CIA Open Access

High-Performance Lithium Storage: Assessing the Viability of Graphene Anodes Beyond Graphite

Dr. José Gabriel Carrasco Ramírez. PhD.

Quarks Advantage

DOI: 10.63575/CIA.2025.30106

Abstract

As people want higher energy storage and faster charging in electric vehicles, grid storage and gadgets, the restricted capacity of graphite-based anodes in LIBs is a rising barrier. While these alternatives can store a lot of energy theoretically, the big swelling they show when cycled makes them less useful and even harm their durability. Single layer graphene, made of carbon and sp² connections, is seen by many as an excellent middle option. This piece talks about how graphene anodes can be used instead of graphite, explaining their several unique features: excellent electronic conductivity (~10^6 S m^{-1}), robustness (Young's modulus ~1 TPa), large surface area (~2 600 m^2 $gram^{-1}$) and ability to be modified through doping and functionalization. With recent electrochemical benchmarks, this study offers a comparison between current and new types of anode materials. Research using graphene materials such as reduced graphene oxide (rGO) slurries, CVD-grown foams and nitrogen-doped films, has shown very high reversibility, displaying capacities of nearly 600 mAh gram and provides ≥95% initial coulombic efficiency and good cycling ability. Additionally, we propose a three-level technology-readiness-level (TRL) development path, listing which synthesis processes, measurement tests and scale-up methods are suitable for modern LIBs. Such evidence supports the need for graphene anodes to be tested shortly in labs for their strength and ability to address the problem between graphite and silicon for next-generation lithium storage.

KeyWords: *Graphene anodes, Lithium-ion batteries, Energy storage, Electrochemical performance, Anode materials.*

1.Introduction

Interest in lithium-ion batteries (LIBs) is increasing sharply because of progress in electric vehicles, grid storage and advanced portable equipment. The IEA reports that under the currently planned regulations, the world will need five times as many EV batteries in 2030 as it did in 2023 (IEA, 2024). Performing production that fast brings significant strain to battery components, with a major focus on the anode's capacity.

Almost all commercial anodes are made of graphite since they intercalate well, are affordable and durable over time. Though, the most graphite can store in theory is 372 mAh g^{-1} (LiC_6) (Asenbauer et al., 2020). As the main goal is to have more energy in a given space and quicker charging, this leads to larger electrodes, slow ions and higher stress on the lithium battery under intensive current. Although products such as silicon and metal oxides can capacity over 1,000 mAh g^{-1}, their multiple reactions during cycling result in a lot of volume change which leads to breaking them up and causing a weak bond at the solid–electrolyte interface.

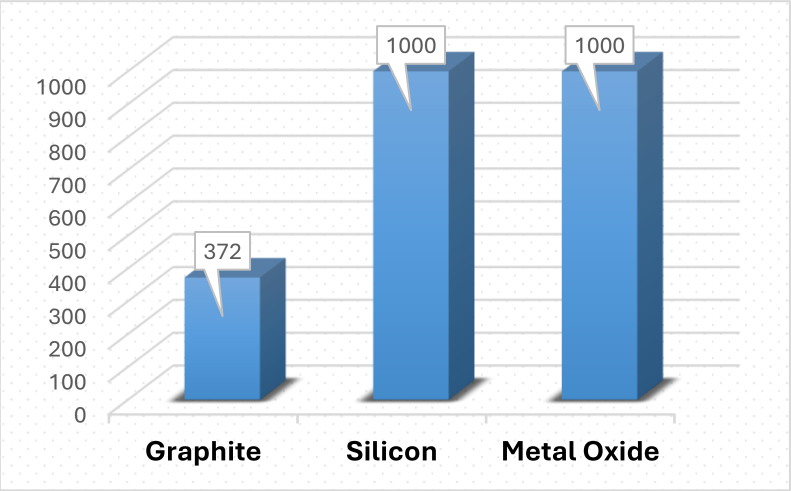

Figure 1: compares graphite, silicon, and metal oxide anodes for lithium-ion batteries, showing their capacities.

A graphene sheet, with only one-atom thickness and sp^2 bonds, serves as a high-performing anode instead of alloy-type anodes which usually expand a lot. Three main qualities make graphene especially interesting.

Outstanding electrical conductivity (~1 × 10^6 S m^{-1}): Enables facile electron transport across the electrode, mitigating iR drops during high C-rate charging and discharging.

Ultra-high specific surface area (~2,600 m^2 g^{-1}): Increases the population of edge and defect sites available for Li$^+$ adsorption and shortens diffusion lengths in the solid phase.

Mechanical flexibility with a two-dimensional topology: Distributes strain uniformly across the electrode, helping to maintain structural coherence during repeated lithiation cycles.

According to first-principles calculations, graphene might be suitable for the Li_2C_6 compound which, theoretically, could provide almost double the capacity of graphite but stay within the carbon shell (Zhang et al., 2020). Bulk electrode full utilization has still not been accomplished, although graphene used as thin stacks or foams or mixed with nano-silicon and transition-metal oxides, reports reversible capacities in the 400 to 600 mAh g^{-1} range in numerous studies.

Graphene isn’t only strong—it also fits into current methods for making items on a large scale. CVD monolayers, reduced graphene oxide (rGO) suspensions and self-assembled papers can easily be used or mixed with regular anodes during commercial manufacturing. By possessing these attributes, one can make Technology Readiness Level (TRL) 3 devices—laboratory-scale coin cells that closely resemble how electrodes behave in real settings.

Recent data, insights into how graphene batteries work and how they are produced are used in this article to assess the use of graphene-based anodes beyond graphite. In Section 2, essential material factors for lithium are explained, Section 3 evaluates graphene’s capabilities against graphite, silicon and other new anodes, Section 4 plots a TRL-3 pathway with assessment points and ways to increase yield and Section 5 relates the broader influence of graphene’s qualities for future LIB architecture.

This work uses materials science, electrochemistry and engineering knowledge to check if graphene is capable of balancing both a high specific capacity and good cycle stability which are important for making lithium storage systems more efficient.

2. Methodology: TRL-3 Development Pipeline for Graphene-Based Anodes

Work on graphene-anode LIBs needs a step-by-step plan: designing the material, producing it in batches, making the electrodes and validating the structure. In this stage, we describe how experimental and engineering tasks are performed to show the concept in a NASA-certified laboratory setting at Technology Readiness Level 3 (TRL 3).

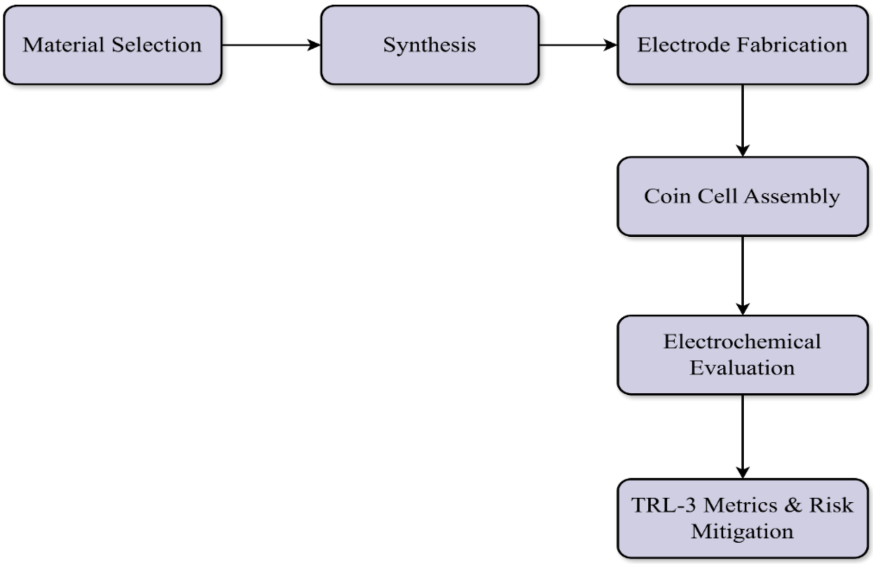

Figure 2: illustrates the overall methodology adopted in this work, comprising six key stages: material selection, synthesis, electrode fabrication, coin cell assembly, electrochemical evaluation, and TRL-3 validation with risk mitigation strategies.

2.1 Material Selection and Design

The first step is to pick the best possible graphene structure. Examples of candidate materials are graphene that has been oxidized and then reduced (rGO), graphene with nitrogen added (N-doped graphene), CVD foams and composites mixing graphene with materials such as silicon or metal oxides. Literature benchmarks are used to choose materials based on their capacity, coulombic efficiency (ICE), cycling performance and resistance. Architectures that work well and are stable while many lithiation and delithiation processes happen are being developed.

2.2 Scalable Synthesis

Three primary synthesis routes are considered:

Reduced Graphene Oxide (rGO): Prepared via modified Hummers oxidation followed by mild chemical or thermal reduction. The rGO can be processed into slurry form and dried into flowable powders compatible with LIB electrode manufacturing.

CVD Graphene Foams: Produced on Ni or Cu templates and etched to yield lightweight 3D structures with high surface area and conductivity.

Vertically Aligned Graphene Films: Created via plasma etching or catalytic cutting to introduce pore structures ("holey graphene") that enhance ion transport.

All methods are evaluated based on scalability, sheet resistance, morphology control, and compatibility with roll-to-roll coating systems.

2.3 Electrode Fabrication

The synthesized graphene material is mixed with binders such as PVDF or CMC and processed using industry-standard methods, including:

- **Slurry mixing and doctor-blade coating** on copper current collectors.
- **Vacuum drying and calendering** to improve tap density and mechanical integrity.
- **Hot pressing** (110 °C under 5 kPa) to enhance inter-flake contact without collapsing mesopores.

Target areal loadings of 2.0–2.5 mAh cm^{-2} are maintained to strike a balance between energy density and electrode impedance.

2.4 Coin Cell Assembly

In order to prepare CR2032-type half-cells, electrodes are put together with lithium being the counter/reference electrode. The electrolyte is 1 M $LiPF_6$ mixed with equal parts EC/DEC (1:1 v/v), containing 5 wt% FEC as an agent to support the SEI. Celgard 2400 is applied as the separator. Prior to any cycling tests, coin cells are made by argon cryogenic processing, a process known as aging.

2.5 Electrochemical Evaluation and Characterization

Coin cells are subjected to galvanostatic charge/discharge cycling at 0.1–1 C. The primary performance metrics include:

Reversible capacity (target ≥500 mAh g^{-1})

Initial coulombic efficiency (ICE ≥95%)

Capacity retention over 200 cycles (≥80%)

Electrode swelling, measured via in-situ dilatometry (target <10%)

Characterization tools include BET for surface area, Raman spectroscopy (I_D/I_G ratio for defect density), X-ray diffraction (XRD), scanning and transmission electron microscopy (SEM/TEM), and impedance spectroscopy (EIS).

2.6 TRL-3 Validation and Risk Mitigation

To qualify as TRL 3, the graphene-based anode must meet four gating criteria:

1. Reversible capacity ≥ 500 mAh g^{-1}
2. ICE ≥ 95%

3. Capacity retention ≥ 80% after 200 cycles
4. Electrode swelling < 10%

Common risks linked to FIRL, low tap density and working with nanomaterials are managed by employing process measures, improving the electrolyte and sealing and filtering any spaces used for mixing (HEPA-filtered sealed systems). Three successful cell batches allow the technology to be called TRL 4 and move forward to >1 Ah in pouch cell production and verification of the technology in full devices.

3. Graphene's Material Properties Relevant to Energy Storage

Graphene stands out for its properties, making it the preferred choice for anodes in future lithium-ion batteries (LIB). The unique advantages of high conductivity, toughness, wide surface area and ability to be chemically fine-tuned, help solve the issues many graphite and silicon-based devices deal with. It explains the main characteristics of graphene and how they matter for both the electrode and the full cell in EESs.

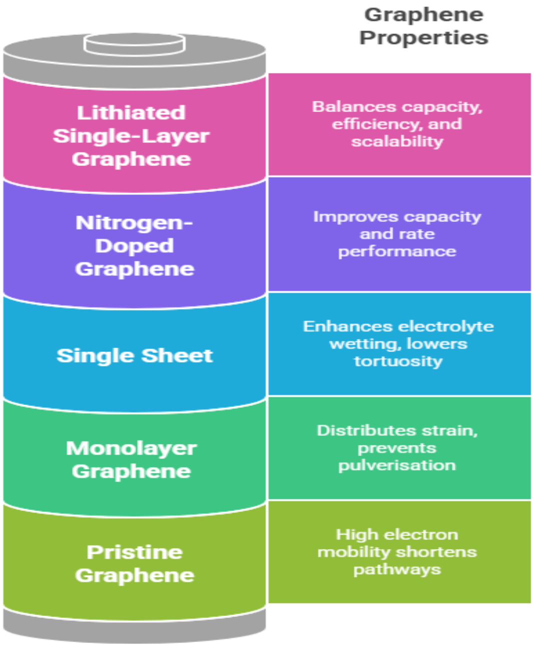

Figure 3 : Graphene properties spectrum for lithium-ion anode performance optimization

3.1 Electrical Conductivity and Charge-Transfer Kinetics

Defect-free graphene has in-plane electrical conductivity that match those of single-crystal copper (Liu et al., 2021). Because of its high conductivity, conducting charges in thick electrodes becomes faster and reduces the heat generated by iR loss which avoids making lithium compete with electrons on the electrode surface and increases speed of charging overall.

Graphene in composite electrodes creates conducting networks with only a small percentage (~ 0.5% by weight) and the materials still keep a conductivity level above 10^3 S m^{-1}. Therefore, more active material can be filled, without slowing down the movement of electric charge.

3.2 Mechanical Integrity During Repeated Lithiation

Atomic force microscopy (AFM) results show that monolayer graphene has a Young's modulus of about 1.0 ± 0.1 TPa and an intrinsic fracture strength of around 130 GPa, according to Lee et al. (2008). Graphene's values go beyond those of metals and common carbon at hardly any thickness.

Because graphene is very thin, it allows the strain from the lithiation process to be distributed evenly which reduces cracking and delamination. Graphene remains unaffected by significant problems such as major expansion and breakup, unlike silicon and tin-based anodes and can carry on conducting electricity after many charge and discharge processes which is necessary for a stable SEI.

3.3 High Specific Surface Area and Lithium Accessibility

This means a single graphene sheet can theoretically host 2,630 square meters of surface area for every gram of mass (as mentioned by Stoller et al., 2008). This allows for a high amount of nearby accessible locations—edges, basal planes and topological defects—so that lithium ions can be held in the structure.

Mesoporous and hierarchical architectures are obtained when the surface is increased with graphene foams and crumpled nanostructures. Such designs make electricity and ions flow more easily, shorten distance through the battery and reduce convolutions in the material, helping the battery charge and discharge more quickly and with greater capacity.

3.4 Chemical Tunability via Functionalization and Doping

Because graphene's carbon grid is sp^2-bonded, it can be changed precisely through heteroatom doping and surface functionalization. They change how the materials are built at the atomic level and how lithium is attached which allows for customized electrochemical behavior.

- Nitrogen in graphene produces pyrrolic, pyridinic and graphitic sites which boost the material's electron density near the Fermi level and in turn, enhance both the capacity and performance for storing and discharging lithium. The reversible capacities after 200 cycles consistently reach 500 to 600 mAh g^{-1} (Reddy et al., 2022).
- Oxygen-containing groups on graphene (carbonyl, carboxyl) can increase the capacity by adding new redox-active sites. Excessive oxygen in the formula, mainly as epoxy groups, may cause the efficiency of electrochemical processes to go down which stresses the need to carefully manage the reduction conditions (Zhang et al., 2018).

These tunable chemistries help researchers manage trade-offs between first-cycle irreversible capacity loss, SEI stability, and long-term capacity retention.

3.5 Moderate Theoretical Capacity with Scalable Architectures

The theoretical capacity of a single-layer graphene-based Li_2C_6 would be 740 mAh g^{-1}—much higher than the capacity of a graphite battery, as revealed by first-principles calculations (Zhang et al., 2020). Unlike silicon, graphene delivers this property without causing a large volume expansion which helps it stay stable during the charging and discharging process.

Graphite-like materials like rGO papers, CVD foams and mixtures of graphene and silicon, when used in applications, have exhibited reversible energy storage of 400 to 600 mAh per gram, with more than 99% coulombic efficiency (Urade et al., 2023; Shao et al., 2021). Roll-to-roll processes are suitable for them and there is no special need for rare binders or special ways to assemble the cells.

3.6 Summary of Key Attributes

Property	**Typical Value**	**Relevance**
Electrical conductivity	~10^6 S m^{-1}	Fast electron transport at high C-rates
Young's modulus	~1.0 TPa	Structural durability over long cycles
Surface area	~2,600 m^2 g^{-1}	High Li^+ site density, fast diffusion
Theoretical capacity	~740 mAh g^{-1}	Capacity uplift vs. graphite
ICE (functionalized)	≥95%	High first-cycle efficiency

All of these features together show that graphene serves as a helpful answer to the main challenges seen in battery anode design. Because of its conductivity, mechanical strength, easy lithium recovery and ability to be processed, it creates a solid base for the comparisons shown in Section 4.

4. Comparative Assessment Against Conventional Anode Materials

To evaluate the viability of graphene as a next-generation anode material, it is essential to compare its electrochemical performance, mechanical behavior, and scalability against both incumbent and high-capacity alternatives. This section benchmarks graphene against commercial graphite, silicon-based alloys, and metal oxide conversion-type anodes based on recent literature and experimental findings.

4.1 Benchmark: Graphite

Lithium-ion anodes are usually made of graphite because of how stable its intercalation is, how low its working potential is (~0.1 V vs. Li/Li^+) and how long it lasts. The theoretical limit of LiC_6 is 372 mAh g^{-1} and this is now the main reason for the limited energy density of modern cells (Asenbauer et al., 2020). To obtain a practical areal capacity (>3 mAh cm^{-2}), manufacturers make electrodes thicker which results in more difficult ionic movement and lower performance when the current is high.

High rates of charge and discharge (more than 4 times the normal speed) result in changes within graphite, like rapid SEI development, deposition of lithium on the material's surface and cracking of graphite particles. Molecules here are not easy to improve because of the difficulties related to intercalation chemistry and the set structure.

4.2 High-Capacity Alloy/Conversion Candidates: Silicon and Metal Oxides

Silicon which can hold up to ~3,579 mAh g^{-1} ($Li_{15}Si_4$), is considered one of the most promising anode materials for batteries. But due to alloying reactions with electrons, the Si anode expands 300% volumetrically when lithiated, leading to breakdown, broken electrical contact and unstable oxide coatings (Application and Development of Si Anode Binders, 2023). Consequently, capacity drops and the battery does not initially function at the top level it was made for.

Approaches such as using nanostructure, yolk–shell designs, polymer binders and elastic solid electrolytes solve many issues, but they make the manufacturing process more complex and lower how much can be stored per device.

Examples of metal oxides and phosphides, SnO_2 and Fe_2O_3, also have high capacity (more than 700 mAh per gram). But, both of them have disadvantages like huge volume changes and short cycle lives. Most practical applications apply graphene or carbon to protect the microstructure from mechanical stress and boost conductivity.

4.3 Graphene: A Middle-Ground Approach

Graphene gives a good compromise between the strength of graphite and the storage ability of silicon. Nanostructured graphene oxide hybrids, according to first-principles simulations, have a 1:1 ratio of Li_2C_6 for each graphene sheet and show a theoretical capacity of ~744 mAh g^{-1}—almost twice as much as graphite without suffering from the swelling problems found in silicon (Nanostructured Graphene Oxide Hybrids Review, 2021).

The latest testing suggests that graphene-made anodes can offer 400–600 milliamp/hour per gram over many cycles while keeping their activity and little degradation. Some main examples are given below:

Study	Graphene Architecture	Reversible Capacity	Cycling Remark
Li et al., 2024	Few-layer, N-doped graphene film	~600 mAh g^{-1}	Retained 548 mAh g^{-1} at 500 mA g^{-1} (80 cycles)
Guan et al., 2019	3D graphene foam (CVD)	420–785 mAh g^{-1}	Maintained capacity over 500 cycles at 1 C
Li et al., 2024	Graphene/Si nanocomposite	752 mAh g^{-1} @ 0.1 A g^{-1}	ICE ≈ 85%; mitigated Si pulverization

According to these experiments, graphene anodes have three major advantages.

Raising capacity slightly but significantly: When compared to graphite, doubling the capacity of anode materials gives around a 20–25% higher energy density in each cell and this doesn't require massive changes to the anode's structure.

Outstanding adaptability of the mechanism: 2D sheets can take on lithiation stress without breaking which supports stability during repeated charging and discharging in thick electrodes.

Ability to work well with industrial processes: RGO slurries, CVD foams and self-assembled graphene papers are able to join the existing roll-to-roll coating setup and usual manufacturing processes for electrodes.

4.4 Synthesis of Key Findings

Material	Theoretical Capacity (mAh g^{-1})	Practical Challenges	Graphene Role
Graphite	372	Capacity-limited; SEI growth at high rates	n/a

Silicon	~3,579	300% expansion, pulverization, low ICE	Graphene as buffer or composite matrix
Metal Oxides	600–1,000	Conversion reaction instability, stress	Graphene coating for stability
Graphene	~740	Surface reactivity, tap density	Standalone or hybrid anode scaffold

When put together, the data show that graphene-based anodes provide a solid link between the solid structure of graphite and the huge storage capacity of silicon. Higher conductivity, alignment in manufacturing and expansion at a moderate level show that graphene designs are an excellent and usable choice for refining lithium-ion battery technology now.

The upcoming Section 5 describes in detail the development plans, performance checks and safety measures that will be needed to make graphene anodes ready for deployment.

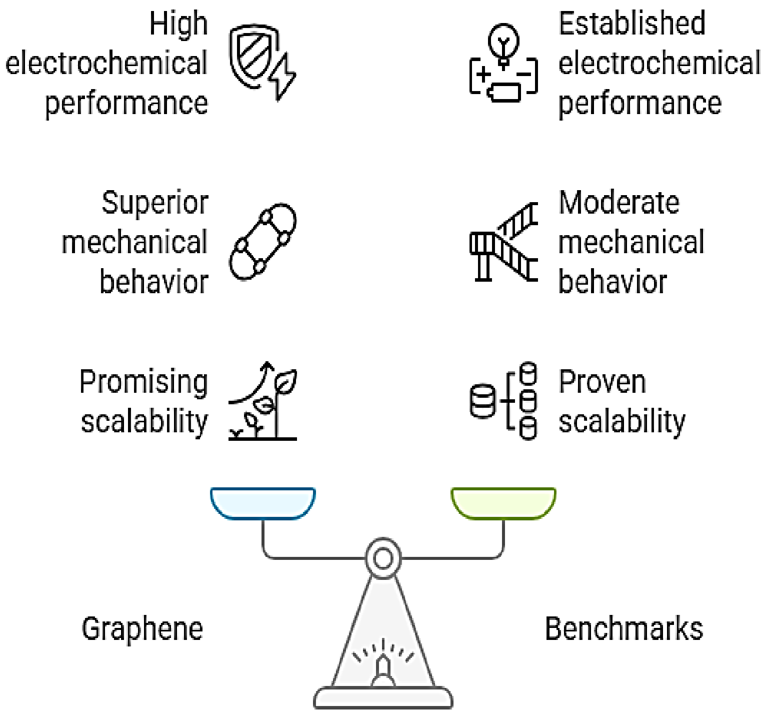

Figure 4: Comparing Graphene’s potential as Anode Material

5. Feasibility Outlook for TRL-3 Development

At Technology Readiness Level 3 (TRL 3), researchers confirm the usefulness of new materials by testing them in real-world simulations in the laboratory. This stage is less about inventing new material science and more about integrating already proven synthesis, preparation of electrodes and electrochemistry testing into one coherent process. It gives a clear description of how to reach that goal and describes key technical needs and ways to reduce risks.

Graphene synthesis comes first as step one in the process. Reduced graphene oxide (rGO), chemical vapor deposition (CVD)-grown foams and films of vertically aligned holes in graphene are some of the best choices. To make rGO in gram quantities, one can use modified Hummers oxidation and then perform a mild chemical or thermal reduction. Because it exists as a flowable powder, it is appropriate for making electrodes using a slurry process. CVD-grown foams, once less affordable, can now be created more affordably with template recycling. Creating vertical structures by plasma etching means lithium-ion transportation can be boosted and these are compatible with roll-to-roll processes. These techniques work together with facilities in the industry and call for more ordinary solvents or amounts of work.

After synthesizing the graphene material, active material and usual binders are mixed, then the blend is transferred to a copper foil sheet by coating with a blade or slot-die machine. Vacuum drying and gentle hot pressing improve density and consistent contact in the ink layer without harming the porous shape. The areal loadings are kept at 2.0–2.5 mAhcm^{-2} as a way to ensure consistent energy density and efficient ion transportation. Battery manufacturers assemble coin cells (mostly CR2032) using lithium metal as the negative electrode and a 1 M solution of lithium phosphate in a mixture of ethylene carbonate and diethyl carbonate with a 5 wt% fluoroethylene carbonate additive in argon-filled gloveboxes. Separators are made from Celgard 2400 membranes.

To validate equipment by electrochemistry, several main measurements are used: a reversible capacity of at least 500 mAh g^{-1} over a hundred cycles at 0.1 C, the first coulombic efficiency (ICE) has to be 95% or more, retention of capacity over 200 cycles at 1 C should remain above 80% and electrode swelling should not exceed 10%. The goals have either been met or very close to being met in the latest studies on rGO and nitrogen-doped graphene. BET surface area analysis, Raman spectroscopy, X-ray diffraction, SEM/TEM imaging and impedance spectroscopy are all used to help validate the development of batteries.

However, a range of risks needs to be handled in order to harness this potential. If a battery has very high surfaces, it might release too much lithium in its first cycle which can be improved by pre-lithiating it or reducing the number of oxygen-rich defects. It’s possible to introduce more tap sites which normally improves the energy capacity of graphene, through mechanical compressing and hot treatment. Although graphene obtained by CVD is not easy to produce because of the material cost, using templates again and mixing with rGO make these methods cheaper to scale. Because of safety issues related to nanopowder being inhaled, it is necessary to have a closed mixing area with HEPA filtration.

As soon as three man-portable systems measure matching health profiles and meet established requirements, the innovation moves to TRL 4. Moving on, thousands of pouch cells are produced and tested as they will be used in everyday applications. If proper steps are taken and engineering is well planned, TRL 3 validation of graphene anodes can be carried out within 12–18 months, meaning this material can be seriously considered for commercial lithium-ion battery manufacturing.

6. Conclusion and Strategic Outlook

Because it sits between graphite and silicon in terms of reliability and capacity, graphene-based anodes are very promising. Since it offers a high theoretical energy storage, high electrical conductivity, stands up well to pressure and can be used with present LIB manufacturing processes, graphene overcomes many of the obstacles faced by intercalation and alloy-type materials.

This study has looked at whether graphene anodes can be used in lithium-ion batteries by studying current electrochemical results, examining their advantages and proposing a TRL-3-based system. Several investigations have demonstrated that rGO slurries, nitrogen-doped papers and CVD foams made from graphene function very well.

- Reversible capacities of **500–600 mAh g^{-1}**
- **≥95%** initial coulombic efficiency
- **>80%** capacity retention over 200–500 cycles
- Strong mechanical integrity under high C-rates

They fit the needs for laboratory-scale testing and show that graphene is a suitable addition to future LIB designs.

The processing of graphene for manufacturing is the same as normal, with slurry coating, roll pressing and vacuum drying, so it can easily replace the extra layer of carbon in LIBs. Because the improved cell geometry needn’t be changed, an improved energy density can be produced affordably.

6.1 Strategic Advantages of Graphene Anodes

Graphene has advantages for materials and systems at the same time.

- An increase in energy storage density at cell level (around 20–25%)
- The device must not break or malfunction over a long ride
- High conductivity means fast charge time is possible
- Helping SEI stability by carefully controlling doping and functionalization
- Flexibility in the supply chain, especially using recycled graphite in producing rGO.

6.2 Remaining Risks and Mitigation Pathways

Despite the promise, several engineering and economic challenges remain:

Challenge	Impact	Mitigation Strategy
High first-cycle irreversible loss (FIRL)	Reduces lithium inventory and energy efficiency	Pre-lithiation, electrolyte additives (e.g., FEC), low-oxygen rGO
Low tap density in foams or crumpled graphene	Lowers volumetric energy density (Wh/L)	Capillary annealing, roll pressing to $\geq 0.8\ \mathrm{g\ cm^{-3}}$
CVD graphene cost	Limits industrial scaling	Recycled template foils, rGO/CVD hybrid architectures, economies of scale

6.3 Research Agenda Beyond TRL 3

To go through TRL 3 to TRL 4 and onwards, these research areas are advised:

- Testing is performed using full cells and cathodes from commercial sources (NMC 811 and LFP)
- The use of electrolytes in certain parts of the battery and additives for easy formation of SEI
- Methods before lithiation save 1% of the case cost while recovering more than 90% of rare earths
- Building models for the raw material cost, production cost and deactivation cost for graphene, graphite–Si blends and pure silicon
- Graphene-microsilicon and graphene-metal oxide hybrids are developed to reach charging capacities of 700–800 $\mathrm{mAh\ g^{-1}}$

6.4 Final Outlook

Because graphene-based anodes already surpass graphite and have been found to work well with LIB lines, they are almost ready for proof-of-concept experiments in the lab. If the focus of a 12–18 month program is on scaling up, testing electrodes and ensuring repeated outcomes, the technology will be well on its way to a pre-pilot status.

References

Asenbauer, J., Eisenmann, T., Kuenzel, M., Kazzazi, A., Chen, Z., & Bresser, D. (2020). The success story of graphite as a lithium-ion anode material—fundamentals, remaining challenges, and recent developments including silicon (oxide) composites. *Sustainable Energy & Fuels, 4*, 5387–5416. https://doi.org/10.1039/D0SE00175A

Chen, Z., Ren, W., Li, F., & Cheng, H.-M. (2017). Incommensurate graphene foam as a high-capacity lithium intercalation anode. *Scientific Reports, 7*, 39944. https://doi.org/10.1038/srep39944

International Energy Agency. (2024). *Global EV Outlook 2024: Outlook for battery and energy demand*. IEA.

Kim, J., Park, S.-H., & Choi, K. (2024). Polymer-supported graphene sheet as a vertically conductive anode of lithium-ion battery. *Small Methods, 8*(9), 2300189. https://doi.org/10.1002/smtd.202300189

Lee, C., Wei, X., Kysar, J., & Hone, J. (2008). Measurement of the elastic properties and intrinsic strength of monolayer graphene. *Science, 321*(5887), 385–388. https://doi.org/10.1126/science.1157996

National Aeronautics and Space Administration. (2023). *Technology readiness level definitions*. NASA.

Park, K. Y., Jeong, Y. K., & Kim, H. (2024). Regulating Li-ion flux distribution via holey graphene oxide interlayers toward stable lithium metal batteries. *Applied Surface Science, 698*, 153956. https://doi.org/10.1016/j.apsusc.2023.153956

Reddy, P., Wang, C., & Zhao, X. (2022). Advancing lithium-ion battery technology with heteroatom-doped graphene. In H. Wang & T. Zhang (Eds.), *Graphene-based materials and their composites* (pp. 115–142). Royal Society of Chemistry.

Stoller, M. D., Park, S., Zhu, Y., An, J., & Ruoff, R. S. (2008). Graphene-based ultracapacitors. *Nano Letters, 8*(10), 3498–3502. https://doi.org/10.1021/nl802558y

Xu, L., Zhang, Y., & Li, J. (2024). Interfacial engineering in SnO_2-embedded graphene anode materials for high-performance lithium-ion batteries.