Hard-to-abate, hard-to-ignore: The case for CCUS in the global metals industry

Executive summary

This paper presents an action agenda on the importance of Carbon Capture, Utilization, and Storage (CCUS) in decarbonizing the metals and mining sector—one of the largest industrial contributors to CO_2 emissions. Steel and aluminium production alone account for over 10% of global energy-related emissions, with emissions intensity as high as 2.5 to 17 tonnes of CO_2 per tonne of output.

CCUS offers a viable solution by capturing CO_2 from high-temperature industrial processes and either storing it underground or utilizing it in value-added applications such as fuels, concrete, or chemicals. It enables continued production while aligning with net-zero targets and upcoming carbon regulations like the EU's Carbon Border Adjustment Mechanism (CBAM).

This paper is the outcome of a webinar discussion hosted by ICF that brought together a diverse group of stakeholders, including decarbonization experts, policy advisors, technologists, and researchers to deliberate on the current state and future role of CCUS in the metals and mining sector. The session highlighted critical themes such as the need for integration of CCUS into industrial transition roadmaps, the importance of aligning technology readiness with cost economics, the urgency of scaling capture- ready infrastructure, and the potential of CCUS hubs to drive down per-unit costs through aggregation.

Hard-to-abate sectors such as steel, cement, aluminium, and chemical industries for nearly 30% of India's industrial CO_2 emissions. These sectors generate emissions not only from energy use but also from essential chemical and thermal processes.

For instance, steelmaking emits around 2.5 tons of CO_2 per ton of steel, while cement production releases 750–800 kg of CO_2 per ton due to limestone calcination. Since these emissions are process-inherent, they cannot be mitigated solely by switching to renewable energy. This makes CCUS a critical solution. CCUS enables existing industrial facilities to continue operations while capturing and managing emissions either through permanent geological storage or conversion into value-added products like methanol or construction aggregates.

Based on the discussions, this paper outlines a strategic approach to advancing CCUS in the metals and mining sector. It emphasizes the need for early-stage pilot projects within key industrial operations, creation of common transport and storage infrastructure, integration with developing carbon market frameworks, and adoption of innovative financing models to mitigate investment risks. Drawing from both policy insights and international examples, the paper seeks to guide stakeholders toward an industrial transformation that is low in carbon emissions, financially sustainable, and aligned with India's broader environmental and economic goals.

Introduction: India's decarbonization imperative

India faces a complex and formidable challenge in decarbonizing its rapidly growing economy, particularly within its "hard-to-abate" industrial sectors, which encompass crucial industries like steel, aluminium, and chemicals. These sectors are significant contributors to the nation's carbon footprint, accounting for nearly 30% of India's total CO_2 emissions. This proportion is substantial, and projections indicate these emissions could increase two to three times by mid-century without aggressive intervention.

Unlike many developed nations that have historically relied on fossil fuels for industrialization, India's energy landscape remains heavily reliant on its vast domestic coal reserves. Coal currently contributes about 55% to the national energy mix and fuels over 74% of total power generation, underpinning key industries like steel and cement. This deep reliance on coal creates a "carbon lock-in" effect, making the transition to cleaner energy pathways multifaceted and complex, balancing energy security with climate goals.

The dual objective of ensuring reliable and affordable energy access for its large and growing population while simultaneously adhering to ambitious climate goals necessitates innovative and comprehensive solutions like CCUS. This urgency is further amplified by India's explicit commitment to achieving net-zero emissions by 2070. To meet this target, and its intermediate Nationally Determined Contributions (NDC) targets for 2030, a diversified approach is essential. Studies by institutions like CEEW suggest that a significant portion of emissions from sectors like steel and cement—up to 56%—can only be mitigated effectively through the CCUS pathway, highlighting its indispensable role in India's journey toward a sustainable, decarbonized future.

Vision

- Future: Net-zero, thriving Indian industry.
- Sustainable growth, a cleaner Bharat.
- Carbon neutral: India's secure energy.

Mission

- Capture, utilize, store industrial CO_2.
- Accelerate CCUS deployment for growth.
- Decarbonize critical hard-to-abate sectors.

Current landscape

India's hard-to-abate sectors—particularly steel, aluminum, and cement—are among the highest contributors to industrial CO_2 emissions. Steel production emits approximately 2.5 tonnes of CO_2 per tonne of steel, while aluminium production can emit up to 17 tonnes per tonne, underscoring the urgent need for decarbonization measures.

Global and domestic momentum

Global developments: Leading steelmakers like ArcelorMittal, Thyssenkrupp, and BHP, in collaboration with technology partners such as Mitsubishi Heavy Industries Engineering, are actively piloting CCUS solutions. For instance, ArcelorMittal is testing carbon capture in blast furnace operations in Gent (Belgium) and North America as part of its "Smart Carbon" decarbonization route.

Domestic progress: In India, Tata Steel has commissioned a 5 tonnes per day (TPD) carbon capture plant at its Jamshedpur Works, making it the country's first steel company to adopt such a carbon capture technology that extracts CO_2 directly from the Blast Furnace gas.

Sectoral diversification and industrial focus

Shift beyond natural gas

While natural gas processing continues to dominate global CCUS deployment, the sector is rapidly diversifying. New projects increasingly focus on cement, steel, chemicals, and power generation industries that are essential for economic growth but difficult to decarbonize through conventional means.

Decarbonizing heavy industry

These hard-to-abate sectors are now central to CCUS strategies due to their process- related emissions, which cannot be fully addressed by renewable energy or efficiency improvements alone.

Hydrogen integration

CCUS is becoming a cornerstone of low-carbon hydrogen production, especially for blue hydrogen and low-carbon ammonia. Projects combining steam methane reforming with CO_2 capture are expanding rapidly in North America, the Middle East, and parts of Asia.

Direct Air Capture (DAC)

Commercial-scale DAC facilities are now under construction in the U.S., Iceland, and Canada, representing a paradigm shift toward atmospheric CO_2 removal. These plants complement point source capture and are increasingly viewed as part of long-term net-zero pathways.

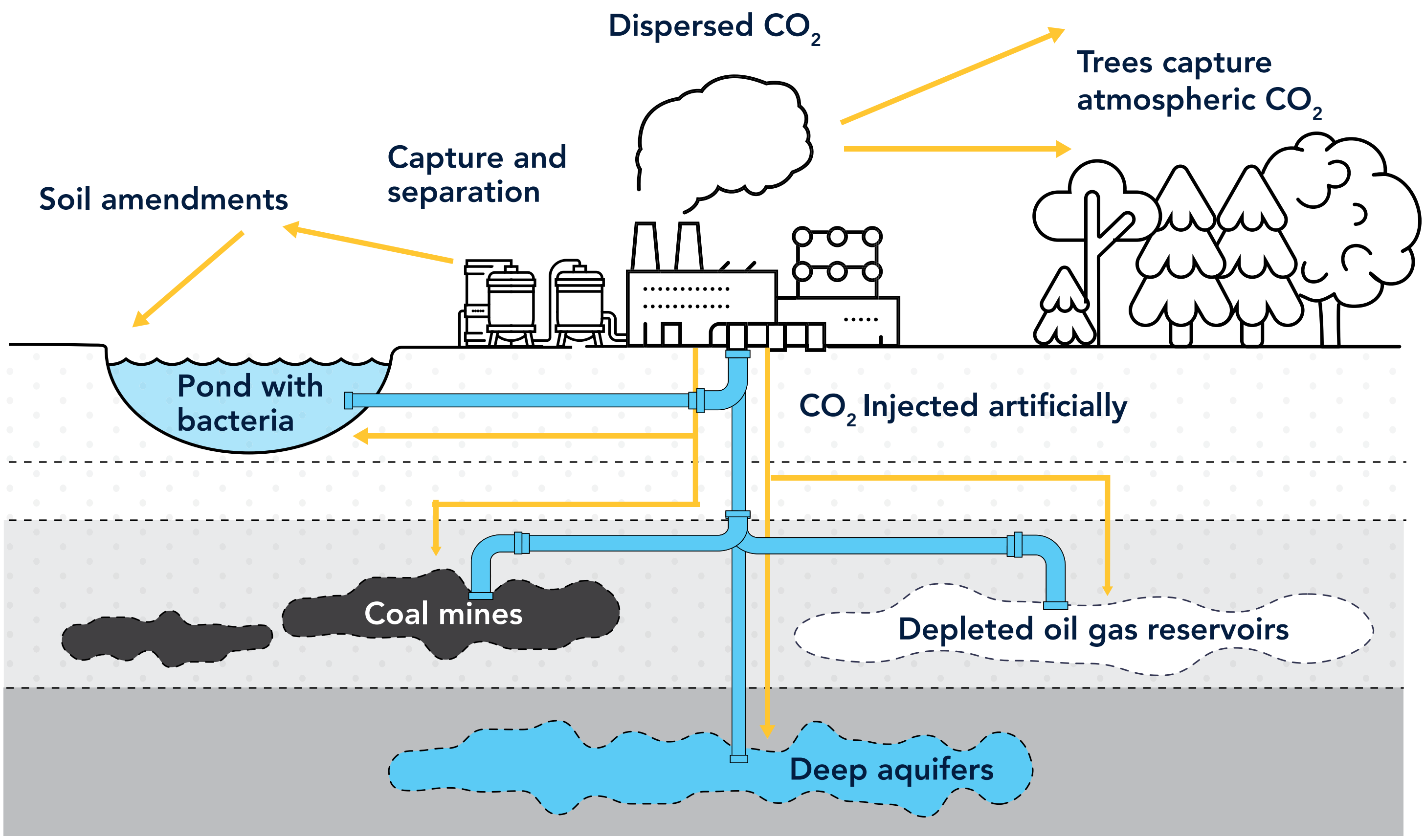
Understanding Carbon Capture, Utilization, and Storage (CCUS)

CCUS encompasses a sophisticated suite of technologies meticulously engineered to capture CO_2 emissions directly from large point sources, such as industrial facilities, power plants, and chemical production. Once captured, this CO_2 is then either beneficially reused or permanently stored in secure geological formations. While the fundamental principles have been in practice for over 40-50 years, with approximately 50 million tons of CO_2 globally sequestered to date, the scope and ambition of CCUS are rapidly expanding.

From an expert standpoint, CCUS is vital for decarbonizing hard-to-abate sectors such as steel, power, chemicals, and energy. Often paired with clean fuels like hydrogen, it plays a central role in CO_2 emissions reduction. Globally, around **1800 million tons** of carbon capture capacity are in various stages of planning, reflecting widespread commitment. Notably, **within the steel and cement industries alone,** over **55 million tons** of dedicated CCUS capacity is currently being developed—underscoring the International Energy Agency's assertion that achieving net-zero is "impossible without CCUS."

Sector	CO_2 emissions per unit	Source of emissions	CCUS role	Current status in India
Steel	2.5 tons CO_2/ ton of steel	Carbon as a reducing agent in blast furnaces	Captures process emissions, enabling continued production	Pilot in progress (e.g., Tata Steel 5 TPD facility)
Cement	750–800 kg CO_2/ ton of cement	Calcination of limestone ($CaCO_3 \rightarrow CaO + CO_2$)	Captures unavoidable kiln/ process emissions	High potential, early-stage pilots
Aluminium	12–16 tons CO_2/ton (global avg.)	Electricity-intensive electrolysis process	Supports upstream CO_2 capture; lowers indirect emissions	Focus on renewables; CCUS at concept stage
Refineries and chemicals	Varies (high intensity)	Fuel combustion and chemical transformation	Captures flue/ process emissions; supports CCU for fuels	In R&D phase, no large-scale adoption yet
Fertilizer (Ammonia/ Urea)	1.6–2.5 tons CO_2/ ton of ammonia	CO_2 from natural gas reforming (H_2 production)	Captures concentrated CO_2 streams from H_2 plants	Pilot-scale potential under review

Carbon sequestration



Carbon utilization opportunities in India

Geological capacity

Theoretical studies indicate that India possesses a significant CO_2 storage capacity, estimated at over 600 gigatons, particularly within saline aquifers located along the eastern coast.

Site identification and mapping

To operationalize this capacity, thorough geological mapping and site identification are critical. The Indian government has already mandated institutions like IIT Bombay to conduct such studies to pinpoint suitable and secure sequestration sites. CO_2 is typically sequestered approximately 1200 meters below the surface to ensure long-term stability. These detailed subsurface investigations guarantee the permanent and safe containment of CO_2.

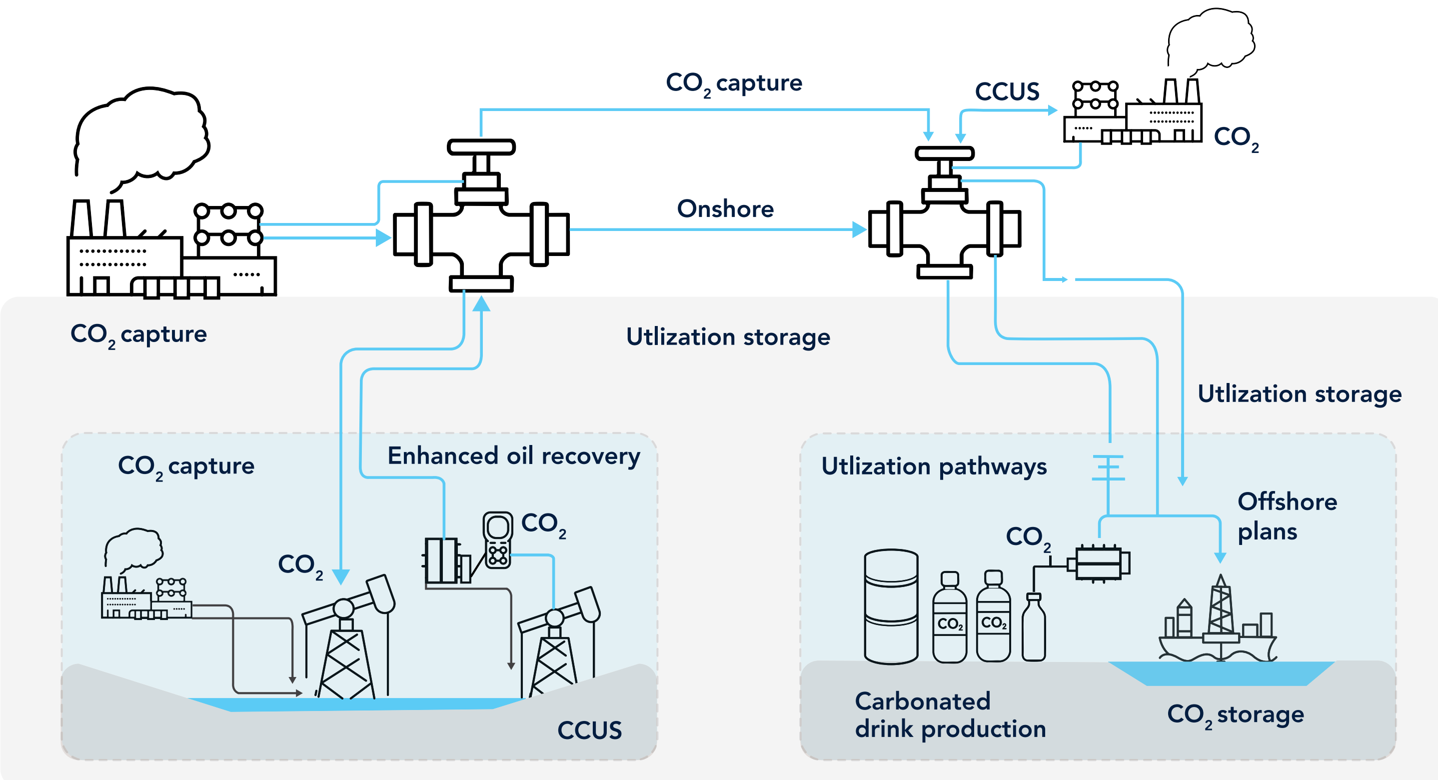
Permanent sequestration

A key advantage of geological storage is the long-term integrity, where CO_2 can eventually react with reservoir rocks to form stable carbonates, effectively "filing it, shutting it, and forgetting it" for thousands of years.

Cost of storage

While carbon capture incurs the primary cost, the incremental cost for storage is relatively low, estimated at around \$4-\$5 per ton of CO_2. However, the cumulative cost can be substantial given the vast quantities of CO_2 needing to be stored (e.g., a single medium-sized blast furnace emits 2.5-3 million tons of CO_2 annually). This highlights the necessity of long-term financial planning and investment in robust storage infrastructure.

CCUS utilization



Carbon storage opportunities in India

Enhanced Oil Recovery (EOR)

In this application, captured CO_2 is injected into mature oil reservoirs to increase crude oil extraction by enhancing reservoir pressure and oil mobility. While EOR is a globally proven and effective method for CO_2 utilization and sequestration, India's comparatively limited domestic oil reserves suggest a smaller long-term role for EOR compared to other, more pressing utilization pathways.

Chemical and fuel production

CO_2 can be chemically converted into a diverse range of valuable chemicals and synthetic fuels, such as methanol, urea, and even advanced biofuels. This opens up vast possibilities within organic chemistry, enabling the creation of a cascade of valuable products, thus integrating CO_2 to industrial supply chains. Such processes can reduce reliance on fossil fuel-derived feedstocks.

Construction material

The utilization of captured CO_2 for producing concrete aggregates, curing concrete, or manufacturing other building materials is identified as a highly promising and scalable solution for India.

Other applications

It includes enriching atmospheres for enhanced crop growth in greenhouses, its use in the food and beverage industries (e.g., carbonation), and in specialized manufacturing processes such as dry ice production or as a solvent in certain chemical reactions.

Challenges associated with CCUS

While the rationale for CCUS is strong, several challenges need to be addressed, alongside significant drivers that are pushing its adoption.

High capital and operational costs

CCUS projects involve significant upfront and ongoing expenditures. For instance, the Boundary Dam project in Canada initially reported a CO_2 capture cost of around **$110 per ton**, which later reduced to **$60 per ton** in the Petra Nova project. Currently, the average cost ranges between **$40 to $60 per ton** globally. In India, where **2.5 tons of CO_2 are emitted per ton of steel produced**, the cost of carbon capture can add approximately **₹8000 per ton** or **₹8 per kg** of steel, significantly affecting pricing and margins unless subsidized or supported by strong carbon pricing mechanisms.

Absence of integrated infrastructure in existing facilities

Most industrial units in India—particularly in steel, cement, and aluminium—have not been designed with carbon capture integration in mind. Retrofitting these facilities is technically complex and financially burdensome. Additionally, the high temperature of flue gases from furnaces and boilers poses further operational hurdles, as it requires energy-intensive cooling before CO_2 can be effectively captured and treated.

Weak carbon pricing and market-based signals

India's carbon trading system is still in its early stages. In the absence of a meaningful price on CO_2 emissions, industries lack a strong economic rationale to adopt CCUS. However, with international mechanisms like the **EU's CBAM** approaching implementation, Indian exporters may soon be compelled to price carbon, which could drive domestic interest in capture technologies.

Lack of CO_2 transport and aggregation infrastructure

A critical component of CCUS deployment is the ability to transport captured CO_2 from multiple sources to centralized storage or utilization sites. Developing such infrastructure such as pipelines and CO_2 hubs requires large-scale coordination, often through public-private partnerships. India currently lacks such coordinated efforts, making it uneconomical for individual emitters to manage transport and storage independently.

Economic implications and viability in the metals sector

Cost trends in carbon capture

Historical data indicates a significant reduction in CO_2 capture costs. For instance, the Boundary Dam project in Canada, one of the earliest, had a capture cost of around **$110 per ton** of CO_2. Further technological advancements and process improvements are expected to drive these costs down further.

Impact on product pricing

For a sector like steel, where 2.5 tons of CO_2 are emitted per ton of steel, capturing 2 tons could add approximately **$100** (equivalent to **₹8000**) to the cost of one ton of steel, or **₹8 per kilogram**.

Offsetting costs through carbon utilization

The potential to generate revenue from captured carbon through utilization pathways (e.g., producing mineral aggregates, fuels) is critical for improving the overall economic viability and attractiveness for investors. Projects that demonstrate a "value from waste" approach are more likely to secure investment.

Role of carbon pricing and trading

The development of carbon markets in India, including carbon trading mechanisms, is essential. Until there is a tangible cost associated with carbon emissions, industries may lack sufficient incentive to invest in abatement technologies. A robust carbon price can significantly offset the financial burden on end-customers and internalize the environmental cost of emissions.

Policy and regulatory framework

Government policies, incentives, and strong regulatory support are paramount for the large-scale deployment of CCUS in India.

Government as a facilitator

The government's primary role is to act as a facilitator, creating an enabling environment for CCUS adoption. This includes developing incentive policies, such as benefits for capturing certain amounts of CO_2.

Decarbonization roadmaps

The Ministry of Environment, Forest and Climate Change (MOEF) has already taken proactive steps by mandating that all new industrial projects seeking environmental clearance must now include a comprehensive decarbonization roadmap. This policy decision indirectly but significantly encourages the consideration and integration of CCUS solutions, as such roadmaps necessitate clear strategies for emission reduction beyond conventional measures.clt positions CCUS as a vital component for projects aiming to secure regulatory approval and align with national climate goals.

Public-Private Partnerships (PPPs)

Given the massive capital expenditure required for CCUS infrastructure, especially for shared transport and storage networks, PPPs are likely to be the most viable model. The government, potentially through public sector undertakings, could invest in the foundational infrastructure, with private industries paying for usage.

Regulatory monopolies and licensing

To ensure the safe and efficient transport and sequestration of CO_2, establishing a robust regulatory framework, potentially including a regulated monopoly or a clear licensing authority, is paramount. This dedicated entity would be responsible for comprehensive oversight, ensuring stringent safety protocols, and fixing accountability in the critical processes of CO_2 transportation and its long-term underground storage. The proactive investment by European countries in offshore CO_2 storage, as seen in the development of major CO_2 hubs, suggests future possibilities for India, including potentially exploring options for CO_2 export or international collaboration on storage solutions.

Key insights and recommendations

Establish a robust carbon pricing framework

- It is crucial to implement a clear, predictable, and sufficiently high carbon price or a well-designed carbon trading mechanism.
- This will internalize the cost of emissions, providing a strong economic incentive for industries to invest in CCUS and driving the market for carbon abatement. As highlighted, "until there is a cost to emit carbon, why anyone will care for that?"

Develop shared infrastructure

- The government, in collaboration with public sector undertakings and private industry, should strategically invest in common-user infrastructure.
- Including trunk CO_2 pipelines and centralized storage hubs, which will significantly reduce the prohibitive upfront capital expenditure for individual industrial players and enable economies of scale. This is crucial because "even for one customer to justify investing into the infrastructure" alone is difficult.

Incentivize carbon capture and utilization (CCU) pathways

- Actively promote and incentivize research, development, and commercialization of CO_2 utilization technologies.
- Policies should support the creation of viable business models that generate revenue from captured carbon, making CCUS projects more financially attractive to investors and fostering a circular carbon economy, aligning with the "value from waste" concept.

Integrate CCUS into future industrial planning

- Mandate that all new industrial facilities, especially in hard-to-abate sectors, include "capture-ready" designs and provisions for future CCUS integration during initial planning and environmental clearance. The Ministry of Environment, Forest and Climate Change (MOEF) already supports this by requiring decarbonization roadmaps for clearances, encouraging future- ready infrastructure.
- Case study: Tata Steel's 5 tonne per day carbon capture pilot at its steel plant in India marks a crucial step, demonstrating CCUS feasibility and offering practical insights for integration. It builds confidence and informs future policy decisions.

Strategic role in India's energy mix and global momentum

- Given India's heavy reliance on domestic coal, CCUS is a critical element for ensuring reliable, affordable energy while pursuing climate goals. Globally, nearly 1,800 million tons of carbon capture capacity is in various stages of planning, with 55 million tons specifically in steel and cement—highlighting its strategic importance.
- Case study: UK's Net Zero Teesside and Humber Clusters large-scale projects combine fossil fuel-based power with CCUS to generate "clean power" and "clean hydrogen." They are expected to abate approximately 5% of UK emissions by injecting captured CO_2 underground, showcasing national-level commitment and the potential for a regulated monopoly in CO_2 transport and storage.

Facilitate technology transfer and local manufacturing

- Promote the transfer of advanced CCUS technologies and boost local manufacturing to cut costs and strengthen self-reliance. With the current focus on lowering capture costs crucial for adoption indigenous production tailored to local needs can reduce import dependence, create jobs, and build a strong domestic supply chain to accelerate CCUS deployment.

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