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Review article

Sodium-Ion Batteries, Direct Lithium Extraction, Bidirectional Grid Integration, and Advanced Nuclear Power: A Review of Their Transition to Commercial Deployment, 2020–2026

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Abstract

This review asks why four technologies that were technically feasible a decade or more ago, namely sodium-ion batteries, direct lithium extraction, bidirectional grid integration, and advanced nuclear power, all reached commercial inflection points in the same period, 2024 to 2026. It tests the thesis that these transitions were driven primarily by changes in demand context, manufacturing scale, and policy support rather than by discrete technical breakthroughs, and that the four technologies are interdependent parts of a single energy portfolio rather than independent options. This narrative review synthesizes peer-reviewed literature, agency reports (including those of the International Energy Agency and the International Atomic Energy Agency), and industry disclosures published up to mid-2026. For each technology, the evidence is examined against three questions: when the core technical capability was first demonstrated, what changed between 2020 and 2026 to enable commercial deployment, and which barriers remain. The interactions among the four fields are then analyzed. Sodium-ion batteries entered mass production in 2025 and now offer a lower-cost, more resource-abundant alternative to lithium chemistries for grid storage and entry-level electric vehicles, although their energy density still lags that of lithium iron phosphate cells. Direct lithium extraction recovers lithium from brines within hours rather than months, with a smaller land and water footprint, and has opened geothermal and oilfield brines as new resources. Bidirectional charging is converting idle vehicle and home batteries into distributed grid assets through a four-layer architecture spanning batteries, power conversion, aggregation, and markets. Advanced nuclear power, including small modular reactors and accident-tolerant fuels, has attracted renewed investment driven mainly by data center electricity demand. In all four cases, the enabling science predates 2015, whereas the commercial triggers emerged after 2020. The evidence supports the thesis. Commercial timing was set by demand context, manufacturing scale, and policy rather than by laboratory breakthroughs, and the four technologies interact through shared variables such as lithium scarcity, stationary storage requirements, and the need for firm capacity. Energy systems are consequently becoming more distributed, more materially diverse, and more responsive to demand reshaped by computing, and technology forecasts should track markets and institutions at least as closely as laboratory performance.

Keywords: Sodium-ion batteries; direct lithium extraction; vehicle-to-grid; small modular reactors; energy storage; grid flexibility.

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1. Introduction

Electricity systems built during the twentieth century assumed steady demand growth and centralized supply. Both assumptions are now under strain. Electricity demand is rising again in advanced economies after nearly two decades of stagnation, driven largely by data centers, electrified transport, and industrial electrification [1].

At the same time, supply is shifting toward variable renewable sources that require storage and flexibility to remain reliable [2, 3]. This review examines four technologies that independent assessments published in 2026 identified as having reached commercial inflection points between 2024 and 2026.

MIT Technology Review placed sodium-ion batteries on its list of breakthrough technologies for 2026, citing their reliance on abundant materials and their readiness to power grids and affordable electric vehicles [4]. The World Economic Forum highlighted direct lithium extraction and everything-to-grid technology in its annual survey of emerging technologies, noting that both have left the laboratory and are already in commercial use [5]. Advanced nuclear power features in several recent outlooks, propelled by power purchase agreements signed by technology companies seeking firm, clean electricity [6].

These technologies are usually reviewed separately, and most existing reviews describe their technical progress without asking why commercialization occurred when it did. The coincidence in timing is notable, because the core science of each technology was established well before 2015, as Section 6 documents.

This review therefore addresses the following research question: why did sodium-ion batteries, direct lithium extraction, bidirectional grid integration, and advanced nuclear power reach commercial deployment in the same narrow window of 2024 to 2026? It tests two linked propositions. The first is that the timing of each transition was determined mainly by changes in demand context, manufacturing scale, and policy support rather than by a discrete technical breakthrough. The second is that the four technologies are interdependent, so that progress or failure in one alters the case for the others; they are therefore better evaluated as parts of a single portfolio than as competing options.

The temporal stance of the paper is as follows. Developments up to mid-2026 are treated as the recent past and the present and are described on the basis of published evidence; forward-looking statements are confined to the signposts identified in Section 7. The review is narrative rather than systematic. It draws on peer-reviewed literature, agency reports, and industry disclosures, and for each technology it examines when the core capability was first demonstrated, what changed between 2020 and 2026, and which barriers remain. Section 2 covers sodium-ion batteries, Section 3 direct lithium extraction, Section 4 bidirectional grid integration, and Section 5 advanced nuclear power. Section 6 evaluates the two propositions against the combined evidence, and Section 7 presents the conclusions and an outlook.

2. Sodium-Ion Batteries

2.1 Technical principles

Sodium-ion batteries operate on the same “rocking-chair” principle as lithium-ion cells. During charging, sodium ions leave a layered oxide or polyanionic cathode, travel through the electrolyte, and

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insert into the anode; during discharging, the ions return to the cathode and release energy through an external circuit [7]. The architecture of a typical cell is shown in Figure 1. The chemistry differs from that of lithium-ion cells in several important ways. Sodium ions are larger and heavier than lithium ions, which lowers gravimetric energy density. Graphite does not intercalate sodium effectively, so most designs use hard carbon anodes derived from biomass or petroleum precursors [8, 9]. On the cathode side, layered transition metal oxides, Prussian blue analogues, and polyanionic compounds such as sodium vanadium phosphate compete for dominance, each with distinct trade-offs in energy, cost, and cycle life [10, 11].

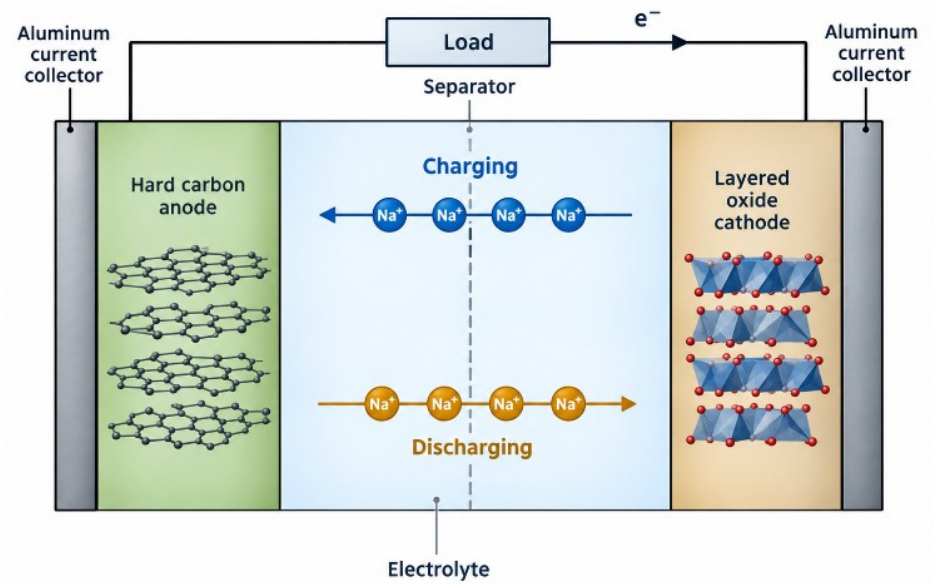


Figure 1. Schematic of a sodium-ion battery cell showing the hard carbon anode, layered oxide cathode, electrolyte, and movement of sodium ions during charging and discharging, with aluminum current collectors on both electrodes.

Two structural advantages follow from this chemistry. First, sodium-ion cells can use aluminum current collectors on both electrodes, because sodium does not alloy with aluminum at low potentials. This removes copper from the bill of materials and allows cells to be transported and stored at zero volts, which improves safety [12]. Second, sodium raw materials such as sodium carbonate are geographically widespread and inexpensive. A cost and resource analysis by Vaalma et al. [13] concluded that sodium chemistries reduce exposure to lithium, cobalt, and copper price volatility, even when cell-level costs remain similar during early production [14].

2.2 Performance status

Commercial sodium-ion cells announced between 2023 and 2025 reached energy densities of 160 to 175 Wh/kg, and laboratory cells have exceeded 200 Wh/kg [11, 12, 15]. These values remain below those of mainstream lithium iron phosphate (LFP) cells, at approximately 180 to 210 Wh/kg, and well below those of nickel-rich chemistries [16, 17]. The gap matters less for stationary storage, where footprint and cost per cycle dominate, than for long-range vehicles. Sodium-ion cells also perform well at low temperatures: manufacturers report usable capacity retention at −30 to −40 °C, a range in which LFP cells lose substantial capacity [15, 18]. Cycle life claims for recent commercial cells reach 8,000 to 10,000 cycles, which suits daily cycling in grid applications [19]. Table 1 compares representative characteristics of sodium-ion and lithium-ion chemistries, with the source of each row given beneath

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the table. The values are indicative rather than exact, because both fields are evolving rapidly and specifications vary by manufacturer.

Table 1. Comparison of representative sodium-ion and lithium-ion battery characteristics.

Characteristic	Sodium-ion	Lithium iron phosphate	Nickel-rich lithium-ion
Gravimetric energy density (Wh/kg)	140 to 200	180 to 210	250 to 300
Low-temperature performance	Strong to −40 °C	Weak below −10 °C	Moderate
Cycle life (full cycles)	5,000 to 10,000	4,000 to 8,000	1,000 to 2,000
Anode current collector	Aluminum	Copper	Copper
Critical mineral exposure	Low	Lithium	Lithium, nickel, cobalt
Safe transport at 0 V	Yes	No	No
Primary near-term markets	Grid storage, entry-level EVs, starter batteries	EVs, grid storage	Premium EVs, electronics

Sources: energy density from Schmuch et al. [16], Abraham [17], Rudola et al. [12], and CATL [15]; low-temperature performance from Jaguemont et al. [18], Hwang et al. [10], and CATL [15]; cycle life from Preger et al. [20] and Hirsh et al. [19]; current collectors and zero-volt transport from Rudola et al. [12]; critical mineral exposure from Vaalma et al. [13] and Schmuch et al. [16]; near-term markets from Abraham [17] and CATL [15]. Values are indicative ranges for commercial cells. EV, electric vehicle.

2.3 Commercial deployment

The decisive shift came when large manufacturers committed production capacity. CATL, the world's largest battery producer, unveiled its second-generation sodium-ion product line under the Naxtra brand in April 2025, with mass production scheduled from December 2025 for passenger vehicle batteries and heavy-truck start-stop batteries [15]. BYD and several Chinese grid storage integrators followed with sodium-ion energy storage stations at the 100 MWh scale. Chinese public investment supported this scale-up, and analysts expect sodium-ion capacity to grow fastest in markets where lithium supply security is a policy concern [4]. Outside China, start-ups in the United States and Europe, including Natron Energy and Northvolt, pursued Prussian blue and layered oxide designs for industrial power and grid niches. Both companies had entered bankruptcy or ceased operations by late 2025, which shows how strongly commercial outcomes depended on access to capital and manufacturing scale rather than on cell chemistry alone.

Deployment has followed price dynamics. When lithium carbonate prices spiked in 2022, sodium-ion cells appeared immediately competitive. When lithium prices collapsed in 2023 and 2024, the cost case narrowed, and advocates of sodium-ion technology shifted their emphasis to supply diversification, safety, and cold-climate performance [21]. The long-term case rests on learning curves. Sodium-ion production borrows most of its equipment and processes from lithium-ion lines, so factories can be converted quickly, and costs can fall with cumulative production, as they did for lithium-ion cells [22, 23].

2.4 Barriers

Three barriers deserve attention. First, limited energy density restricts penetration into mid-range and long-range vehicles, so sodium-ion cells are likely to coexist with lithium chemistries rather than

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replace them [17]. Second, hard carbon anode supply chains remain immature, and precursor quality strongly affects first-cycle efficiency [9]. Third, the field must avoid repeating the early safety complacency of the lithium-ion industry. Sodium-ion cells are more tolerant of abuse in many tests, yet large installations still require rigorous thermal management and fire codes.

3. Direct Lithium Extraction

3.1 The problem with incumbent methods

Even as sodium-ion technology diversifies storage chemistry, lithium demand continues to grow with electric vehicle production [21]. Most brine-derived lithium is currently produced from evaporation ponds in the South American Altiplano. Brine is pumped from underground aquifers into shallow ponds and concentrated by solar evaporation over 12 to 24 months. The method has low operating costs but is slow, land-intensive, and water-intensive, and it typically recovers only 40 to 60 percent of the lithium in the brine [24, 25]. Hard-rock mining of spodumene, the other main route, involves high energy use and processing emissions.

3.2 How direct lithium extraction works

Direct lithium extraction (DLE) replaces evaporation with selective chemical separation. Brine passes through an engineered medium that captures lithium ions while rejecting sodium, magnesium, calcium, and other competing species. Lithium is then stripped from the medium with water or a mild acid, producing a concentrated lithium solution ready for conversion to carbonate or hydroxide. The spent brine can be reinjected into the aquifer, which reduces net water extraction [26]. A generic process flow is shown in Figure 2.

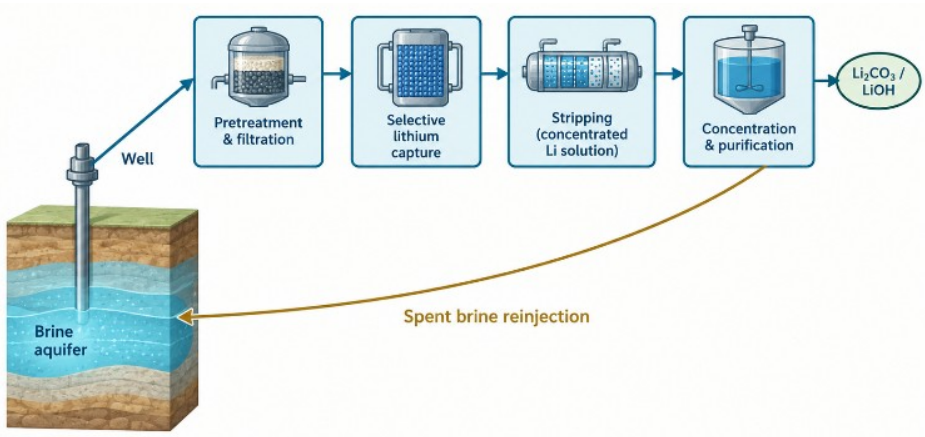


Figure 2. Generic process flow for direct lithium extraction, from brine intake through selective capture, stripping, concentration, and conversion to lithium carbonate or hydroxide, to reinjection of spent brine.

Several separation mechanisms compete. Adsorption uses aluminum-based sorbents that host lithium in their layered structure; it is the most commercially mature route, with decades of operation at plants in Argentina and China [27]. Ion exchange uses ceramic or polymeric materials with lithium-selective lattice sites and offers higher selectivity at the cost of more demanding regeneration chemistry. Solvent extraction and membrane processes, including nanofiltration and electrodialysis, are advancing in pilot programs [26, 28]. Across all routes, the headline advantages are recovery rates above 80 percent and processing times measured in hours rather than months.

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3.3 Deployment and new resources

DLE changes the map of viable lithium resources. Brines that are too dilute, too rich in magnesium, or located in climates unsuitable for evaporation become accessible. The most closely watched examples are geothermal brines at the Salton Sea in California, where operators plan to co-produce lithium and geothermal electricity [29], and oilfield brines [30] in the Smackover Formation across Arkansas and Texas, where ExxonMobil and Standard Lithium hold projects. Chinese producers have deployed adsorption-based DLE at scale on the Qinghai Plateau, and Eramet commissioned a commercial DLE plant in Argentina in 2024. The World Economic Forum included DLE in its 2026 list of emerging technologies on the grounds that it extracts essential raw materials with less environmental impact and is ready to scale [5].

3.4 Open questions

The technology still faces genuine uncertainties. Sorbent lifetime under harsh brine chemistry determines operating cost, and few public datasets cover multiyear performance. Freshwater consumption during sorbent washing can be significant in arid basins, which complicates the environmental case unless closed-loop water systems are used [25]. Reinjection of spent brine must be managed carefully to avoid diluting the resource. Finally, DLE projects have repeatedly slipped their schedules, and the sector still needs several full-scale plants operating profitably outside China to prove the model across diverse brine chemistries.

4. Bidirectional Grid Integration

4.1 From vehicle-to-grid to everything-to-grid

The concept of using electric vehicle batteries as grid resources dates back at least to the foundational analysis of Kempton and Tomić [31], who showed that vehicles are parked for more than 90 percent of the day and that their combined power capacity could rival national generation fleets. Twenty years later, the enabling conditions are in place: electric vehicle fleets are large, bidirectional chargers are commercially available, and grid operators face a growing need for flexible capacity [32, 33]. The framing has also widened. Everything-to-grid (X2G) includes home batteries, heat pump thermal storage, and commercial equipment alongside vehicles. The World Economic Forum summarizes the core idea as follows: electric vehicles and home batteries sit idle for much of the day, and everything-to-grid technology puts their stored energy to work when the grid needs it most [5].

4.2 System architecture

A bidirectional system has four layers, as illustrated in Figure 3. The first layer is the battery asset itself, whether in a vehicle or mounted on a garage wall. The second is the power conversion hardware, either an onboard bidirectional inverter or a DC charger that manages the power flow [34]. The third is the aggregation platform, that is, software that pools thousands of small assets into a virtual power plant that can bid into electricity markets [35]. The fourth is the market and regulatory interface that compensates participants for energy, capacity, or ancillary services. Vehicle-to-home operation, in which a car powers a house during an outage, requires only the first two layers and has become a mainstream selling point on models such as the Ford F-150 Lightning. Full vehicle-to-grid (V2G) participation requires all four layers and depends on interconnection rules that vary widely across jurisdictions.

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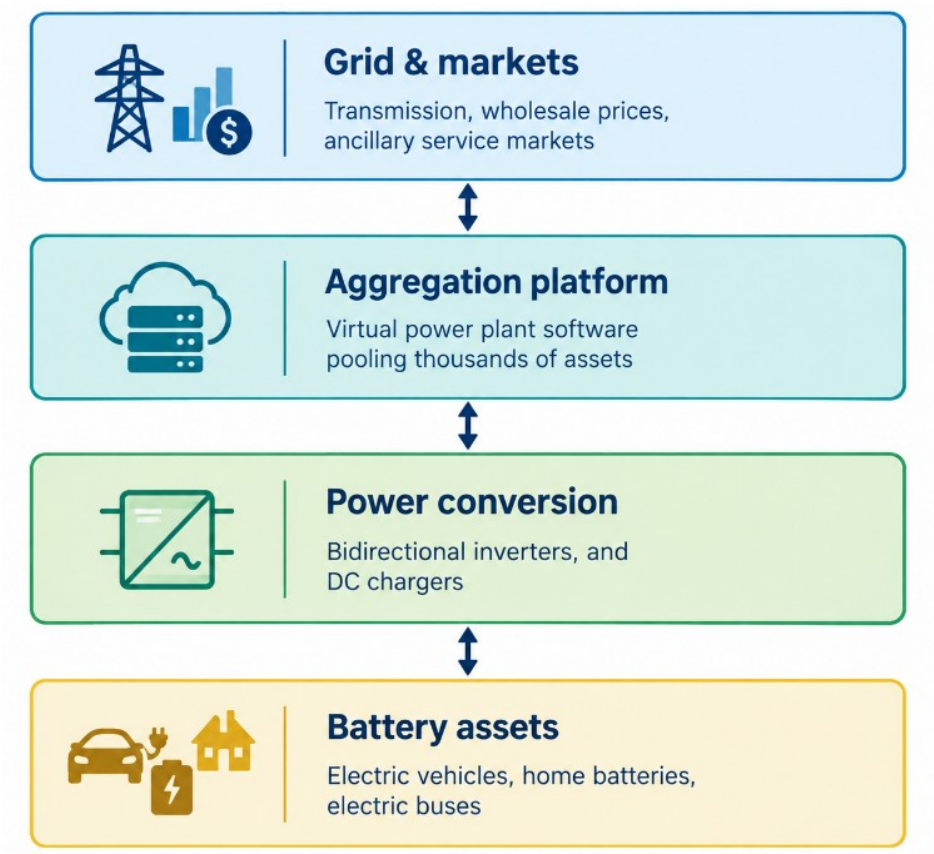


Figure 3. Four-layer architecture of a bidirectional everything-to-grid system, spanning battery assets, power conversion hardware, aggregation software, and market interfaces.

4.3 Value and evidence

The value streams are diverse. Frequency regulation pays for fast response and was the focus of early pilots [32]. Capacity payments reward availability during peak hours, and energy arbitrage exploits the price spread between inexpensive overnight charging and expensive evening discharge. Utility pilots in California, the Netherlands, Denmark, the United Kingdom, and Japan have demonstrated each of these streams. School buses have proven especially attractive, because their large batteries and predictable summer idle periods match grid needs. On the home battery side, virtual power plants operated by Tesla, Sunrun, and several utilities dispatched hundreds of megawatts during heat waves between 2023 and 2025, providing evidence that aggregated behind-the-meter storage performs when called upon.

4.4 Barriers

Battery degradation worries vehicle owners. Laboratory testing has shown that additional bidirectional cycling can accelerate capacity loss [36], but the authors of the leading studies subsequently concluded that smart management of state of charge and depth of discharge can limit this wear and, in some cases, extend battery life [37]. Warranty terms have begun to adapt, with some manufacturers explicitly covering approved bidirectional use. Interconnection and metering rules remain the largest practical obstacle, since many utilities still treat a discharging vehicle as an unfamiliar generator. Social dimensions matter as well: Sovacool et al. [38] argued that user trust, clarity of compensation, and control preferences will determine participation rates as much as hardware will. Standardization is improving through the ISO 15118 communication protocols, which allow the vehicle and charger to negotiate power flows securely [39].

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5. Advanced Nuclear Power

5.1 Demand pull from computing

Nuclear power supplies steady, low-carbon electricity, and its economics improve when buyers value firm supply around the clock [3]. The surge in data center construction for artificial intelligence has created exactly such buyers. Technology companies signed a wave of nuclear procurement agreements between 2024 and 2026, including agreements to restart Three Mile Island Unit 1 for Microsoft, to purchase output from planned small modular reactors for Google, and to support new capacity at existing plants for Amazon. Global electricity demand from data centers is projected to more than double by 2030, reaching a level comparable to the current electricity consumption of Japan [6]. This demand pull, more than any technical breakthrough, explains the renewed investor interest in nuclear energy.

5.2 Small modular reactors

Small modular reactors (SMRs) are designed with electrical outputs below approximately 300 MW and are built largely in factories rather than on site. Their intended advantages are serial production, shorter construction schedules, lower capital at risk per project, and flexibility to be sited near industrial loads [40, 41]. Design families include light-water SMRs, such as those developed by NuScale and GE Hitachi; high-temperature gas-cooled reactors, such as X-energy's Xe-100; and sodium-cooled fast reactors, such as TerraPower's Natrium plant under construction in Wyoming. China connected the HTR-PM high-temperature gas-cooled reactor to the grid in 2021 and is building the Linglong One light-water SMR, giving it the most operational experience to date [42, 43]. Figure 4 places SMR capacity in the context of projected data center demand growth.

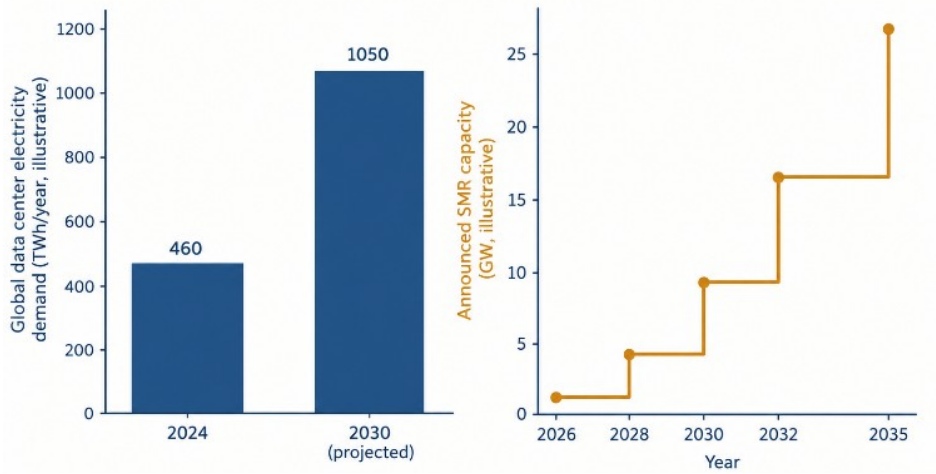


Figure 4. Projected growth of global data center electricity demand to 2030 alongside announced small modular reactor capacity, illustrating the demand pull behind advanced nuclear investment (illustrative values).

The economic case remains unproven at scale. NuScale's first planned project in Utah, the Carbon Free Power Project, was terminated in 2023 after it failed to attract sufficient utility subscription following a sharp rise in its estimated power price [44]. Advocates respond that first-of-a-kind units always carry cost premiums and that learning across identical factory-built units is the central premise of the model [45]. Construction programs scheduled for 2026 to 2030 in the United States, Canada, China, and the United Kingdom will test that claim directly.

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5.3 Safer fuel

Fuel innovation is proceeding in parallel with reactor design. Conventional reactors use uranium dioxide pellets in zirconium alloy cladding. Under severe accident conditions, the cladding can oxidize in steam and generate hydrogen, which contributed to the explosions at Fukushima Daiichi. Accident-tolerant fuels address this pathway with coated claddings, doped pellets, and alternative materials that resist oxidation and retain fission products at higher temperatures [46, 47]. TRISO fuel takes the concept further by encapsulating each uranium kernel in layers of carbon and silicon carbide, creating particles that act as their own containment and remain intact well beyond normal accident temperatures [48]. Several SMR designs pair TRISO fuel with passive cooling, so that decay heat is removed by conduction and natural circulation without operator action or external power.

5.4 Constraints

Advanced nuclear power faces constraints that engineering alone cannot remove. Many designs require high-assay low-enriched uranium (HALEU), which is enriched to between 5 and 20 percent uranium-235; Russia dominated its commercial supply until recently, prompting new Western investment in enrichment [49]. Licensing processes remain lengthy, although regulators in the United States and Canada have created dedicated pathways for advanced designs. Public acceptance varies by country, and waste management policy remains unresolved in most markets [50]. Cost, however, is the decisive variable. Nuclear power does not need to beat solar power on price per megawatt-hour; it needs to beat the combination of renewables, storage, and transmission for the specific service of firm, carbon-free power delivered continuously [3].

6. Discussion: Evaluating the Two Propositions

Consider first the proposition of interdependence. Although the four technologies are usually treated separately, their interactions are where the most important dynamics appear. Sodium-ion batteries and direct lithium extraction pull in opposite directions on the same variable, namely lithium scarcity. If DLE succeeds broadly, abundant and inexpensive lithium weakens the resource-security argument for sodium-ion cells; if DLE disappoints, sodium-ion adoption accelerates. Both outcomes reduce the risk of storage bottlenecks, which explains why investors fund both simultaneously.

Bidirectional integration changes the arithmetic of how much stationary storage the grid must build. A national fleet of electric vehicles with even partial V2G participation represents terawatt-hours of distributed capacity that already exists for another purpose [32]. Every megawatt-hour supplied from a parked car is a megawatt-hour of grid battery capacity that does not need to be manufactured, which in turn feeds back into demand projections for both lithium and sodium chemistries.

Advanced nuclear power interacts with all three. Data center demand growth is the strongest force pushing utilities toward new firm capacity, and the same growth raises peak stresses that storage and V2G can relieve [6]. High-temperature reactors could also supply industrial heat for materials processing, including battery precursor manufacturing and brine treatment. The evidence therefore supports the proposition of interdependence: energy systems in 2026 are best understood not as a contest between generation and storage but as a portfolio problem, in which flexibility, firmness, and material supply must be optimized together [3].

The other proposition concerns the drivers of timing, and Table 2 summarizes the relevant evidence. In each case, the core technical capability was demonstrated well before 2015: sodium intercalation

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chemistry was studied in the 1980s [51], adsorption-based DLE has operated in Argentina since the 1990s [27], V2G economics were formalized in 2005 [31], and SMR concepts date to the earliest years of civil nuclear power [40]. What changed between 2020 and 2026 was the demand context, manufacturing scale, and policy support. The contrasting fortunes of sodium-ion producers reinforce this reading: the same chemistry succeeded commercially where it was backed by established gigawatt-hour-scale manufacturing and failed where start-ups could not finance scale-up. This pattern is consistent with the historical record of energy technology diffusion, in which market formation and institutional support have repeatedly determined the pace of adoption [52]. The evidence therefore supports the timing proposition, with one qualification: incremental engineering, such as higher sodium-ion energy density and more selective DLE sorbents, was necessary for commercialization, even though it was not sufficient to trigger it. Forecasting technology impact consequently requires watching markets and institutions at least as closely as laboratories.

Table 2. Evidence on the timing of commercial inflection for the four technologies.

Technology	Core capability first shown	Main triggers, 2020–2026	Main remaining barriers
Sodium-ion batteries	1980s (intercalation chemistry)	2022 lithium price spike; conversion of gigawatt-hour lithium-ion lines; Chinese industrial policy	Energy density; hard carbon supply
Direct lithium extraction	1990s (commercial adsorption plants)	Rising EV lithium demand; supply-security policy; geothermal and oilfield resources	Sorbent lifetime; freshwater use; project delays
Bidirectional grid integration	2005 (V2G economics)	Large EV fleets; commercial bidirectional chargers; ISO 15118-20	Interconnection rules; user trust
Advanced nuclear power	1950s–1960s (small reactors; TRISO fuel)	Data center demand for firm power; corporate procurement	Cost; HALEU supply; licensing

Sources: Delmas [51], Rudola et al. [12], and CATL [15] for sodium-ion batteries; Liu et al. [27], Warren [29], and International Energy Agency [21] for direct lithium extraction; Kempton and Tomić [31] and International Organization for Standardization [39] for bidirectional integration; Ingersoll [40], Demkowicz et al. [48], and International Energy Agency [6] for advanced nuclear power. EV, electric vehicle; HALEU, high-assay low-enriched uranium; V2G, vehicle-to-grid.

7. Conclusion and Outlook

This review asked why sodium-ion batteries, direct lithium extraction, bidirectional grid integration, and advanced nuclear power all reached commercial deployment between 2024 and 2026. The evidence supports two conclusions. First, the timing was set less by technical breakthroughs than by shifts in demand context, manufacturing scale, and policy support, since each technology was technically plausible a decade or more earlier. Second, the four technologies are interdependent: DLE and sodium-ion chemistry act on the same lithium-scarcity variable, bidirectional integration reduces the amount of stationary storage that must be manufactured, and data center demand links firm nuclear capacity to the flexibility provided by storage. Together, they are producing energy systems that are more distributed, more materially diverse, and more responsive to a demand curve increasingly shaped

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by computing. None of the four technologies is free of unresolved barriers, from anode supply chains and sorbent lifetimes to interconnection rules and enrichment supply.

Several signposts will indicate the direction of travel between 2026 and 2030. For sodium-ion batteries, the key indicators are cell prices falling below those of LFP cells on a sustained basis and the first gigawatt-hour-scale deployments outside China. For DLE, the test is whether commercial plants achieve nameplate recovery rates on geothermal and oilfield brines, particularly at the Salton Sea and in the Smackover Formation. For bidirectional integration, the indicators are interconnection reform and whether automakers standardize bidirectional capability across mass-market models rather than premium trims. For advanced nuclear power, completion of the Natrium and Xe-100 projects near their revised budgets would validate the factory-build thesis, whereas further large overruns would push buyers back toward renewables paired with storage. Because the analysis indicates that markets and institutions govern timing, these signposts are deliberately commercial and regulatory rather than purely technical.

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