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# REVIEW ARTICLE

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# The Role of Boron in Next-Generation Technologies and a Sustainable Future

Farah Mutlag[a], Hussein Elaibi[a,b*], Ebru Halvacı[a], Halit Demir[c], Ismet Meydan[d], Tugba Karahan[d], Fatih Sen[a*]

*[a] Sen Research Group, Department of Biochemistry, Dumlupinar University, Kutahya 43000, Türkiye.*
*[b] Department of Pharmacy, Al Safwa University College, Karbala 56001, Iraq*
*[c] Department of Biochemistry, Faculty of Science, Van Yuzuncu Yil University, Türkiye.*
*[d] Van Vocational School of Health Services, Van Yuzuncu Yil University, Zeve Campus, Van, Türkiye.*

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## Abstract

Boron-doped and boron-containing nanomaterials exhibit promising characteristics in advanced energy research because boron can existence of boron could modulate electronic structure, defect chemistry, ion transport and extensive interfacial stability within different material systems. These characteristics make boron-based nanostructures promising candidates for improving lithium-ion batteries, supercapacitors, hydrogen-storage systems, and solar-energy devices. Although a wide range of recent studies has demonstrated the conductivity improvement, charge-transfer reaction promotion, electrochemical interface stabilization and surface catalytic efficiency enhancement attributable to boron incorporation, these merits still rely heavily upon the host material, structural construction and test environment. Key barriers remain despite significant advances, including limited mechanistic consistency across studies, an absence of device-level validation and challenges with scaling and long-term stability. This review provides a timely and comprehensive overview of recent advances in boron-modified nanotechnologies for energy storage and conversion systems, including their functional roles/performance advantages and limitations, major research gaps.

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*Keywords:* Boron-doped nanomaterials; lithium-ion batteries; hydrogen storage; fuel cells; solar cells; boron nitride; borophene; boron carbon nitride

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## 1.Introduction

The global transition to renewable energy has created major opportunities for research on new materials that can be used to improve energy storage and energy conversion technology. Due to the problems of low conductivity, slow ion transport, poor interfacial stability and low catalytic activity for conventional materials, nanotechnology has proven to be a key method to obtain better performance and longer lifetimes of modern energy systems. Boron-based materials have become particularly important in this context; boron can modify the electronic and structural properties of host materials through charge redistribution, atomic substitution, defect engineering, bond polarization [1], [2]**.**

The topic of boron-based nanostructures has been investigated in several important contexts, such as lithium-ion batteries, supercapacitors, hydrogen-storage materials, fuel cells, catalytic processes, and solar-energy systems. However, the literature around this topic is rather limited in general with many studies reporting performance improvements but only limited understanding of why these improvements occurs and whether they remain valid under practical device operating conditions for devices. Variations in synthesis techniques, material architectures and assessment protocols have further prevented unified comparability between studies [3]**.**

This article is a structured literature review of boron-doped and boron-containing nanomaterials for energy storage and conversion applications. Relevant studies were retrieved from Scopus, Web of Science, ScienceDirect, SpringerLink and Wiley Online Library databases, and the search strategy was limited primarily to publications published between 2020 and 2026 but also while also including earlier foundational studies relevant to the topic.

## 2. Energy Crisis and Sustainable Solutions

Reflecting on the recent challenges in energy supply, we see that the modern-day energy crisis is less about absolute shortages of primary energy factors, but more about a growing imbalance between electricity demand and flexibility in existing energy infrastructures. And as the International Energy Agency (IEA) recently noted, global electricity demand grew by 4.3% in 2024 alone. In turn, renewable electricity will grow from 32% of global electricity generation in 2024 to at least 43% of global generation by 2030. The share of variable renewable sources, particularly solar photovoltaic (PV) and wind, is slated to almost double over the same period to 27%, with renewables set to cover more than 90% of the growth in electricity demand worldwide from 2025–2030. This is good news from a decarbonization standpoint, but it highlights an underlying shortcoming in current energy systems: generation capacity is growing faster than the materials and devices needed to store intermittent electricity, smooth out short-term fluctuations, and sustain conversion efficiency under evolving operating conditions [4].

From a technological perspective, then, the energy crisis is also a problem of materials. Large-scale storage will also need to grow significantly to help resolve the hour-to-hour variability of solar and wind generation; in its Net Zero Scenario, installed grid-scale battery capacity needs to increase 35-fold from 2022 levels by 2030, reaching nearly 970 GW [5]. But scaling storage and conversion technologies is not just “a matter of deploying more batteries or catalysts.” Traditional materials are limited by low intrinsic conductivity, slow ion diffusion, unfavorable electrode electrolyte interfacial stability, poor catalytic selectivity and decay of performance under long-time cycling or thermal stress. This is why nanotechnology came to dominate energy research: not because nanoscale materials are necessarily better, but because they enable purposeful control over transport length and surface reactivity, defect density, and interfacial energetics, the manipulable metrics that govern whether a device works well under realistically operating conditions [6], [7].

In the context of nanotechnology, boron-based materials are particularly relevant because boron imparts a unique type of electronic asymmetry to host lattices. Because of its electron deficiency, boron can further delocalize charge density, create chemically active defect sites, and modulate the bond polarity present in carbon frameworks, silicon matrices, boron nitride architectures, as well as emerging two-dimensional materials like borophene [8], [9], [10], [11], [12].

Recent reviews underscore that functionalization, and interfacial engineering can make h-BN useful in energy storage and conversion despite its intrinsic insulating nature. In addition, borophene and other boron-rich nanostructures have stimulated new research and other boron-rich nanostructures have stimulated new research into batteries, supercapacitors, catalysis, and hydrogen-related systems with unique properties such as high carrier mobility and tunable electronic properties [8], [9], [10], [11], [12].

Simultaneously, it is well established in the literature that these opportunities come hand in hand with unanswered challenges, notably poor structural stability for some boron nanostructures and ongoing challenges surrounding manufacturing capacity, characterization, scalability and safety assessment. In other words, boron shows promise not as a cure-all, but rather as an exquisitely sensitive design variable whose value remains contingent on how well it is choreographed within an operant energy architecture [8], [9], [10], [11], [12], as shown in Figure 1.

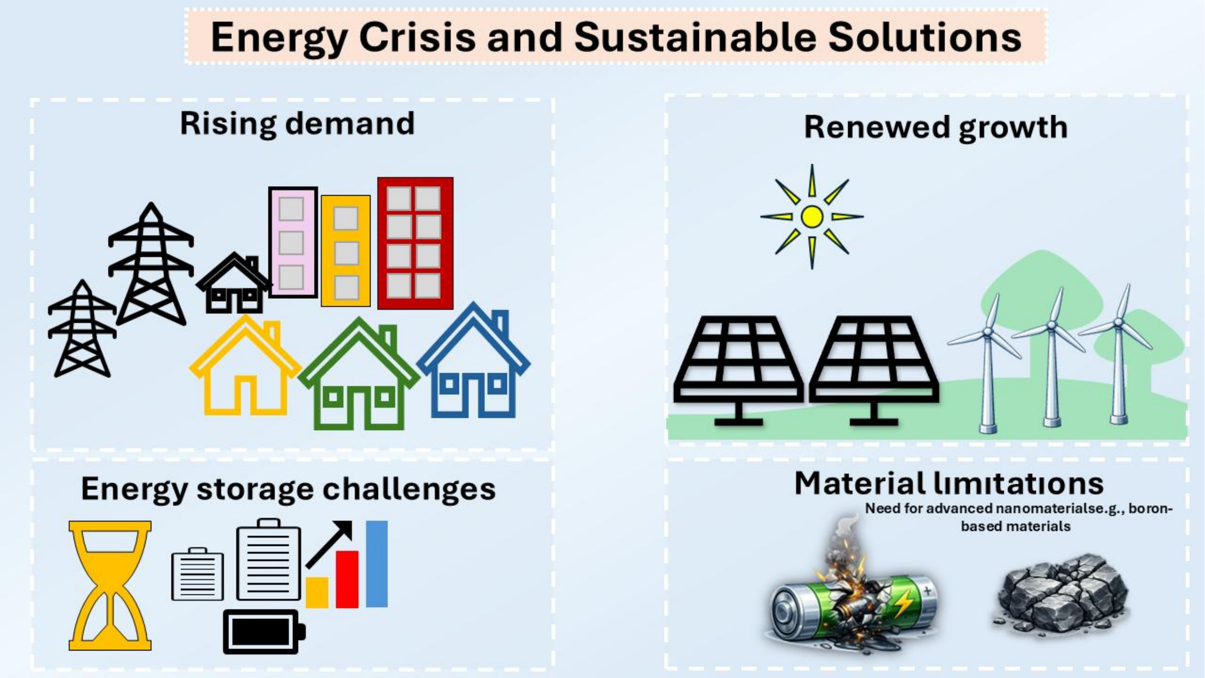

**Fig 1.** Conceptual overview of the energy crisis, renewable energy expansion, storage challenges, and the need for advanced nanomaterial solutions.

### 3. Boron-Based Nanomaterials and Their Role in the Energy Field

Figure 2 illustrates that boron-based nanomaterials do not belong to a homogeneous family; rather, their behavior depends on crystal structure, dimensionality, and the local boron environment, since the crystal structure, dimensionality, and chemical microenvironment surrounding boron in the matrix strongly dictate its behavior in energy systems.

Recent reviews demonstrate the breadth of the field, which now encompasses hexagonal boron nitride, boron carbon nitride, boron-doped carbons, as well as structures based on modified silicon and even those derived from borophene, all possessing unique structure–property characteristics. Indeed, h-BN has seen a resurgence with the understanding that while traditionally insulating in character, functionalization, defect engineering and interface design can render it relevant to energy storage and conversion. Its wide bandgap, strong in-plane/out-of-plane anisotropy, high thermal and chemical stability and tunable surface chemistry make it particularly relevant for applications where interfacial control/stability is on par with conductivity per se [8], [13], [14], [15], [16].

BCN-based materials are positioned at an intermediate point between carbonaceous conductive networks and BN-rich chemically stable systems; such characteristics might be the reason that BCN composites are now of increased interest relating to energy applications. In a 2025 review of BCN and BN materials, it was reported that they are second to none for photocatalytic energy applications with desirable electronic structures, chemical stability, and optical properties; however, pristine BCN and BN are plagued by low surface area, limited active sites, poor light absorption and rapid charge-carrier recombination. That is to say, the energy significance of BCN does not come from its nominal composition only, but from the extent to which material can be customized with heteroatom-doping, heterojunction construction and interface engineering strategies to conquer these inherent limitations. Analytically, boron is valuable here if it plays into a tunable framework vs. existing in a structurally passive phase [13], [16], [17], [18].

Borophene is the most electronically adventurous family member of boron nanotechnology, but also the one with the lowest practical maturity. Reviews from 2025–2026 identify borophene as an exceptionally promising two-dimensional boron allotrope for energy storage and conversion, due to its remarkable electronic, optical, and mechanical properties and applicability to batteries, super capacitors, electrocatalysis, and hydrogen-based systems.

However, those same reviews also pen some unusually vivid elucidation of its structural core weakness: free-standing borophene is intrinsically unstable at room temperature, while its utility remains limited by the difficulty of synthesis, susceptibility to oxidative degradation and limited scalable processing. So while borophene has frequently been promoted as a next-generation boron material, the literature currently supports a much more prudent take: its scientific significance, primarily, rests with theories and being exploratory as opposed to something in immediate technological readiness [11], [12], [19], [20], [21].

However, boron is a less explored system as boron-based nano-micro materials are emerging as a high-potential and ideal choice in terms of tackling the different bottlenecks for different systems. Boron nanoengineering in the energy sector was reviewed in 2025 and identified boron nitride's contribution as an electroactive material in Li-ion and Li-S batteries, while another perspective describes h-BN as contributing to ionic transport, thermal management, and mechanical/electrochemical stability in a range of liquid-, gel-polymer- and solid-state electrolytes. These observations are significant as they transition the language around boron from a simple dopant to that of a multifunctional design element with the ability to modulate ion transport, interphase stability and thermal tolerance depending on where in the device it is incorporated [8], [9].

Advances in synthesis strategies, defect and dopant engineering, and surface functionalization are repeatedly noted in recent reviews, respectively, but the comparative mechanistic studies remain scarce. Many papers show enhanced electrochemical or catalytic performance from boron incorporation, but far fewer decouple how the final device response under standardized conditions is set up by boron bonding configuration, defect topology, dimensionality and interface structure. This mechanistic inconsistency complicates differentiation of whether performance enhancements stem from boron specifically, the host framework or non-reproducible synergistic effects between the two [15], [22].

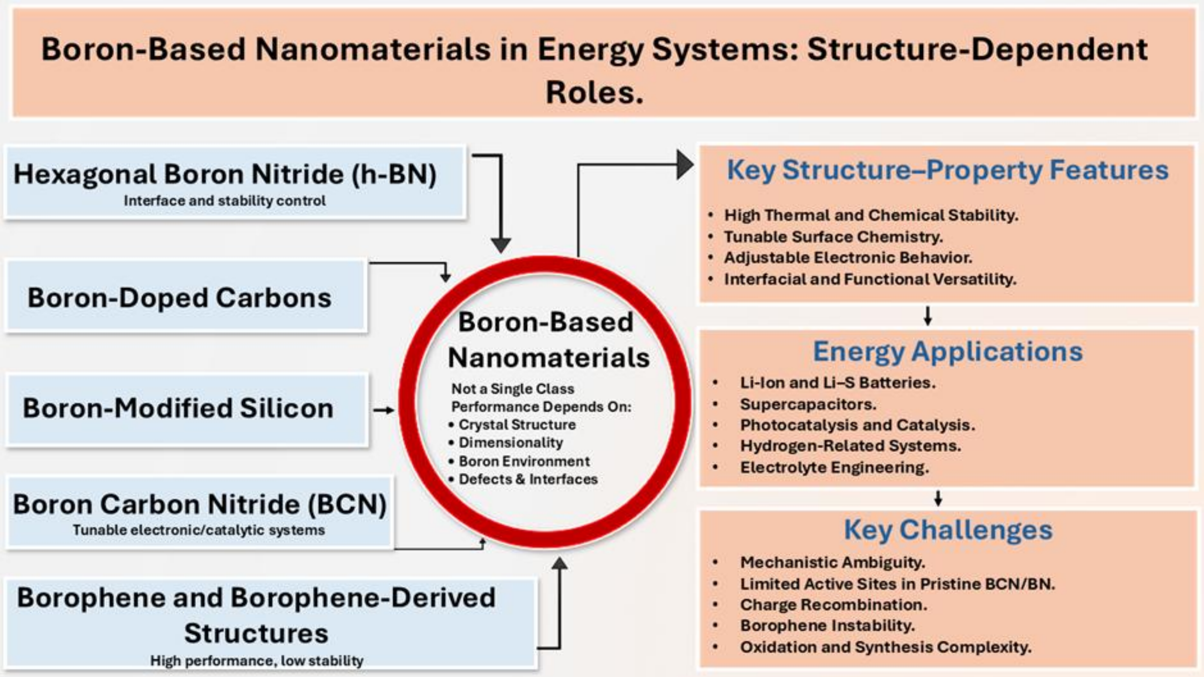

**Fig 2.** Structure-dependent roles of boron-based nanomaterials in energy systems. The figure summarizes major material classes (h-BN, BCN, boron-doped carbons, boron-modified silicon, and borophene-derived structures) and illustrates how their performance is governed by crystal structure, dimensionality, boron environment, and defect/interface engineering, along with key properties, applications, and challenges.

## 4. Boron-Doped Electrodes in Lithium-Ion Batteries

When it comes to application areas where boron-based nanoengineering has been best developed, lithium-ion batteries are among the most advanced because virtually all of the dominant restrictions on many electrode materials, low electronic conductivity, sluggish $Li^+$ transport, unstable interfaces during cycling and structural deterioration during cycling at the atomic scale, can be influenced by boron. Recent work has indicated that boron is not universally effective in all electrode systems, and instead only proves beneficial when it is incorporated into a material for which transport or interface instability serves as the actual rate-limiting step. That is why boron has had small but significant effects on phosphate cathodes, but much more pronounced ones for silica anodes, where conductivity and mechanical instability are intertwined rather than distinct problems [23], [24], [25], [26].

In cathode materials, the role of boron is mainly kinetic and interfacial rather than structural in the bulk sense. A representative example is the 2020 study on boron-doped graphene-decorated $LiFePO_4$@C, where the composite delivered a reversible capacity of 162.2 mAh $g^{-1}$ at 0.1C and maintained 109.9 mAh $g^{-1}$ after 200 cycles at 20C, corresponding to 95.2% capacity retention. Rather than the absolute capacity itself, the key significance of this result lies in the improved rate capability and cycling stability. Here, boron-doped graphene reinforces the electronic percolation network around intrinsically low-conductivity $LiFePO_4$ particles and stabilizes conductive interparticle contact. Thus, for cathodes such as $LiFePO_4$, boron must be perceived in transport and contact quality as an enabler rather than a direct capacity creator [27], [28], [29].

This arises prominently for silicon-based anodes due to their simultaneously low intrinsic conductivity and extreme volume change during lithiation. A multilayer B-Si@$SiO_x$/C anode derived from a Si–Ca alloy demonstrated a reversible capacity of 423.48 mAh $g^{-1}$ and a retention of 659.3 mAh $g^{-1}$ over the first 500 cycles at current density of 1 A $g^{-1}$in a 2024 study. The value of this architecture lies not only in boron incorporation but also in combining boron with a multilayer $Si/SiO_x/C$ framework that relieves stress, enhances conductivity, and regulates the surface-controlled electrochemical process, enhance conductivity and surface-controlled electrochemical process. This leads to an important mechanistic consideration: boron is most beneficial in high-strain anodes when combined with a structural design that controls electron conduction while controlling mechanical deformation [30], [31].

The advantage of structure-dependence is also more evident for the 2025 boron-doped porous micro-sized silicon study. It also demonstrated a discharge specific capacity of 3279.12 mAh $g^{-1}$, 86.6% initial Coulombic efficiency at 0.2 A $g^{-1}$, a second cycle of 1099.4 mAh $g^{-1}$ at 4 A $g^{-1}$ and after 300 cycles, it retained about 80% of its original capacity, corresponding to approximately 766.6 mAh $g^{-1}$. Significantly, the study also presented $LiFePO_4$||B-pSi/graphite full cells with 90% retention after 100 cycles at 0.5C, thereby making it more relevant than many half-cell only reports. This is a more analytical demonstration of boron's utility, as it goes beyond the mere statement "boron enhances conductivity." The porous microstructure ensures reduced diffusion length and buffers the volume expansion, whereas boron improves charge transport and lowers resistance; the performance benefits come from this synergy, not doping alone [32].

Recent review articles also suggest that functionalization of lithium with boron could go beyond just active electrodes, serving as a general tool for electrolyte and interface engineering in lithium-based batteries. It is envisaged that with this 2025 preview of hexagonal boron nitride, the multifunctional roles of h-BN in lithium platforms can be underscored for continued strengthening of ionic transport, thermal management and interfacial stability in liquid, gel-polymer, solid-state electrolytes. In parallel, 2025 first principles work demonstrated that h-BN vacancy defects tune Li-ion diffusion pathways and associated kinetics, indicating that boron-containing phases can influence battery performance not only by acting as a bulk fast conductor, but also through defect-mediated ion transport. These results conceptually broaden the role of boron in LIBs: it continues to contribute as a dopant within electrode particles but increasingly functions as a multifunctional interfacial design element [9], [33].

Although many studies report improved capacity, rate capability or cycling stability after incorporation of boron, far fewer distinguish unambiguously the contributions of the boron bonding configuration to morphology of host material, surface oxide chemistry and SEI growth under comparable test conditions. This makes it difficult to distinguish whether the measured improvements are due primarily to boron or purely an effect of the structure that contains a certain amount of boron. In addition, full-cell validation, high areal loading, and long-term degradation studies have not yet been compared to the half-cell demonstrations[34], [35], [36].

The critical, and we believe most outstanding question in lithium-ion battery research is thus not whether boron can improve performance at electrodes, but rather what structural or interfacial form of boron imparts sustainable, scalable improvement at the device level. The situation becomes more pronounced for the next domain of application for which fast charge transfer and interfacial polarization is prioritized over bulk insertion chemistry: supercapacitors [34], [35], [36].

Table 1 provides a structured summary of the representative studies discussed in Section 4. It highlights boron-based material systems used in lithium-ion batteries and clarifies how boron contributes to conductivity enhancement, ion transport, interfacial stabilization, and structural durability. Where possible, the table also distinguishes between improvements directly attributable to boron incorporation and those arising from the broader composite architecture.

Table 1. Representative boron-based nanomaterials and their functional roles in lithium-ion battery systems.

| **Material system** | **Boron-engineering strategy** | **Principal role of boron** | **Representative electrochemical performance** | **Scientific significance** | **Remaining challenge** |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| Boron-doped graphene-decorated LiFePO$_4$@C cathode | Incorporation of boron into the graphene conductive network surrounding LiFePO$_4$ particles | Enhances electronic percolation, accelerates charge transfer, and stabilizes conductive interparticle contact | 162.2 mAh g$^{-1}$ at 0.1C; 109.9 mAh g$^{-1}$ after 200 cycles at 20C; 95.2% capacity retention | Demonstrates that boron is particularly effective in kinetically limited cathodes when integrated into conductive carbon frameworks | Difficult to isolate the intrinsic boron effect from the contribution of the graphene/carbon architecture |
| Multilayer B-Si@SiO$_x$/C anode | Boron doping coupled with multilayer Si/SiO$_x$/C structural design | Improves electronic conductivity and contributes to stress redistribution during cycling | 423.48 mAh g$^{-1}$ at 4 A g$^{-1}$; 659.3 mAh g$^{-1}$ after 500 cycles at 1 A g$^{-1}$ | Shows that boron is most beneficial in silicon anodes when combined with architectures that simultaneously address transport and mechanical instability | Performance enhancement cannot be attributed to boron alone because of strong structural synergy |
| Boron-doped porous micro-sized silicon anode (B-pSi) | Boron incorporation into a porous micro-sized silicon framework | Lowers charge-transfer resistance, improves conductivity, and works synergistically with pore-mediated stress buffering | 3279.12 mAh g$^{-1}$ discharge capacity; 86.6% initial Coulombic efficiency at 0.2 A g$^{-1}$; 1099.4 mAh g$^{-1}$ at 4 A g$^{-1}$; 766.6 mAh g$^{-1}$ after 300 cycles at 4 A g$^{-1}$; 80% retention | Represents one of the strongest practical examples because it combines high capacity, rate capability, and partial full-cell validation | Long-term full-cell durability, areal loading, and scale-up compatibility remain insufficiently established |
| LiFePO$_4$ | | B-pSi/graphite full-cell configuration | Practical pairing of boron-doped porous silicon with commercial-type cathode/anode components | Extends boron relevance from half-cell demonstration to device-level feasibility | 90% capacity retention after 100 cycles at 0.5C |
| h-BN in battery electrolytes and interphases | Use of hexagonal boron nitride in liquid, gel-polymer, and solid-state battery components | Enhances ionic transport, thermal tolerance, and electrochemical/mechanical interfacial stability | Reported as a multifunctional additive/component for safer and more efficient lithium-based batteries | Broadens the role of boron from active electrode modification to full-cell interfacial engineering | Needs standardized comparative validation under realistic cell configurations and long-term cycling protocols |
| Defect-engineered h-BN for Li-ion transport | Creation of vacancy-mediated transport pathways in h-BN | Regulates Li-ion diffusion kinetics through defect-controlled transport pathways | First-principles evidence for defect-mediated Li transport in boron-containing phases | Provides mechanistic support for boron-containing materials as ion-transport regulators rather than only conductivity modifiers | Experimental confirmation under realistic electrochemical conditions remains limited |

## 5. Boron Nanostructures in Supercapacitors

In supercapacitors, the function of boron differs fundamentally from its role in lithium-ion batteries. The dominant objective is not deep bulk ion insertion, but rapid surface or near-surface charge storage, low internal resistance, structural integrity under repeated high-rate cycling, and, increasingly, mechanical flexibility for wearable and miniaturized devices [12], [16], [37].

For this reason, boron-containing nanostructures are of interest not just because they modify conductivity but because they simultaneously tune surface polarity, defect density, ion-accessible porosity and interfacial transport. A recent review by Zhang and co-workers on BCN- and borophene-based systems highlights that neither pristine boron phases nor deficient species are optimal for supercapacitors, but adopted through unique hybrid or defect-engineered architectures, the combined architecture facilitates electron transport and promotes storage at chemical equilibrium [12], [16], [37].

A clear early example of this interfacial advantage is the 2021 all-solid-state wearable device based on graphene/boron nitride nanosheet electrodes with a PVA-PEI gel electrolyte. That system reached an areal capacitance of 0.35 F $cm^{-2}$ and a relatively low equivalent series resistance of 6.02 Ω $cm^2$ when KOH was used, indicating that BN nanosheets were not acting merely as an inert mechanical additive; instead, they contributed to better electrode/electrolyte synergy and more efficient charge propagation [38].

This is important because it shows that boron nitride can improve device performance even though it is intrinsically electrically insulating. Its utility emerges through nanoscale arrangement and interface control, not through bulk conductivity alone.

A lot has changed in the state-of-the-art since then, especially with respect to tunable solid-state supercapacitance. In a study, it was observed that functionalized hexagonal boron nitride nanoflakes could offer an important increase in specific capacitance of the order of 75% at ~350 F $g^{-1}$ but still retained more than 80% of capacitance throughout mechanical deformation over 50,000 cycles. Importantly, the scientific relevance of this result lies in that Fh-BN was not only incorporated within the electrode but also at both the separator and gel-polymer-electrolyte interfaces, thereby improving ion transport across entire device architecture. This confirms that the latest supercapacitor designs using boron-based nanostructures treat boron-containing phases as multiphase interfacial modulators rather than single-component electrode dopants [39], [40].

A more recent, and conceptually very different, route is represented in the 2026 nitrogen-doped borane cluster network report with values of 607 F $g^{-1}$ in a three-electrode configuration and 354 F $g^{-1}$ when assembled into an asymmetric supercapacitor device that nevertheless retained 95% of its capacitance even after passing through 15 000 cycles. Whereas in previous systems boron-containing materials primarily enhanced either transport or mechanical stability, this work suggests that boron-rich frameworks participate more directly in electrochemical charge storage. In other words, the field is starting to transition from boron-assisted architectures to boron-containing redox-active networks. This is a major conceptual change as it opens up boron from interface tuning to active capacitance generation, not just under chemically defined pH conditions [12], [41].

Despite this, most boron-based supercapacitor high-performing research work is only reported using three-electrode cells or unrealistic laboratory configurations with little published in terms of stringent device-level performance metrics such as areal capacitance, energy density, self-discharge, leakage current, mechanical fatigue and packaging stability long-term operation for realistic deformation schemes [37], [42], [43].

This limitation becomes even more apparent in the next application area, hydrogen storage, where boron-containing nanomaterials are often highly promising in theory but still struggle to satisfy reversibility, thermodynamic control, and practical process integration at the system level.

## 6. Boron Compounds in Hydrogen Storage Systems

Hydrogen storage is one of the most promising yet experimentally challenging areas for boron-based nanomaterials. Boron chemistry is appealing in this field from both sides of the divide. The first is related to boron nitride nanostructures that have low density, high thermal and chemical stability, tunable porosity as well as polar B–N bonds to strengthen hydrogen adsorption. The second includes borohydride-based systems, mainly $LiBH_4$-derived composites containing boron matrices for hydrides destabilization to allow release of hydrogen and dehydrogenation ability [44], [45].

Recent review literature makes clear, however, that these advantages have not yet translated into a broadly practical hydrogen-storage platform: BN-based systems still lag behind more mature families such as MOFs and ammonia-borane-derived materials, largely because reversibility, operating temperature, and scalable production remain unresolved [44], [45].

The main scientific challenge lies in the gap between promising adsorption characteristics of BN-based materials and their effective storage performance. Accordingly, the review of boron-based materials for solid-state hydrogen storage makes a point that h-BN attracts great attention for thermodynamic stability, chemical inertness and high specific surface area in nanostructured form, while the polar B–N bond introduces an additional dipole moment which can improve hydrogen physisorption. Nonetheless, the same review clearly names what constitutes a main barrier to industrial adoption: a need for well-defined, economical pathways to large-scale manufacture of nanostructured BN as well as straightforward modification routes that consistently improve sorption performance [44], [46].

This means that the research challenge is not merely to demonstrate hydrogen uptake, but to engineer BN-based structures whose adsorption or release behavior can be reproduced economically and under moderate conditions.

Recent work has shown that defect engineering and chemical modification are two of the most promising strategies to overcome the low performance of pristine BN. Investigating how to tailor h-BN nanomaterials for energy-related applications indicates that the formation of defects and metal doping can improve the hydrogen-adsorption performance of h-BN, while oxygen-modified BN nanosheets showed BN nanosheet showed a hydrogen-storage ability of 5.7 wt. % at room temperature and 5 MPa in a hypothesised system [44], [47].

These findings are important because they show that boron nitride becomes significantly more relevant to hydrogen storage only after its surface chemistry is altered; pristine BN is generally too inert to provide competitive uptake under realistic conditions. In analytical terms, the true functional unit in these systems is not "BN" itself, but defective or chemically activated BN.

A more refined area of study focuses on $LiBH_4$-based composite systems that utilize boron-containing hosts to tailor dehydrogenation thermodynamic and/or kinetic properties. The research on $LiBH_4$ infiltrating into $Mo_2N$-doped defective boron nitride ($Mo_2N$-DBN) is very important, since it goes beyond passive support behaviors. The $Mo_2N$-DBN host further allowed for improved thermodynamics and kinetics of hydrogen uptake and release, as well as rapid rehydrogenation at 100 °C, this is analytically critical because it supports the notion that defective BN allows for active destabilization of $LiBH_4$ in addition to just space-filling [48], [49]. This wider perspective is supported by the review as it mentions that $LiBH_4$ dehydrogenation can be improved for example via lattice defects, nitrogen lone pairs and B–H / B–N environment interactions when h-BN additives are added.

According to the same review, nanoporous h-BN/$LiBH_4$ composites released up to 13.9 wt.% $H_2$ upon heating to 300 °C; however, performance deteriorated at higher temperatures and over repeated cycles because of phase evolution, decreasing to 7.6 wt.% $H_2$ over five cycles because of phase formation; acid-treated h-BN composites released hydrogen between 110 −150 °C and maintained 85.7 % of initial capacity after four cycles; other boron-containing destabilization strategies improved release kinetics but were still dependent on relatively high-temperature or limited reversibility mechanisms [50], [51].

These examples show that boron chemistry can clearly improve hydrogen-release behavior, but they also expose the central technological bottleneck: most systems still fail to combine moderate operating temperature, high reversible capacity, and long-cycle stability in the same material platform.

As a result, the key gap in research on this is not the lack of candidate boron-containing materials available but rather that there does not exist a hydrogen-storage system which consists of boron-based nanostructures delivering simultaneously reversible cycling, low-temperature operation, acceptable gravimetric performance and scalable synthesis. Despite recent advances, the current literature is largely divided between promising adsorption predictions for defective BN or borophene-like systems and experimental composites that still require prohibitive thermal conditions. This shortfall shows why hydrogen storage, one of the most conceptually appealing uses of boron chemistry available, falls behind lithium-ion batteries or supercapacitors in its maturity [21], [52].

## 7. Boron in Fuel Cells and Catalytic Processes

Boron is far from being a significant charge-storing species compared to other elements, but within the context of fuel cells and other catalytic applications it may be of great importance due to the ability of boron to modify the surrounding electronic strain background for active sites or catalyst supports. This is a significant step forward regarding the kinetic bottleneck on many fuel-cell cathodes, which is the oxygen reduction reaction (ORR) [53], [54]. There have been several recent publications suggesting a range of nonexclusive mechanisms through which boron can promote catalytic activity, including charge redistribution around nearby heteroatoms, stabilization of broken metal centers and optimization of intermediate adsorption energies and catalyst support interactions.

An early milestone in this direction was the use of hexagonal boron nitride nanosheets as a multifunctional support for ORR electrocatalysts. This study demonstrated that by incorporating ultrathin h-BN into Pd catalysts, well-defined interfacial heterostructures could be formed to improve durable ORR activity across the catalyst surface. Importantly, from a scientific perspective, this result established h-BN as a credible catalytic support BN beyond that of merely an insulating 2D material, but rather as an electronically relevant support for catalysis, which can be enabled via interface engineering. This was an important shift in thinking that suggested boron-containing materials could play a role in fuel-cell catalysis, even when not the principal redox-active phase [53], [55].

More recent work has shown that boron becomes especially effective when it is integrated into multi-heteroatom carbon frameworks. A DFT-guided study on N,B-dual-doped porous carbon reported a half-wave potential of 0.861 V and a limiting current density of $-5.60$ mA $cm^{-2}$, values close to commercial Pt/C under the reported alkaline conditions. The study combined computation and experiment to show that boron alters local charge density and helps optimize adsorption energetics for ORR intermediates. A study, phosphorus-doped boron carbon nitride (P-BCN) further improved the ORR half-wave potential from 0.764 V for BCN to 0.823 V, and the half-wave potential decreased by only 3 mV after 5,000 accelerated durability cycles [54], [56].

These results are analytically significant because they show that boron is most powerful when it acts cooperatively with other heteroatoms rather than as a standalone dopant; the catalytic gain arises from the reorganization of the local electronic landscape, not from boron concentration alone.

The discipline is also advancing toward boron-enabled single-atom and support-mediated catalysis for proton-exchange-membrane fuel cells Explicit design principles for PEMFC oxygen reduction have focused on atomically dispersed iron on functionalized boron nitride nanosheets, further showing that boron nitride may be more than simply a passive support for metal sites. This trend is important because degradation of active coordination environments during fuel-cell operation has, in fact, been one of the critical weaknesses limiting platinum-free catalysts .

Boron-containing supports can possibly help with that problem by stabilizing and tuning the electronic structure of non-precious active centers. Simultaneously, recent literature alludes to boron catalysts used in more general electrocatalytic reactions beyond ORR. For example, boron-doped $CoFe_2O_4$ with enriched oxygen vacancies exhibited higher bifunctional HER/OER activity for water splitting, while the interstitial boron-modulated osmium aerogels lead to low HER overpotentials of 12, 19 and 33 mV at a current density of 10 mA $cm^{-2}$ in acidic, alkaline and neutral media respectively [57], [58].

Together, these studies indicate that boron's catalytic role extends beyond fuel cells into broader energy-conversion chemistry, particularly where intermediate binding and defect-regulated charge transfer determine activity.

Nonetheless, improve the hydrogen-adsorption performance of h-BN, while oxygen-modified BN nanosheets showed . Most of the latest and relevant ORR literature remains focused on rotating-disk-electrode data and alkaline conditions, with significantly fewer studies examining boron-based catalysts under prolonged membrane-electrode-assembly (MEA) conditions in acidic PEM fuel cells. Likewise, while there are many promising boron-containing catalysts with favorable overpotentials and stability in laboratory electrolyzers for HER and OER, fewer reports establish their structural stability over the long-term, degradation pathways, or manufacturability at scale. Hence, the core open question is whether boron can intrinsically promote catalytic behavior or if electronic benefits imparted by boron can still be maintained under practical operating settings where corrosion, poisoning and catalyst reconstruction dominate [59], [60].

## 8. Boron-Containing Materials in Solar Energy Systems

In solar-energy systems, however, boron is probably not used in the same mechanisms or ways as it is for batteries or supercapacitors. Here, boron more typically serves as an interfacial regulator, defect mediator, crystallization control agent or charge-selective contact modifier than as a bulk electroactive species. This distinction is significant because it indicates that the value of boron in solar devices is determined by its ability to reduce non-radiative recombination, enhance carrier extraction, or stabilise structurally fragile absorber layers. Studies have shown that boron is especially effective when incorporated into contact layers, in wide-bandgap perovskite processing, or in photocatalytic semiconductors, where device losses are dominated by surface and interface chemistry [61], [62].

An obvious case study is the study work on boron-doped ZnO (ZnO:B) electron-selective contacts for crystalline silicon solar cells. In that work, $SiO_x$/ZnO:B stacks achieved contact resistivities of approximately 2 mΩ $cm^2$, enhanced passivation quality and provided proof-of-concept n-type c-Si solar cells reaching efficiencies over 22.0%. But the importance of this result is not only in the efficiency, but also that boron doping was able to enhance a technological figure of merit for contact architectures. From an analytical perspective, boron functioned well because it improved contact selectivity and minimized recombination at the silicon/contact interface, a reaction that is frequently the key loss mechanism in passivating-contact solar cells [62], [63].

Boron has been particularly effective in the field of wide-bandgap perovskite photovoltaics, where controlling crystallization and halide distribution remains a major hurdle to efficiency and stability. A study employed tris(pentafluorophenyl)borane (BCF) to modulate the crystallization of 1.68 eV wide-bandgap perovskite films via boron halide and hydrogen-bond interactions simultaneously. This treatment resulted in a more stable halogen distribution, reduced non-radiative recombination kinetics, and improved charge extraction to yield single-junction cells with champion efficiencies reaching 23.49% as well as monolithic perovskite/silicon tandem cells of 31.12% [64], [65].

The paper is also significant in that it specifically addresses an all-solution two-step process, which is more amenable to inexpensive manufacturing but had until now suffered from patchy halide distribution and incomplete transformation. So, boron worked here as crystallization and defect-management agent, not just a dopant.

In addition to photovoltaics, boron-containing nanomaterials are beginning to make their mark in solar-driven photocatalytic conversion. In a 2024 Nature Communications study, boron-doped g-$C_3N_4$ was coupled with coordinatively unsaturated FeOOH and $CoO_x$ clusters to enable sacrificial-agent-free $H_2O_2$ photosynthesis from water and oxygen, circumventing detrimental limitations typically associated with g-$C_3N_4$, like short excited-state electron lifetime and sluggish ORR kinetics. In a similar vein, a 2024 Renewable Energy study reported that 3 wt. % boron-doped $TiO_2$ nanoparticles provided a ~285-fold enhancement in the photoelectrochemical response compared to pristine $TiO_2$ under the tested conditions. These studies indicate that boron becomes privileged in solar-driven conversion when it tunes charge separation and interfacial reaction kinetics of otherwise deficient semiconductor hosts [66], [67].

Thus, the overarching research gap in solar-energy devices is not whether boron can impact device performance but rather whether boron-mediated interface and crystallization effects will hold upon scaling devices from tiny lab cells to large-area modules under thermal, operational, and environmental stress. This consideration is timely regarding tandem solar cells, whose recent scale-up reviews for 2025–2026 highlight persisting barriers in terms of large-area deposition and processing compatibility, but also the efficiency gap that develops during upscaling. Accordingly, boron's future role in solar energy will hinge on whether its laboratory advantages can be incorporated into scalable manufacturing pathways without sacrificing interfacial precision [68], [69]. Table 2 spotlights representative boron-containing material systems for solar-energy applications and elucidates the roles of boron in interfacial regulation, crystallization control, charge extraction, and photocatalytic activity.

**Table 2.** Representative boron-containing nanomaterials and their functional roles in photovoltaic and solar-driven conversion systems.

| **Material system** | **Boron-engineering strategy** | **Principal role of boron** | **Representative performance outcomes** | **Scientific significance** | **Remaining challenge** |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| ZnO:B electron-selective contact for crystalline Si solar cells | Boron doping of ZnO within a $SiO_x$/ZnO:B contact architecture | Improves contact selectivity, reduces interfacial recombination, and enhances passivation-related charge extraction | Contact resistivity of ~2 mΩ cm$^2$; proof-of-concept n-type c-Si solar cells with efficiency >22.0% | Demonstrates that boron can improve technologically relevant contact architectures in crystalline silicon photovoltaics | Requires broader validation under large-area processing and long-term operational conditions |
| Wide-bandgap perovskite treated with tris(pentafluorophenyl)borane (BCF) | Use of a boron-containing molecular additive to regulate crystallization and halide distribution | Suppresses non-radiative recombination, stabilizes phase/halide distribution, and accelerates charge extraction | 23.49% efficiency for single-junction wide-bandgap perovskite devices; 31.12% for monolithic perovskite/silicon tandem cells | Represents one of the clearest examples of boron acting as a crystallization and defect-management regulator rather than a simple dopant | Scale-up, large-area uniformity, and manufacturing compatibility remain unresolved |
| Boron-doped g-$C_3N_4$ coupled with FeOOH and $CoO_x$ clusters | Boron doping combined with coordinatively active cocatalyst clustering | Enhances charge separation and improves photocatalytic interfacial reaction kinetics | Efficient sacrificial-agent-free $H_2O_2$ photosynthesis from water and oxygen under reported conditions | Shows that boron can activate photocatalytic semiconductors by improving carrier dynamics and surface reactivity | Needs broader benchmarking against established photocatalytic systems and long-term stability assessment |
| Boron-doped $TiO_2$ nanoparticles | Boron incorporation into $TiO_2$ semiconductor host | Enhances visible-light response, improves surface-related activity, and strengthens photoelectrochemical behavior | Approximately 285-fold improvement in photoelectrochemical response relative to pristine $TiO_2$ | Strong evidence that boron can significantly activate a conventional oxide semiconductor host | Device-level relevance remains less mature than laboratory-scale photoresponse data |
| Boric-acid-functionalized interfacial layer in tandem solar cells | Boron-containing interfacial functionalization for corrosion mitigation and interface stabilization | Reduces interfacial degradation and improves charge-selective contact stability | Reported enhancement in efficiency and interface stability in all-perovskite tandem systems | Highlights boron’s role as a chemical interface modifier in advanced tandem photovoltaics | Outdoor stability and module-scale validation are still needed |
| Functionalized boron nitride as interface modifier in perovskite solar cells | Incorporation of functionalized BN into | Improves interfacial charge behavior and supports efficient | Reported as a promising interface-engineering | Expands the role of boron-containing materials from | Requires standardized comparison and durable |

| | | | | | |
|---|---|---|---|---|---|
| | critical photovoltaic interfaces | carrier management | strategy for high-efficiency perovskite devices | bulk modification to interfacial photovoltaic engineering | long-term device validation |

## 9. Industrial Applications and Scalability

The industrial promise of boron-based nanotechnologies is much less about peak laboratory performance and far more about whether boron could fit into existing materials platforms without incurring prohibitive economics, instability or processing complexity. Which is also why boron-modified systems stand to be closest to translation when they build on established technologies like silicon anodes, crystalline-silicon contacts or electrolyte architectures rather than rely on structurally fragile or synthesis-intensive boron-rich phases. In a recent review, the major roadblocks preventing deployment of laboratory boron nanomaterials in energy technologies were consistently addressed in terms of stability, reproducibility, scalable synthesis and interfacial complexity [35], [70].

In battery technology, the best indicator of industrial relevance is a transition from nanoscale proof-of-concept to micrometer-sized silicon and validation in a full cell. The recent boron-doped porous micro-sized silicon systems that we have reported demonstrate how boron can be incorporated into architectures that are better suited to practical volumetric energy density and side reaction reduction than the all-nanosilicon strategies. Likewise, h-BN in lithium-based batteries has been flagged as an increasingly relevant separator, electrolyte and interphase. These trends are industrially relevant, as they elucidate boron within the established battery-mechanistic lexicon and avoid the dispersion of energy into new device concepts [32], [71].

In solar technology, industrial relevance is most visible in boron-enabled contact engineering and scalable tandem processing. ZnO:B electron-selective contacts are attractive because they fit within crystalline-silicon device engineering rather than replacing it. At the same time, 2025–2026 reviews on perovskite/silicon tandem scale-up show that commercialization now depends on scalable deposition and drying strategies, compatibility with pilot lines, and minimizing the efficiency loss that appears during upscaling. This is highly relevant to boron-assisted wide-bandgap perovskites, because any laboratory gain derived from boron-mediated crystallization control must ultimately survive the transition to large-area manufacturing [62], [68], [72].

In comparison, systems rich in borophene are considerably further from industrial deployment. Many papers published in 2025–2026 indicate that borophene has considerable electronic and electrochemical potential for energy storage and conversion applications. However, its practical application is still limited by inherent instability, oxidization intolerance, limited processability, synthetic challenge and scalability issues. So even as borophene is scientifically interesting and might one day inform how we build devices, it’s still in a far-more-early-state than boron-decorated silicon or h-BN for electrolyte components or boron-tuned photovoltaic interfaces [12], [73].

A universal framework to link boron chemistry to process compatibility and low-cost scalable synthesis is the common missing link in industrial translation. While numerous studies pursue material performance as would be achievable in a perfect laboratory, comparatively few pay consideration to the manufacturability metrics (e.g., available yield of a target material, batch reproducibility or ability to be integrated into existing processing lines). In the absence of this bridge, boron-based nanomaterials will shed light on scientists but be a technological mess [15], [74].

## 10. Future Perspectives and Next-Generation Energy Technologies

Future boron-based energy research is likely to advance beyond the generic concept of “boron doping” toward functional-specific boron engineering. As the literature increasingly points out, boron is most useful when purposefully tailored to a dominant failure mode: interfacial transport limitations in batteries, ion-accessible surface design in supercapacitors, adsorption-energy tuning in catalysis and crystallization and defect control in solar devices.

Thus, future work will be best focused on revealing the specific boron bonding environment and structural context that induces a measurable device-level result, as opposed to simply reporting better behaviour following boron incorporation.

Another important direction of future studies is the stabilization and rational application of advanced boron-rich phases, particularly those of borophene and borides. Recent reviews in 2026 describe borophene as an extremely promising platform for storage, conversion and electrocatalysis, but they also emphasize that its master issue is still the compromise between outstanding electronic properties and unsatisfactory environmental stability. This means that future advances will not only hinge on finding novel phases, but also on stabilizing these phases through heterostructuring, surface protection, controlled defect design and synthesis routes rationalised for reproducibility and scale. In this respect, the future of borophene is likely to be more influenced by engineering strategy than intrinsic material physics.

A third and more general need is operando and multiscale validation. Across battery, catalysis and solar systems, the current literature is still more enriched by ex situ structural characterization and endpoint performance data than by time-resolved evidence in which how boron-related bonding environments evolve under real operation can be revealed. Such a gap is critical for the understanding of boron-induced benefits, as many are interfacial and dynamic in nature and potentially transient during long-term cycling, irradiation, thermal stress or chemical reconstruction. Moving from promising materials science toward dependable engineering will require next-generation studies to combine rational boron design with oprando spectroscopy, standardized benchmarking and device-level validation.

## Conclusion

Since boron can tailor electronic structure, defect chemistry, interfacial behavior and transport processes over a broad range of material systems, boron-doped and -containing nanotechnologies have proven to be a substantial, versatile platform in modern energy research. From 2020 to 2026, lithium-based storage as well as flexible supercapacitors and ORR-related catalysis have attracted the most powerful and convincing advances; in boron-modified photovoltaic interfaces, boron generally enhances conductivity, interfacial selectivity, structural tolerance, or charge-transfer efficiency. The literature also demonstrates that boron is not a panacea; rather, it is most effective when matched to the limiting chemistry of the host system chemistry. The core knowledge gap is not whether boron can enhance material properties, but under which structural and operational conditions such improvements remain reproducible at the device level.What remains lacking is a broadly applicable mechanistic and technological framework that defines when boron-induced gains remain reproducible at the device level and compatible with scalable manufacturing. within which boron-induced gains are device-level reproducible under standard testing conditions and scalable manufacturing pathways. Thus, this review has viewed boron-based nanotechnologies not only as a collection of promising materials, but also as an emerging portfolio whose future will hinge on the ability to link nanoscale design with realistic energy-system realization. In this sense, the actual value of boron in future energy systems is not due to its novelty but rather in its ability to address well-defined transport, catalytic and interfacial challenges integrated into molecularly engineered functional architectures.

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