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## Review Article

# The Critical Significance of Boron Mine in Future Energy Technologies

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## ABSTRACT

The boron element forms more than 600 compounds with different element roots and shows very different properties. Boron compounds with these different properties deserve to be the most crucial strategic feature in the world as they meet the demands above the targeted standards in industries such as energy, structure, chemistry, weapons, and space. Today, the industries of developed countries have begun to take advantage of these energy sources due to the reduction of fossil energy resources, the inability of the industry to store enough electricity for an entire facility, and the limitations imposed on environmental policies. Developing countries continue to use fossil resources, but health and environmental costs are increasing. Whether they are developed or developing countries, they have attached importance to the research of energy systems that can replace fossil energy systems, which are environmentally friendly, sustainable, and high-performance. Boron has an essential role in the energy field for the isolation, high energy value retention, fuel and ion batteries, solar panels, and high-temperature transistors. In this study, the desired properties of boron compounds in energy studies were investigated by considering the positive effects of boron on the energy demand.

## 1. Introduction

Boron has an atomic weight of 10.81, an atomic diameter of 1.17 Å, a density of 2.84 gr/cm<sup>3</sup>, an electronegativity of 2, an ionization energy of 191 kcal/g atoms, a heat of fusion of 5.3 kcal/g atoms, a melting point of 2300 °C, and a boiling point of 4002 °C (Table 1 and 2). It is classified as a semi-metallic element. It is found in the earth with hydrogen, oxides, hydro-oxides (water), and alkaline metals (such as Mg, Na, and Ca). Boron has a wide range of uses, such as carbon and nitrogen. It demonstrates non-metal properties in the compounds to which it is attached. However, in the elemental state, it has the

property of electrical conductivity [1]–[4]. From this point of view, there is a need for a system that is both environmentally friendly and capable of meeting the demands of the industry. Therefore, it is thought that the compounds of boron with other elements remain within the framework of environmental awareness and high-performance issues [5]–[11]. Boron has played a leading role in the improvement of hydrogen scavengers, the improvement of ion batteries, the increase in the efficiency of solar panels, the reduction of energy losses in direct fuel processes, energy production (electricity) and transportation,

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and the removal of greenhouse gases and heavy metals released as a result of combustion. Boron elements in nanoparticle form and boron compounds such as boric acid and sodium boron hydride are the most demanded in the energy sector. These are critical to ensure sensitivity (such as resistance to

oxidation and catalysis), control of energy reactions, and uniform distribution of reactions in primary cycles [12]–[14]. In this study, the use of boron in energy research was examined, and its effects on energy use performance and efficiency were investigated.

**Table 1.** Boron atom structure

Atomic diameter	1.17 Å
Atomic volume	4.63 cm <sup>3</sup> / mol
Electron array	1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>1</sup>
Valence electrons	2s <sup>2</sup> p <sup>1</sup>
Electron number (no load)	5
Ion diameter	0,23 Å
Proton units	5
Number of neutrons	6
Crystalline	Rhombohedral

**Table 2.** Boron physical properties

Atomic Mass	10,811
Appearance	Yellow-brown ametalic and crystal
Conductivity	Electrical: 1.0 E -12 106 / cm
Thermal Expansion coefficient	0.0000083 cm / °C (0°C)
Density	2,34 g/cc - 300K
Hardness	Mohs: 9,3 (Vickers: 49000M.N.m <sup>-2</sup> )
Flexibility status	Bulk: 320/GPA
Enthalpy	573,2 kJ/mol (25°C)
Enthalpy (Fusion)	22,18 KJ/mol
Enthalpy (Evaporation)	480 kJ/mol
Heat (Evaporation)	489,7 KJ/mol
Pressure value (Steam)	0,348Pa – 2300 °C
Melting point	2573 °K - 2300°C – 4172 °F
Specific heat value	1,02 J/g.K
Boiling point	4275 gr°K – 4002 of – 7236 °F
Molar volume	4,68 cm <sup>3</sup> /mol
Physical form	20°C ve 1atm: Solid state

## 2. Investigation of the Effect of Boron Additives in Fuels

From the past to the present, there has been a decrease in fossil energy sources day by day. The emission of greenhouse gases such as C<sub>x</sub>O<sub>y</sub> and S<sub>x</sub>O<sub>y</sub> to the atmosphere by burning these sources reduces the air quality and causes an increase in global warming. In addition, studies have been started to obtain higher performance from this energy. There has been a focus on clean energy research that can improve these factors and reduce the environmental impact of fossil fuels. In these matters, using the boron element guides in

keeping the energy of hydrogen gas, which has a very high calorific value and does not give any gas other than water vapor to the atmosphere, and ensures that petroleum-based fuels are more efficient and less polluting [7], [9], [15], [16]. Hydrogen is an environmentally friendly energy source with a high combustion degree. However, keeping the reactive heat due to the combustion of this energy source element is a significant problem. Boron has a crucial role in solving this problem. Boron particle materials, loading speed, and base fuel type positively affect suspension quality and combustion behavior. The combustion behavior of dilute and dense suspensions

prevents the reduction of combustion efficiency due to the flocculation of the formed residues and boron particles [17]. The propulsion system's performance in combustion engines directly depends on the energy density and combustion behavior of the combustible material released. Metal particles (such as Al, Fe, and Pb) may be suspended in fuel binders with polymeric properties. The boron element in the fuel containing these particles is ideal due to its energy density. However, boron requires prolonged exposure to combustibles due to its high melting and boiling points. In this, Magnesium seems to be a natural complement to boron fuel. While it has a lower energy density, it burns with a high flame temperature and reacts quickly with a low melting point combustion. The combustion temperature in fuels with Fe content is proportional to the amount of Fe in them. The burning effects of iron can be controlled thanks to the boron element. Doped boron's effect on ferrous iron's burning times appears to be greater for larger particles. In this combustion process, a boron-rich boron-oxygen solution is formed in the first stage, and its temperature rises until saturation. The second stage begins when the solution becomes saturated. Particle temperature concentration decreases, and dissolved oxygen increases. During the second combustion stage, a vapor phase reaction zone is formed. Combustion ends when the composition of the combustion particle is formed. The iron selectively reacts with the surrounding gaseous oxygen, increasing the combustion rate of boron and then easily reducing by boron. Thus, a surface reaction of replacing the boron-containing gas oxidizer with a faster surface results in a rapid reduction in the volume of the iron by oxidation. The reaction complexes between the burning particles boron and oxidized iron occur in the dense phase, and  $B_xO_y$  products are rapidly formed in the composition [6], [18]. Silane-coated boron nanoparticles are highly dispersible in liquid. Hydrocarbon fuels such as decalin can thus increase the energy content of liquid fuels. Since Al and B particle additives are high energy and boron is a suitable catalyst, they increase usability and efficiency by increasing the stability and capability of combustion. It is observed that there is an upward shift at the highest decomposition temperature for B for Al. Adding heat-sensitive metals such as Al, Mg, and Fe is an effective method to overcome the energy release efficiency limitation of boron-based fuels. The duration of combustion of element B has a remarkable contribution.

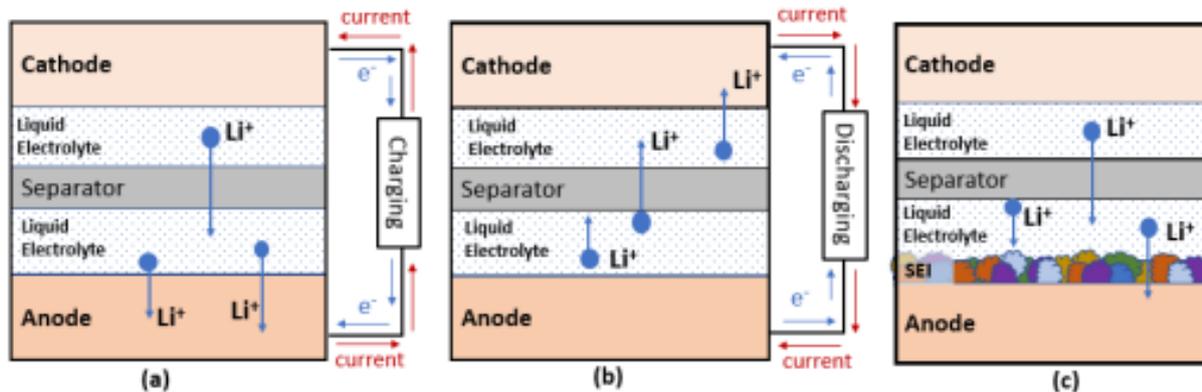
B grains exhibit higher heat release than Al grains [11], [19]–[22]. Removing sulfur from the  $S_xO_y$  release is essential in clean fuel systems. Due to the textural catalyst feature of the boron element, it strengthens the particle dispersion. It improves the high catalytic activity, providing high rates of sulfur removal [23], [24]. Considering all these, it is clear that the element boron will play a vital role in the future of environmentally friendly fuel energy.

### 3. Investigation of the Use of Boron in Battery Systems

Boron is a raw material used in solar cells, fuel cells, and lithium-ion batteries. Battery mainly consists of four primary components: cathodes, anodes, electrolytes, and separators. Figure 1 demonstrates the schematics of these components in conventional Li-ion batteries (LIBs) and the movement of electrons, ions, and current flow during charging and discharging conditions [25]. Sodium boron hydride ( $NaBH_4$ ) is a boron compound that can be preferred because of its advantages, such as hydrogen storage, easy control of reactions, and non-flammable and explosive properties. Boron-containing complex hydrides are also crucial because they are used in liquid conditions and are based on  $NaBH_4$  containing 10.5% hydrogen by weight in solid form.  $NaBH_4$  gives its hydrogen in reaction with water in a catalyst solution environment and turns into sodium metaborate ( $NaBO_2$ ). This reaction makes it possible to store hydrogen gas. This reaction is cyclical. That is, the development of the catalyst suitable for the system and the product of  $NaBO_2$  formed as a result of the reaction into  $NaBH_4$  again emerges. This system can be applied in two primary ways in hydrogen production, other than fuel cells and directly as a fuel cell. Except for the fuel cell, the sodium borohydride solution with the catalyst is passed through the hydrogen production unit and converted to hydrogen. This hydrogen is used in fuel cells because of its low temperature. In this system, sodium borohydride catalytically releases hydrogen in aqueous media and is especially important in applications where hydrogen transport and storage are problematic such as weight, volume, and safety. In a direct sodium borohydride fuel cell, on the other hand, sodium borohydride is directly used as fuel without hydrogen production intermediate stage, and electrical energy is produced. The direct sodium borohydride fuel cell is portable, especially with low power requirements [26], [27]. Boron nitride

nanocomposite increases the hydrogen storage capacity in lithium-ion batteries due to the wide molecular surface area [28]. The decomposition

reactions of  $O_2$  and  $H_2O$  at the cathode of fuel cells are essential for the cells to function well.



**Figure 1** Schematic diagram of LIBs for (a) charging (b) discharging and, (c) formation of SEI.

Although it provides control of these reactions as a platinum catalyst, it is expensive in terms of cost. Here, with the use of boron nanostructures as a cheaper catalyst for reactions, the dissociation energy of  $O_2$  and  $H_2O$  is lower than with the use of platinum [14].

#### 4. The Importance of the Use of Boron Internal Combustion Engines

In using boron in internal combustion engines, the distilled boron enters the combustion chamber with the appropriate amount of pure oxygen gas (with a purity of 99-100%). After the pressure of the oxygen gas is increased to a specific value (approximately 100 bar) with the movement of the piston in the engine, it enters an exothermic reaction with the boron, and by this reaction, the explosion pushes the piston up with the air shock, thus starting the engine. Boron does not have flammable and explosive properties at room temperature. With this feature, it is a reliable and non-hazardous raw material. It releases the energy required for the operation of internal combustion engines by performing combustion or explosion only in certain weather conditions and when combined with certain oxygen. Pure boron can be easily recovered by heating the oxidized boron compound. On the other hand, pure oxygen can be obtained by filtering the oxygen present in the air at the rate of 21% by the silver filters to be placed in front of the vehicle while the vehicle is driving. The residue of boron-fueled engines is  $B_2O_3$ , which has a crystalline liquid structure. This compound can now be stored as ingots by cooling or pressing, repurified, and used as fuel [26]. An improvement in energy performance can be achieved when boron minerals are compared as an additive to the primary

fuels of vehicles used in land and sea transportation (automobile, truck, locomotive, ship). Among the elements that release energy when burned, boron has a high density of 92.77 megajoules/Liter of combustion energy and comes after aluminum [29]–[31]. Boron fuel has a structure that does not burn easily, and its safety is higher than other fuels. There is no risk of spontaneous combustion. 2.2 units of boron can do the work of one unit of hydrogen. However, the weight of boron in the same unit volume is 11 times less than the weight of hydrogen. In other words, hydrogen there is no loss even if it is not used for years. Since boron is an environmentally friendly element, it does not cause environmental pollution. No harmful gas emission occurs as a result of combustion combustion [27], [32], [33].

#### 5. Use of Boron as Rocket Fuel

The use of boron in the aircraft and aviation industry has become a trend. Investigations in this industry, mainly in the USA, Europe, Japan, and Russia are noteworthy. Research in Aerodynamics in Aviation and the desire to travel and study the universe paved the way for space travel operating in the new system and has guided progress on better fuel. For this purpose, it has been realized that the boron-energy issue has a crucial role. In the American air and naval forces, significant investments have been made in R&D studies and projects to use boron hydrogen compounds (Boranes), which can provide approximately 50% more energy than fossil-based hydrocarbon compounds in rockets and aircraft that can move above the atmosphere. As examples of these projects, applications such as HERMES and X-Files High

Energy Boron fuels are used in Ariane rockets. Boron can release high amounts of heat in its exothermic reactions per mass and volume.

When this heat released is analyzed per mass, it is approximately two times the heat released in the reactions of aluminum and 2.5 times that of magnesium. They can perform high-yield reactions with boron, fluorine, and its compounds. The heat energy released in fluorination reactions with exothermic fluorine compounds is about 1.8 times the heat energy released in oxidation reactions. Boron fuels are activated with high activation energy. It creates a working system with high chemical stability and controllable structures. The boron compound adsorbed occupies 11 times more volume than boron at the same weight. This weight provides a significant advantage in terms of storage. In addition, it is located on a reel with its structure in the form of a boron thread. For hydrogen, it should be stored in a thick and cooling tank. Boron fuels are not stored in a fuel tank but in a chain link structure on a reel. Since it does not have volatility, the outer surfaces of the fuels flocculate by forming an interaction network with the fuel. Then, the amorphous boron, which is absorbed by the Hydro-Carbon (H-C) chains in the fuels, can be effective in the combustion waves. Boron atoms undergo oxidation during the combustion of H-C structures, causing heat to emerge on the combustion surface. The effectiveness of the ignition and combustion rate increases depending on the thermal friction sensitivity of the fuel and the substances sensitive to oxidation, such as iron and aluminum in the fuel [16], [18], [20].

## 6. Use of Boron in Electric Motors

Electric motors using boron are associated with fuel cells, an electrochemical battery. It is also used alone in vehicles and can store energy chemically thanks to the anode, cathode, and electrolyte systems. Fuel cells do not decrease efficiency over time and do not need recharging. It continues to produce electricity as long as the fuel and the material that will enable it to oxidize are supplied. Electricity is generated by the interaction of the anode and the cathode and the reaction of hydrogen and oxygen. Pure gaseous water and heat are released as a reaction product. While the required oxygen is supplied from the air, hydrogen is supplied from the fuel used simultaneously. While the structure of fuel cells is similar to the battery, the working system is similar to internal combustion engines. Although it uses electrical energy, it receives from the anode and cathodes in its internal structure. It provides this energy from the energy it produces, not from the energy stored like a battery. This system's operation

depends on the presence of hydrogen; the most important factor of energy production is hydrogen. The purpose of cell use is to ensure energy continuity by preventing power interruption. The desired energy can be obtained if a suitable mass of sodium borohydride solution is created in a fuel cell. Although this energy is approximately equal to half of the energy obtained from the same amount of gasoline, the energy conversion efficiency of the electric motor is approximately three times higher than that of the internal combustion engine. The roads covered with the existing fuel tanks are still valid for sodium borohydride, and sodium borohydride is present in the fuel system. Here, sodium borohydride and water react thanks to the catalyst, and as a result of this reaction, hydrogen and sodium boron powder are released. The released hydrogen feeds the fuel cell and makes it possible to obtain direct current (DC) in the fuel cell. Direct current is stored in the cell, and energy is transferred to the electric motor. The vehicle moves when the electric motor transmits the power to the vehicle's wheels [34]–[39].

## 7. Effects of Boron on Magnetic Working Systems

For the motors to work, the magnets that will provide the magnetic feature must have high B-H characteristic data. Using ferroboron ( $\text{Fe}_x\text{B}_y$ ) alloyed magnetic materials with large coherent force and permanent magnetization values are vital. The production of  $\text{Fe}_x\text{O}_y$ , boron oxide, boric acid, or boron ores (especially colemanite, boron oxide, and boric acid) as raw materials takes place in two stages. In the first stage, Ore + Fe Sawdust + Coke + Quartz mixture is used as a charge in the Electric Arc Furnace with Carbothermic Reduction (High-carbon Ferrobore), and in the second stage, Boron oxide + Hematite + Al, Powder + Igniter ( $\text{BaO}_2$  or  $\text{KClO}_4$  + Al) is used as a charge. It is produced using a mixture of the Aluminothermic Reduction method (Low carbon, high aluminum ferrobore). The essential components in Ferrobore Alloys ( $\text{Fe}_2\text{B}$ ,  $\text{FeB}$ ) are B, C, Si, and Al. According to the amount of B, which can vary between 12-21%, their densities are between about 6.3-7  $\text{g/cm}^3$ , and their hardness is between about 1600-1950 Vickers, their thermal conductivity is between about 0.1-0.3  $\text{W/cm K}$ , their melting temperature is about 1389-1550  $^\circ\text{C}$ . Its Curie Temperatures vary between 1550  $^\circ\text{C}$  and approximately 598-1015  $^\circ\text{K}$ . In the quality of

applications, the behavior of the ferrobore against different chemicals depends on the purity ratio. While it can dissolve with  $\text{Fe}_2\text{B}$  and  $\text{HCl}$  under borane formation, Pure  $\text{FeB}$  has high chemical resistance against  $\text{HCl}$  and  $\text{H}_2\text{SO}_4$  at all temperatures. Due to the presence of  $\text{N}$  molecules in  $\text{HNO}_3$ , it is completely soluble.  $\text{FeB}$  and  $\text{Fe}_2\text{B}$  react with nitrogen gas at temperatures above  $350^\circ\text{C}$ , resulting in  $\text{BN}$  product.

It loses its bright silver color in humid weather and becomes pale gray. A reaction can be seen between pure hot water and ferrobore. In the  $\text{Fe-B}$ -containing material system, alloys containing approximately 0.04-4.2%  $\text{B}$  and steels with a thinly adsorbed  $\text{FeB}$  layer on the surface layer can withstand corrosive oxidation up to approximately  $800\text{-}1000^\circ\text{C}$ . One of the critical magnetic materials in which ferrobore is used is  $\text{Nd-Fe-B}$  (Neodymium Ferrobore) alloy magnets.  $\text{Nd-Fe-B}$  magnets commercially have the greatest strength and the most significant permanent flux density (12 Kg). This density is quite desirable when comparing the density of  $\text{Sm-Co}$  magnets (11.2 Kg) and the density of ferrites (11.5-4.4 Kg). Moreover, an 850 g  $\text{Nd-Fe-B}$  magnet works with 3 kg of ferrite. Due to the reasons mentioned above, boron magnets have an ideal structure thanks to their ability to meet the demands of the industry [40]–[49].

## 8. Use of Boron in Nuclear Energy Systems

Materials with boron elements can be used to prevent the damage of radiation emissions in nuclear energy reactors in nuclear energy systems. The boron material used here is boron carbide. Boron carbide is a material with a melting temperature of  $2450^\circ\text{C}$ , high hardness, and highly resistant to chemical reactions and radiation. Boron carbide is used for loading rods of advanced nuclear power plants. The absorption ability of high-energy neutrons that can create a boron carbide radiation effect is due to the high absorber cross-section of the boron isotope in its structure. As a protective shield material that does not leak neutrons, boron carbides are used in Phenix reactors, fast breeder reactors. The new generation stainless steel called Bor-304 is the material of the tanks used to transport nuclear waste fuels. In the nuclear energy sector, gadolinium and samarium can be used as they have neutron scavenging properties like boron, but it is below the system performance provided on the board. In the fusion reaction of the  $\text{B11}$  atom by colliding with the proton, clean nuclear energy without radioactive

emission was released. During this reaction, the proton fuses with the ion, and as the reaction product,  $\text{C12}$  is formed as an ion with atomic number 6 and mass number 12. Boron, which contains  $\text{B10}$  and  $\text{B11}$  isotopes in its compounds, these isotopes can absorb neutrons during nuclear reactions and slow down the reaction rate. Thanks to this, it is used in the control rods of nuclear reactors as well as in the construction of moderators since it prevents and slows the fission reaction of neutrons with the uranium-235 atom and turns into one of the compounds of boron oxide, boric acid and ferrobore improved with dimethyl ether and amorphous boron. They absorb neutrons in nuclear reactors and prevent or stop fission, which is a chain reaction with uranium-235. In this way, power control is provided in fission energy by terminating the reactor or by adjusting the amount of reacting neutrons [50]–[56]. To provide Nuclear Grade, powdered boron carbide is used as neutron shield components in nuclear reactor systems, boron steels, and boron alloys with titanium. Almost every boron atom can absorb a neutron.

For this reason, boron is used in the control systems of atomic reactors, cooling pools, and closing the reactor with an alarm. Boron emits only a very low-energy gamma ray and absorbs alpha particles smoothly. Neutrons with energies more significant than one mega electron volt ( $1 < \text{MeV}$ ) form an inelastic molecular collision with the target atom. In inelastic collisions, the neutrons that come with the neutron-atom reaction transfer a particular part of their atomic energy to the target atom and excite this atom. This exciting target atom is unstable and then becomes stable by emitting gamma rays. At the beginning of the atomic motions of neutron capture, target atoms absorb neutrons. Then, it is observed that the atom, which becomes excited, transforms into its isotope or gets rid of this excited state by emitting gamma rays and takes its final state. Here, using a boron atom as the target atom leads to the desired results [57]–[62]. It has also been reported that after 2016, a neutron reaction with  $\text{B11}$  in the magnetic field for the tri-alpha reaction took place, and a high amount of energy was produced with a nuclear reaction without the risk of radiation. The way to be used as a nuclear fuel has been opened.

## 9. Conclusion

Boron compounds are used in many critical areas in the energy sector. Innovative boron compounds are

needed in many fields, from nuclear energy to solar panels, from electric motors to internal combustion engines, and from rocket fuel technology to space technologies. Especially the development of a new nuclear engine using the B11 isotope in the tri-alpha reaction and its use by NASA for the journey to Mars are essential heralds that Boron will be an indispensable alternative fuel in future space technologies. However, the transition to fuel technologies that do not contain fossil fuels to compensate for the damages caused by the emissions caused by the use of fossil fuels in the last 100 years is a harbinger of the fact that boron compounds will be used very often in this field.

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**List of abbreviations and nomenclature**

Sodium (Na)

Aluminum (Al)

Calcium (Ca)

Magnesium (Mg)

Iron (Fe)

Lead (Pb)

Hydrochloric acid (HCl)

Nitric acid (HNO<sub>3</sub>)

Solid electrolyte interface (SEI)

Ar-Ge, research, and development (R&D)

Gigapascal (GPa)

Kelvin (°K)

Fahrenheit (°F)

A substance formed naturally in the ground and from which metal can be obtained (Ore)

The dust and small pieces of wood (Sawdust)

A solid substance obtained from coal (Coke)

A hard, transparent mineral substance (Quartz)