salts calmed his animals; he tried the salt on himself, then on his most agitated patients, and in 1949 published the quiet paper that founded modern psychopharmacology. Lithium carbonate remains, three quarters of a century later, a standard treatment for bipolar disorder — the same element that steadies a mood and starts a fire, depending only on the chemistry around it. [1.3] [1.4]

None of this used very much lithium. As late as the 1980s the entire world output of the metal was a few tens of thousands of tonnes a year, drawn from a handful of mines and salt lakes, priced and traded as a specialty chemical for greases and glass. The

element had been sitting in the periodic table for 170 years as a curiosity with a grease job.

The turn

The statistics of the turn are stark enough to quote from a single dry government document. The United States Geological Survey, which has tracked the world's lithium since the metal mattered to no one, records that in 2024 roughly 87 percent of all lithium consumed on Earth went into batteries. Ceramics and glass, the old mainstay, took five percent; lubricating greases, the wartime market, took two. Everything else — the air conditioning, the casting powders, the medicine — shared the remainder. [1.2] A demand that barely existed when the Berlin Wall fell now consumes the element almost entirely, and pulls the mining industry after it: world lithium production, excluding the United States, rose about eighteen percent in 2024 alone, to some 240,000 tonnes of lithium content, six times what the world used a decade earlier. [1.2]

What happened between the grease and the gigafactory is the subject of this book. It is not a story of a single eureka. The lithium-ion battery was assembled over twenty years, in an oil company's research laboratory, in a physics department in Oxford, and in a chemical company in Osaka, by men who mostly did not know one another and were not trying to make the same thing. It was then manufactured into dominance, first by Japanese electronics firms, then by Korean conglomerates, and finally — decisively — by Chinese companies that turned a laboratory device into one of the largest manufacturing industries on Earth. Along the way it dissolved and remade the economics of the telephone, the laptop, the power tool, the automobile, and increasingly the electric grid itself.

The story also has a geography, and the geography is uncomfortable. The metal is torn from salt flats in the Andes and hard rock in Western Australia; the cobalt that steadied its first chemistry comes mostly from the Congo; the nickel that lengthens its reach comes increasingly from Indonesia; and the processing, the refining, the components and the cells themselves are made, in overwhelming proportion, in China. To follow one rechargeable cell from the ground to your pocket is to tour the industrial map of the twenty-first century, and to understand why governments that never thought about batteries before 2020 now write strategy papers about little else.

The naming of a metal that would not come out

The difficulty Arfvedson left behind is worth dwelling on, because it set the pattern for everything lithium did afterward. Davy had shown the way with sodium and potassium: run a current through the molten compound and the metal appears at the negative pole, globules of it, dancing and burning. Lithium refused. Its compounds cling to the electron too tightly — the same stubbornness, measured as electrode potential, that would one day make it precious to batteries — and the methods that liberated sodium produced, from lithia, nothing. Brande's 1821 success was a whisper of metal, enough to say the element existed, not enough to weigh. The element existed on paper, in flame tests, in the arithmetic of analyses that refused to close — a metal known by its absence for nearly forty years. [1.1]

When Bunsen and Matthiessen finally ran molten lithium chloride through a strong cell in 1855 and collected the metal properly, the character reported in the textbooks was already fixed: soft as wax, light beyond precedent, reactive beyond convenience. It floated on petroleum. It cut like cheese. It disappeared the moment you gave it air to work with. The metallurgists of the nineteenth century had

a category for such substances: laboratory curiosities, elements that completed the periodic table's bookkeeping and otherwise paid no rent. [1.1]

The lithia waters

There is a stranger footpath through the century, and it runs through medicine. Lithium salts dissolve easily, and nineteenth-century medicine, meeting a soluble salt of an alkali metal, did what it did with everything soluble: prescribed it. Gout was the great target — the theory held that lithium dissolved uric acid, and lithium waters and lithium tablets were dispensed across Europe and America for "uric acid diathesis," gout, rheumatism, and the whole swollen catalogue of Victorian complaints. Alexander Garrod, the London physician whose name Cade would cite a century later, gave lithium its respectable medical footing in the 1850s and 60s. [1.4] The fashion left traces in odd places: mineral springs advertised their lithium content as a virtue, and when a St. Louis soft-drink maker launched a lemon-lime "lithiated" soda in 1929 — the drink that became 7 Up — lithium citrate was in the recipe, and stayed there until 1948. The element's first mass market, long before the battery, was the claim that it made people feel better. [1.4]

Cade's 1949 paper belongs to this lineage even as it transcends it. Working in a Victorian-era hospital kitchen-laboratory with no research budget, testing a hypothesis about uric acid and mania, he injected guinea pigs with lithium urate and watched the animals grow placid; the careful chain from that observation to the first patient, a man with chronic mania who improved enough to leave the hospital, is the founding story of psychopharmacology. The detail that matters here is the material one: the treatment is lithium carbonate, a simple salt, given in gram quantities, working by mechanisms still argued about seventy-five years later. The

same element that would not leave its compounds for forty years, given to a mind, changes the weather of it. Material thinking has no better exhibit. [1.4]

But the element comes first. Before the industry, before the science, before the money: a pale stone from an old iron mine, a crimson flame, and a metal so restless it took mankind a century and a half to find its use. The use, when it came, turned out to be storing the weather.

CHAPTER 2

The Lightest Metal’s Problem

A battery is a machine for turning chemistry into current. Strip away the casings and the marketing and every battery ever made is the same arrangement: two materials that want to trade electrons, separated so that the trade cannot happen directly, forced instead to send the electrons the long way round — through a wire, through a phone, through a motor — while ions slip across inside to keep the books balanced. The voltage of the battery is the measure of how badly the two materials want to make the trade. The capacity is how much trading they can do before they reach equilibrium and die.

If you accept that definition, the logic that leads to lithium is almost a syllogism. You want one partner that gives up electrons as eagerly as possible — that fixes the anode — and one that accepts them as hungrily as possible, for the cathode. Run down the periodic table with a table of electrode potentials and the anode search ends quickly. At −3.04 volts against the standard hydrogen electrode, lithium stands at the extreme of the metals: nothing common wants to be oxidised more. [2.1] And because the energy

a battery stores is charge multiplied by voltage, a light anode at an extreme potential is the theoretical summit: lithium metal can in principle carry about 3,860 milliamp-hours of charge per gram, the highest specific capacity of any practical anode material, at the lowest electrochemical potential. [2.2] On paper, no better battery anode can exist. The whole subsequent history of the lithium battery is the story of engineers discovering why “on paper” was doing a great deal of work in that sentence.

Three problems

The first problem is water. The chemistry of the classical battery — the zinc-carbon torch cell, the lead-acid car battery — is aqueous. Lithium will not tolerate it. Drop lithium metal into water and it does not merely corrode like sodium’s quieter cousin; it skates across the surface fizzing violently, generating hydrogen, and if the piece is large enough the hydrogen ignites. Any electrolyte that touches lithium must therefore be built from organic solvents or solids, and everything that follows — the cost, the flammability, the factory dry rooms — descends from that exclusion.

The second problem is that lithium does not deposit tidily. When you recharge a lithium-metal anode, you are plating fresh lithium back onto it from the electrolyte, and metal plating at a surface is rarely smooth. Under repeated charging the lithium grows not as an even film but as filaments — dendrites, whiskers of metal that reach out through the electrolyte like frost on a window. Left long enough, a whisker crosses the gap and touches the other electrode. The cell then has an internal short circuit: all its stored energy dumps through a metal thread that heats like a fuse wire, in contact with a flammable organic electrolyte. The result, in the dry language of the Nobel Prize’s own scientific background, is that the dendrites “grew across the electrolyte to the cathode to create an internal short circuit, which would ignite the flammable

electrolyte.” [2.1] This is not a marginal failure mode. It is the central engineering problem of lithium batteries, and it was still making headlines — in laptops, airliners and grid-storage plants — half a century later.

The third problem is subtler. Even where nothing catches fire, a fresh lithium surface reacts with any organic electrolyte it touches, consuming both metal and solvent in parasitic side reactions. Every charge cycle spends a little of the battery on chemistry that stores nothing. A rechargeable cell that eats itself is a product with a short, expensive life.

The compromise that worked first: do not recharge

The industry that grew up around lithium in the 1970s made an entirely rational decision: it gave up on recharging. Primary lithium batteries — built once, discharged once, thrown away — avoid the dendrite problem because the lithium anode is only ever consumed, never re-plated. Freed from the need to reverse anything, chemists could pair lithium metal with cathodes of spectacular appetite. The lithium–thionyl chloride cell delivered enormous energy and a twenty-year shelf life for meters, sensors and military kit. The lithium–manganese dioxide cell became the coin battery that still runs watches, calculators, car keys and motherboards. And in 1972 came the most consequential primary lithium cell of all: Wilson Greatbatch’s lithium–iodine battery for implantable cardiac pacemakers. [2.3]

The pacemaker battery deserves a paragraph, because it shows what lithium could do even in chains. Earlier pacemakers ran on zinc–mercury cells that faded within two years; a patient faced repeated surgery just to change the power source. Greatbatch’s cell was chemistry of an elegant poverty: a lithium anode, an iodine cathode, and between them nothing but a thin skin of lithium iodide that formed where the two met — a solid electrolyte,

self-healing, so stable that the battery could be welded hermetically into the steel case of the pacemaker itself and trusted inside a human chest for a decade. [2.3] Millions of people are alive because lithium, sealed away from air and water and never asked to reverse, is the most dependable source of trickle current chemistry knows. But a battery that cannot be recharged is, for most purposes, a fuel canister, not an engine. The world kept burning its lithium once and throwing it away, and everyone in the field knew the prize was a cell that could be run backwards.

Why not something calmer?

It is worth asking, as many did in the 1970s, whether the prize was worth the element. Sodium sits directly beneath lithium in the periodic table, is a thousand times more abundant, costs almost nothing, and behaves similarly — similarly, but measurably worse: its electrode potential is less extreme, its ion is larger and heavier, and a sodium battery is simply a lithium battery with the energy taken out. (Sodium's time would come, but only fifty years later, and for reasons of cost and geopolitics rather than physics.) Lead, cadmium, nickel — the incumbents — were heavier still and lower in voltage. Physics had picked lithium; the question was whether engineering could tame it.

The measures of the trade

A working vocabulary for what follows, since the industry speaks in these units and this book will not translate them again. Energy is measured in watt-hours; a phone cell holds about fifteen, a car pack fifty to a hundred thousand, a grid container five million. Specific energy — watt-hours per kilogram — decides what can move; energy density — watt-hours per litre — decides what can fit. The first commercial cells of 1991 carried about 80 watt-hours per kilogram and 200 per litre; the best nickel-rich cells of the late

2010s exceeded 250 and 700 respectively, and the improvement continues. [2.4] Power — the rate of delivery — is measured against capacity as the C-rate: a 1C discharge empties a cell in an hour, and the 12C charging rates now claimed for the fastest cells mean a full charge in five minutes, heat and chemistry permitting. [2.5] Cycle life counts full charges before the cell holds only eighty percent of what it did; 500 cycles made a good phone battery of 2005, 3,000 makes a car cell, 10,000 and more an LFP storage cell today. Behind all four numbers sits the fifth, the one that decides everything else: cost per kilowatt-hour, whose long collapse is the subject of Chapter 22.

These measures trade against one another, and the trades are the industry's daily bread. Raise the nickel for specific energy and you spend cycle life and thermal margin; thicken the electrode for energy density and you lose power; chase 4C charging and the anode designer starts sleeping badly. A battery datasheet is a negotiated settlement among five competing virtues, and every product segment — phone, car, grid, drill, satellite — settles differently. The chapters ahead will treat those settlements as the fingerprints of their industries.

The primary empire

The throwaway lithium battery built an empire of its own before the rechargeable one existed, and it still prospers in the rechargeable's shadow. The lithium-thionyl chloride cell — liquid-cathode chemistry, 3.6 volts, shelf lives measured in decades — is the standard power source of the world's utility meters, its offshore and downhole instruments, and much of its military electronics: anywhere a battery must work after ten years of neglect. The lithium-manganese dioxide cell owns the coin format: the CR2032 on every motherboard and in every car key is a small embassy of the primary empire, shipped by the billion. Lithium-

iron disulphide took over the premium AA slot on the supermarket shelf. [2.6] None of these chemistries can be recharged; none needs to be. Their combined lesson for the industry that followed was institutional rather than technical: they proved, in meters and pacemakers and coin cells, that lithium chemistry could be manufactured by the billion with defect rates low enough to stake lives and infrastructure on. When the rechargeable cell finally arrived, the manufacturing culture that received it had been practicing on primaries for twenty years.

The answer, when it came, did not tame lithium at all. It removed the metal from the finished battery entirely. The lithium-ion cell that now runs the world contains no metallic lithium — only lithium ions, shuttling between two host materials that take them in like guests into a lattice, the way the original petalite took them into its silicate structure two hundred years ago. Getting from the metal to the ion took three separate inventions, in three countries, over fifteen years. The first began, improbably, inside an oil company.

PART TWO

The Invention

Three laboratories, three countries, twenty years. An oil company chasing a crisis, an Oxford physicist who saw further than his funders, and a Japanese chemist who assembled the pieces into a product the world did not know it needed.

CHAPTER 3

Two Centuries of Stored Lightning

The battery was born in an argument about frogs. In the 1780s Luigi Galvani had noticed that a dead frog’s legs twitched when touched with two different metals, and concluded that animal tissue harboured a fluid electricity. Alessandro Volta, professor at Pavia, doubted the frog. The electricity, he argued, came from the metals themselves — from the junction of two dissimilar conductors bridged by something moist. In 1800 he settled the

matter by removing the animal entirely: alternating discs of zinc and copper, separated by cloth soaked in brine, stacked into a pile. The voltaic pile produced a continuous, steady current — the first device in history to do so — and within weeks of the news reaching London, William Nicholson and Anthony Carlisle had used one to split water into hydrogen and oxygen. Within a decade Humphry Davy had built a battery of two thousand cells in the basement of the Royal Institution and used it to tear apart potash and soda, isolating potassium and sodium and founding electrochemistry in the process. [3.1]

The pile had a flaw everyone could see: it died. The zinc dissolved, the brine fizzed, the current faded, and no amount of ingenuity brought it back. For sixty years the battery was a one-way device, a way of spending zinc to make electricity, more expensive per unit of energy than the steam engine and useful only where steam could not go.

The reversible cell

Gaston Planté changed the terms in 1859. His cell was a spiral of two lead sheets separated by rubber strips, immersed in dilute sulphuric acid. Charged from another battery, it developed a skin of lead dioxide on one plate; disconnected, it would then deliver current as that skin and the lead beneath slowly converted to lead sulphate. And — the point — passing current backwards drove the chemistry backwards. The lead–acid battery, the first rechargeable cell, was born with the structure it still has: a negative plate of lead, a positive plate of lead dioxide, sulphuric acid between them, both electrodes turning to lead sulphate as the cell discharges and being restored as it charges. Camille Alphonse Faure made it manufacturable in 1881 by pasting lead oxides onto a lead grid, and the design settled into the role it has never left: cheap, heavy, tolerant of abuse, delivering the few hundred amps that spin a

starter motor. [3.1] Every car on Earth still carries a descendant of Planté's spiral, even the electric ones, and global production of lead–acid storage still dwarfs every other chemistry by weight, a hundred and sixty-five years on.

The half century after Planté was a furnace of invention. Waldemar Jungner in Sweden spent the 1890s trying to replace lead's heaviness with nickel and iron, then nickel and cadmium; Thomas Edison, across the Atlantic, took the nickel–iron battery through tens of thousands of test cycles and sold it for mine lamps, railway signals and his own electric car experiments — heavy, durable cells that could be abused for decades and forgave everything except their cost. Jungner's nickel–cadmium cell, patented in 1899, found its own virtue: sealed and later miniaturised, it became the rechargeable battery of the mid-twentieth century, the cell inside the first cordless tools, shavers and early portable electronics. [3.1] By 1970 the state of the art for a rechargeable battery was nickel–cadmium at perhaps thirty-five watt-hours per kilogram, and lead–acid at about the same, with nickel–metal-hydride still over the horizon.

Notice the number. Thirty-odd watt-hours per kilogram is the natural ceiling of aqueous chemistry: water itself breaks down electrolytically above about 1.23 volts per cell, so no water-based battery can run much beyond two volts, and water is heavy. A petrol engine's fuel carries energy at a density batteries could not approach by two orders of magnitude. The rechargeable battery of 1970 was a device for starting engines and powering shavers, not for replacing them.

The crisis that funded the search

What pushed electrochemistry past its aqueous ceiling was not a consumer product but a geopolitical shock. In October 1973 the Arab oil-exporting states embargoed the United States and its

allies; within months the price of crude had quadrupled, queues circled petrol stations from California to Kent, and every industrial government discovered an urgent, funded interest in anything that might displace oil — solar cells, synthetic fuels, and batteries that might one day move a car. [3.2] The second shock followed in 1979 with the Iranian revolution. For a decade, energy research was flush in a way it had never been before and rarely has been since.

It mattered that the money arrived with a specific question attached. The oil shocks did not ask for better torch batteries; they asked, essentially, whether electrochemistry could do anything at the scale of transport. At the two-volt ceiling of water, the answer was obviously no. The question was therefore precise: was there any reversible chemistry with a voltage and a lightness that water could never give?

The age of the accumulator

Planté's invention spent its first decades as a curiosity of telegraph offices and country-house lighting, because it had nothing to be recharged from. The dynamo changed that: once Gramme's machines could make current on demand, the accumulator — the French word stuck — became the buffer between intermittent generation and steady load. By the 1880s lead-acid batteries were lighting theatres and railway carriages; by the 1890s they ran the first electric vehicles, which briefly outsold every other kind of car on the roads of Paris and New York. The electric hansom and the delivery van of 1900 were lead-acid machines, quiet, clean and doomed — not by the battery but by the road network and the petrol engine's march. [3.1]

The battery's decisive alliance of the early twentieth century was neither glamorous nor mobile: it was the starter. When Cadillac fit the electric self-starter in 1912, eliminating the hand crank whose kick broke arms, every petrol car became a battery customer, and

the lead-acid cell acquired the job it still holds: three seconds of enormous current, a hundred thousand times. [3.3] The arrangement is so successful it has become invisible. Well over a billion starter batteries circulate in the world's vehicles; lead for batteries is one of the largest single uses of any metal on Earth; and the recycling loop around the starter battery — over ninety-five percent collection rates in the rich world, the most recycled consumer product ever made — is the working proof that a battery economy can close its own material circle, a lesson the lithium industry is only now beginning to learn at its own scale.

The nickel pretenders

The search for something lighter than lead produced the two nickel chemistries that carried the twentieth century's portable load. Waldemar Jungner, working through the 1890s in Sweden, first tried nickel against iron — the Edison cell, as it became after Thomas Edison's decade of obsessive refinement across the Atlantic — and then, when iron's self-discharge proved incurable, nickel against cadmium: the NiCd battery, patented in 1899. [3.1] Edison's nickel-iron cells were nearly indestructible, served fifty years in railway signalling and mine lamps, and lost every mass market to their own weight and gassing. Jungner's nickel-cadmium won the portable century: sealed from the 1940s, it went into everything cordless — drills, shavers, phones, camcorders, early laptops — and taught consumers both the convenience of recharging and its miseries: the "memory effect," the toxic cadmium, the two-year fade. [3.1]

The last pretender arrived just before the curtain. Nickel-metal hydride, commercialised around 1990, doubled NiCd's capacity without its cadmium and inherited the portable world just in time to meet lithium-ion in the laptop and lose, segment by segment, through the 1990s. Its survival was strategic rather than

competitive: patent encumbrances and a Japanese-American alliance around large-format NiMH kept it in hybrid vehicles for two decades — the Prius ran on NiMH into the 2020s, long after lithium-ion had won everywhere else, a monument to how slowly automotive qualification forgives. [3.4] By the time NiMH yielded the hybrid, the chemistry that had replaced it everywhere else had already rewritten the industry's map — the subject of the rest of this book.

The answer had been sitting in the literature since the mid-1960s, in papers on an odd class of solids that could absorb ions the way a sponge absorbs water, without changing shape. The men who would put those solids together with the lightest metal were already in place — one of them, as it happened, on the payroll of the Exxon Corporation, which had concluded, in the middle of the embargo decade, that it had better learn to make batteries.

CHAPTER 4

An Oil Company's Battery

Of all the institutions that might have midwifed the modern battery, Exxon was among the least likely and the best funded. In the early 1970s the corporation stood at the centre of the world oil system and, being staffed by people who could read a reserve depletion curve as well as anyone, had begun to wonder what an oil company becomes when the oil runs short. Its research arm in Linden, New Jersey — one of the largest private laboratories on Earth — was spun outward into solar cells, synthetic fuels and energy storage, and in 1972 it hired a young solid-state chemist away from Stanford to think about batteries. His name was M. Stanley Whittingham. [4.1]

Whittingham brought with him an idea with an unusual pedigree. In 1965 Walter Rüdorff, working in Tübingen, had shown that titanium disulphide — a solid built like a deck of cards, sheets of sulphur-titanium-sulphur stacked with only weak forces between the sheets — could take lithium atoms into the gaps between its layers. The lithium slipped in and out without wrecking the host: the crystal swelled a little and recovered, like a deck of cards accommodating a few extra. Jean Rouxel's group in Nantes had seen the same family of behaviour, and Whittingham himself, with Fred Gamble, had shown at Stanford that lithium could be loaded across the full range from TiS_2 to $LiTiS_2$ with barely any structural strain. [4.2] The phenomenon had a name: intercalation, from the Latin for inserting between the leaves of a book. Every previous battery worked by conversion — the electrodes were chemically consumed and rebuilt each cycle, with all the crumbling and shape-change that implies. Intercalation promised something cleaner: an electrode that stayed itself while guests came and went.

At Exxon, Whittingham made it electrochemical. By 1973 he was proposing such materials as battery electrodes; by 1976 his group had a working rechargeable cell: a titanium disulphide cathode, an anode of lithium metal, and an organic electrolyte carrying lithium hexafluorophosphate. The cell delivered about 2.5 volts — already beyond anything aqueous chemistry could reach from a single cell — and it recharged. Exxon built demonstration cells, talked publicly about batteries for cars, and briefly made the future look like a division of an oil major. [4.2]

The flaw was the anode. Recharging meant plating lithium metal back onto the negative electrode, and the plated lithium grew as dendrites — metallic whiskers reaching through the electrolyte toward the cathode. Given enough cycles, a whisker completed the circuit. The cell shorted internally, dumped its energy into the

whisker, and the flammable solvent did the rest. Exxon's engineers fought the problem with electrolyte additives and mechanical separators and made progress on paper, but the physics was unforgiving: metal that plates unevenly will eventually plate through. "As a result," Goodenough later wrote flatly, "the program was abandoned a few years later." [4.1] When oil prices sagged in the early 1980s, Exxon's management shed no tears; the battery division was closed and its patents licensed away. The first lithium battery boom ended inside an oil company, undone by the element's own eagerness.

The cautionary tale of Maple Ridge

The idea with the long pedigree

Intercalation itself was older than any of the men in this story. Chemists had known since the 1840s that graphite would swallow foreign atoms between its carbon sheets; the alkali metals went in eagerly, and the compounds that resulted — bronze, blue, metallic — were laboratory exotica for a century. [4.4] Rüdorff's 1965 demonstration extended the trick to the transition-metal dichalcogenides and, crucially, showed the host surviving: the sulphide sheets parted for the lithium and closed again behind it. Rouxel's school in Nantes catalogued the family; Whittingham and Gamble, at Stanford in the early 1970s, mapped the titanium disulphide system across its whole range and measured how little the lattice strained — the small lattice expansion that made the reaction a candidate for a reversible electrode rather than a one-way conversion. [4.2]

What Exxon added was the circuit. Intercalation in a jar is chemistry; intercalation across an electrolyte, driven by a load, is a battery. Whittingham's 1976 cell — lithium metal anode, TiS_2 cathode, lithium salts in organic solvents — delivered about 2.5

volts and, in its best-behaved variant with a perchlorate electrolyte in dimethoxyethane and tetrahydrofuran, cycled more than a thousand times at gentle rates. [4.2] The corporation built demonstration cells, published, patented, and for a few years behaved like a battery company. The published record of the period still reads with the confidence of an institution that believes it owns a future.

Why the metal lost

The autopsy deserves precision, because the same verdict would be appealed for fifty years. Charging the cell means reducing lithium ions back to metal at the anode surface. The reduction happens wherever the current finds the easiest path, and the easiest path, once a microscopic bump exists, is the bump's tip — so the deposit grows as filaments, and each cycle lengthens them. The filaments are the dendrites. They do not always short the cell; mostly they break off, become electrically isolated "dead lithium," and quietly consume the battery's inventory. But across enough cells and enough cycles, some filament completes the journey, and a cell that shorts internally in the presence of a flammable solvent is a fire with a chemical supply. [4.1] [4.2]

Every remedy of the next half-century attacks the same physics from a different angle. Yoshino's carbon anode abolished the plating altogether — ions park in the lattice instead of depositing on a surface. Electrolyte additives tune the film that guides deposition. Pressure, temperature windows and charging algorithms manage it. The solid-state programmes of Chapter 30 propose to stop the filament mechanically with a ceramic wall. And the lithium-metal anode keeps returning to the bench, because the prize — a ten-fold anode — never stops being worth the risk. The metal lost the twentieth century. Its case in the twenty-first is still being heard.

Before leaving the metal anode behind, history insisted on demonstrating the point in public. In the late 1970s a small company in Maple Ridge, British Columbia — Moli Energy — took up the same wager Whittingham had lost, pairing lithium metal with molybdenum disulphide. Through the 1980s it raised money, built a factory, and by 1988 was shipping its Molicel AA cells to Japan for mobile phones. The cells were remarkable: rechargeable lithium, years ahead of anything else on sale. Then, on August 10, 1989, a Japanese phone fitted with a Molicel caught fire and burned its user. Ten thousand phones were recalled; the investigation found internal shorts born of the manufacturing line and the dendrite problem wearing a new face. [4.3] Moli never recovered as a battery maker (the name survives, obscurely, as Molicel, after passing through NEC's hands), and the episode fixed the industry's mind for a generation: metallic lithium in a rechargeable consumer cell was a fire waiting for its phone number. Whatever came next could not have a metal anode. It had to be made of something that merely hosted lithium — something that did to the anode side what Rüdorff's sulphide did to the cathode side: a second deck of cards.

CHAPTER 5

The Oxide That Held the Ions

John Bannister Goodenough arrived at the problem from the far side of the periodic table and, in a sense, from the far side of science. Trained as a mathematician at Yale, converted to physics under the G.I. Bill at Chicago, he had spent two decades at MIT's Lincoln Laboratory working on the magnetic oxides that went into the core memory of early computers — work that left him with an almost tactile intuition for how metal ions and

oxygen stack together, and how electrons and holes move through the result. In 1976, the year Whittingham published the Exxon cell, Goodenough took up the headship of the Inorganic Chemistry Laboratory at Oxford. He was fifty-four, an age when academic careers coast. He read the Exxon paper and saw immediately both what it had achieved and what it had missed. [5.1]

What it had missed, in his view, was the ceiling. Whittingham's titanium disulphide was a sulphide, and sulphur is mild: the chemistry limited the cell to about 2.5 volts. Goodenough reasoned that the same layered architecture built from oxides instead — oxygen being far more electronegative than sulphur — would grip its electrons harder, push the cathode potential up, and roughly double the voltage. The reasoning was clean; the objection was cleaner. Every oxide anyone had tried as an intercalation host had collapsed. And there was a deeper puzzle: a charged cathode, by definition, must already contain lithium to give up. Whoever made the cell would have to synthesise the lithiated oxide first and build the battery in its discharged state — backwards from how everyone thought about batteries. Goodenough saw that this was not an obstacle but the key: if you started with lithium already inside the cathode, the anode no longer had to supply it. The metal anode could, in principle, be replaced by any material willing to receive lithium ions on charge. [5.2]

The experiment

In 1979 and 1980, working with Koichi Mizushima, a visiting Japanese researcher, Goodenough's group pushed lithium cobalt oxide — $LiCoO_2$, a layered oxide with lithium sheets sandwiched between cobalt-oxygen slabs — up to potentials no one had dared. They pulled more than half the lithium out of the structure, reversibly, at around four volts against lithium metal. The layered

framework held. A cathode of $LiCoO_2$ against any reasonable anode promised a four-volt rechargeable cell: twice the voltage of Whittingham's sulphide, three times that of nickel–cadmium. [5.2] The paper appeared in 1980, with Mizushima, Philip Jones and Philip Wiseman as co-authors, and it is the founding document of the modern battery industry.

The industrial world yawned. Oxford's patent office declined to patent the invention at all — the university saw no value in it — and Goodenough signed the rights over to the UK's Atomic Energy Research Establishment at Harwell, which patented it and then failed, for years, to interest anyone. Battery makers in America and Europe, burned by lithium's fires and wedded to their nickel and lead lines, passed. The most important patent in the history of portable electronics sat in a drawer in the English countryside, available for licence, unlicensed. [5.1] Goodenough himself was never a beneficiary; the fortune that lithium cobalt oxide eventually minted flowed elsewhere, a fact he noted in later life with more amusement than bitterness.

He was not finished. In 1983 his group identified a second great cathode family — the manganese spinel, $LiMn_2O_4$, a three-dimensional host that traded some capacity for cheapness and safety — and in 1986, aged sixty-four, he moved to the University of Texas at Austin, where his laboratory would produce, in 1997, the third: lithium iron phosphate, the chemistry that would eventually dominate the world market. [5.1] [5.3] Three of the four cathode families that power nearly every device and vehicle in this book came out of one man's laboratories over seventeen years, most of them after his sixtieth birthday. When the Nobel committee finally called, in 2019, Goodenough was ninety-seven, the oldest laureate in the prize's history. [5.4]

The patent that went home

The filing story deserves its own paragraph, because it is the battery industry's original sin and its favourite dinner anecdote. In 1980, when Goodenough's group had the layered cobalt oxide characterised, the British technology-transfer machinery looked at a ceramic electrode for a battery nobody had asked for and declined to file. The patent was eventually pursued through other channels, and Goodenough signed the rights away for nothing — no royalties on the chemistry that would be manufactured, eventually, by the tonne-kilometre. [5.1] He said afterward that no one at Oxford had imagined an application. The line is usually told as a joke about universities. It is better read as a structural diagnosis: the institutions that fund fundamental materials research are systematically blind at the moment of conception, because the market that would value the discovery does not yet exist — the device that would need $LiCoO_2$ had not been imagined either. Sony would complete the circuit eleven years later and capture the value. The lesson recurs through this book: in materials, the discovery is cheap; the decade of engineering between the discovery and the product is where the money and the moats live.

What the spinels and the layered oxides argued about

Mizushima's confirmation — $LiCoO_2$ reversible at four volts — opened an argument that has never really closed: which host structure holds ions best? Thackeray, arriving at Oxford from South Africa, came from the spinel side: his group had shown that the manganese spinel $LiMn_2O_4$, with its three-dimensional channels, intercalated lithium cheaply and safely, if at lower energy. [5.3] The layered oxides held more lithium and reached higher voltage; the spinels were stabler, cheaper, poorer in

capacity. The argument propagated into product lines a decade apart: Sony chose the layered cobalt oxide for energy; the American tool-and-vehicle programmes of the 2000s would choose the manganese spinel for safety and power; and the modern high-nickel cathodes are layered oxides engineered to steal back some of the spinel's stability. [5.3] Every cathode family since — phosphate included — is a position in this same argument: how much lithium can the host hold, at what voltage, through how many cycles, at whose expense. The periodic table offers perhaps a dozen serious answers. Goodenough's group found two of them in one decade, in one basement, on one salary.

The man and the machine

The human facts are part of the technology's texture, and the Nobel committee honoured them. Goodenough was fifty-eight when $LiCoO_2$ was published — an age when, by academic convention, a career is summarising itself. He was sixty-four when the iron phosphate work appeared, ninety-four when the Nobel came, and publishing at ninety-seven. [5.4] The obverse of the lone-genius story is this: the genius was neither lone nor young. The cobalt oxide was a group product — Mizushima on the bench, Wiseman on the physics, an Oxford materials department willing to let a physicist moonlight as a chemist. The battery that runs the world is, among other things, a proof that institutions which fund patient people past their conventional sell-by dates occasionally change the periodic table's employment prospects.

But in 1985, none of that had happened. What existed was a published result, an unlicensed patent, and a problem waiting for its complement: someone, somewhere, had to build the other electrode — a deck of cards that would take lithium ions in, at low potential, without being lithium metal. That someone was a chemist at the Asahi Kasei Corporation in Osaka who had been

working on conducting polymers, and who had been reading Oxford.

CHAPTER 6

The Coke, the Cathode, and the Camera Company

Akira Yoshino was a company chemist in the most literal sense: hired by Asahi Kasei in 1972 straight out of Kyoto University, and still there half a century later when the Nobel Foundation came to call. In the early 1980s his assignment was conducting polymers — polyacetylene had just made plastics conduct electricity, and Asahi Kasei wanted to know if such materials could be electrodes. The polymer route went nowhere practical, but it taught Yoshino the landscape of carbon, and it left him reading the battery literature when, in 1982 or so, he came across the Oxford result: a layered oxide that held lithium at four volts and let it go. [6.1]

He understood at once what Goodenough's cathode demanded. A battery built from a cathode that arrives already full of lithium needs an anode that starts empty — a host, not a metal. The candidate class was carbon: graphite's layers are the original deck of cards, and it had long been known that alkali metals could be intercalated between them. The difficulty was doing it electrochemically, in an organic electrolyte, reversibly. Graphite itself tended to fall apart — the solvent molecules rode in with the lithium ions and prised the layers open, a failure called exfoliation. A French researcher, Rachid Yazami, had shown at Grenoble in the early 1980s that lithium could in fact be reversibly intercalated into graphite in a polymer electrolyte; but polymer electrolytes

were a laboratory material, not a product. [6.2] The field needed a carbon that worked in a real liquid cell.

Yoshino found it by going down the periodic table of cokes. Vapour-grown carbon fibre behaved promisingly; heat-treated petroleum coke — the carbon residue of oil refining, a material his own industry made by the megatonne — behaved better. Certain grades of coke, with a precise mixture of graphitic and disordered domains, took lithium ions in at low potential (about half a volt above lithium metal), held a great deal of them, and gave them back, cycle after cycle, without disintegrating. The disordered regions, Yoshino reasoned, armoured the ordered ones. In 1985 he assembled the pieces: a cathode of Goodenough's lithium cobalt oxide, an anode of petroleum coke, a polyethylene separator, an organic electrolyte — and, crucially, no lithium metal anywhere in the finished device. Charged for the first time, the cell itself moved lithium from the oxide into the carbon; the battery was born discharged and safe. [6.3]

The dropped weight

Yoshino's next contribution was to distrust his own invention in a productive way. Every lithium battery before his had ended in fire; the world would reasonably assume the same of this one. So he devised the test that has since become an industry ritual: he dropped a heavy weight, remotely, onto his cells, and filmed what happened. Where a lithium-metal cell would have gone up, the coke–oxide cell vented and smouldered but did not explode — the stored energy simply had less violent chemistry to call upon. [6.3] That distinction, between a cell that can misbehave and a cell that must detonate, is the entire safety argument of lithium-ion, and Yoshino had it on film in 1985.

Asahi Kasei patented the configuration — Yoshino's name is on the foundational patents of the lithium-ion cell — and then did what

sensible chemical companies do with strange devices: it looked for someone who knew how to sell batteries. It found Sony.

1991

Sony in the late 1980s was the most consequential battery customer on Earth. The Walkman had untethered music; Handycam camcorders were shrinking yearly; the mobile phone was visibly coming. Every one of these products was throttled by nickel–cadmium cells — heavy, memory-prone, low in voltage — and Sony's battery division had been hunting for a next chemistry when Yoshino's cell arrived. Sony combined Asahi Kasei's configuration with its own manufacturing craft, solved the thousand small problems of coating, sealing and quality that separate a lab cell from a product, and in 1991 shipped the first commercial lithium-ion batteries, building them into its camcorders. [6.1] [6.4] The early cells held about 80 watt-hours per kilogram and 200 per litre — modest by modern measure, and roughly double anything rechargeable then on sale. [6.5]

The market's verdict was immediate and total. Through the 1990s lithium-ion colonised the camcorder, the laptop and then the mobile phone; by 2000 it was the default chemistry of portable electronics, and Sony, briefly, the world's largest battery maker. The configuration Yoshino assembled in 1985 — cobalt oxide cathode, carbon anode, organic electrolyte, polymer separator — has never been fundamentally altered since. Everything that follows in this book, the gigafactories and the electric cars and the grid-scale farms of containers, is an elaboration of that one cell.

The camera company's cold arithmetic

Why Sony? The question has a material answer, not a corporate one. By the late 1980s Sony's camcorder business faced an energy wall: nickel-cadmium cells could not get meaningfully lighter, and

the company's whole product trajectory — the Handycam shrinking toward the palm — required a step change in watt-hours per kilogram, on the order of a doubling. [6.2] Marketing departments ask for doublings; chemistries that deliver them arrive perhaps once a generation. Sony's battery division, led on the technical side by Yoshino and commercially by Nishi, ran the numbers on every known system and reached the same conclusion the data forced: the only credible doubling in view was the lithium-ion configuration — four-volt cathode, carbon anode — with all its unsolved manufacturing problems. The camcorder paid for the risk. It is worth stating plainly: the lithium-ion battery was commercialised to sell video cameras. The cars and grids of this book's later chapters are the camcorder's unforeseen children.

The agreement that filled a factory

A battery is a product only when someone builds the plant. In May 1991 — five months before the launch — Sony signed the agreement that actually industrialised the cell: a joint venture with Asahi Kasei, Yoshino's employer, to manufacture lithium-ion batteries together, pooling Yoshino's patents and process knowledge with Sony's product pull. [6.4] The decision structure matters. Sony did not merely license a recipe; it stood up a dedicated manufacturing organisation — Sony Energytec would follow — because the cell's secrets were process secrets: coating thicknesses, electrolyte filling, formation cycling, the hygiene of a dry room. Nobody had ever mass-produced an organic-electrolyte battery at consumer volumes. The defect economics were unforgiving: a cellphone pack holds four cells, a laptop eight, and a one-in-a-thousand cell defect rate is a one-in-a-hundred product failure rate. The factory had to be right before the first sale, which is why the launch cell was a cobalt-coke 18650 of unremarkable capacity and very remarkable consistency.

The coke that coked out

The anode's first material has a footnote that the industry remembers with a shudder. Asahi's petroleum coke was a soft carbon — it graphitised poorly, which was precisely its virtue against propylene carbonate — but its capacity was modest, its voltage profile sloped, and its supply was a refinery by-product stream. By 1993 Sony had moved the 18650 to hard carbon and then, by the mid-1990s, the industry settled on the answer that has held for thirty years: graphitised carbon, spherical, coated, the mesocarbon microbeads and their successors, with ethylene carbonate finally admitted to the electrolyte once the SEI chemistry was understood — Dahn's 1990-91 papers had shown the film could be made to form protectively rather than reactively. [6.5] The coke cell of 1991 was thus a bridge chemistry, commercially decisive and technically transient: it existed for exactly as long as it took the industry to learn to use graphite. Chapter 20 tells what the bridge led to.

There is a footnote worth keeping. In the same years, the lithium-metal road that Moli had crashed on was closed to traffic, and the metal anode became a byword for a dead end. It would stay closed for thirty years — until, in the 2020s, a new generation of solid-state designs began cautiously reopening it, on the argument that a solid electrolyte might finally hold the dendrites back. The industry's longest-running story is still not finished.

CHAPTER 7

Stockholm, 2019

The Royal Swedish Academy of Sciences does not hurry. The discovery of radioactivity waited a handful of years for its prize;

the lithium-ion battery waited twenty-eight. When the call finally came on 9 October 2019, the chemistry prize went three ways, as chemistry prizes for great machines often do: to M. Stanley Whittingham, then seventy-seven and still teaching at Binghamton University in New York; to John B. Goodenough, ninety-seven, still going in to his laboratory at the University of Texas; and to Akira Yoshino, seventy-one, of Asahi Kasei and Meijo University. The citation was seven words long: “for the development of lithium-ion batteries.” [7.1]

The Academy’s own scientific background document — a forty-page history that reads like a detective story told in free energies — laid out the division of credit with unusual clarity, and it is the spine this book has followed. Whittingham built the first rechargeable lithium cell and proved that intercalation could be electrochemistry rather than a curiosity. Goodenough supplied the cathode that doubled the voltage and, with it, the energy. Yoshino replaced the metal anode with a carbon host and, in doing so, made the battery safe enough to sell. Each contribution was necessary; remove any one and the device in your pocket does not exist. [7.2]

There is a pleasing asymmetry in how the three men got there. Whittingham was funded by an oil crisis and abandoned by an oil company; his employer’s laboratories had the cell first and let it go. Goodenough made his decisive contribution at an age when scientists are meant to be emeritus, gave his patent away because his university did not want it, and watched it become the most valuable unlicensed invention in electronics before industry finally noticed. Yoshino, the company man, worked the problem for a corporation that kept him, his laboratory, and his patent for life. An oil major, an English university, and an Osaka chemical firm: the battery’s institutions could hardly have been more different, and none of them was a battery company. The battery companies, Sony

first among them, arrived only when the science was already done — which is itself one of the deep patterns of industrial history this library exists to record.

What the prize was really for

The Nobel lectures in Stockholm that December are worth summarising, because each laureate chose to describe not a eureka but a process. Whittingham talked about intercalation chemistry as a whole field of solids with guests. Goodenough, ninety-seven and sharp enough to tease the audience, walked through the logic of oxide potentials and observed that at his age "you don't have to worry about keeping your job." Yoshino showed the films: the weight dropping on the cells, the smoulder instead of the bang. The message common to all three was that the lithium-ion battery was not a discovery but an assembly — a system in which the cathode, the anode, the electrolyte and the separator each constrain the others, and progress consists of relaxing one constraint without tightening another. [7.2]

That systems view is why the prize, though awarded to chemistry, mattered far beyond it. By 2019 the cell had become the load-bearing component of two civilisational projects at once: the digitisation of daily life (phones, laptops, wearables, everything with a chip and no cord) and the electrification of energy (vehicles first, then the grid). The Academy noted that the battery "laid the foundation of a wireless, fossil-fuel-free society" — uncharacteristically sweeping language, and defensible. Few inventions have carried two revolutions simultaneously.

The committee's reading of the field

The Nobel citation is worth pausing on, because the committee's choice of three defined the official story — and the official story had to make delicate decisions. Whittingham was credited with the

first functional lithium battery and the intercalation cathode concept. Goodenough was credited with doubling the cathode's potential. Yoshino was credited with the first commercially viable configuration: carbon anode, oxide cathode, the elimination of metallic lithium. [7.2] The citation's architecture quietly answered two controversies. It passed over the question of the electrolyte and the SEI — no prize for Dahn, Peled, or the graphite-solvent story — on the logic that configuration, not components, was the conceptual leap. And it implicitly adjudicated the titanium disulphide lineage: Exxon's cell was honoured as the founding proof, not blamed as the commercial dead end. Committees, like batteries, optimise several variables at once.

The lecture hall as archive

Each laureate's December lecture is a primary source this book has leaned on. Whittingham used his to argue that the future remained chemical — new materials, new hosts — and to recall, with dry precision, that Exxon had built a working battery business and walked away from it. [7.3] Goodenough, at ninety-seven the oldest person ever to receive a Nobel, spoke about glass electrolytes and sodium, still working the problem. Yoshino gave the most instructive lecture of the three: a manufacturer's memoir, describing how the cell was engineered around what could be coated, filled, formed and inspected at volume — and ending with the judgment that the battery's second act, electrifying transport, would matter more than its first. [7.3] Three lectures, three temperaments: the physicist, the materials man, the engineer. The battery needed all three, in that order, across four decades and four institutions, which is as close as a Nobel citation comes to an honest account of how technology actually happens.

The 97-percent solution

One number from the chemistry prize deserves its own mention because it governs everything the battery does in the world. The lithium-ion cell's round-trip efficiency — energy out over energy in — sits around 95 percent and often higher, far beyond the round trip of hydrogen (electrolyse, compress, fuel-cell: perhaps 40 percent) and beyond any heat engine's dreams. [7.5] This is why the battery, and only the battery, could electrify transport directly: nearly every joule bought arrives at the wheel. It is also why grid-storage economics turned on cell cost rather than efficiency — the physics was already paid for. When this book later describes the grid learning to store, or the car abandoning its engine, the enabling fact is a number from the laureates' blackboards: nearly everything that goes in comes back out.

Goodenough did not live to see the chemistry's next act. He died on 25 June 2023, one month short of his 101st birthday, working more or less to the end; his university's obituary records thirty-seven years on the Texas faculty, and colleagues record that his laboratory was still chasing solid-state cells into his late nineties. [7.3] Whittingham and Yoshino remain, at this writing, active elders of a field that has grown from three laboratories into an industry of several hundred billion dollars a year. The cell they made possible now leaves the world's production lines at a rate of tens of billions a year — each one, still, a cobalt-oxide or iron-phosphate cathode, a carbon anode, an organic electrolyte, and a polymer separator, arranged as Yoshino arranged them in Osaka in 1985.

PART THREE

The Science

What actually happens inside the sealed can: ions rocking between two hosts, a film thinner than a wavelength holding the whole reaction together, and a chemistry of trade-offs that engineers still tune a quarter-point at a time.

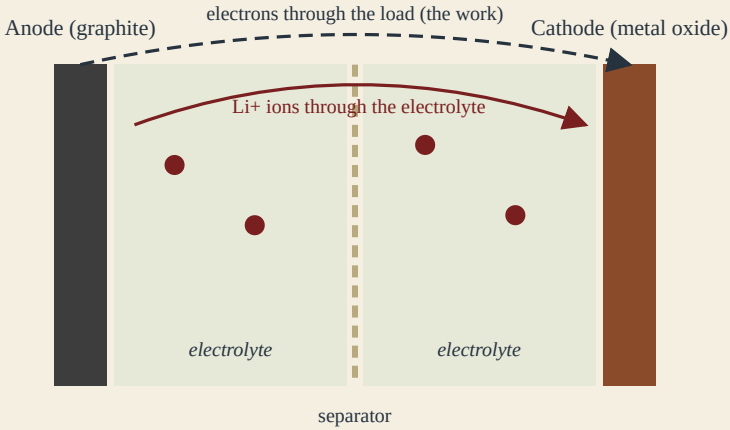
CHAPTER 8

The Rocking Chair

Open a charged lithium-ion cell — do not do this, but imagine it — and inside the foil pouch or steel can you find no lithium metal at all. What you find is two sheets: a cathode, a thin aluminium foil painted black with lithium cobalt oxide or one of its descendants; and an anode, a copper foil painted with graphite. Between them, a microporous plastic film soaked in an organic liquid. That is the whole machine. The lithium is inside

the black cathode paint, sitting as ions between the oxide layers, and the entire action of the battery is that those ions cross to the graphite, and come back, and cross again, thousands of times. The French call it la batterie à bascule: the rocking-chair battery. Charge the cell and the ions rock from cathode to anode; discharge it and they rock home. The electrons they cannot take with them — the separator is an electronic insulator — travel around the outside, through your phone, and that external current is the product being sold. [8.1]

The rocking chair: a lithium-ion cell, discharging



Charge reverses both currents. Neither electrode is consumed; the ion rocks.

Three features of this arrangement deserve slow attention, because between them they explain everything the industry does.

The hosts do the work

In a lead-acid battery the electrodes are the fuel: lead and lead dioxide are consumed into lead sulphate, and the whole electrode

changes phase each cycle, swelling and crumbling, which is why deep-cycled lead batteries die young. In a lithium-ion cell the electrodes are landlords. The oxide layers and the graphite galleries stay standing while lithium ions check in and out; ideally nothing about the host changes except its occupancy. This topotactic hospitality — the technical literature calls the reaction *topotactic intercalation*, meaning the framework is preserved — is what lets a lithium-ion cell survive a thousand, three thousand, ten thousand cycles where a conversion battery would be rubble. [8.1] The energy density comes from the chemistry; the longevity comes from the architecture. The Nobel background document lists the demands on a good host with the air of a landlord's requirements: an open framework with sites for the guest, minimal structural change across the whole occupancy range, fast diffusion of the guest ion, reversibility, electronic conductivity, insolubility in the electrolyte, and indifference to the solvent. [8.2] No material meets all seven perfectly. The entire cathode industry, as we will see, is the search for the least-bad compromise, priced in dollars per kilowatt-hour.

The film that makes it possible

The single most important thing inside a lithium-ion cell is not a component anyone sells. It is a skin. When a fresh cell is charged for the very first time — the step the factory calls formation — the graphite anode's surface reacts with the electrolyte and decomposes a thin layer of it, plating the carbon with a film of decomposition products a few dozen atoms thick. This film, named the solid electrolyte interphase (SEI) by Emanuel Peled in 1979, is the battery's silent partner: it conducts lithium ions but blocks electrons and solvent molecules, so once it has formed, the electrolyte stops decomposing and the graphite stops exfoliating. The cell is thereafter protected by the scar tissue of its first charge. [8.2]

Everything about the SEI is a trade. Forming it consumes lithium — five to fifteen percent of the cell's inventory, gone before the cell ships — which is why formation is done slowly and carefully, and why it is one of the most expensive steps in manufacturing. Its quality fixes the cell's life: a well-formed SEI is a self-healing passivation layer that lasts a decade; a badly formed one grows, cracks, eats lithium continuously, and kills the cell early. And its existence explains why graphite works at all. The exfoliation problem that defeated every naive attempt to use graphite in a liquid cell is solved, in practice, by choosing electrolytes whose decomposition products make a good film — ethylene carbonate, present in nearly every commercial electrolyte for forty years, is there precisely because the SEI it grows is the best anyone has found. Yoshino's petroleum coke was a way of living without that film; modern graphite anodes are a way of living with it. Both are chapters of the same story.

The tyranny of the volt

The third feature is the electrolyte's narrow window. The organic solvents that tolerate lithium's potentials are stable only across a band of roughly one to four-and-a-half volts against lithium. Push the cathode above about 4.3-4.4 volts and the electrolyte begins to oxidise at its surface; push the anode below the SEI's protection and the solvent reduces. The cell's whole chemistry must live inside the window, and the industry's slow climb — from 4.1-volt cells in 1991 to 4.35-4.4-volt high-voltage cobalt cells in phones today — has been fought for hundredths of a volt at a time, each step bought with electrolyte additives and coatings that hold the surfaces together a little longer. [8.2]

The window is also why the whole system is flammable in a way lead-acid never was. The electrolyte is a mixture of organic carbonates — cousins of dry-cleaning fluid — chosen because

nothing aqueous can survive next to charged electrodes at these potentials. The battery stores energy chemically, and its solvent is fuel. That is not a design error; it is the price of the voltage, and the industry's safety engineering, examined in Chapter 12, exists to keep that price from being collected.

The voltage, honestly arrived at

A cell's voltage is the difference in chemical potential of lithium between its two hosts — how badly the ion wants to leave one and join the other. Intercalated into graphite, lithium sits about 0.1 to 0.2 volts above lithium metal; intercalated into cobalt oxide, it sits about 3.9 volts below it. The difference, roughly 3.7 volts nominal and 4.2 at full charge, is the cell's electromotive force, and it is why the lithium-ion battery replaced three nickel-cadmium cells with one of its own. [8.2] The number has a ceiling with a chemical explanation: push the cathode potential much above 4.2 volts against lithium and the carbonate electrolyte begins to oxidise at the cathode surface — the solvent, not the host, sets the roof. The industry's decade-long crawl from 4.2 to 4.35 to 4.4 and beyond in consumer cells has been a crawl along that roofline, each tenth of a volt bought with additives, coatings and engineering that stabilise the interface a little longer. [8.4] Voltage is capacity multiplied: raising it is the cheapest capacity there is, which is why the roof keeps being tested.

What the cycle costs

Each rock of the chair is not free. The anode's SEI, the film that makes the cell possible, thickens microscopically with use — each thickening consumes lithium that will never rock back, which is why a cell's capacity fades even in a drawer. At the cathode, the high-voltage surface slowly reconstructs: layered oxides lose oxygen, form resistive crusts, crack their particles under the strain

of breathing. Mechanical fatigue adds its tax: graphite swells and shrinks roughly a tenth per cycle, silicon several times over. [8.3] Temperature scripts all of it — cold slows the rocking into lithium-plating risk, heat accelerates every parasite reaction. The engineering response fills the last third of this book: formation protocols that grow better films, additives that patch them, battery-management systems that keep the cell inside its comfort envelope, and cell designs — tabless geometries, thicker foils, better cooling — that share the strain. Cycle life, the consumer's experience of all this chemistry, is where the laboratory's promises meet the calendar: hundreds of cycles for the phone replaced on contract, thousands for the car under warranty, ten thousand and climbing for the LFP grid cells now deployed, where the accounting counts in decades.

Put the three features together and the modern cell is a kind of negotiated peace: two host lattices holding a reactive ion, a sacrificial film holding back the solvent, and a voltage chosen as high as the peace will bear. The peace holds, on average, astonishingly well — a modern cell endures a decade and several thousand full cycles — but it holds within limits, and the limits define the industry's map: why cathodes matter most, why silicon tempts and terrifies the anode side, why factories are built like semiconductor fabs, and why a manufacturing defect in a single cell can ground an airliner. The next four chapters take each element of the settlement in turn.

CHAPTER 9

The Cathode Families

Ask a battery engineer what a cell is and you will be told its cathode. The anode is nearly always graphite, the electrolyte

nearly always a carbonate brew, the separator a polyolefin film; the cathode is where identity lives. It fixes the voltage, most of the capacity, most of the cost, and most of the danger. Forty years of industrial competition have reduced a hundred candidate materials to five working families, and the politics of the battery world — China versus the West, cheap versus long-range, safe versus dense — can be told almost entirely as a story of which family a company chose.

LCO — lithium cobalt oxide. The original. Goodenough's 1980 layered oxide still powers most of the world's phones and laptops, because nothing since has matched its combination of energy density and compact volume at the few-watt-hour scale. Its liabilities are cobalt's price and politics, and a temper: fully charged LCO is an oxidiser waiting for a short circuit. Consumer electronics accept the risk for the density; carmakers mostly do not. [9.1]

LMO — lithium manganese spinel. The second Goodenough family (1983) trades the layered deck of cards for a three-dimensional manganese-oxide framework with tunnels the ions run through. Cheap, safe, happy to discharge fast — and short-lived, because manganese dissolves into the electrolyte over a hot summer. LMO rarely appears alone; blended with other cathodes it powered the first Nissan Leaf and a generation of power tools.

NMC — nickel, manganese, cobalt in one lattice. The workhorse of the long-range electric car. The insight, developed across many laboratories in the 1990s and 2000s, is that the three metals cover one another's weaknesses: nickel carries capacity, cobalt keeps the layers ordered, manganese keeps the structure cool-headed. The industry reads the recipe like a football formation — NMC 111, 622, 811 — and the march from equal parts toward eight parts nickel is the story of squeezing cobalt out while holding

the cell together. High-nickel NMC (the 811s and beyond) sits at the top of the automotive density league at roughly 260 watt-hours per kilogram at cell level, and it is what a premium Western or Korean EV mostly carries. [9.2]

NCA — nickel, cobalt, aluminium. The same architecture with aluminium as the stabiliser, developed to industrial maturity by Panasonic and bound for decades to one customer: Tesla. The cylindrical cells in a Model S or Model 3 from Panasonic's lines are NCA; its character is much like high-nickel NMC, with aluminium playing manganese's steadying role.

LFP — lithium iron phosphate. The people's chemistry, and the quiet victor of the whole contest. In 1997, in Goodenough's Texas laboratory, Arumugam Manthiram's group and the visiting Indian researcher Akshaya Padhi demonstrated that an iron phosphate framework — cheap iron, cheap phosphate, an olivine structure related to a common mineral — could host lithium reversibly at about 3.4 volts. [9.3] On the metrics that made headlines, LFP lost: lower voltage, lower capacity, roughly 170 watt-hours per kilogram at the cell against NMC's 260. [9.2] On every metric that mattered to a factory, it won: no cobalt, no nickel, ingredients that cost almost nothing, a structure so stable it almost cannot be made to run away thermally, and a cycle life measured in tens of thousands. For twenty years LFP was the chemistry of buses and Chinese city cars. Then three things converged: the key patents expired; Chinese cell makers, led by BYD's blade design, learned to pack LFP cells so cleverly that the pack-level density penalty all but vanished; and the world market pivoted from subsidised premium cars to mass-market ones where cost is king. By 2024 LFP accounted for nearly half of global EV battery demand — 45 percent in 2023, a projected 48 percent in 2024 by Benchmark's count — and in China itself it passed everything else combined. [9.4]

The family table, in the industry's own working numbers:

Cathode	Cell specific energy (typical)	Character	Typical home
LCO	~200-240 Wh/kg	Dense, costly, touchy	Phones, laptops
LMO	~120-150 Wh/kg	Safe, cheap, short-lived	Blends, tools
NMC (high-Ni)	~220-260 Wh/kg	Long range, cobalt-lite	Premium EVs
NCA	~240-260 Wh/kg	Dense, Tesla lineage	Long-range EVs
LFP	~170-205 Wh/kg	Cheap, safe, long-lived	Mass EVs, storage

Typical cell-level values as published by IDTechEx (LFP ~170 vs NMC811 ~260 Wh/kg) and industry data; specific products vary by design and year. [9.2]

Reading a cathode datasheet

The shorthand deserves decoding, since it appears everywhere in what follows. NCM (elsewhere NMC) is nickel-cobalt-manganese in a layered oxide; the digits give the proportions — NCM 811 is eight parts nickel to one each of cobalt and manganese. NCA swaps manganese for aluminium. LFP is lithium iron phosphate, the olivine. LMO is the manganese spinel; LCO the original cobalt oxide. Each label compresses a position on four axes at once: energy (nickel pushes it up, phosphate concedes it), cycle and calendar life (phosphate and manganese structures endure, high-nickel spends), thermal margin (iron phosphate is the industry's safety anchor; high-nickel layers are its anxiety), and material

exposure (cobalt and nickel carry the dependency risks of Chapters 18 and 19; iron and phosphate carry almost none). [9.2] There is no best cathode, only best-for-a-segment — which is precisely why the market, as Chapter 21 documents, split rather than converged.

The secondary particles

Between the crystal and the electrode sits a manufacturing fact the textbooks skip: cathode powders are not used as single crystals but as secondary particles — micron-scale spheres agglomerated from nanoscale crystallites, engineered for tap density, coating rheology and electrolyte access. The sphere's internal architecture decides how the particle survives cycling: single-crystal cathodes, a refinement of the late 2010s, trade some rate capability to eliminate the grain-boundary cracking that ages polycrystalline spheres. [9.4] The details — precursor co-precipitation, sintering atmospheres, dopant gradients — are the cathode industry's actual competitive content, guarded accordingly. When Chapter 13 walks the factory floor, remember this powder: the gigafactory's input is not lithium and nickel but these engineered spheres, already carrying most of the cell's cost and all of its electrochemical destiny.

The anode's quiet upgrade path

Cathode families get the headlines; the anode's history is quieter and nearly as decisive. Graphite's 372 mAh/g has been effectively unchanged for decades — the gains came from engineering around it: binder chemistry, coating porosity, and the incremental admission of silicon. Silicon stores roughly ten times graphite's lithium per gram and swells threefold doing it; the industry's answer, arriving at scale in the 2020s, is to blend single-digit percentages of silicon oxide into graphite anodes, and, in advanced

designs, to use silicon-carbon composite particles that cage the swelling inside carbon scaffolds. [9.5] Each percentage point of silicon is worth a few percent of cell energy, and the roadmap — five, ten, twenty percent — is one of the industry's firmest near-term upgrade paths, requiring no new cathode, no new factory, and no new periodic table. The rocking chair's two seats are improving at different speeds; the asymmetry shapes every chemistry choice ahead.

Two closing observations. First, the families are converging rather than dying: LMFP (manganese-doped LFP) pushes the cheap chemistry's voltage up; high-manganese NMC pushes nickel down; single-crystal and coated variants blur every line. The frontier is no longer a new element but a better-negotiated compromise. Second, notice where the leverage sits. A carmaker chooses a cathode the way a nation chooses an ally: the choice fixes its exposure to the Congo (cobalt), to Indonesia (nickel), to China (iron-phosphate supply chains), and to the price of a tonne of lithium carbonate. The materials map in Part Five is the political geography of this one table.

CHAPTER 10

The Other Electrode

The cathode gets the headlines, but the anode is where the battery's oldest ghost lives. Every proposal for the negative electrode of a lithium cell, from Whittingham's day to the present, is one of three answers to the same question: what do you do about the metal?

The first answer, chronologically, was *use it* — and Chapter 4 recorded how that ended: dendrites, shorts, fires, Exxon's

abandoned programme and Moli's recalled phones. The theoretical prize is so large — 3,860 milliamp-hours per gram, ten times graphite's — that the metal anode has never been truly abandoned, only postponed, awaiting an electrolyte strong enough to hold back its own deposition. [10.1]

The second answer was Yoshino's: *host it in carbon*. Petroleum coke gave way within a few years to graphite proper, once electrolyte formulations grew SEI films good enough to keep the layers from peeling. Graphite's deck of cards accepts one lithium for every six carbons — LiC_6 — which works out to a theoretical 372 milliamp-hours per gram, and in good commercial cells the anode delivers close to that limit, cycle after cycle, for a decade. It is one of the quiet triumphs of industrial chemistry: a material at ninety-plus percent of its theoretical best, manufactured by the hundreds of thousands of tonnes, so reliable that the industry has spent thirty years optimising everything else. [10.1]

But 372 is a ceiling, and the car industry lives under ceilings. The third answer is *alloy it*. Silicon, one row down from carbon, takes lithium not as a guest between layers but as an alloy — up to roughly 3.75 lithiums per silicon atom, a theoretical capacity near 3,600 milliamp-hours per gram, graphite's ten-fold rival in a fraction of the weight. The catch is mechanical, and brutal: a silicon particle swells to three times its size on charging and shrinks back on discharge. Pulled apart and crushed by its own breathing, a bulk silicon anode pulverises itself within a few cycles, each fresh crack exposing new surface that grows new SEI and drinks more lithium. [10.2]

Forty years of ingenuity have gone into domesticating that swelling. The industry's compromise, standard now in premium cells, is dilution: a few percent of silicon oxide or silicon-carbon composite blended into the graphite, adding capacity without handing the anode's mechanics to silicon outright. Startups push

the fraction higher — Sila Nanotechnologies, founded by a former Tesla battery engineer, raised $375 million in 2024 to finish its Moses Lake plant and ship its Titan Silicon anode material to carmakers from late 2025; Mercedes-Benz signed on years earlier for the EQG. [10.3] Group14, OneD, Amprius and a dozen Chinese suppliers run the same race with different micro-architectures — porous carbon scaffolds that give the silicon room to breathe, nanowires that bend instead of break. Amprius, using silicon nanowires, has shipped cells above 450 watt-hours per kilogram into aviation and defence niches — the highest specific energy of any commercial lithium-ion cell — at prices that confine it, for now, to customers who buy range by the gram. [10.4]

And the metal itself is back at the door. The solid-state programmes examined in Chapter 30 are, at bottom, an attempt to reopen the first answer: if the electrolyte is a ceramic or a stiff polymer rather than a liquid, perhaps the dendrites can be mechanically held down, and the anode can be lithium metal again — Whittingham's original dream, with sixty years of scar tissue. Should any of them succeed at scale, the anode chapter of this industry will have come full circle: metal, to carbon, to silicon, to metal again, each turn of the spiral at a higher voltage and a lower temperature of discourse.

Why graphite refuses to leave

Forecasters have been burying graphite for twenty years, and the corpse keeps getting up. The reasons are intercalation's own virtues: graphite's layered structure breathes only modestly as lithium enters, the staging chemistry proceeds through well-defined plateaus that give the cell a flat, manageable voltage, and the material itself is carbon — abundant, processable, and, once the graphitisation industry matured, cheap. The theoretical 372 mAh/g is not a frontier; it is a floor that engineering has polished

to within a few percent of theory — modern anodes realise 355-360 mAh/g routinely. [10.3] The consequence is an industry optimisation problem with no slack left at the material level: every further joule must come from somewhere else — from silicon blends, from thinner foils and separators, from higher cathode voltage. Graphite's entrenchment is thus partly a story of perfection achieved early. Displacing a near-perfect incumbent requires not a better material but a better system, which is why lithium metal's challenge, when it comes in Chapter 30, arrives dressed as an electrolyte revolution.

The hard-carbon annex

Graphite has one sibling that matters, and sodium gave it a job. Hard carbons — disordered, non-graphitising carbons made from resins or biomass — store sodium well where graphite barely stores it at all, because sodium's ion is too large for graphite's galleries. The same disorder that frustrated lithium engineers is sodium's opportunity: hard-carbon anodes are the enabling component of the sodium-ion cells now entering mass production. [10.5] The manufacturing implication runs against the deglobalisation grain of Chapter 25: hard carbon's precursors and process know-how also concentrate in East Asia, so the chemistry intended to free the industry from lithium's geography inherits carbon's instead. Dependencies, this book keeps finding, migrate rather than disappear.

Counting the anode's share

It is worth fixing the anode's economic weight early, because later chapters will argue about cathodes and leave graphite's billion-dollar scale implicit. The anode is typically the second or third most expensive component in a cell — behind the cathode, alongside the electrolyte and separator cluster — and its cost

curve is driven by the graphitisation step: weeks in an Acheson furnace at 3,000 degrees, an electricity bill measured in tens of kilowatt-hours per kilogram. [10.6] That electricity dependence is the hidden reason Chapter 20's map looks as it does: anode production went where power was cheap and environmental patience long. When the teardown literature prices a cell's bill of materials, graphite is the line item that looks least like a technology and most like a utility — which is exactly what it is.

One final asymmetry deserves naming. The anode's raw material is not scarce: graphite is common, silicon is sand. Yet the anode supply chain is among the most concentrated in the whole battery — not because of geology but because of process. Turning flake graphite into battery-grade spherical graphite, and coke into synthetic graphite, is a dirty, energy-hungry art that China spent twenty years mastering while the West outsourced it. By 2023 China held about three-quarters of the graphite anode supply chain, and less than one percent of spherical graphite was produced anywhere else. [10.5] When Beijing added graphite to its export-control list in December 2023, the anode — the electrode nobody writes about — briefly became front-page news. The ghost had learned politics.

CHAPTER 11

The Quiet Components

A lithium-ion cell is maybe sixty percent cathode, anode and collector foils by weight, and the balance is a cast of components that never appear in the chemistry's name and would stop the show if any one of them failed. Two of them — the electrolyte and the separator — are industries unto

themselves, with their own giants, their own chokepoints, and their own quiet histories.

The electrolyte

The ion's highway is a liquid: lithium hexafluorophosphate, $LiPF_6$, dissolved in a blend of organic carbonates — ethylene carbonate, dimethyl carbonate, ethyl methyl carbonate — with a few percent of additives that grow the SEI, scavenge stray acid, and set the wetting and high-voltage behaviour. The formulation is among the most guarded art in the industry: a cell maker's electrolyte recipe is as sensitive as its cathode powder. $LiPF_6$ itself is a compromise no one loves — the salt is moisture-sensitive and decomposes, in the presence of water, to hydrofluoric acid, which is why water is the mortal enemy of every stage of cell manufacture and why battery factories are built around dry rooms. But after forty years no general replacement has displaced it, though the newer salt LiFSI is gaining in premium cells. [11.1]

The market's shape is a preview of Part Six. Global electrolyte shipments reached about 1.66 million tonnes in 2024, up 26.7 percent year on year — and Chinese producers supplied more than ninety percent of it. The leader, Guangzhou Tinci Materials, shipped close to half a million tonnes, nearly a third of the Chinese market, with Capchem, BYD and Ruifin behind; yet competition is so fierce that the average selling price halved in two years and the industry's concentration actually fell. [11.1] Even in the components China dominates utterly, it competes with itself.

The separator

The least glamorous component is in some ways the most critical: a microporous film of polyethylene or polypropylene, ten to twenty-five micrometres thick, whose only job is to keep the electrodes apart while letting ions soak through in the electrolyte. It must be

uniform to within microns, strong against puncture by a dendrite, chemically inert, and — the trick that saves lives — it must fail gracefully. Polyethylene's melting behaviour is exploited as a built-in fuse: if a cell overheats toward about 130°C, the PE pores collapse and seal, strangling ion flow and shutting the cell down before the polypropylene skeleton gives way higher up. A multilayer PP/PE/PP separator is, in effect, a thermal switch woven into every cell. [11.2]

The separator business descends directly from the invention: Asahi Kasei, Yoshino's employer, has made its Hipore wet-process separator for forty years, and in 2015 it bought the American pioneer Celgard — the firm whose dry-process film had gone into the earliest cells — consolidating much of the high end of the market under one Osaka roof. [11.3] Wet-process films, stretched from paraffin-oil gels, dominate premium cells; dry-process films serve cheaper ones; ceramic coatings, painted on to resist shrinkage and puncture, have become standard in automotive grades. Chinese makers — Shanghai Energy (Semcorp) above all — have since taken the volume lead, and Asahi Kasei is building a ¥180 billion integrated plant in Ontario to give North America a non-Chinese source, targeting thirty percent of that market. [11.3] The component nobody sees is being re-fought, factory by factory, on three continents.

The supporting cast

Around the big four materials circle the specialists. Copper foil for the anode collector, rolled to six micrometres — thinner than cling film — so that a cell carries as little dead weight as possible; aluminium foil for the cathode. Binders: PVDF for cathodes, and for anodes the water-based CMC/SBR system that lets graphite lines avoid solvent recovery. Conductive carbons that wire the active particles together. Tabs, gaskets, vents, and — in cylindrical

cells — the current interrupt device, a mechanical fuse that physically severs the circuit if internal pressure spikes. Each is a niche with its own leaders, margins and shortages: during the 2021-22 boom, copper foil and PVDF were rationed as tightly as lithium itself.

The electrolyte’s recipe

The ion bridge is, chemically speaking, a small formulary: lithium hexafluorophosphate dissolved in a blend of ethylene carbonate and linear carbonates — dimethyl, diethyl, ethyl methyl — plus a few percent of additives that are the formulator’s real intellectual property. $LiPF_6$ earned its position by a rare combination: it passivates the aluminium current collector (other salts corrode it), it conducts well, and it tolerates the cathode’s high voltage — against serious flaws: it decomposes with traces of water to hydrofluoric acid, and it is thermally fragile. The industry has lived with the flaws for thirty years because every candidate replacement fails a different test. [11.3] The additives are where the margins live: a percent or two of vinylene carbonate, fluoroethylene carbonate and proprietary compounds that repair the SEI, scavenge HF, widen the temperature window. A modern electrolyte is a generic base carrying bespoke medicine, sold at bespoke prices.

The separator’s hidden physics

The separator looks like packaging and behaves like safety equipment. Its pores — sub-micron, engineered by stretching or by solvent extraction — must hold electrolyte, pass ions, and block electrons and dendrites simultaneously; its shutdown function is a deliberate failure mode, a polyethylene layer designed to melt and seal its own pores at about 130 degrees, strangling the ion traffic before the cell runs away — with a polypropylene layer behind it

holding structure to 165. [11.4] The ceramic coatings added since the 2000s exist because that elegant design has a gap: between shutdown and structural failure lies a temperature band where shrinkage can expose electrodes anyway. The coating bridges it. Separator manufacturing — wet-process film lines of extreme precision — is one of the battery chain's least glamorous and most concentrated businesses, a reminder that in this industry the commodity-looking components are often the hardest to make.

The quiet cost share

Together the quiet components — electrolyte, separator, foils, tabs, cans, pouches, the binders and conductive carbons that never appear in marketing — account for roughly a third of a cell's bill of materials, and they decide a disproportionate share of its yield, safety and life. [11.6] The factory chapters ahead will keep returning to them, because manufacturing failures are usually quiet-component failures: a wrinkle in a coating, a bubble in a fill, a burr on a cut, a separator pinhole that passes inspection and fails in a car in Oslo. The lithium-ion battery's reliability record — billions of cells, vanishingly few fires per unit of energy delivered — is a quality-control achievement belonging largely to components with no Nobel Prizes attached.

The lesson of the quiet components is the one this whole book keeps arriving at. The lithium-ion battery is not a chemistry; it is a stack of industries, each with its own physics, its own oligopoly, and its own geopolitics, laminated together at the coating line. A cell is only ever as available as its scarcest film, salt or foil — a truth the carmakers learned, expensively and repeatedly, between 2020 and 2023.

When Batteries Burn

Every lithium-ion cell is a bargain with flammability, and the terms of the bargain were set in Chapter 8: a four-volt chemistry requires an organic electrolyte, and an organic electrolyte is fuel. The engineering question is never whether energy can escape, but how the escape is managed. When it escapes gradually, nobody notices — a cell ages, swells slightly, dies. When it escapes at once, the industry calls the event thermal runaway, and the rest of the world calls it a battery fire.

The sequence is now well understood, down to the degree. Somewhere past about 80°C, the SEI — the protective film on the anode — begins to break down, exposing fresh lithiated graphite to the electrolyte; the reaction that follows is exothermic and self-feeding. Around 130°C the polyethylene separator's pores collapse — a designed shutdown that strangles the current but not the chemistry; the film's polypropylene backbone holds its shape to about 165°C before melting too. Past about 130°C the charged oxide itself begins to decompose and release oxygen — the exact threshold is the cathode chemistry's own, layered oxides first, iron phosphate hundreds of degrees later — and now the cell carries its own oxidiser, which is why lithium-ion fires do not need air, smother themselves poorly under extinguishers, and can reignite hours or days after appearing dead. Past that point the electrolyte vapour ignites, the cell vents flares of gas, and if the heat spreads to neighbouring cells the failure becomes a propagating wave: one cell, one module, one pack, one building. [12.1]

The industry's entire safety apparatus is an attempt to interrupt that staircase at its lowest step. Cell-level fuses and vents, flame-

retardant electrolyte additives, ceramic separator coatings, module partitions, pack-level liquid cooling, battery-management computers watching every cell's voltage and temperature — each is a brake on a particular stair. The brakes work: measured per gigawatt-hour deployed, fires are rare and becoming rarer. But the exceptions write the headlines, and four of them mark the industry's growing pains.

2006: the laptop recalls. Microscopic metal particles introduced on Sony's cell lines could, with bad luck, pierce a separator and short a cell. The result was the largest consumer recall in battery history: Dell recalled 4.1 million notebook batteries in August 2006, Apple 1.8 million, and the total across makers approached ten million; Sony's costs ran into the hundreds of millions of dollars and its battery business never again led the industry it had created. [12.2] The lesson the industry drew — that ppm-level contamination control was now a core competency — pushed cell manufacturing decisively toward semiconductor-grade discipline.

2013: the Dreamliner. In January, a Japan Airlines 787 parked at Boston Logan suffered an APU-battery fire; days later an ANA 787 made an emergency landing in Japan with a smoking main battery. The world's entire 787 fleet was grounded for months — the first grounding of a commercial airliner type since 1979 — while Boeing re-engineered the battery system: the cells themselves were retained, but encased in a stainless-steel box vented directly overboard, with charging limits tightened and spacers added between cells. [12.3] The episode taught aviation the core doctrine of battery safety: assume cells will occasionally fail, and design so that a failed cell is a maintenance event, not an accident.

2020-21: the Bolt. General Motors recalled every Chevrolet Bolt it had built — ultimately about 141,000 cars — after a manufacturing defect in LG cells (a torn anode tab and a folded separator, sometimes in the same cell) caused a series of fires. The

remedy was extraordinary: replace every battery module in every car, at a cost GM put at $1.9-2.0 billion, nearly all of it reimbursed by LG under a settlement announced in October 2021. [12.4] It remains the most expensive battery defect in history, and the most instructive: two simultaneous manufacturing flaws, at defect rates of parts per million, in a supply of millions of cells, were enough.

2025: Moss Landing. On 16 January 2025, fire broke out in the 300-megawatt building of the Moss Landing storage plant in Monterey County — one of the largest battery installations on Earth, holding roughly 100,000 lithium-ion modules. About 55 percent of them burned over days of smouldering; thousands of nearby residents were evacuated, the EPA ran air monitoring, and the state ordered health studies as fine metals settled over the surrounding wetlands. [12.5] The plant's remaining phases survived, and the industry's argument — that grid batteries sit outdoors, unoccupied, far from the people their electrons serve — held. But the pictures of the burning building did more than any white paper to push the industry toward the next generation of designs: LFP chemistry in place of nickel-rich cells, compartmentalised containers instead of warehouse halls, and per-cell detection.

The recall that taught the industry arithmetic

The 2006 notebook recalls — millions of cells across Dell, Apple, Sony itself — were a manufacturing-defect story, and the public lesson was statistical. The defect was metal contamination inside cells: microscopic particles that could, with unlucky placement and time, pierce the separator and short a cell internally. At production volumes of hundreds of millions of cells a year, a defect rate invisible to sampling — a few per million — yields hundreds of incidents and headline probability approaching certainty. [12.2] The industry's response rewired quality assurance: contamination

control entered the dry room’s creed, cell-level traceability became standard, and the regulatory scaffolding around transport and certification tightened. The deeper lesson, which Chapter 15’s gigafactories inherit, is that a battery is a product whose acceptable defect rate approaches zero because its failure mode is energetic and its production volume is astronomical. No other mass product combines those two properties so completely.

Anatomy of a runaway

Thermal runaway rewards precise description, because the phrase hides a sequence. A trigger — internal short, overcharge, crush, external heat — pushes some region of the cell past a threshold where exothermic side reactions begin: SEI decomposition near 90-120 degrees, then reaction of lithiated anode with electrolyte, then, at the cathode, the oxygen-releasing decomposition of the charged oxide. Each reaction’s heat feeds the next; past the cathode threshold the process is self-sustaining; the separator melts, the full electrode area participates, and the cell vents gas, flame and fragments. [12.1] Two material facts govern the stakes. First, the charged cathode carries its own oxidiser — the fire is chemically self-sufficient and cannot be smothered by excluding air. Second, the chemistry chooses the violence: LFP’s phosphate lattice holds its oxygen hundreds of degrees longer than layered oxides, which is the physical root of its safety reputation. [12.1] Cell design, fuses, vents and battery-management systems all fight the same battle: detect the sequence early, isolate the cell, and never let one cell’s failure become a pack’s.

The Moss Landing lesson

The grid era scaled the problem from cells to warehouses. The fires at utility installations — Moss Landing’s 2025 blaze among the most prominent — burned for days, defied water, and taught

fire services a doctrine of monitored burn-down: protect exposures, let the energy leave. [12.5] The regulatory response is reshaping stationary storage: spacing rules, containerised designs with deflagration panels, cell-to-pack isolation, and, increasingly, chemistry selection — LFP's grid dominance is as much a fire-code outcome as a cost one. [12.6] The industry treats each incident as tuition; the public record suggests the tuition is being spent well — failure rates per gigawatt-hour deployed have fallen as installations multiply — but the absolute number of installations is now so large that the rare event remains a certainty somewhere, every year. The honest summary is this book's own: a technology that stores lightning must expect, occasionally, to be struck by it.

The trajectory matters more than the incidents. Each generation of failure has been a manufacturing or integration failure, priced, recalled, engineered against, and absorbed — while deployment grew a hundredfold. The same industry that recalled ten million laptop cells in 2006 now ships over a terawatt-hour a year, and the share of that capacity that burns is small and falling. The fires are not a sign that the technology fails; they are the tuition of the only energy-storage technology that has ever scaled this fast. The tuition, at Moss Landing prices, is still being paid.

PART FOUR

The Factory

The battery is not discovered anymore; it is manufactured. Slurry, foil, dry rooms and formation towers - the least visible and most decisive part of the industry.

CHAPTER 13

How a Cell Is Made

The least visible part of the battery industry is the one that decides who wins it. Chemistry papers are published worldwide; patents can be licensed; money, as the gigafactory boom proved, is available to almost anyone. What cannot be bought off the shelf is the ability to run the factory — to turn powders and foils into ten million identical cells a month, at yields where the scrap bin does not eat the margin. Cell manufacturing is a process industry wearing a high-tech costume, and its

disciplines would be recognised by any veteran of papermaking or photographic film: coating, drying, calendering, slitting. The product just happens to be electrochemistry.

How a cell is made: the gigafactory line



Red: inside the dry room. Formation and aging are the line's slowest, costliest steps.

The line begins with mud. Cathode powder — the black lithium-metal-oxide that is the cell's heart — is mixed with conductive carbon and a binder into a slurry, in mixers the size of cement trucks. The anode line does the same with graphite, using a water-based binder. Everything from here on is a battle against variation: the slurry must be homogeneous to within microns of every later dimension, because every downstream tolerance multiplies this one.

The slurry then goes to the coating machines, the signature equipment of the industry: slot dies that lay the wet film onto metal foil — aluminium for the cathode, copper for the anode —

running at web speeds around eighty metres a minute, coating widths up to a metre, both sides of a foil that is itself barely thicker than household wrap. The wet film passes through tens of metres of convection drying; the cathode line must also recover its solvent (NMP, a toxic organic, captured and recycled). What emerges is a painted foil whose loading — milligrams of active material per square centimetre — is the first number a cell maker guards with NDAs. [13.1]

Next, the calender: a pair of steel rolls that press the dried coating, at up to a hundred metres a minute, to a precisely chosen porosity. Too loose and the cell wastes volume; too tight and the electrolyte cannot wet it. Then slitting cuts the master roll into the narrow electrode tracks the cell design needs, stamping tabs as it goes. [13.1]

From here the work moves into the dry room, and the economics change. Lithium chemistry hates water: moisture decomposes the $LiPF_6$ salt into hydrofluoric acid, which attacks everything else. So assembly happens in rooms held to dew points of −40°C and below — air dried to a fraction of a percent of ordinary humidity, in the most expensive square metres of the factory. Inside, the electrode tracks are wound or stacked with separator film between them: round winding for cylindrical cells, flat winding or Z-folded stacking for prismatic and pouch. The stack goes into its housing — a steel can, an aluminium case, or an aluminium-plastic pouch — is filled with a few grams of electrolyte under vacuum, wetted, and sealed. [13.1]

The cell is now built but not yet a battery. It goes to formation: the first charge, run slowly over hours in racks of chargers — towers holding up to eight hundred cells each — during which the SEI film grows on the anode (Chapter 8), gas is evolved and vented, and the cell’s true capacity is measured for the first time. Then aging: days to weeks of rest at controlled temperature while quality

engineers watch for the self-discharge that betrays a microscopic defect. The formation-and-aging block is the slowest, most capital-hungry part of the whole line — a recent analysis of gigafactory cost structure puts formation and aging at about a third of manufacturing cost, ahead of coating and drying at fifteen percent — and its ten-day dwell times are why cell plants measure their inventories in weeks. [13.2] Only then does end-of-line testing release a cell to be packed.

The dry room, at last, in detail

Of all the factory's rooms, one deserves the visitor's full attention, because it is the one no other industry has: the dry room. $LiPF_6$ decomposes with water to hydrofluoric acid; moisture anywhere in the process — in a powder, a solvent, an operator's breath — becomes an acid that eats the SEI, corrodes the foils and shortens the cell's life. So the final assembly steps run in air dried to dew points of minus 40 to minus 60 degrees Celsius — one part water vapour in ten thousand, drier than any desert. [13.3] The cost is not the drying equipment alone but the physics of maintaining it: every door opening, every person, every pallet is a moisture source to be engineered around. Cost studies put the dry room's share of factory capital and a striking share of its operating energy; some lines have been moved to smaller "dry enclosures" around the critical stations precisely to shrink the expensive volume. [13.3] When later chapters compare manufacturing geographies, remember this room: it is energy-hungry, unforgiving, and unforgivingly necessary. A gigafactory is, in the driest possible sense, a humidity-control business with a battery attached.

Formation, the cell's first breath

After filling comes the step that converts hardware into a battery: formation. The fresh cell is charged for the first time, slowly, under

controlled temperature and pressure, and in those first hours the solid-electrolyte interphase grows on the anode — the passivating film, a few dozen atoms thick, on which the cell's entire working life depends. Formation is chemistry performed by a factory: the charge protocols, rest periods and degassing steps are tuned recipes, guarded accordingly, and they take time — hours to days per cell — and therefore capital: formation and aging equipment is the single largest block of process cost, about a third of manufacturing cost in detailed models, because thousands of cells must occupy expensive channels for a long, patient time. [13.5] Aging follows: cells rest, warm, for days to weeks while the factory watches for self-discharge — the ones with internal defects quietly drain and are culled. It is quality control performed by time itself, and it is why a battery plant's inventory includes warehouses full of cells doing, to all appearances, nothing at all.

The tolerance stack

Every stage compounds, and the compounding is the industry. A coating one percent too thick becomes a cell one percent too heavy; a misaligned wind becomes a soft spot; a contaminated fill becomes a cull at aging — or worse, a pass. Yield — the fraction of started cells that ship — is the industry's most confidential number and its most honest one: it converts process discipline directly into cost per kilowatt-hour. New factories famously burn through months of single-digit yields; mature lines run far higher. [13.6] This is the real content of the "learning curve" that Chapter 22 quantifies: not abstract experience but the slow, expensive conversion of a temperamental chemical process into a routine one, coat by coat, cell by cell.

Two numbers summarise the discipline. First, yield: the difference between a good line and a bad one is the difference between ninety-something and seventy-something percent of cells passing,

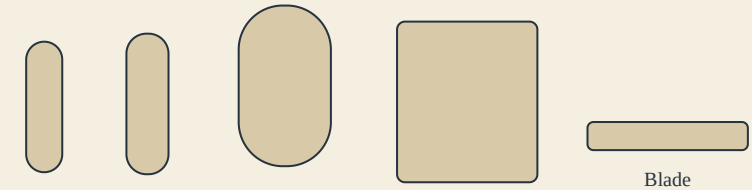
and at gigafactory scale that gap is the whole profit margin — which is why Tesla, Panasonic, CATL and BYD guard their process knowledge more jealously than their patents. Second, scale: modern lines are planned in gigawatt-hours per year, and the industry's reference plant is a 10 GWh block, because the cost curve keeps rewarding size. The consequence is an industry where the entry ticket is a billion dollars and a decade of process learning — a combination that, as Part Six records, has humbled some of the richest newcomers in industrial history.

CHAPTER 14

The Shape of the Cell

Lithium-ion cells come in three bodies, and the choice among them is a genuine industrial fork — three different answers to the question of how to pack jelly-rolled electrodes into a volume that must be cooled, crash-proofed, and manufactured by the million.

The shape of the cell (schematic, not to scale)



Teardown data: Blade 432 Wh, LFP, 160 Wh/kg; 4680: 85.6 Wh, NMC811, 241 Wh/kg
(Cell Reports Physical Science, 2025)

Cylinders contain; prisms integrate; the Blade deletes the module.

The cylindrical cell is the veteran, descended from the AA. Sony's first lithium-ion cells were cylindrical, and in the 1990s the laptop industry standardised the 18650 — eighteen millimetres across, sixty-five long — as its building block. When Tesla set out in 2006 to build an electric car, its founders made the contrarian decision to use the consumer cell rather than wait for an automotive one: the Roadster's pack, shipped in 2008, wired together 6,831 commodity 18650s. [14.1] The bet was that laptop-scale manufacturing had already ridden the cost curve down, and it paid. Tesla has stayed cylindrical ever since — 2170 cells (twenty-one by seventy millimetres) with Panasonic at the Nevada Gigafactory, then its own 4680 (forty-six by eighty), a tabless design unveiled on Battery Day in 2020 with promises of five times the energy and, via dry-electrode coating, a revolution in factory cost. The revolution proved hard: the dry cathode took five years to reach vehicles, with the first Cybertrucks on in-house dry-cathode 4680s entering validation only in 2024; by 2025 Tesla could at least claim its Texas-made 4680 was its cheapest cell per kilowatt-hour. [14.2]

The prismatic cell is a flat-wound or stacked rectangle in a hard aluminium case — the natural format for packing densely into a vehicle floor, and the default of the German and Chinese industries. The pouch cell replaces the case with an aluminised plastic bag: lightest of all, swell-prone, needing external pressure, used by the old LG-SK school and in the Nissan Leaf's laminated AESC cells. [14.3]

The argument has lately been settled by going around it. BYD's Blade battery (2020) is a prismatic cell stretched to absurdity — ninety-six centimetres long, nine high, a centimetre and a half thick, a beam rather than a brick — laid in rows that are themselves the pack's structure. A German teardown comparison of the Blade against Tesla's 4680 captures the state of the art neatly: the Blade cell carries 432 watt-hours and 135 amp-hours in a format that deletes most of the module hardware, while the 4680 carries 85.6 watt-hours as an energy-dense cylinder; both are explicitly designed for "cell-to-pack" construction, in which modules disappear and cells bolt straight into the vehicle. [14.4] CATL's Qilin and the industry's CTP/CTC (cell-to-pack, cell-to-chassis) programmes generalise the idea: the pack stops being a box of boxes and becomes a structure of cells, with space savings of ten to twenty percent and, for LFP, enough recovered density to close the gap with nickel chemistries at the pack level.

The format war, in other words, ended in a truce drawn by the pack designers. Cylindrical cells win on manufacturing speed and thermal containment — a can is a pressure vessel that fails politely; prismatic and pouch win on packing efficiency. What changed is the unit of competition: the industry no longer sells cells so much as cell-shaped load-bearing structure. The battery is becoming the car.

Format	Dimensions	Nominal energy	Notes
18650	18 x 65 mm	~10-12 Wh	Laptop standard; Roadster used 6,831
2170	21 x 70 mm	~18 Wh	Tesla/Panasonic, Nevada
4680	46 x 80 mm	85.56 Wh (teardown)	Tesla tabless; dry-cathode ramp
BYD Blade	965 x 90 x 13.5 mm	432 Wh (teardown)	Prismatic LFP beam; cell-to-pack

The tab problem

A cell’s shape is partly an electrical decision, and the deciding detail is the tab — the metal whisker that carries current out of the jellyroll. In a classic cylindrical cell, the whole electrode’s current funnels through one or two tabs; as cells grew larger and faster-charging, that funnel became the bottleneck: heat concentrates at the tab, current density peaks there, and the cell’s useful speed is limited by its own anatomy. The engineering answer, industrialised in the 2020s, is the tabless design: the foil’s uncoated edge runs the full length of the winding, so every point of the electrode is its own tab, current flows radially through centimetres instead of metres, and resistance and hot spots collapse. [14.4] Tesla’s 4680 announcement made the idea famous; the teardowns that followed showed how hard the execution is — laser-cutting and welding foils at that geometry is a manufacturing art in itself. The prismatic world answered the same problem differently, with multi-tab windings and, in BYD’s Blade, with the shape itself: a cell so long and thin that its whole length is effectively terminal.

The chemistry-format bargain

Format and chemistry negotiate constantly. LFP's lower energy density argued against small cells — too much packaging per joule — and for large prismatic cans, where the packaging fraction shrinks; the Blade pushed that logic to its extreme, a cell nearly a metre long doubling as structure. High-nickel chemistries, energy-rich and thermally nervous, preferred small cylinders, whose steel cans and small per-cell energy content make failures containable — one reason the 18650 and 21700 fleets ran nickel-rich while the prismatic world ran phosphate. [14.5] The pouch sits between: format-free, pack-efficient, and dependent on the pack for the discipline a can provides. There is no correct shape; there is a correct shape per chemistry per application, and the industry's format wars are really its chemistry wars fought with calipers.

Counting the wrappers

The packaging's share is worth fixing in numbers. In a small cylindrical cell the can, caps and inactive margins can consume a fifth or more of the cell's mass and volume; scale the cell up and the fraction falls — the 4680's case for existence is largely this ratio. A pouch cell carries the least wrapper of all, which is why the highest pack-level energy densities claimed in the industry tend to involve pouches — and why they demand the most from pack engineering. [14.6] The wrapper is not waste, though: cans are pressure vessels, safety devices and heat sinks; the art is using structure once for three jobs. The cell-to-pack designs of Chapter 26 take the final step — delete the module, let cells be the pack — and with the Blade, let the cell be the car's floor. Each step transfers function from packaging to structure, and each makes the format question less about the cell and more about the vehicle around it.

Dimensions and measured values for the 4680 and Blade from the Cell Reports Physical Science teardown study (2025); 18650/2170 energies are typical commercial values. [14.1] [14.4]

CHAPTER 15

The Gigafactory

In June 2014, in a press release drafted in the plain style of a supply agreement, Panasonic and Tesla announced that they would build “a large-scale battery manufacturing plant in the United States, known as the Gigafactory.” Tesla would provide land, buildings and utilities; Panasonic would make cylindrical cells inside it; supplier partners would produce precursor materials on the same site. The stated purpose was “a continuous reduction in the cost of long range battery packs” at volumes that would let Tesla build a mass-market car. [15.1] The word — gigafactory, for a plant whose output is measured in gigawatt-hours per year — passed immediately into the language, and the building outside Reno, Nevada became, for a few years, the largest factory footprint on Earth.

The logic was arithmetic. Tesla’s planned Model 3 alone would consume more lithium-ion cells than the entire world then produced; the choice was to build supply or to stop existing. Panasonic brought the process knowledge of two decades at the top of the cylindrical-cell business; Tesla brought the demand, the capital markets, and a willingness to locate a chemical plant in the desert next to a rail line. The factory’s deeper significance was the fusion it embodied: car company and cell maker, demand and process, inside one fence. Every major manufacturer on Earth has since copied the arrangement — as joint venture, long-term offtake, or in-house division.

The build-out that followed is the largest factory-construction wave since the Second World War. By 2024, according to the IEA, global battery-cell manufacturing capacity had reached about three terawatt-hours per year — against actual demand that year of one terawatt-hour. [15.2] Read that again: the world built, in barely a decade, three times the cell-making capacity it could use, on the expectation that demand would keep doubling until it caught up. Most of it stands in China, which produces over three-quarters of all batteries sold and holds about eighty-five percent of cell-making capacity. [15.3] The United States, after the Inflation Reduction Act's production tax credits, doubled its capacity in two years to over 200 GWh in 2024, with nearly 700 GWh more under construction; Korea's cell makers, though they build little at home, operate nearly 400 GWh of overseas capacity — the industry's itinerant professional class. [15.2] Announced projects, if all are built, would triple global capacity again by 2030.

The naming of a scale

Before the word there was the arithmetic, and the arithmetic is worth repeating because it founded an industry. In 2013, Tesla's planners calculated that the company's 2020 car production target would require more lithium-ion capacity than the entire world's output at that moment — every laptop, phone and camcorder cell on Earth. The conclusion was not a procurement strategy but a construction programme: build one factory larger than the world had, and let its scale cut the cost. The Nevada plant's announced ambition — 35 gigawatt-hours of cells a year, more than 2013's global total — gave the industry its unit of account. [15.2] A decade later the word gigafactory is generic, the count worldwide runs into the hundreds built or announced, and the original insight looks less like audacity than like the first honest reading of an exponential: if demand doubles on schedule, your supply must be built ahead of the curve, not behind it.

What scale actually buys

The gigafactory's economics are more subtle than "bigger is cheaper." Scale buys, first, utilisation: coating lines and formation channels are expensive whether or not they run, so throughput per line is the real lever — wider webs, faster coaters, longer ovens. Second, integration: co-locating cell production with cathode, foil or pack lines cuts logistics, inventory and, not least, the dry room's enemy — transport moisture. Third, learning: one site repeating one process accumulates yield faster than ten sites improvising. [15.5] Against these stand diseconomies the industry learned expensively: a single chemistry bet at giant scale strands giant capital when the market shifts (Europe's Chapter 16 is the case study), and a giant factory amplifies ramp risk — every percentage point of yield, at gigawatt-hour volumes, is millions of dollars a month. The successful gigafactory is thus less a monument than a metabolism: steady chemistry, steady process, steady ramp.

The geography of the giga

The map of these factories is the shortest summary of this book's middle chapters. China's count dwarfs all others — the largest plants exceed a hundred gigawatt-hours of capacity, built by companies that grew with the domestic EV market. North America's wave arrived with the Inflation Reduction Act's production incentives after 2022: dozens of plants announced, joint ventures between cell makers and car companies, a belt of construction from Michigan to Georgia to Nevada. Europe's wave, launched with such hope, met Chapter 16's weather. [15.6] India's plants, still counted on fingers, appear in Chapter 31. The striking pattern is that cell factories follow policy as much as markets: production credits, content rules and tariff walls have become as load-bearing as cathode chemistry. The gigafactory, born as a

business calculation, has grown up into an instrument of state — which is precisely the subject of Chapter 25.

The consequences of building three times the demand are the subject of Chapter 22's price war; the strategic consequence is visible on the map. Battery capacity has become the new industrial statistic of statecraft, tracked by the IEA the way steel tonnage once was. Regions measure their industrial health in gigawatt-hours announced, cancelled and delayed — and none more anxiously than Europe, whose home-grown champion had, by 2025, become the most instructive failure in the industry's short history.

CHAPTER 16

Europe's Experiment

Northvolt was Europe's answer to a question it had asked too late. By the mid-2010s the European car industry — the continent's industrial crown — had woken to find that the component that would decide its future was made almost entirely in East Asia. Brussels talked of an "Airbus of batteries"; two former Tesla supply-chain executives, Peter Carlsson and Paolo Cerruti, founded Northvolt in 2016 to build it: green gigafactories in Sweden, powered by hydropower, making cells for BMW, Volkswagen and Volvo, recycling built in from the start. The company raised more money than any private startup in European history — over $15 billion across equity, debt and government support — hired thousands to Skellefteå, two hundred kilometres below the Arctic Circle, and shipped its first cell in 2021. [16.1]

What killed it was not a lack of demand, money, or political will. It was Chapter 13. Cell manufacturing is a yield business, and yield is a craft accumulated over decades of production. Northvolt's lines ran slowly and scrapped heavily; a flagship expansion collapsed under its own complexity; a BMW order worth two billion euros was cancelled in 2024 when deliveries failed. The company cut staff, sold pieces of itself, filed for Chapter 11 protection in the United States in November 2024, and — after failing to find a rescuer — filed for bankruptcy in Sweden on 12 March 2025. The trustee's statement was dignified and exact: serial production had in fact been improving — output from the Skellefteå lines had doubled and yields had risen fifty percent since September — but "the company was unable to secure the necessary financial conditions to continue." [16.2] The largest industrial startup in European history was undone by the discipline that this book's thirteenth chapter describes: slurry, coating, formation, and the slow accumulation of the ten thousand things that must all go right at once.

Northvolt was not alone. The British equivalent, Britishvolt, collapsed in 2023 before producing a saleable cell. Several announced gigafactories across the continent were paused, shrunk or re-scoped in 2024-25 as EV demand grew slower than the factories. Yet it would be wrong to read the episode as Europe's exit. The incumbents' joint ventures soldier on — ACC (Stellantis-Mercedes-TotalEnergies), the Korean and Chinese plants in Hungary, Germany, Poland and Spain — and the hard assets and harder lessons of Northvolt itself were bought out of bankruptcy and are being restarted by new owners. [16.3] What ended was the belief that the industry could be bought rather than learned.

What Northvolt actually proved

Autopsies should list achievements alongside causes, and Northvolt's were real. The company proved that a European venture could attract capital at a scale the continent's battery ambitions required — billions raised from Goldman, Volkswagen, BMW, BlackRock, pension funds and governments — and could sign offtake contracts worth tens of billions with premium carmakers. It recruited credibly from the Asian industry's talent pool, stood up a research campus in Västerås that produced genuine cell-development work, and built a factory whose sustainability thesis — hydroelectric power, recycled content targets, traceable materials — set the benchmark the European industry still cites. [16.2] Its demonstration line shipped cells. Customers did not flee the chemistry; they fled the calendar. The distinction matters for what follows: Europe's failure in this chapter was not scientific and not primarily commercial. It was executional, in the specific sense that a company tried to ramp multiple gigafactories, a cathode plant and a recycling operation simultaneously, on a learning curve that even incumbent Asian giants climb one line at a time.

The sequence that could not be skipped

The battery industry's accumulated wisdom about ramps is unglamorous: yield is earned per line, per chemistry, per format; a new entrant's first plant is a school that loses money; and vertical integration — making your own cathode material before you have mastered cells — multiplies the school's tuition. Northvolt's plan ran the sequence in parallel under deadline pressure, and the deadlines were set by customer contracts signed before the capability existed. [16.3] Each delay then propagated: BMW's cancelled order in 2024 removed revenue the ramp was counting on; the German and Canadian expansions consumed management

attention and capital the Swedish line needed. When the bankruptcy came, in Sweden in March 2025 after a US Chapter 11 process, the statement blamed capital markets and geopolitics — true, and incomplete: the capital had been forthcoming for years, and no geopolitical wind compelled the parallel-expansion strategy. [16.4] The operational truth is simpler and harder: nobody has yet found a shortcut across the yield curve, and a balance sheet is not one.

What remains standing

The continent's battery story did not end at Skellefteå, and this chapter should close on what survived. Asian incumbents — CATL in Germany and Hungary, LG, Samsung and SK in Poland and Hungary — operate European plants successfully, which proves the geography was never the problem; the ownership was. Chinese and Korean process knowledge, transplanted, ramps in Europe as it does at home. [16.5] The European policy question has accordingly narrowed from "can Europe have its own champions?" to "what share of value, employment and know-how must production on European soil capture, whoever owns it?" — a question the EU Battery Regulation and local-content debates now address. Northvolt's assets, meanwhile, did not vanish: the site, the workforce and the knowledge passed to successors. The ion, as this book's closing chapter will suggest, is patient with ownership changes. It only insists on being made somewhere, by somebody who has climbed the curve.

The episode belongs in this book because it is the cleanest demonstration of the battery industry's real moat. Not patents: the chemistries are forty years old. Not capital: Northvolt had more than almost anyone. Not customers: it had the best order book in Europe. The moat is process knowledge — the ability to run the coating line at speed and sleep at night — and it is held, today,

disproportionately by the Chinese firms that spent the 2010s accumulating it. Europe’s experiment proved the moat exists by dying against it. What China built, and how, is the subject of Part Six.

PART FIVE

The Materials Map

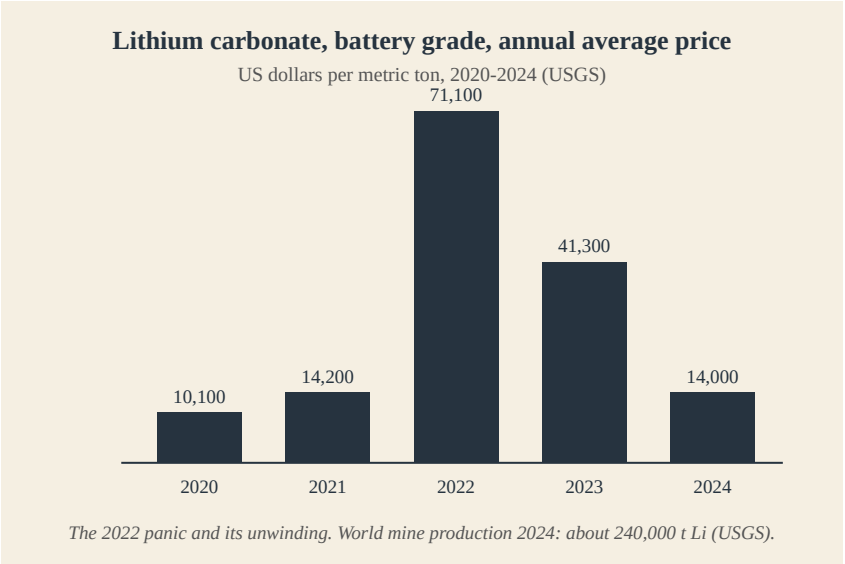
Follow the bill of materials out of the factory and into the ground: lithium from salt flats and hard rock, cobalt from the Congo, nickel from Indonesia, graphite from China, iron and phosphate from everywhere.

CHAPTER 17

Lithium Country

Follow the battery’s bill of materials out of the factory and the first stop is the element itself — and the first surprise is that lithium is not rare. It is about as abundant in the Earth’s crust as chlorine, scattered through brines, clays and granites on every continent. The scarcity is not geological but industrial: there are only a handful of places on Earth where the element is concentrated enough, and the chemistry cooperative enough, to dig or pump profitably, and only one country that knows how to

turn most of it into battery-grade chemical. The map of lithium is a map of three ways of winning the same metal.



The 2022 panic and its unwinding. World mine production 2024: about 240,000 t Li (USGS).

Hard rock: Australia. The spodumene belt of Western Australia — Greenbushes above all, the largest and richest hard-rock lithium mine on Earth, together with Wodgina, Pilgangoora and Mt Marion — made Australia the world's biggest producer: nine mineral operations, roughly a third of world output, shipping spodumene concentrate to Chinese refineries. [17.1] The process is brute force refined: blast, crush, roast the ore past 1,000°C to crack its crystal structure, leach with acid, and convert to lithium carbonate or hydroxide. It is energy-hungry and fast — a mine can respond to price in months — and it made Australia the Saudi Arabia of the 2021-22 boom, and the first casualty of the bust that followed, with mines like Finniss and Bald Hill mothballed as prices fell. [17.2]

Brine: the Lithium Triangle. Beneath the salt flats of Chile, Argentina and Bolivia — the Salar de Atacama above all — lie

brines carrying lithium at hundreds of parts per million. The extraction method is the desert's own: pump the brine into ponds and let the sun evaporate it for the better part of a year and more, precipitating salts in sequence until the liquor reaches about six percent lithium, then process it to carbonate. [17.3] Cheap in cash cost, slow to build and slower to respond, and thirsty in places with little water to spare — the Atacama's water politics are now as contested as its lithium. Chile's SQM and America's Albemarle have run the Atacama for decades; Argentina's salars are the industry's growth frontier, with four brine operations and a pipeline of projects — including, as Chapter 31 records, one under Indian flags. Bolivia holds the largest resource of all beneath the Salar de Uyuni and has never managed to produce at scale — a reminder that reserves are not supply.

The refinery: China. Digging and pumping is not the chokepoint; chemistry is. Turning concentrate or brine into battery-grade lithium carbonate or hydroxide — 99.5 percent pure, particle size controlled — is refining, and China built most of the world's capacity while the West watched. The IEA's accounting is blunt: between 2020 and 2024, some ninety percent of the growth in refined lithium supply came from China, and the top three refining nations of the battery minerals now average eighty-six percent of world output between them. [17.4] An Australian mine without a Chinese refinery is, for now, a quarry.

The price cycle completed the education. Lithium carbonate averaged $71,100 a tonne in 2022 — a spot peak near $83,000 in China that November — as demand outran every mine plan on Earth. The response was a supply wave (Australia, China, Zimbabwe, Argentina) that landed just as EV growth cooled: prices fell to $41,300 in 2023 and $14,000 in 2024, spodumene concentrate from $1,250 to $730 a tonne over 2024, and by January 2025 Chinese carbonate traded under $11,000 — an

eighty-five percent collapse that put marginal mines on care-and-maintenance and deferred a generation of projects. [17.1] [17.2] Yet demand itself never stopped growing: 220,000 tonnes consumed in 2024, up twenty-nine percent in a single year. [17.1] Lithium's boom-bust is not a story of a fad; it is the growing pain of the fastest-scaling mining industry in history, learning to build a decade of supply for a demand curve nobody can see clearly.

The chemistry of the ponds

Salar production is a process the sun performs and patience supervises. Brine pumped from beneath the salt flat — lithium at concentrations of a few hundred to over a thousand parts per million — moves through a sequence of ponds over nine months to a year and more, evaporating from one to the next as successive salts saturate and crystallise out: halite first, then sylvite, then the magnesium salts, until the residual liquor reaches several percent lithium. [17.4] The chemistry is unglamorous and the geography is the technology: it works because the Atacama combines extreme aridity, altitude sun and a basin that holds the pond. Every tonne is thus a product of two years of weather, which is why brine supply cannot be ramped like a factory — you cannot hurry an evaporation. Direct lithium extraction, the suite of technologies promising to pull lithium from brine in hours instead of months and from brines too dilute for ponds, has attracted billions in investment and, as of the mid-2020s, delivers a small fraction of world supply: the chemistry works at pilot scale at several sites, and the industry waits to see which designs survive contact with full-rate operation. [17.5]

The hard rock's second life

Spodumene's story is the opposite: a nineteenth-century mineral, mined for ceramics, that became the swing supply of the twenty-

first because a factory route exists. Australia digs the rock — Greenbushes, Pilgangoora and their neighbours among the world's great orebodies — crushes it, concentrates it to about six percent lithium oxide, and ships the concentrate overwhelmingly to China, where converters roast it, acid-bake it, and leach it into battery-grade carbonate or hydroxide. [17.6] The chain's geography is its risk: the mine and the refinery are a hemisphere apart, joined by a single dominant processing nation, and every Western "supply chain resilience" plan of the 2020s is, at rock bottom, a plan to build converters. Some are being built — in Australia itself, in North America, in Europe — but the commissioning curve is measured in years, and China's converters hold decades of process lead. Hard rock's virtue remains what it was: unlike brine, a mine and a roaster can be ramped on an industrial schedule, which is why spodumene, not the salars, absorbed the demand shocks of 2021-22 and why its price, not brine's, swings the market.

Reading a lithium price

Lithium's price history is a compressed education in commodity cycles. A decade near five to ten thousand dollars a tonne; the 2021-22 panic to peaks above eighty thousand for carbonate at the extremes; then the collapse through 2023-25 as new Australian and Chinese-leveraged supply met a demand growth rate that was enormous yet below the hysteria — spot prices fell back toward ten thousand and below the cost curve's higher reaches, idling mines and cancelling projects. [17.7] Each phase taught the same lesson in a different costume: the resource is large, the reserve is whatever price makes it, and the bottleneck is never the crust but the conversion — the ponds' patience and the roasters' capacity. For the battery industry the practical consequence of the crash was benign: lithium fell to a few percent of cell cost, and the cost curve of Chapter 22 kept falling. For the mining industry it was the

old law: the cure for high prices is high prices, administered, as usual, without anaesthetic.

One technical wild card deserves its sentence: direct lithium extraction — pulling lithium from brine with sorbents or membranes in hours instead of evaporating it over months — has been ten years away for thirty years, but is now operating commercially in China and Argentina and being piloted from the Salton Sea to Arkansas. [17.3] If it matures, the map above redraws itself: every oilfield brine and geothermal loop becomes a prospective lithium field, and the deserts lose their monopoly.

CHAPTER 18

The Cobalt Question

Every gram of the first commercial lithium-ion battery's cathode was half cobalt by design, and the chemistry's success created a dependence the industry has spent fifteen years trying to escape. Cobalt is what keeps the layered oxide ordered as lithium leaves; remove it carelessly and the cathode loses capacity, life and eventually structural integrity. It is also — not coincidentally — the battery metal with the most uncomfortable address: the Democratic Republic of the Congo produced an estimated 226,000 tonnes of mined cobalt in 2024, roughly three-quarters of world supply, from the copper-cobalt belt of Katanga. [18.1]

The Katanga story has two faces. The industrial face is Chinese: CMOC's Tenke Fungurume and Kisanfu mines produced 114,165 tonnes of cobalt hydroxide in 2024 — thirty-one percent above their stated capacity, a flood that took CMOC from a quarter of the world market to forty-one percent in a single year — while

Glencore's Kamoto and Mutanda operations anchor the rest. Three majors now account for eighty-five percent of Congolese exports. [18.2] The artisanal face is the one the newspapers know: tens of thousands of creuseurs digging by hand at the edges of the industrial concessions, children among them, selling sacks of heterogenite into a trading chain that washes into the official one. The industry's answer has been audits, standards and traceability schemes; the sceptic's answer is that nothing short of demand destruction cleans a supply chain, and both answers are now being tested simultaneously.

For the demand destruction is real. The price of cobalt, which touched $80,000 a tonne in the panic of 2018, collapsed through the 2020s under the CMOC flood and hit levels in 2024-25 low enough that the DRC itself imposed export quotas to defend the price. Carmakers responded to both the ethics and the economics in the same direction: out. NMC recipes marched from 111 to 622 to 811 — a six-fold cut in cobalt intensity — and the fastest-growing chemistry of all, LFP, contains no cobalt at all. [18.3] Tesla's reported cathode plans, BYD's Blade, the entire grid-storage industry: the growth segments of the battery world are the cobalt-free ones. The Cobalt Institute's own 2024 report reads like a eulogy written by the deceased's family: demand keeps rising in absolute terms — phones and planes still need their cobalt — but the growth market has left.

The artisanal problem, precisely stated

Cobalt's shadow has a specific shape, and precision serves better than outrage. Of the DRC's roughly 220,000-plus tonnes of 2024 mine production, the great majority now comes from industrial mines — CMOC's giant Tenke Fungurume and Kisanfu operations and Glencore's Mutanda and Katanga among them — mechanised, audited, and entangled in their own disputes over royalties and

contracts with the Congolese state. The artisanal sector — diggers working by hand, often in and around the industrial concessions — is estimated by the research groups that track it at somewhere on the order of a tenth of national output, varying year to year with price. [18.3] It is that artisanal stream, unmechanised and largely untraceable, that carries the documented harms: child labour in the worst pits, lethal tunnel collapses, and a trading chain of intermediaries that mixes hand-dug ore into the industrial supply at buying stations. [18.3] The industry's traceability programmes — blockchain pilots, bagging-and-tagging, OECD-aligned due diligence — are attempts to cut that stream out or clean it; none has yet made the mixing physically impossible, which is why the chemistry response — engineering cobalt out of the cathode — remains the only certain exit.

The Congolese state's countermove

The dependency table has another row that appeared only in the mid-2020s: the resource state learning to behave like one. In 2025, facing a cobalt price crushed by CMOC's ramp-up, the DRC suspended cobalt exports for months and then moved to a quota system — an attempt, openly stated, to manage the market for a metal of which it produces over seventy percent. [18.4] The episode matters beyond cobalt: it is the template Chapter 25 calls statecraft, applied from the resource end rather than the processing end. A country that controls three-quarters of a battery metal's mine supply has discovered it can act like the OPEC its commentators have long proposed. Whether quotas can be administered cleanly in the DRC's institutional conditions is doubtful; that they were attempted at all marks the battery-materials era's arrival at classic resource geopolitics.

The by-product’s dilemma

Cobalt’s economics contain a trap that policy cannot repeal: it is mostly a by-product. Roughly speaking, the world’s cobalt arrives as a companion to copper (in the DRC) and nickel (in Indonesia and elsewhere); almost no mine is a “cobalt mine” whose output responds to cobalt’s price alone. [18.5] When CMOC expands copper production, cobalt floods out regardless of cobalt’s price; when nickel laterite projects ramp in Indonesia, cobalt follows nickel’s logic. A by-product market cannot balance itself: supply is decided elsewhere, so price whips between famine and glut — as the 2022 peak and 2024 trough demonstrated. For cathode buyers, this is the final argument for thrift with cobalt: not only ethics and dependency, but a price structurally incapable of calm.

The Congo remains the cautionary chapter of the materials map. A chemistry decision taken in an Oxford laboratory in 1980 built, four decades later, a resource economy in central Africa, a Chinese mining champion, a human-rights dossier, and a technological response that is now unwinding the whole arrangement. The cobalt question’s final answer may be the one no one in 2010 predicted: not a cleaner supply chain, but a different periodic table.

CHAPTER 19

Nickel’s Second Act

Nickel is the oldest battery metal with the newest boom. It was in Jungner’s 1899 cell and Edison’s; it put the N in NiMH; and when the electric car demanded range, it was nickel — the capacity-carrier of the NMC and NCA cathodes — that answered. More nickel in the layered oxide means more lithium

that can leave and return; the industry's march to NMC 811 and beyond is, functionally, a nickel-intensification programme, and it made "battery-grade nickel" a category that had never existed before: not the class-2 nickel of stainless steel (ferronickel, NPI, anything will do) but class-1 purity fit for a sulphate crystal a cell maker can use.

The geological answer came from an archipelago. Indonesia holds the world's largest laterite nickel resources, and after banning ore exports in 2020 to force processing onshore, it became the industry's gravity well: mined production of about 2.31 million tonnes in 2024 — sixty-two percent of the world total — up from two million the year before, with Chinese-built industrial parks at Morowali and Weda Bay turning ore into NPI, matte and, critically, MHP: mixed hydroxide precipitate, the battery-ready intermediate produced by high-pressure acid leaching (HPAL) of low-grade limonite. [19.1] HPAL is the technology that broke the class barrier: notoriously difficult chemistry — autoclaves, acid, tailings — mastered at Indonesian scale with Chinese engineering, delivering battery feedstock from ore that used to be marginal. Indonesia's rise was fast enough to swamp the market: nickel prices halved from their 2022 spike, high-cost sulphide mines from Australia to New Caledonia closed or begged, and the IEA now lists nickel among the minerals whose refining concentration has *increased* — some ninety percent of 2020-24 refined supply growth came from the single leading supplier. [19.2]

The costs are written on the landscape: coal-fired power for the parks, deforestation at the mine mouths, and the unresolved question of what to do with millions of tonnes of HPAL tailings in a seismically active, coral-fringed sea. Indonesia's answer to critics is that this is what industrialisation looks like from the receiving end — and its leverage is real. When the world's carmakers needed nickel they could sign for, they signed in Jakarta: Ford,

Volkswagen, Hyundai and Tesla's suppliers all have Indonesian positions.

The chemistry of a tonne of nickel

Indonesia's rise is a process story, and the process deserves its description. The archipelago's laterite ores — low-grade, surface-mined, abundant — were historically suited to making ferronickel for stainless steel. Two technologies converted them into battery material. The first, HPAL — high-pressure acid leaching — dissolves the limonitic ore in sulphuric acid at 250-plus degrees and recovers nickel and cobalt as a mixed hydroxide precipitate, MHP, ready for refiners; it is capital-hungry, technically temperamental, and was mastered at Indonesian scale, with Chinese engineering and finance, in the early 2020s. The second is more audacious: converting the saprolitic ore's ferronickel into a matte, and the matte into battery-grade product — turning a stainless-steel route into a battery route. [19.3] Together they explain the speed: Indonesia did not discover new ore; it industrialised old ore with new metallurgy, financed largely from China and built at a pace the Western mining industry no longer attempts.

The environmental ledger

The nickel boom's costs are not abstract, and this book's rule — follow the material — requires naming them. Laterite mining is surface mining: forests cleared, topsoils stripped, rivers silted. HPAL generates tailings whose disposal has divided projects between deep-sea placement — cheap, contested, and opposed by scientists and downstream buyers — and dry stacking on land, safer for reefs, riskier in earthquakes and rain. The matte route's energy is coal-heavy: Indonesia's nickel industrial parks run largely on captive coal power, giving the resulting battery nickel a

carbon footprint several times that of sulphide nickel from Canada or Australia — an uncomfortable fact for a product whose purpose is decarbonisation, and a live issue in EU battery-passport debates. [19.4] The ledger is not a verdict — Indonesia's nickel has electrified more transport than any moral purity would have — but it is a price, and the passport era will put it on the label.

The sulphide provinces stir

High prices and passport pressure have revived the old nickel world: sulphide deposits in Canada, Australia and Finland — scarcer, deeper, costlier, but lower-carbon and allied-jurisdiction — are back in favour with Western automakers signing offtakes directly with miners. The volumes are modest beside Indonesia's flood, and the lead times are the mining industry's usual decade; but the strategic logic of Chapter 25 applies with full force: a cathode industry wholly dependent on one archipelago and one investor nation's metallurgy is a dependency table with a single row. [19.5] The 2020s thus produced a two-tier nickel world — volume from laterites, virtue from sulphides — and the battery, indifferent to virtue, will take whichever the cathode economics prefer.

For the battery, nickel's second act has an asterisk. The same LFP wave that ejected cobalt needs no nickel either; the chemistry's share of the EV market keeps growing at NMC's expense. The nickel industry's consolation is the same as cobalt's: absolute demand still rises with every EV sold that carries a nickel cathode, and premium range still demands nickel. But the direction of the mass market is clear enough that the smartest Indonesian strategists already describe MHP as a bridge product. The bridge's far end is the subject of Chapter 21.

The Invisible Half

Every lithium-ion cell is, by weight, roughly as much anode as cathode, and the anode is graphite. Not the pencil-lead abstraction: a precisely engineered carbon, either natural flake graphite purified to 99.95 percent and spheronised into potato-shaped particles of a specified size distribution, or synthetic graphite made by baking petroleum coke in furnaces at 2,800°C for weeks. The two blend in commercial anodes — natural for capacity, synthetic for fast charging and life — and together they form what Benchmark Mineral Intelligence calls the most concentrated link in the whole battery chain: China holds about three-quarters of the graphite-anode supply chain end to end, and in 2023 less than one percent of the world's uncoated spherical graphite was made anywhere else. [20.1]

The concentration is a process story, not a geology story. Flake graphite is mined on four continents — Mozambique, Brazil, Madagascar, Canada — but the micronising, spheronising, purifying (hydrofluoric acid or furnaces) and coating that turn a fifty-dollar mineral into a five-thousand-dollar battery material were perfected in China over twenty years of serving its electronics industry. Synthetic graphite is even more lopsided: the graphitisation furnaces cluster in Inner Mongolia and Sichuan, where power is cheap and coal-fired, giving the average synthetic anode roughly three times the carbon footprint of natural graphite — an awkward fact now priced into Europe's battery passports. [20.1]

The world noticed late. In December 2023 Beijing brought graphite under export licensing; shipments promptly plunged, and every anode-buying nation discovered a dependency it had never mapped. [20.2] The response is now one of the busiest construction niches in the battery economy: Syrah's Louisiana plant upgrading Mozambican flake; Nouveau Monde and Northern Graphite in Quebec; Posco Future M's Korean lines; synthetic-graphite furnaces announced from Tennessee to Finland. None of it will dent Chinese dominance this decade — the furnaces, the acid plants, and the people who know how to run them are there — but the anode, of all components, has become the test case for whether "de-risking" is a policy or a slogan.

The furnace in the supply chain

Graphitisation deserves a closer look, because it is where the anode's geography is actually decided. Purified carbon — needle coke for synthetics, flaked natural graphite for the rest — must be heated near 3,000 degrees Celsius for days to weeks to order its layers into battery-grade graphite. The step consumes roughly ten to fifteen kilowatt-hours of electricity per kilogram — an Acheson furnace is a power plant's best customer — and it historically vented whatever the purification chemistry left behind. [20.3] Industry estimates put China's share of graphite anode-chain production around three-quarters and, for some processed forms, higher still; the reason is not geology — graphite ore is widespread — but the industrial combination of cheap power, tolerant siting and two decades of accumulated process scale. [20.4] Every Western anode project announced since 2022 is, in essence, an attempt to rebuild that furnace economy under Western power prices and environmental law: possible, capital-intensive, and slow. The export-licensing measures China introduced for graphite products in late 2023 converted this industrial fact into a

diplomatic one — licensing, not banning, being the precise instrument of Chapter 25's statecraft. [20.5]

Silicon arrives, cautiously

The anode's frontier is silicon, and its arrival is proceeding in the industry's preferred manner: one percentage point at a time. Silicon oxide blended into graphite anodes at single-digit percentages is now standard in premium cells; each point adds a few percent of capacity at the cost of cycle-life engineering — the swelling problem caged, for now, by blending rather than solved. The bolder entrants — silicon-carbon composites that host silicon in porous carbon scaffolds, promising several times graphite's capacity — reached early commercial scale in the mid-2020s in consumer and aviation cells, with automotive qualification underway. [20.6] The strategic significance is easy to miss: silicon's supply chain is the metallurgical silicon industry — vast, western-friendly, and utterly unlike graphite's furnace geography. If the anode's future is substantially silicon, one row of the dependency table quietly rewrites itself.

The recycling wildcard

Natural graphite's rival may yet be the city's own waste. Spent anodes retain their graphite — already purified, already graphitised, already spherical — and recyclers have demonstrated re-manufactured anode material from recovered stock at performance near virgin. [20.7] The volumes today are trivial, because the spent batteries of the EV era have not yet retired; but the arithmetic of Chapter 29 applies here with special force, since graphite, unlike lithium, is already at battery grade inside the waste. In a closed-loop future the anode's furnace economy shrinks with every generation of recycled cells — a small irony: the dirtiest step in the chain is the one recycling removes first.

The invisible half has one more twist. As Chapter 10 recorded, the anode's future is silicon — and silicon's raw material is quartz sand, the least scarce battery input imaginable. If silicon-carbon composites take the volume the startups promise, the geopolitics of the anode transforms: from a Chinese process monopoly in an obscure carbon, to a materials competition anyone with a furnace and a chemist can enter. The battery's map is redrawn not only by mines but by the chemistry that chooses which mines matter.

CHAPTER 21

Iron and Phosphate for Everyone

The most consequential battery-materials story of the 2020s is the victory of the two cheapest ingredients on the cathode menu. Lithium iron phosphate — iron from anywhere, phosphate from fertiliser country, no cobalt, no nickel — was the chemistry that lost the 2010s. Denser rivals won the subsidy-rich premium car market; LFP kept buses, city cars and China's domestic standard-range segment. Then, between 2020 and 2024, the chemistry took the mass market.

The mechanism was a pile-up of small advantages that crossed a threshold. The key composition-of-matter patents from the Goodenough-UT era expired, freeing everyone to make it. Chinese cell makers — BYD's Blade the emblem — learned to pack LFP's long cells so efficiently that the pack-level density gap with NMC shrank to a rounding error for the ranges mass buyers actually need. LFP's safety and cycle life, once consolation prizes, became selling points as fleets and grids counted total cost per cycle rather than kilograms per car. And its cost advantage compounded: by 2025 the cheapest observed lithium-ion cells in the world — $36 per kilowatt-hour — were Chinese LFP cells for stationary storage.

[21.1] The market responded: LFP was 45 percent of global EV battery demand in 2023 and about half in 2024 by Benchmark's count; in China it passed sixty percent of installations; even the American and Korean incumbents — Tesla for standard ranges, Ford, GM, Samsung SDI, LGES — spent 2023-25 announcing LFP lines. [21.2]

The geopolitics is double-edged and worth stating plainly. LFP is the chemistry of resource independence — every input is abundant and widely distributed — *and* it is, today, almost entirely a Chinese industry: the precursor phosphate chains, the cathode plants, the cell lines and the process knowledge are in China, and Beijing moved in 2025 to keep it that way, adding key LFP and lithium-processing technologies to its export-control catalogue. [21.3] The West can adopt the people's chemistry; making it without Chinese licences and Chinese equipment is the slower project now underway from Tennessee to Morocco.

The patents that kept LFP honest

LFP's commercial history carries a subplot that shaped the world market: the patent wars. Goodenough's University of Texas patents on the olivine structure, and the carbon-coating patents of the Hydro-Québec/Armand lineage, were licensed through consortia and litigated across three continents through the 2000s and 2010s — invalidation actions in China and Europe, royalty demands in North America. The effect was geographic sorting: Chinese producers, sheltered by domestic rulings and scale, industrialised LFP at home while Western adoption waited for patent cliffs. [21.4] When the core patents expired in the early 2020s, the Western industry's sudden enthusiasm for LFP — every major automaker announcing iron-phosphate variants — was not a discovery but a release. The episode is a clean case study in how intellectual

property, not physics, can set a chemistry's geography for twenty years.

The LMFP bridge

The phosphate family's next member is already at the door: lithium manganese iron phosphate, which substitutes manganese for part of the iron and lifts the operating voltage — and with it energy density by perhaps fifteen to twenty percent — while keeping the olivine's safety and cost character. Chinese cell makers began shipping LMFP-blend products in the mid-2020s, often mixed with NCM to balance the blend's virtues. [21.5] Its significance for this book's map is strategic: each increment of phosphate energy density narrows the application space where nickel chemistries are worth their cost and risk, pushing the nickel world up-market into a shrinking premium tier. The industry's centre of gravity follows.

Counting what iron costs

The final irony of the phosphate turn deserves explicit arithmetic. The materials LFP needs — iron, phosphorus, lithium, carbon — are among the Earth's most ordinary; the cathode's cost is dominated by its processing and its lithium, not by any scarce metal. At the mid-2020s lithium prices, industry cost estimates put LFP cathode material at a small fraction of NCM's cost per kilowatt-hour. [21.6] The consequence is a floor effect: once the cheapest adequate chemistry approaches the cost of its processing, the battery's price story migrates entirely to manufacturing — to yield, scale and the chapters of Part Four. Iron's revenge is that it ended the materials excuse: after LFP, no one could claim the battery was expensive because the Earth was stingy.

The successor is already in the queue: LMFP, lithium manganese iron phosphate, dopes manganese into the olivine to raise the voltage — and thus the energy — while keeping the iron's cost and the phosphate's stability; CATL's M3P and several Chinese rivals put it into cars from 2023. And beyond it, the sodium-ion wave (Chapter 30) borrows LFP's entire industrial playbook — layered oxides or polyanionic hosts, hard-carbon anodes, the same coating lines — with no lithium at all. The chemistry Goodenough's laboratory demonstrated in 1997 with the two most ordinary metals in the catalogue has become the default setting of the battery world, and the template for whatever dethrones lithium itself.

PART SIX

The Business

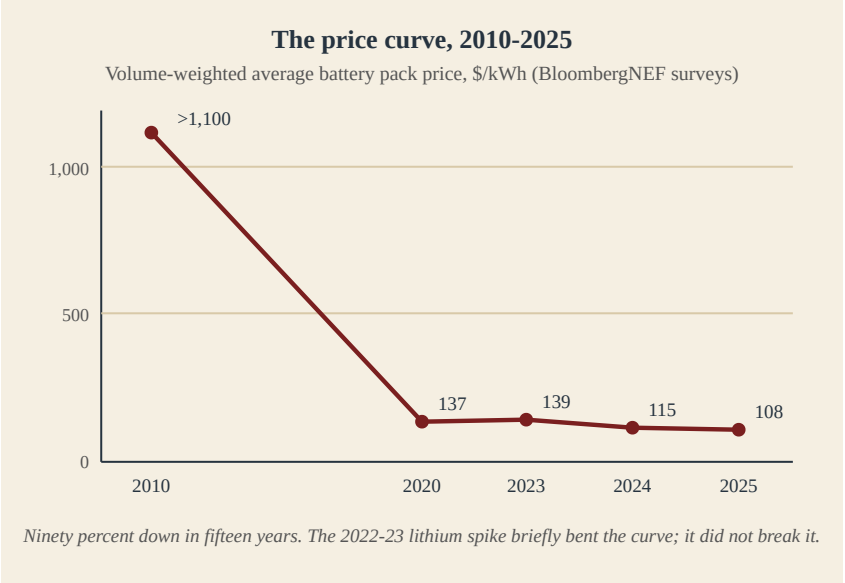
Prices that fell ninety-seven percent, companies that rose from nothing to industrial pillars in fifteen years, and governments that discovered the battery was strategic about a decade late.

CHAPTER 22

The Price Curve

The single most important fact about the lithium-ion battery is a slope. In 1991, Sony’s first cells cost, in real terms, somewhere around thirty times what a comparable cell costs today; measured carefully across thirty years of price series, Ziegler and Trancik put the real decline in price per unit of energy capacity at ninety-seven percent between commercial introduction and 2018 — thirteen percent a year, year after year, through booms and busts, with a learning rate of about

twenty percent per doubling of cumulative production. [22.1] Almost no other manufactured product of comparable complexity has matched that record; the battery's curve sits in the company of photovoltaics and, behind it, semiconductors. The curve is the reason the electric car exists, the reason grid storage is bankable, and the reason every forecast that assumed batteries would stay expensive — which is to say, most energy forecasting before 2015 — is now landfill.



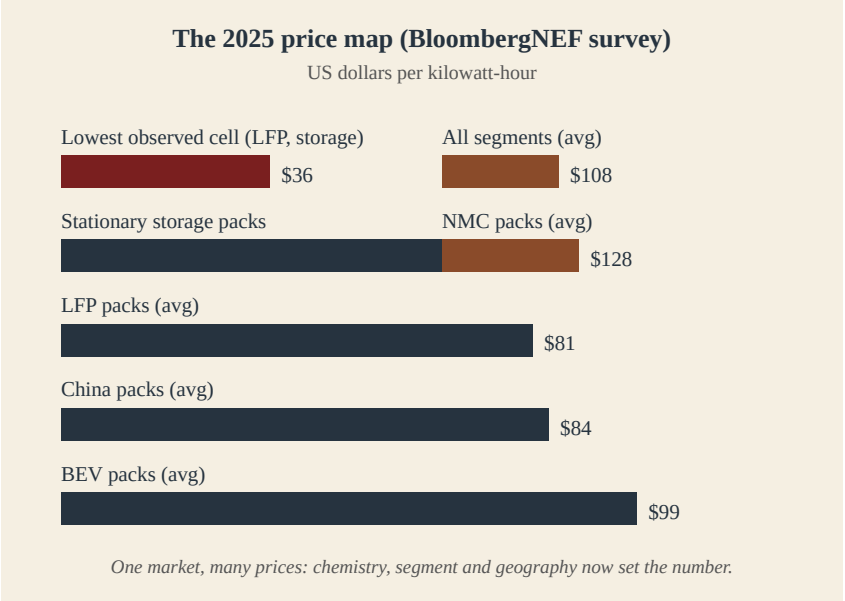
Ninety percent down in fifteen years. The 2022-23 lithium spike briefly bent the curve; it did not break it.

The curve's modern segment is documented with unusual precision by BloombergNEF's annual survey, the industry's reference price. Its recent history tells the second half of the story: after a blip upward in 2022 (the lithium spike fed straight through to packs), pack prices fell twenty percent in 2024 — the largest single-year drop since 2017 — to $115 per kilowatt-hour, and fell again in 2025, eight percent, to a record $108. [22.2] Beneath the average, the survey reads like a map of the industry's fault lines.

Stationary-storage packs are now the cheapest segment at $70 — down forty-five percent in a single year — having undercut even cars; battery-electric-vehicle packs averaged $99, a second consecutive year below the hundred-dollar threshold once considered the marker of cost parity with combustion. Chemistry splits the world: LFP packs averaged $81 against NMC's $128. Geography splits it wider: Chinese packs averaged $84, with North American packs forty-four percent and European packs fifty-six percent more expensive — a gap that explains more about the EV markets of Detroit and Wolfsburg than any industrial-policy white paper. And at the bleeding edge, the lowest observed cell price in the world in 2025 was $36 per kilowatt-hour: LFP, destined for storage, with a matching pack price of $50. [22.2]

What makes prices fall? The survey's decomposition is instructive because the answer changed over time. In the 2010s the driver was engineering: better energy density (the same materials holding more watt-hours), larger factories, standardised designs. In the early 2020s the driver was, unusually, metal — the lithium spike of 2022 showed that raw materials had become the marginal cost, which is why the subsequent crash in lithium, cobalt and nickel prices translated directly into cheaper cells. And in 2024-25 the driver is manufacturing overcapacity: three terawatt-hours of capacity chasing one terawatt-hour of demand forces price war, and price war in China — where, per the IEA, over seventy percent of all EV batteries ever made were produced, and where yields and learning are highest — exports deflation to the world. [22.3]

Anatomy of a year’s decline



One year’s price movement, examined closely, teaches more than the curve’s whole length. BloombergNEF’s 2025 survey reported an average pack price of $108 per kilowatt-hour — down eight percent in a year in which raw-material prices were largely calm. [22.2] Where did the eight percent come from? Not from lithium, which had already crashed the year before and merely drifted. The survey’s own decomposition points to the industry’s three standing levers working together: cell-manufacturing overcapacity in China intensifying price competition — the survey’s segment detail showed stationary-storage packs at $70 per kilowatt-hour, the lowest price ever recorded for a major segment, because stationary buyers take the industry’s cheapest adequate product; continued spread of LFP, whose average pack price of $81 sat far below NCM’s $128; and manufacturing scale, as newer plants climbed their yield curves. [22.2] The year’s lesson: the learning

curve no longer needs a materials crash to fall — the manufacturing machine alone can now carry it.

The China discount

The same survey exposed a geographic fact with strategic weight: average pack prices in China, at $84 per kilowatt-hour, sat far below the rest of the world: the survey puts North American packs forty-four percent and European packs fifty-six percent above China's. [22.2] Some of the gap is input cost and labour; most is structure — the world's densest supply chain competing against itself, cell makers bidding below comfortable margins into an overcapacity they themselves built. For the rest of the world's battery ambitions, the discount is the real tariff problem: a factory in Michigan or Thuringia does not compete against "China's price" in the abstract but against a $84 pack landed from a subsidised, amortised, ruthlessly optimised supply chain. Chapter 25's trade walls are, arithmetically, attempts to price that gap.

What a forecast can and cannot say

This book labels its forecasts, and the price curve is where the labelling matters most. The curve's three decades are fact: over ninety percent decline in real terms, the steepest sustained cost fall of any major energy technology, faster than every expert projection made along the way — including, repeatedly, the projections of the surveyors themselves. [22.3] The extrapolations are not fact. Sub-$100 pack averages, solid-state cost curves, sodium's trajectory: each depends on capacity, competition and materials prices that have surprised in both directions within the last five years. The honest reading of the curve is a statement about mechanism, not destiny: costs fall because yields improve, formats standardise and chemistries substitute — processes that continue until they meet physics or cartels. Neither limit is visible

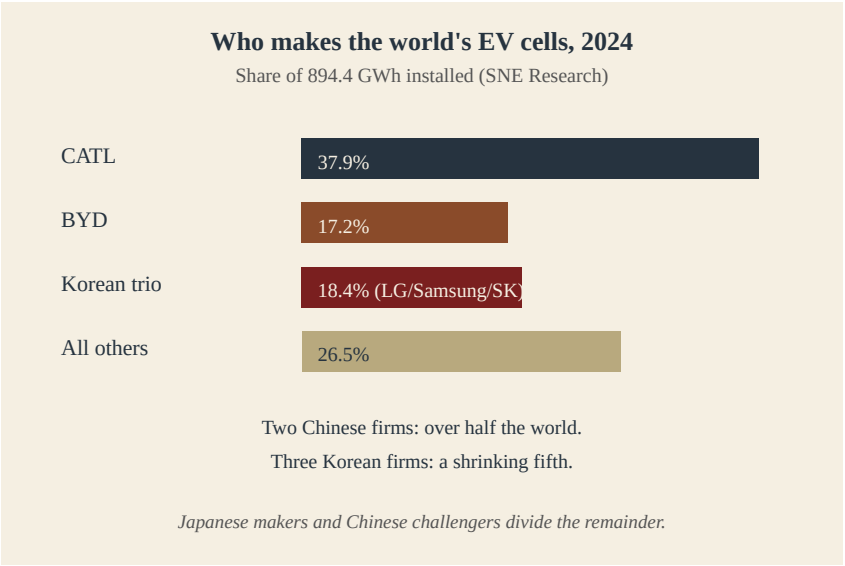
yet. The reader should hold the forecast loosely and the mechanism tightly.

The question everyone asks the curve now is where it floors. The optimists note that the learning rate has survived every obituary and that sodium-ion threatens a harder floor beneath lithium altogether. The pessimists note that at $36 a cell, the price increasingly *is* the metal and the factory overhead, and the easy doublings are done. Both can be right: the era of halving prices is over; the era of grinding single-digit declines at civilisational scale has begun. For the purposes of this book the significance is simpler. The price curve is the mechanism by which a laboratory curiosity became infrastructure — and it is still running.

CHAPTER 23

The Giants

The battery industry has a shape no other industry would design: a duopoly atop a pyramid, located almost entirely in three countries. In 2024, the world's EVs took delivery of 894.4 gigawatt-hours of cells — 27.2 percent more than the year before — and two Chinese companies shipped more than half of them. CATL alone held 37.9 percent of the global market; BYD held 17.2. The three Korean champions together — LG Energy Solution, SK On, Samsung SDI — held 18.4 percent and falling; Panasonic, the last Japanese giant, held a single-digit share. [23.1] The story of the battery business is the story of how that happened in fifteen years, and whether anything can change it.



CATL — Contemporary Amperex Technology Co. Limited — is the largest battery company that has ever existed, and by some measures the largest industrial company of the energy transition. Founded in 2011 in Ningde as a spin-off of ATL, a consumer-cell maker, it rode the Chinese state's electric-vehicle programme with an aggression that even its domestic rivals found startling: building capacity ahead of demand, signing every global carmaker it could find — Tesla, BMW, Mercedes, Volkswagen — and out-engineering the field in the unglamorous arts of Chapter 13. The results defy the usual grammar of manufacturing: in 2024, revenue of ¥362 billion (roughly $50 billion) and net profit of ¥50.7 billion, up fifteen percent in a year when its prices were falling twenty — a company growing profits while waging a price war, which is the signature of a genuine cost advantage. [23.2] Its reach now extends upstream into mines, downstream into charging networks and grid storage, and sideways into licensing: the Ford-CATL arrangement in Michigan, in which an American carmaker pays to use Chinese battery technology on American soil, is the precise

inversion of the technology-transfer deals that built China's car industry forty years ago. History rhymes, loudly.

BYD is the other half of the duopoly and the stranger animal: a battery company that became a car company and now runs both at full scale. Wang Chuanfu founded it in 1995 making nickel-cadmium cells, moved into lithium-ion for Motorola and Nokia, bought a failing state carmaker in 2003, and spent two decades being underestimated. The Blade battery (2020) and the DM-i hybrids changed that: in 2024 BYD sold 4.14 million electrified vehicles — more than any other company — with virtually every cell made in-house, making it simultaneously the world's second-largest battery maker and its most vertically integrated. [23.1] BYD is what the oil companies of 1975 feared Exxon might become: an energy company that ate the car.

The Koreans invented the automotive lithium-ion business as a merchant industry: LG Chem (later LG Energy Solution) won the Volt, the Bolt and the German carmakers; Samsung SDI and SK On built the premium end. Their model — NMC excellence, global plants, long contracts — was the industry's default until China undercut it, and their share has slid for three straight years. Their counterattack runs through America: the IRA's production credits made Korean cells in Georgia, Michigan and Hungary briefly the only bankable non-Chinese option, and LGES remains the largest battery maker not headquartered in China. [23.3]

Panasonic, the founding giant — Sony's heir, Toyota's and Tesla's partner, maker of the 18650s in the Roadster and the 2170s in Nevada — chose concentration over scale: high-nickel NCA, a handful of plants, margins over share. It remains the industry's quality benchmark and its most consequential strategic question mark.

The tier beneath the giants

The headline duopoly hides a second tier whose contest is the industry's most instructive competition. Between CATL's and BYD's combined half of the market and the long tail sit the Korean trio — LG Energy Solution, Samsung SDI, SK On, at a combined 18.4 percent of 2024's global EV battery installations — and China's challengers: CALB, EVE, Gotion, SVOLT, Sunwoda, each with tens of gigawatt-hours of capacity and national-champion ambitions. [23.3] The Koreans' position is the tier's drama: technologically first-rate, long the premium supplier to Western automakers, they have watched LFP — their historic weak spot — take the volume market while their high-nickel forte shrank to the premium segment, and their 2020s strategy is a forced march into LFP, sodium, and North American plants under subsidy terms. [23.3] The Chinese challengers' position is simpler and scarier: they learned the trade inside the world's most competitive domestic market, and several now build plants in Europe and Southeast Asia with customer lists that would have been unthinkable in 2015.

The customer alliance problem

A structural feature separates batteries from most component industries: the customer needs the supplier more than the reverse, and both know it. An automaker designing a vehicle around a cell commits for the model's life; a cell maker's capacity is booked years ahead; switching costs run through crash tests, thermal design and factory retooling. The 2020s' answer, across three continents, was the joint venture: GM-LG, Ford-SK, Stellantis-Samsung, Toyota-Panasonic, and their Chinese counterparts — arrangements that give the automaker secured supply and the cell maker secured demand, at the price of entangling competitors. [23.4] The ventures' mixed record — recalls at Ultium's early plants, ramp delays across the board — shows the alliance cannot

buy the yield curve either. What it buys is a seat: in an industry where capacity is sovereignty, the joint venture is the automaker's admission ticket, and the table of who has partnered whom is, functionally, the map of the next decade's EV industry.

The vertical exception

BYD breaks every rule the tier structure implies, and the exception is the point. A battery company that became a car company — not the reverse — BYD books its cells inside its own vehicles, sells the surplus, and controls its chain from lithium mining stakes through cathode plants, cell factories, semiconductors and the ships that export the cars. [23.5] Its 17.2 percent global installation share in 2024 understates its system share, because its cells avoid the merchant market's margins entirely. The model's advantages in the price wars of 2023-25 were decisive: where a merchant cell maker had to defend a price, BYD could defend a vehicle. Whether the model travels — whether BYD's plants abroad can replicate the home chain's depth — is one of the industry's open questions; but as a demonstration of this book's thesis, the company is complete: in batteries, integration is destiny, and the firm that owns the most steps owns the future.

Behind them, a second tier fights for the future: EVE, CALB, Gotion (with Volkswagen as anchor shareholder), SVOLT (spun out of Great Wall), Sunwoda — Chinese all — plus Europe's ACC and the remnants of Northvolt, Japan's Toyota-backed Prime Planet, and India's aspirants (Chapter 31). The pyramid's lesson is the book's recurring one. The battery business looks from a distance like chemistry and up close like scale manufacturing; the winners are the firms that learned both, in a country that let them practice on the largest market in the world. Catching them, as every region is now discovering, costs more than money.

The Machine Tool of the Energy Transition

Behind every gigafactory stands a second industry that almost nobody outside the battery world can name: the makers of the machines that make the cells. It is a revealing omission, because the equipment industry is where the physical knowledge of cell manufacturing is actually warehoused — and its geography explains, as much as any policy paper, why the battery industry is where it is.

The tools of Chapter 13 are special-purpose and hard. The slot-die coater — a machine that lays a film of slurry a hundred microns thick onto a foil running at eighty metres a minute, holding thickness tolerance to a micron or two across a metre of width — is the signature tool of the trade, and a good one is as much a precision instrument as anything in a chip fab. Around it cluster the mixers, calenders, slitters, winders and stackers, the vacuum filling lines, the formation towers with their thousands of charging channels, and the dry rooms themselves. [24.1] A 10 GWh cell plant carries a machine bill in the hundreds of millions of dollars, and the supplier's process engineers effectively co-design the customer's line: buying equipment is how a new entrant rents a decade of learning.

That industry is Chinese. Wuxi Lead Intelligent Equipment — "Lead" — is its champion: founded in 2002 making capacitor machines, converted to battery equipment as the domestic cell industry exploded, and grown into the world's largest battery-tool maker, supplying complete turnkey lines to CATL, BYD, LGES,

Northvolt (whose fate hung, in part, on making Lead's machines sing) and now to the American and European plants of the Korean giants. Around it: Yinghe Technology (Shenzhen), HangKe (formation and test), Putailai (coating and materials-equipment hybrids), Colibri and a bench of specialists. [24.2] Japan and Korea retain fine niches — Hirano and CKD in coaters, PNT and mPlus in Korean lines — but the volume, the turnkey capability, and the reference designs are Chinese, for the same reason the cells are: the toolmakers grew up inside the largest customer base in the world, iterating at Chinese speed.

The strategic consequence arrived slowly and then all at once. When Europe decided to build a battery industry, it discovered that the blueprints and the machines both had to be imported — that a "European" gigafactory was, in its first generation, a Chinese production line flown into a Swedish building and operated by engineers flown in to teach it. When the United States followed, the same fact reasserted itself: the IRA could subsidise factories, but the tooling still sailed from Shenzhen and Wuxi. Beijing, which missed nothing about the arrangement's value, moved in 2025 to license the export of key battery-manufacturing technologies — turning its toolmakers' knowledge into an instrument of policy. [24.3]

The coaters of Wuxi

The machine-tool story has a geography as concentrated as any in this book, and it centres on equipment most people have never seen: the electrode coater. A coating line is a hundred metres of precision — unwinding foil a dozen microns thick, laying a slurry film to tolerances of a percent or two, drying it through tens of metres of oven without cracking, rewinding without a wrinkle — at speeds now exceeding a hundred metres a minute. The industry's leading equipment suppliers, Wuxi Lead Intelligent and Yinghe

Technology among them, grew with CATL and BYD from the 2010s, and by the 2020s supplied complete turnkey gigafactory lines to the world — including to the Western entrants who were trying, simultaneously, to build supply chains independent of China. [24.3] The dependency is symmetrical and telling: you may buy a battery factory without Chinese cells, but not without Chinese machines — or a decade of your own machine-building, which is the road not taken.

What the machines encode

A turnkey line's price buys more than steel: it buys process recipes. Coater settings, drying profiles, formation protocols — the parameter sets that make yield — ship with the equipment, as software and as the commissioning engineers who stay for a year. This is the machine tool's deepest role in the industry's history: it is how process knowledge migrates. Japan exported the 1990s battery industry to Korea partly through equipment sales; Korea and China repeated the pattern; China's turnkey exports of the 2020s are the third wave, and they explain a puzzle from Chapter 16 — how Asian incumbents ramp European plants on schedule while a European champion could not. The incumbents brought their machines and their machine-makers. [24.4] Every "domestic" battery programme that imports turnkey lines is, in the honest accounting, licensing a process — which is not an argument against doing so, only for knowing what is being bought.

The next machine generation

The equipment frontier now leads the chemistry frontier, in a reversal of the industry's youth. Dry-electrode coating — eliminating the solvent and its ovens entirely — is a machine problem before it is a materials one, and the companies racing to industrialise it are equipment and cell makers together. Solid-

state’s laminated, sintered, pressure-managed cells need machines that do not yet exist at speed; whoever builds them first manufactures the next battery era. [24.5] The pattern, three decades on, holds: the battery advances when someone builds the machine that builds it.

There is a historical resonance the reader of this library will recognise. The industries that endure are the ones that own their machine tools: nineteenth-century America’s armory practice, Germany’s Mittelstand, Japan’s postwar machine builders. The battery is the defining manufactured good of the energy transition, and its machine tools speak Mandarin. Everything else in Part Six follows from that sentence.

CHAPTER 25

Batteries as Statecraft

Somewhere around 2020, the battery stopped being a component and became a strategic asset, and the world’s major governments began writing rules about it with a fervour usually reserved for semiconductors and missiles. The result, half a decade on, is a thicket of subsidies, mandates, tariffs and export controls that has already reshaped where batteries are made — and has so far failed, everywhere, to break the incumbent’s grip. The thicket deserves a map.

The United States: buy it back. The Inflation Reduction Act of 2022 attacked the dependency with two instruments. Section 30D tied the consumer’s $7,500 EV credit to North American assembly and escalating thresholds of domestic battery content — with an absolute bar, from 2024-25, on any content from a “foreign entity of concern,” meaning China. Section 45X paid manufacturers

directly: $35 per kilowatt-hour of cells and $10 for packs produced on American soil, plus ten-percent credits for domestic electrode materials and critical minerals — a production subsidy large enough, by design, to close the cost gap with China on its own. [25.1] The response was a construction boom: US capacity doubled in two years to over 200 GWh by 2024, with nearly 700 GWh more under construction, much of it Korean-cell-maker joint ventures with Detroit. [25.2] The vulnerabilities are the ones Chapter 24 predicts: the cathode and anode inside the American cells still sail mostly from Asia, the machines mostly from China, and the whole edifice reprices with every election.

The European Union: regulate it forward. Europe's instrument is the Battery Regulation (2023/1542), the most ambitious product law the industry has faced: carbon-footprint declarations and then maximum footprints for EV batteries; due-diligence obligations down the cobalt and graphite chains; recycled-content minima from 2031 — sixteen percent cobalt, six percent lithium, six percent nickel in new EV batteries — recovery targets (fifty percent of lithium by 2027, eighty by 2031; ninety percent of cobalt, copper, lead and nickel); and, from February 2027, a digital battery passport recording composition, footprint and history for every EV and industrial battery sold in the Union. [25.3] The strategy is to make the rules the moat: if you must document a battery to sell it in Europe, the documenting becomes a competitive asset. Its risk is symmetric — rules bind the honest local producer first, and Europe's cell industry is the one least able to absorb another cost.

China: hold the high ground. Beijing's battery policy is twenty years old (the "new energy vehicle" programme, the ten-cities-thousand-vehicles pilots, the whitelist that steered subsidies to domestic cells) and has lately turned from promotion to protection. Graphite export licensing (December 2023) was the opening move;

in 2025 came licensing requirements on key LFP and lithium-processing technologies — the know-how of Chapters 21 and 24 converted into controlled assets. [25.4] The world's largest battery industry intends to be consulted before it is copied.

The rest: host or specialise. Indonesia leverages nickel into whole supply chains (Chapter 19); Japan and Korea sell excellence abroad; Canada and Australia sell rock and proximity; India (Chapter 31) is building demand first and supply second, on the theory that the factory follows the market.

The instruments, catalogued

Statecraft in batteries is not a metaphor but a toolkit, and the 2020s catalogued it in public. China's instruments: export licensing on graphite products (2023) and on selected battery and processing technologies (2025), production subsidies at provincial scale, and the original stroke — the 2015-2019 subsidy catalogue that steered domestic demand toward domestic cells and is widely credited with forcing foreign cell makers' retreat from the China market. America's: the Inflation Reduction Act's production tax credits, which pay per kilowatt-hour manufactured on US soil, and its content rules, which deny credits to vehicles with materials from "foreign entities of concern." Europe's: the Battery Regulation's carbon declarations, due-diligence duties and recycling quotas — regulation as industrial policy by other means. [25.2] India's: the PLI-ACC scheme's subsidised gigafactories and the mining diplomacy of Chapter 31. Each instrument has the same purpose — to move one or more rows of the dependency table — and each carries the same risk, which the table makes vivid: retaliation lands on the rows you still depend on.

The processing wall

The table's hardest rows are neither mines nor factories but the converters in between: lithium hydroxide plants, nickel sulphate refineries, precursor and cathode plants, the graphite furnaces of Chapter 20 — the stages where China's share commonly exceeds two-thirds and in places nine-tenths. [25.3] These are the rows tariffs cannot move, because the capacity does not exist elsewhere at any price in the short run; a refinery takes years and permits, and the West's 2020s programmes discovered that permitting, not money, was the binding constraint. The strategic consequence is a hierarchy of urgency every planner in Washington, Brussels, Delhi and Tokyo now recites: cells can be onshored fastest, because machines can be bought; cathode and precursor capacity follows with subsidies; refining and graphitisation take a decade; and the mines take a generation — or Chapter 29's shortcut, the cities.

The efficiency objection, honestly faced

The counterargument deserves its strongest form: subsidised duplication wastes capital, tariffs raise the price of the transition, and the fastest decarbonisation buys the cheapest cell whatever its flag — every dollar of protection is a dollar taken from deployment. The 2023-25 price collapse gives the objection empirical force: it was Chinese overcapacity, not Western policy, that drove storage packs to $70 and put grid batteries within reach of utilities worldwide. [25.4] The state's reply is Chapter 18's and Chapter 20's: a supply chain is a strategic asset precisely when it is not for sale — export licences and export quotas have now been used, by multiple states, as instruments of pressure. Between pure efficiency and pure autarky the actual world is choosing, messily, cell by cell and law by law. This book's only claim is the one it began with: the choice is being made about a material object, and

the object — the ion, the cell, the charge — will go on being made regardless, in the quantities the century requires.

The honest summary of five years of battery statecraft is that it has moved assembly and barely touched the chokepoints. Cells are now made on four continents; the materials, machines and margins still answer to the old geography. The second five years will test whether rules can do what markets haven’t — or whether the price curve of Chapter 22, which is indifferent to passports, keeps picking the winners.

PART SEVEN

The World It Built

What a cheap, dense, rechargeable cell makes possible: the remade car, the grid that stores sunshine, and the ten billion small devices that untethered daily life.

CHAPTER 26

The Car, Remade

The automobile did not adopt the lithium-ion battery; the lithium-ion battery adopted the automobile, and then remodelled it from the floorpan up. The numbers of the adoption are now so large they require effort to see: 17 million electric cars sold in 2024, up twenty-five percent in a year, and 20.7 million in 2025 — one car in four sold on Earth, in a segment that did not meaningfully exist in 2010. [26.1] [26.2] Behind each of those cars sits a battery of forty to a hundred kilowatt-hours — the load that pulled the industry through its terawatt-

hour milestone in 2024, with EV batteries alone accounting for over 950 GWh, eighty-five percent of everything. [26.3]

The courtship began as farce. The established car industry of the early 2000s had tried batteries and buried them — GM's EV1, lead-acid and then NiMH, recalled and crushed, became the symbol of the incumbent's verdict: batteries were too heavy, too short-legged, too dear. What broke the verdict was not a car company but a startup with a laptop trick. Tesla's 2008 Roadster — 6,831 commodity 18650 cells, 53 kilowatt-hours, 244 EPA miles, 0-60 in 3.9 seconds, $109,000 — was expensive, impractical and decisive: it proved that cells already in mass production for camcorders could outperform every automotive battery ever built, if you were willing to engineer the pack around thousands of small fires-in-waiting. [26.4] The incumbents' response split. Nissan went the other way — a purpose-built automotive cell, laminated pouch, 24 kWh in the 2010 Leaf, the first mass-market EV of the lithium age, engineered by its AESC joint venture with NEC. [26.5] Tesla doubled down on commodity-plus-engineering through the Model S, the Gigafactory, and the Model 3; Nissan's conservative pack, air-cooled and under-warrantied, taught the opposite lesson about thermal management. Both lessons were absorbed by everyone.

What the battery did to the car, once inside, was architectural. The pack is the heaviest and most expensive component — for years a third or more of the vehicle's cost, and still its single costliest item — so it went into the floor, lowering the centre of gravity and freeing the cabin; the "skateboard" became the industry's default platform. The falling price curve (Chapter 22) then rewrote the economics in public: with BEV packs averaging $99 per kilowatt-hour in 2025 and Chinese packs at $84, the EV reached purchase-price parity in China across most segments, while remaining stubbornly dearer in the West, where packs cost half again as much. [26.6] The geography of the 20.7 million follows from that

one fact: China bought 12.9 million of 2025's EVs, Europe 4.3 million, North America 1.8 and falling — the only major region where the battery is still too expensive to have won the argument. [26.2]

The platform inverts

The deepest change the battery forces on the car is not the motor but the floor. An electric platform inverts a century of packaging logic: the heavy, flat battery goes low and central — improving handling and crash structure — the drivetrain shrinks to axle-mounted motors, and the cabin expands into the space the transmission tunnel and engine bay vacated. Designers call the result the skateboard, and its consequence is industrial as much as aesthetic: one platform, one cell format, many bodies. The cell-to-pack and cell-to-body designs of the 2020s complete the inversion — the battery case becomes the car's structure, stamped and cast around the cells, deleting modules and cross-members. [26.3] A vehicle engineered this way cannot be "converted" back; the battery is not a component of the car but its chassis, which is why the industry's old plan — one architecture, any powertrain — died in the late 2010s, and why every credible automaker now designs electric-first.

The charging question

If the pack is the new engine, the charger is the new fuel system, and its engineering is now the consumer-facing frontier. Charging speed is a negotiation among the cell's lithium-plating limits, the pack's cooling, the charger's current and the grid connection behind it; the industry's progress — from 50-kilowatt fast charging in the early 2010s to 350-kilowatt highway stations and Chinese megawatt-class announcements by 2025 — has steadily converted "refuelling time" from the EV's disqualifier into a coffee stop.

[26.4] The battery's role is the binding one: 800-volt pack architectures, cell designs that survive repeated 4C charging, and thermal systems that pre-condition the pack on the way to the charger. Range, meanwhile, quietly stopped being the argument: with 400-600 kilometre vehicles common and LFP removing the cost penalty of big packs, the market's attention moved to price — which is to say, back to Chapter 22's curve.

The two-wheeler and the bus, again

The car remade is only the largest piece of the remaking. The same cells, arranged differently, remade the segments the headlines skip: the electric bus, which Chinese cities converted by the tens of thousands — Shenzhen's entire fleet of some sixteen thousand buses electrified in the 2010s — cutting urban diesel emissions where they are breathed; the two- and three-wheeler, the developing world's true EV vanguard, running on kilowatt-hours rather than tens of them, sold by the million in China and India; the delivery van, the ferry, the mining truck, the first short-haul aircraft. [26.5] Each segment electrifies on its own arithmetic — duty cycle, dwell time, energy per day — and the battery, divisible by design, fits every arithmetic that fits its curve. The car was the proof; the fleet is the consequence.

What the oil age notices

The remade car's materials echo runs backwards through the supply chain this book has already walked: an EV fleet displaces oil in barrels per day that now register in demand forecasts — the IEA estimated EVs avoided well over a million barrels a day by 2024 — and demands, in return, the lithium, nickel, cobalt, graphite and copper of Parts Five and Six. [26.6] The substitution is not symmetric: oil is burned and must be bought forever; the battery's materials are installed once and, per Chapter 29, increasingly

recovered. That asymmetry — flow replaced by stock — is the energy transition's deepest material fact, and the automobile is where it becomes visible on the street.

And the remaking is not finished. The cell-to-chassis designs of Chapter 14 are dissolving the boundary between battery and body; 800-volt architectures and megawatt charging are compressing the refuelling gap (CATL's latest Shenxing cells claim a ten-to-eighty-percent charge in under four minutes — a maker's claim, awaiting independent abuse-testing, like every such claim); and the chemistry split — LFP for the masses, high-nickel for the long-legged — is sorting the market by use rather than by brand. [26.7] The car industry's own strategists now say the quiet part plainly: the battery is the car. Whoever owns the cell owns the vehicle's cost, its performance, its supply chain and its politics. The twentieth century's defining machine is being rebuilt around a device invented for a camcorder, at the speed of the price curve.

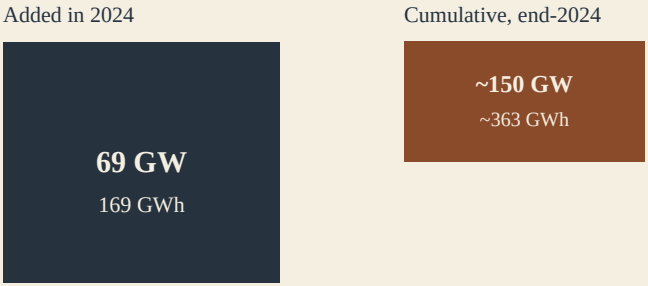
CHAPTER 27

The Grid Learns to Store

For a hundred and thirty years the electric grid ran on a brutal rule: generation must equal consumption, instant by instant, because electricity could not be warehoused. The rule built the modern world and constrained it absolutely — power plants sized for the hottest afternoon of the year, spinning reserves burning fuel to do nothing, and, later, wind and solar treated as uninvited guests whose output arrived on the weather's schedule. The lithium-ion battery is breaking the rule. In 2024 the world installed 69 gigawatts — 169 gigawatt-hours — of battery storage on its grids, a jump of about seventy-six percent

in one year, bringing cumulative capacity to some 150 GW and 363 GWh, more than ninety-eight percent of it lithium-ion. [27.1] The grid is learning to store, and it is learning on the same cells that run the car.

The grid learns to store: 2024 in one year



A single year roughly doubled the world's grid battery fleet.

Volta Foundation Battery Report 2024, corroborated by BNEF. Storage packs: $70/kWh in 2025 (BNEF).

The demonstration project of the age arrived as a Twitter bet. In 2017, after South Australia’s statewide blackout, Elon Musk wagered that Tesla could install a 100 MW / 129 MWh battery in a hundred days “or it’s free.” The Hornsdale Power Reserve — next to a wind farm in the mid-north of the state, built on time — proceeded to do two things the power industry had insisted could not be done: respond to grid faults in milliseconds, faster than any thermal plant’s governor, and make money doing it, saving South Australian consumers over $150 million in its first two years by collapsing the price of frequency-control services that had been a cosy fossil-fuel monopoly. [27.2] Hornsdale’s true export was not electricity but proof: every grid operator on Earth could now see the business case, and the wave followed — expanded to 150 MW

in 2020, and since joined by thousands of installations from California to Guangdong. [27.1]

The economics that powered the wave are Chapter 22's tailwind applied to a new customer. Storage packs averaged $70 per kilowatt-hour in 2025 — the cheapest segment in the BNEF survey, down forty-five percent in a year — because the grid asks less of a cell than a car does: no crash safety, generous space, shallow daily cycling, and chemistry chosen purely on cost per warranted cycle, which today means LFP and only LFP. [27.3] At those prices the four-hour battery is the default companion of new solar in every sunny market; China's co-location mandates made it the largest buyer; the United States follows; India, Germany, Australia, Italy and Japan round out the map. [27.1]

The growing pains are real and this book has already met the largest of them: the Moss Landing fire of January 2025 (Chapter 12), which burned the biggest American installation and taught the industry to spread its containers, isolate its modules and prefer LFP's cooler temper in its warehouses. Interconnection queues, revenue-stack complexity and duration limits (four hours shifts a day; it does not bridge a calm, dark week) remain the binding constraints — which is why the long-duration frontier, from iron-air to flow batteries, gets its own moment in Chapter 30.

The four-hour wall falls

Storage economics turned when duration became affordable. A grid battery's value rises with hours of discharge; its cost, per kilowatt-hour, follows Chapter 22's curve. Through the 2010s the affordable configuration was one hour — enough for frequency services, not for shifting solar into evening. By the early 2020s, at $100-and-falling pack prices, four-hour systems became the default product, and the 2025 survey's $70 storage packs made longer durations thinkable. [27.3] The deployment numbers

followed the cost with a lag and then violently: 69 gigawatts and 169 gigawatt-hours added worldwide in 2024 alone, roughly doubling the installed base in a single year. [27.4] The four-hour wall did not fall to a breakthrough; it fell to the price curve reaching it.

The inverter learns manners

A grid of rotating machines forgives; a grid of power electronics must be taught. As solar and wind displaced synchronous generators, the grid lost the physical inertia that steadied its frequency — and batteries, millisecond-fast, became the substitute: synthetic inertia, frequency regulation, ramp control. Grid-forming inverters — power electronics that behave like generators rather than followers — moved from research to procurement specifications in the mid-2020s, with grid batteries as their first large application. [27.5] The chemistry's part is prosaic and crucial: these services cycle the battery shallowly and often, exactly the duty LFP tolerates for decades, which is one more reason the grid and the phosphate cell found each other.

The duck curve, domesticated

The canonical problem of the solar grid — midday surplus, evening ramp, the duck curve of California's operator — has become the canonical application: charge at noon, discharge at seven. California, which installed essentially no grid storage before 2017, passed ten gigawatts of batteries in the mid-2020s and now regularly meets a fifth or more of evening peak demand from batteries; Australia's grid batteries arbitrage its solar floods; China's pairing mandates made storage a condition of renewables construction. [27.6] Each market learned the same lesson in its own accent: the battery does not merely store the weather, it reprices it — collapsing the midday price trough, flattening the

evening peak, and converting intermittency from a grid threat into a trading opportunity. The grid did not learn to store so much as to trade time.

The long-duration frontier

Honesty about limits: lithium-ion's domain ends where duration lengthens into days. Beyond roughly eight to twelve hours, the economics of adding cell capacity to idle capacity strain, and the frontier belongs to other chemistries — flow batteries, iron-air, compressed air, pumped hydro's enduring bulk — and, in the industry's own roadmap, to sodium-ion's cheaper kilowatt-hours. [27.7] The lithium-ion battery made the daily grid storable; the seasonal grid remains an open material question, and one of the few in this book whose answer is not yet written.

It is worth standing back to see what is being built. A grid with storage is a different machine from the one electrified the twentieth century: supply no longer chases demand in real time; weather becomes inventory. The battery is to electricity what the warehouse was to the river port — and the historian's eye notes that this is the second time storage has remade an energy system. The first was the coal stockpile. This one charges in milliseconds.

CHAPTER 28

Ten Billion Small Suns

Before the car and the grid, there was the device in your pocket — and it is worth recovering just how completely the lithium-ion battery authored modern personal electronics. The camcorder that Sony powered in 1991 was the first pebble of a landslide: within a decade the chemistry had taken the laptop (Apple's

PowerBook, the ThinkPad, the whole mobile-office world), the mobile phone (whose entire smartphone era is unthinkable at nickel-cadmium energy density), and the camera; within two decades it had absorbed the tablet, the e-reader, the wireless earbud, the smartwatch, the power bank, and the drone — a category that simply could not exist without lithium-polymer cells' willingness to dump their charge in minutes. Global production of small lithium-ion cells is counted today in the tens of billions per year; the consumer-electronics segment that created the industry is now its smallest growth engine and still its largest by unit count. [28.1]

The pattern repeats at every scale between the earbud and the container ship, and the census is worth making, because the uses are the industry. **Power tools:** the cordless drill's lithium conversion after 2005 turned a tethered trade into a battery-platform business, where the pack is the lock-in and the tools are accessories. **Two-wheelers:** China's 300-million-strong electric-scooter fleet ran for years on lead-acid and is converting to lithium as prices fall and safety rules bite; India's electric two-wheelers — 1.15 million sold in FY2024-25 alone — are lithium-native. [28.2] **Medical devices:** from the Greatbatch pacemaker cell of 1972 to today's insulin pumps, defibrillators and surgical tools, medicine remains the application where battery failure is measured in lives and quality standards are set accordingly. **The sea:** ferries in Norway and China now run as pure battery vessels on scheduled routes, and hybrid packs are standard fit on everything from tugboats to cruise ships for peak-shaving and harbour manoeuvring. **The air:** drones own the small end; the electric-aircraft industry — eVTOL air taxis, electric trainers, CATL's aviation-aimed condensed cells — is betting companies on batteries' continued improvement, since flight is energy-density's strictest examiner. [28.3] **Space:** satellites and rovers are lithium-

ion natives — the chemistry's high specific energy and zero-maintenance profile displaced nickel-hydrogen across the 2000s, and every Mars rover of the modern era has carried lithium-ion through nights at −60°C. [28.4] **The grid's edge:** home batteries paired with rooftop solar, telecom backup towers across the developing world replacing diesel, and data-centre uninterruptible power — the newest volume market, as the AI build-out discovers that the lithium-ion rack is the fastest-responding asset in the power chain.

The billion-device baseline

Before the vehicles and the grids, the consumer empire never left. Phones, laptops, tablets, watches, earbuds, tools, toys — the 18650's grandchildren still ship by the billion, and the consumer segment's engineering quietly leads in ways the giants borrow: the silicon-carbon anodes of premium phones, the 4.4-volt cathodes of flagship handsets, the stacked-electrode "stacked pouch" constructions that squeeze five percent more from a familiar volume. [28.3] Consumer cells are where new chemistry earns its first revenue at small scale and short warranty — the industry's paid pilot plant, as it has been since the camcorder. The torch Chapter 7 passed from electronics to transport still burns at its origin.

The drone, the robot, the satellite

The cell's mobility premium created markets that did not exist to ask for it. The consumer and commercial drone industry is a battery industry with wings — flight time is cell specific energy multiplied by engineering discipline, and the drone's whole product category dates from lithium polymer's power density. Cordless tools crossed the last trade threshold when battery packs matched corded power; the leaf blower and the chainsaw went

electric not by regulation but by cell. Satellites, medical implants, ocean gliders: each niche is small, each is complete, and each rehearses a discipline — cycle life, safety case, energy density — that the mass markets inherit. [28.4] Material thinking's lesson repeats at every scale: look for the object whose existence a battery made possible, and you find an industry.

The sun in a box

The last small sun is the largest idea: the pairing of a solar panel with a battery, at every scale from lantern to village, is closing the electrification frontier the grid never reached. The numbers live in the off-grid sector's ledgers — hundreds of millions of people whose first electricity is a panel, a battery and a lamp, or a pay-as-you-go home system whose LFP pack outlives its payment plan. [28.5] It is the book's oldest pattern in its newest setting: as with the telephone and the satellite dish, a technology arrives in the developing world after the wires would have, and skips them. The battery began, in Chapter 4, as an oil company's hedge against its own product. It ends this chapter as the sun's portable twin — fire's full circle, stored.

The census has a moral. The lithium-ion battery is not one industry but a platform technology on the pattern this library has met in steel, electricity and the transistor: a general-purpose capability that enters host industries and reorganises them around its own economics. Sugar built colonies; the container built trade routes; the cell builds untetheredness. Every device that moved off the wire in the last thirty years — which is to say, most of the material culture of daily life — is its colony.

PART EIGHT

The Reckoning and the Road

What happens when the first giant wave of cells wears out, what chemistries wait in the wings, and where India - the country this library exists for - stands in the battery century.

CHAPTER 29

The Second Life and the Grave

Every battery ever made is future waste or future ore, and the wave now arriving at the industry’s back door is the first great test of which. The EVs of 2015-2020 are reaching retirement; the consumer cells of the 2010s are landfill unless someone collects them; and the manufacturing scrap of the gigafactory era — the coating defects, the formation failures, ten to thirty

percent of output in a young plant — is already, at global scale, a mountain of the richest metal-bearing "ore" humanity has ever concentrated in one place. The recycling industry that has grown up to meet it is at once one of the battery economy's most promising businesses and, as its casualties show, one of its hardest.

The metallurgy comes in three families. **Pyrometallurgy** — burn the cells in a furnace, recover a cobalt-nickel-copper alloy, lose the lithium, aluminium and graphite to slag — is the rugged incumbent: forgiving of feed, unforgiving of value. **Hydrometallurgy** — shred the cells under inert gas to a "black mass," then leach the metals out with acid and separate them by solvent extraction — is the ascendant Chinese art, recovering ninety-plus percent of cobalt, nickel and, in good plants, lithium. **Direct recycling** — preserve the cathode crystal itself, re-lithiate it, and sell it back as cathode — is the elegant frontier, promising to keep the embodied value of the powder rather than reducing it to elements, and still fighting its way out of the pilot stage. [29.1]

The economics are subtler than the technology, and 2024-25 taught the difference violently. Li-Cycle, the North American hub-and-spoke champion, grew fast on the premise that black mass from a network of shredding "spokes" would feed a grand Rochester hydrometallurgical "hub"; the hub's costs overran, the market for its product slumped with the metals themselves, and in 2025 the company went through credit-event, sale process, and absorption — its spokes, the Rochester project and its patents acquired by Glencore, the century-old metals trader, in August 2025. [29.2] The obituary writes itself: recycling's feedstock prices move with the metal markets, its costs are fixed, and the margin between them is the business. Redwood Materials, the other American champion — founded by Tesla co-founder JB Straubel, hydrometallurgy-first and integrated forward into copper foil and

cathode production — has fared better by selling products rather than promises: it reports ninety-five percent lithium recovery, a calciner processing over 40,000 tonnes of feedstock a year, and the first anode copper foil made in North America. [29.3] The lesson is Chapter 13 again: in batteries, the process *is* the company.

Where the industry will actually be built is visible in the regulatory numbers. The EU Battery Regulation sets the floor: fifty percent of lithium recovered from waste batteries by the end of 2027 and eighty percent by 2031; ninety percent of cobalt, copper, lead and nickel by 2027, ninety-five by 2031; and — the demand-side masterstroke — minimum recycled content in new EV batteries from 2031: sixteen percent cobalt, six percent lithium, six percent nickel. [29.4] Mandated buyers change everything: a recycler with a guaranteed customer is a financeable business. China, characteristically, is furthest along in fact rather than law — two-thirds of all battery-recycling capacity added since 2020 stands there, built by the same cell giants who make the virgin product and intend to own the loop. [29.5]

The triage at the gate

Every retired pack faces the same fork, and the fork is economic before it is technical. A vehicle battery retires at seventy to eighty percent of its original capacity — spent for the car, rich for almost anything less demanding. The triage question is whether a given pack is worth testing, grading and redeploying — second life — or worth more as feedstock for materials recovery today. The answer moves with new-battery prices: when new LFP packs fell toward $70 per kilowatt-hour in the mid-2020s, the margin that justified elaborate second-life refurbishment narrowed sharply — why buy tested used capacity when new capacity is nearly as cheap and warranted? [29.3] The honest industry assessment of the mid-2020s is that second life thrives in niches — stationary storage

with gentle duty, off-grid systems, backup power — while the mass of retired packs increasingly goes straight to the shredder. The grave and the second life compete, and the price curve referees.

The chemistry of the grave

Recycling's process chain has matured into a recognisable industrial form: discharge and dismantle, shred under inert atmosphere, separate the "black mass" — the powder containing the cathode and anode materials — then refine. Pyrometallurgy burns the problem down to a metal alloy and a slag, recovering cobalt, nickel and copper but losing lithium, manganese, graphite and the electrolyte. Hydrometallurgy leaches the black mass in acids and precipitates the metals one by one — lithium last and hardest, which is why lithium recovery rates lag the others and why the EU's targets single it out: half of the lithium in waste batteries recovered by the end of 2027, eighty percent by 2031, alongside the cobalt-copper-lead-nickel quotas and the recycled-content minimums for new batteries from 2031. [29.4] The frontier processes — direct recycling, which refurbishes cathode material without reducing it to elements — promise to keep the value embodied in the crystal structure itself, and remain, like so much in this book, at the pilot-to-industrial threshold. [29.5]

The orebody that grows in the streets

The strategic arithmetic is the chapter's real payload. Today's feedstock is mostly manufacturing scrap — gigafactory start-up waste — because the EV fleet is too young to have retired. From the early 2030s the wave arrives: the millions of vehicles sold in the 2020s reaching end of life, each carrying hundreds of kilograms of battery. Industry projections put recycling's contribution at a meaningful and rising share of lithium, nickel and cobalt supply through the 2030s and beyond — in some scenarios,

the majority of cobalt and nickel demand met from recovered material by mid-century. [29.6] The dependency table's last column is thus a promise written in chemistry: a battery civilisation, unlike an oil one, digs its orebody once. The mines of Part Five become the seed stock; the cities become the mines; and the grave, properly engineered, is a nursery. Li-Cycle's collapse and Glencore's rescue show the road is not smooth; the destination's logic is unaffected. [29.7]

Between the first life and the grave lies a second: EV packs retired at seventy or eighty percent of capacity are too valuable to shred and too tired to drive, and a market in repurposing them — as stationary storage for solar farms, factories and charging plazas — has been five years away for a decade, held back by testing costs, warranty questions and, lately, the plunging price of new cells that undercut used ones. The honest summary: the grave is winning. But the deeper point stands. A battery industry that recycles becomes, asymptotically, a mining industry that needs no mines — the metals, once dug, circulate. The century's extraction bill for lithium, cobalt and nickel is a one-time cost if the loop closes; the entire project of Part Five's map is, seen this way, the building of the first inventory.

CHAPTER 30

What Comes Next

The lithium-ion battery is a mature industry built on an unfinished technology, and the gap between the two is where its futures live. As of late 2026, four candidates contend to inherit, extend or overthrow the incumbent chemistry. They differ less in promise than in proximity.

Sodium-ion: already here. The most important “future” battery is one that reached mass production while this book was being written. In April 2025 CATL launched Naxtra, the first major-brand sodium-ion cell — 175 watt-hours per kilogram, nearly level with LFP — with mass production from December 2025; BYD, HiNa and a bench of Chinese rivals are building lines, and India’s Reliance owns Faradion, the British pioneer it bought in 2021. [30.1] Sodium’s case is resource arithmetic: sodium is a thousand times more abundant than lithium, costs almost nothing, and needs no lithium, cobalt or copper (aluminium serves both electrodes). Its ceiling is physics — the sodium ion is bigger and heavier, and its cells will not soon reach nickel-chemistries’ density — which confines it to storage, city cars and two-wheelers: precisely the volume segments where cost rules. The technology’s strategic meaning is larger than its market share: it puts a floor under the lithium price, a hedge under the whole supply chain, and a second platform under the industry that no mine can embargo.

Silicon anodes: arriving. Chapter 10 told this story: silicon blended into graphite is already in premium cells, and the dedicated plants — Sila’s Moses Lake among them — began shipping to carmakers from late 2025. The prize is a step-function in density at the anode alone; the cost is the swelling that has defeated forty years of chemists. Expect steady percentage-point gains, not a takeover. [30.2]

Solid-state: the perennial heir, still in the antechamber. Replacing the liquid electrolyte with a solid — ceramic sulphide, oxide, or polymer — promises the closed circle of this book’s history: a lithium-metal anode, held flat by the solid, restoring Whittingham’s dream at double the energy density and with nothing flammable to burn. The programmes are real and their targets have all slipped: Toyota — the patent leader — holds Japanese production approval and aims at 2027-28; Samsung SDI,

with BMW and Solid Power, targets 2027; QuantumScape ships samples and builds its pilot line with 2027-28 aspirations. As one industry tracker put it in 2026: you cannot buy a car with an all-solid-state battery, and more than ten billion dollars have not yet changed that. [30.3] The industry's grown-ups increasingly say the quiet part: mass production, when it comes, will be the beginning of the hard part — yield, cost, qualification — not the end. Semi-solid and hybrid designs (China's "condensed" and quasi-solid cells, already shipping in niches) may capture much of the value on the way.

The long tail. Lithium-sulphur (the airline's chemistry, if cycle life can be fixed), lithium-air (the laboratory's), magnesium and calcium ions, iron-air for the grid's hundred-hour problem, and the whole zoo of flow batteries: each is a real programme with real physics and a specific niche that might be large. And the incumbent itself is not standing still — CATL's condensed battery claims 500 Wh/kg for aviation; its third-generation Shenxing claims ten-to-eighty-percent charges in under four minutes at 12C peak rates; LMFP and manganese-rich cathodes push the cheap chemistries upward. [30.4] The safest prediction in the field has been the same for thirty years: the next battery will be lithium-ion, again — and the safest refinement, lately, is "or sodium-ion."

The sulphide sprint

The solid-state race has a technical geography worth mapping, because the front-runners converged on different walls of the same room. The sulphide electrolytes — high conductivity, soft enough to process — lead the pack: Toyota, Samsung, and much of China's programme bet on them, fighting their moisture sensitivity and their need for stack pressure. The oxides — stable, stiff, brittle — suit different architectures and different factories. Polymer hybrids trade performance for manufacturability. [30.3] What changed in

the mid-2020s is not a winner but a stage: multiple manufacturers moved from coin-cell demonstrations to automotive-format samples and pilot lines — Honda's demonstration line, Nissan's Yokohama pilot plant, Chinese semi-solid cells already shipping in premium cars — with mass-production targets clustering at 2027-28, a date this book treats as a labelled forecast, since the industry's history with its own solid-state deadlines is a litany of slips. [30.4]

Sodium grows up

While solid-state chased the summit, sodium-ion quietly took the valley. CATL's Naxtra brand launch in April 2025 — 175 watt-hours per kilogram, mass production from December 2025, targets on starter batteries and commercial vehicles first — marked the chemistry's arrival as a product line rather than a press release. [30.5] The strategic case needs no performance argument: sodium is everywhere, its cathodes need no lithium, nickel or cobalt, and the cells reuse lithium-ion's factories wholesale — same coaters, same formation, same machines. The economics currently run against it at low lithium prices — when lithium carbonate crashed, sodium's cost advantage thinned — but the industry's commitment is a hedge, and hedges are bought for the scenario, not the average. [30.6] For the grid and the scooter, adequate-and-abundant beats excellent-and-crowded.

The lab bench beyond

Behind both runs the longer game, and this book's honesty rule applies to it most strictly. Lithium-sulphur offers a theoretical specific energy far beyond intercalation's ceiling and a cycle life, so far, far below a car's needs; lithium-air remains, after five decades, a beautiful electrode in search of a reversible one; the anion-shuttle and magnesium and calcium chemistries wait their

turn at the spiral. [30.7] The record justifies neither hype nor dismissal: in 1980 the lithium-ion battery was a spin-off, a basement and a coke oven away from existing. Somewhere in today's literature sits the equivalent of Mizushima's voltage chart — a measurement whose consequences will look obvious in 2050. Forecast: the rocking chair has decades left to rule. The dynasty will end, as dynasties do, from a direction it is not watching.

What the futures share is a dependence on the present. Every candidate is manufactured on the incumbent's lines, with the incumbent's equipment, sold to the incumbent's customers, through the supply chains of Parts Five and Six. The revolution, when it arrives, will be coated on the same slot dies. Whoever owns the machine tools owns the future too.

CHAPTER 31

The Indian Hour

This library exists to map the industries of India, and the battery poses the map's hardest case: an industry that will define India's century, currently happening mostly elsewhere. The honest account has three layers — demand that is real and growing, manufacturing that is promised and barely begun, and a resource position that is being assembled, piece by piece, abroad and at home.

India's electric wedge, FY2025

1,149,334

electric two-wheelers sold, up 21% on the year



Each pack: 2-4 kWh. A million scooters match about 15,000 long-range cars in cells.

The world's largest two-wheeler market electrifies from the bottom up.

Source: Press Information Bureau, Government of India (FY25 release).

Demand first, because it is India’s trump. India sold over a million electric two-wheelers in FY2024-25 — 1,149,334 units, up twenty-one percent on the year — plus 159,235 electric three-wheelers (up fifty-seven percent), a growing fleet of electric cars led by Tata and Mahindra, and buses by the thousand under state tenders. [31.1] The two-wheeler matters more than the car here: India’s motorisation is a scooter story, and the electric scooter is a battery story; the country’s EV fleet is, characteristically, bottom-up. Behind the vehicles stands the grid: India has announced storage tenders at a pace that made it, by 2024, one of the world’s top five battery-storage markets by pipeline. [31.2] Every one of these electrons, today, passes through a cell made abroad: India imported some $4.93 billion of critical-mineral-linked goods in FY24, battery packs accounting for sixty-eight percent of them, seventy-two-point-eight percent of those from China. [31.3] The dependency is the policy.

Manufacturing, promised. The instrument is the PLI-ACC scheme: ₹18,100 crore approved in May 2021 to create 50 GWh of

domestic Advanced Chemistry Cell capacity, with 40 GWh awarded to four firms — Reliance, Ola Electric, Rajesh Exports, and (via a later rebid) others. The Ministry of Heavy Industries' own status statement, tabled in Parliament, records the sobering detail: as of its latest report, no beneficiary had yet claimed an incentive, and installed capacity stood at the beginning of its curve. [31.4] The frontier is real, though: Ola's Krishnagiri gigafactory in Tamil Nadu began commercial production of its own 4680-format cells — the Bharat cell — for its scooters in FY2025, the first made-in-India automotive-format cell of the modern era; Exide and Amara Raja are building multi-gigawatt plants with Chinese and Korean technology partners; Reliance is building its Jamnagar complex around Faradion's sodium-ion, acquired for £100 million in 2021. [31.5] [31.6] The pattern is the one this book has seen elsewhere: assembly first, materials later, process learning throughout — with the difference that India's market is large enough that the factory genuinely follows it.

Resources, assembled. India has lithium on paper and little in the ground in production: the Geological Survey of India's 2023 announcement of 5.9 million tonnes of inferred lithium ore at Salal-Haimna in Reasi, Jammu & Kashmir — the find that made headlines worldwide — is a G3-stage (inferred) resource in clay-hosted mineralisation that has never been commercially processed anywhere; its auction has been attempted and re-attempted. [31.7] The pragmatic arm is KABIL — Khanij Bidesh India Ltd, the state joint venture for minerals abroad — which in January 2024 signed for five lithium blocks in Argentina's Catamarca province, India's first overseas lithium exploration agreement. [31.8] Cobalt and nickel India barely has; recycling it is beginning to regulate (the Battery Waste Management Rules, 2022, impose extended producer responsibility with escalating recovery targets); and the processing middle — refineries, cathode and anode plants — is the gap every serious Indian battery document now names.

The scheme’s arithmetic

PLI-ACC’s design deserves a closer reading than the headlines gave it, because it encodes India’s theory of the game. The scheme committed ₹18,100 crore — about $2.2 billion at announcement — to subsidise fifty gigawatt-hours of advanced-chemistry cell manufacturing, with the subsidy paid per kilowatt-hour sold and conditioned on domestic value-addition milestones: recipients must localise the chain inward, from pack to cell to materials, on a schedule. [31.2] The structure is a deliberate mirror of Chapter 25’s toolkit — production subsidy plus content rules — scaled to a latecomer’s budget. The results, five years on, are mixed in the instructive way: the full complement of gigawatt-hours was awarded to a handful of conglomerates, but ground-breaking lagged award, cell lines slipped, and by the mid-2020s India’s actual commissioned cell capacity remained a small fraction of the scheme’s ambition — while pack assembly, the easy first rung, boomed. [31.2] The scheme bought the intent to climb the curve; the curve, as Chapter 16 taught, accepts no promissory notes.

The two-wheeled wedge

Where the cell policy has met friction, the vehicle policy has met physics: India’s electrification is proceeding from the bottom of the vehicle pyramid upward, and the battery sizes make it possible. An electric two-wheeler’s pack is two to four kilowatt-hours — the annual battery demand of a million scooters equals perhaps fifteen thousand long-range cars. India’s FY25 electric two-wheeler sales — 1,149,334 units, up twenty-one percent on the year — thus represent a gigawatt-hour-scale market that pack assemblers can serve with imported cells today and domestic cells tomorrow, at price points where petrol’s total cost of ownership has already lost. [31.4] The three-wheeler electrified even faster. The wedge strategy — electrify the smallest vehicles first, build the chain

behind them, climb — is not a consolation prize; it is the sequence by which the world's largest two-wheeler market actually converts.

The diplomatic circuit

The minerals offensive continued through the mid-2020s on every front the geology allowed. KABIL's Argentina offtake — the January 2024 CAMYEN agreement, five blocks, lithium brine exploration and offtake rights — was followed by agreements and scouting in Australia, Chile, Africa; the domestic exploration pipeline lengthened, with new blocks auctioned and the Reasi find progressing through early exploration — a discovery of scale whose grade, depth and metallurgy will take years to prove, as discoveries do. [31.5] The recycling option sits naturally with India's informal-sector genius for materials recovery — an industry to be formalised rather than invented, and one where the dependency math of Chapter 29 applies with special force to a country without mines. [31.6] None of it is fast. All of it is the same sentence, written in a new hand: the item must come from somewhere, and the somewhere is negotiable — with money, with diplomacy, with time. India, which missed the battery's first three decades, is paying for its seat at the table the century's way: deliberately, and at scale.

The Indian hour, then, has not struck; it is being assembled. The country enters the battery age later than China entered it, but with advantages China did not have: a gigantic two-wheeler-led market, a solar build-out pulling storage behind it, and the whole accumulated technology of the previous thirty chapters available for licence, joint venture or purchase — the second-mover's discount. The risks are the mirror image: that the window closes while the licences are signed abroad; that the PLI gigawatt-hours remain paper; that Reasi remains a headline. The library's verdict is the one this book keeps reaching: in batteries, demand is a

beginning and process knowledge is the rest. India has the first. The second is now, visibly, the national project.

CHAPTER 32

The Hinge

This library's premise is that philosophy begins with material thinking: pick up any object and ask who made it, from what, through which pipelines, at whose cost. The lithium-ion battery survives that interrogation better than most objects, because it answers in plain sight. Take it apart and you hold the periodic table's argument with itself — the lightest metal, hosted in carbon, shuttled through a fluorinated salt, between films and foils rolled to the thickness of a breath. Follow it backwards and you stand, in a single afternoon of reading, in the Atacama's evaporation ponds, in Katanga's pits, on Morowali's wharves, in an Inner Mongolian graphitisation hall, at a Wuxi coater, in a dry room in Ningde where a film a few atoms thick is being grown that will decide whether a car in Oslo burns in 2031. Few items concentrate the whole industrial Earth into so small a can.

Its history rebukes two comfortable stories at once. Against the lone-inventor story, the battery shows an assembly: an oil company's abandoned project, an unfunded Oxford patent, a company chemist's coke, a camera company's product decision — four institutions, three countries, twenty years — and a Nobel committee that needed three chairs. Against the inevitable-march story, it shows contingency at every step: if Exxon had persisted, if Oxford's patent office had bothered, if Sony had passed, if China had not made electrification a national project in 2009, the curve of Chapter 22 would sit elsewhere, and so would the world's

emissions. The modern battery was not destined. It was decided, repeatedly, by identifiable people and policies — which is the optimistic reading, since decisions can be made again.

Its present is the energy transition's load-bearing wall. The car is becoming an electric appliance; the grid is learning to store the weather; the developing world's leapfrog — past the landline to the phone, past the coal grid to solar-plus-storage — runs on this cell. The dependency table is the book's recurring discomfort: an elementary technology of human emancipation, manufactured overwhelmingly in one country, from materials dug in a handful, on machines made in one city. Whether that concentration is a phase (as steel's and oil's early maps were phases) or a settlement, the 2030s will tell.

And its future is, characteristically, material. Sodium takes the volume end; silicon stretches the density; the solid-state laboratories chase the metal anode around the spiral once more; recycling promises that the mining is, asymptotically, a one-time extraction. The battery will not be the last word in storage — no technology is — but it has already secured the title this book set out to document: the device that made electricity portable, durable and cheap enough to rebuild the world's two largest machines, the car and the grid, around it.

Sugar built an empire on a crystal; the container built one on a box. The battery is building one on an ion — three electrons' worth of element, borrowed from a stone, rocking back and forth in the dark of a sealed can, powering the century.