CII

Confederation of Indian Industry

Addressing National Strategic Needs

CII Report on Advanced Materials, Critical Minerals, and Metals

Graphene | Titanium and Its Alloys | Ceramics | Biomaterials and Implants | Composites | Recycling Materials | Critical Minerals and Rare Earth Elements | Steel | Semiconductors | Aluminium

2024

Published by Confederation of Indian Industry (CII), The Mantosh Sondhi Centre; 23, Institutional Area, Lodi Road, New Delhi 110003, India, Tel: +91–11–45771000 | Email: info@cii.in | Web: www.cii.in

Table of Contents

Mr Chandrajit Banerjee
Director General
Confederation of Indian Industry (CII)

Foreword

In the landscape of 21st century innovation, the strategic development and application of advanced materials, minerals, and metals are foundational in driving forward the boundaries of technological progress. As part of the Initiative on Critical and Emerging Technologies (i-CET), the strategic development and deployment of these critical and emerging technologies will be paramount.

As we all know, the advanced materials are not merely incremental improvements but represent groundbreaking shifts that enable innovations previously considered unattainable. Minerals, often overlooked in the broader discourse on technological progress, are fundamental to the modern industrial ecosystem. The strategic importance of critical minerals, such as rare earth elements, lithium, and cobalt, cannot be overstated, and their sustainable extraction and use are vital to maintaining technological and economic leadership. The innovations in metals are enhancing the durability, efficiency, and environmental friendliness, addressing contemporary challenges.

With this in view, this report provides comprehensive insights on the latest advancements in advanced materials, minerals, and metals. It highlights their properties, applications, and transformative potential, thereby providing guidance and direction for those at the forefront of this dynamic field, fostering a collaborative effort to harness the full potential of these materials.

The CII Task Force on Advanced Materials, Minerals and Metals, as also under i-CET initiative is hence committed to ensure that the potential of these materials is fully realized. The report prepared by the Task Force sets the stage for a comprehensive analysis of the opportunities and challenges ahead, providing a roadmap for strategic investment and innovation in advanced materials, minerals, and metals.

Together, we can create a future marked by unprecedented technological progress and sustainable development. I wholeheartedly thank all the stakeholders and members who have contributed towards the development of this report.

Dr Naushad Forbes

Chairman, CII National Committee on Technology, Innovation, and Research

Past President, Confederation of Indian Industry

Co-Chairman, Forbes Marshall

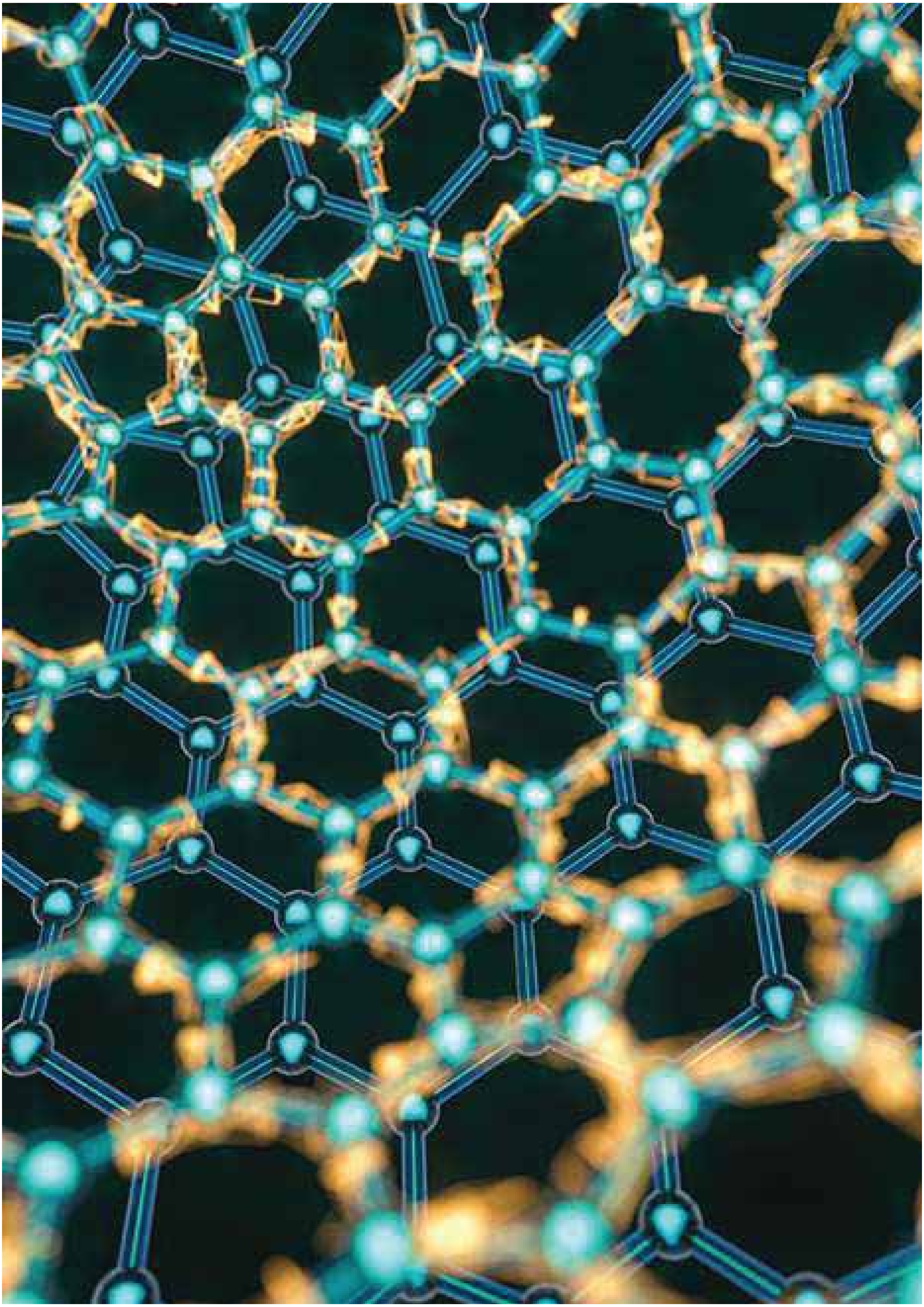
Message

Technological innovation and global development have increased the significance of advanced materials, minerals, and metals in strategic discussions. These fundamental resources are essential for numerous key industries, from renewable energy and electric vehicles to aerospace, defence, and telecommunications. Understanding their role and ensuring their sustainable supply is critical to economic stability, national security, and technological leadership.

This Thought Leadership report explores the dynamic landscape of materials, minerals, and metals that underpin modern technology. It examines the current trends, challenges, and opportunities associated with these resources, providing a detailed analysis of their supply chains, market dynamics, and emerging applications.

The global demand for advanced materials and critical minerals is rapidly increasing, driven by the transition to a low-carbon economy and the proliferation of digital technologies. However, this growing demand also brings challenges, including supply chain vulnerabilities, geopolitical risks, and environmental concerns. This report offers a comprehensive overview of these issues, along with strategic recommendations to mitigate risks and leverage opportunities.

We are grateful for the contributions of the experts, researchers, and industry leaders who have provided their insights and expertise for this report. Their collaborative efforts have been instrumental in developing a detailed understanding. It is clear that a collaborative approach is essential to harness the full potential of these critical resources. This report is a call to action for policymakers, industry stakeholders, and researchers to work together towards such a resilient and innovative future.



Dr Debashish Bhattacharjee

Chairman, CII Advanced Materials Mission
&
Vice President, Technology and R&D,
Tata Steel

Preface

The advent of advanced materials, minerals, and metals has ushered in a new era of technological innovation and industrial progress. From aerospace to healthcare, energy to electronics, the impact of these materials is profound and far-reaching.

The exploration and development of advanced materials such as graphene, carbon nanotubes, and high-entropy alloys have opened doors to possibilities previously considered the realm of science fiction. Minerals, traditionally seen as the foundation of industrial processes, are being reevaluated through the lens of modern science and technology. Rare earth elements, are becoming indispensable in the production of high-tech devices and renewable energy systems, highlighting their strategic importance. Metals, the backbone of civilization since the Bronze Age, are undergoing a renaissance. Advanced metallurgical techniques and the development of new alloys are pushing the boundaries of what metals can achieve. All these advancements in materials, minerals and metals are crucial in addressing contemporary challenges, such as reducing carbon footprints, increasing the durability of infrastructure, and improving sustainability.

With this in view and as Chair of the CII National Task Force on Advanced Materials, Minerals, and Metals we proudly present this Thought Leadership Report on Advanced Materials, Minerals and Metals. The report is prepared by a group of eminent experts focuses on Graphene, Titanium, Biomaterials, Materials from Urban Mining, Composites, Rare Earths Elements, Ceramics, Electronic Materials, Semiconductors, Aluminium and Steel.

This report builds on a previous report published two years ago and delves into the latest developments in advanced materials, minerals, and metals, exploring their properties, applications, and the transformative potential they hold. It aims to provide a comprehensive overview of the background, strategic importance of the material, Indian scenario, gap areas, technology frontiers and relevant, and recommendations. The report also showcases some successful case studies in each of these materials.

As we navigate the complexities of the 21st century, I am sure this report will be pivotal in taking this mission forward, thereby giving a boost to the growth journey of our nation.

Acknowledgements

CII has been spearheading Technology as a mission across the country under the leadership of Dr Naushad Forbes, Chairman, CII National Committee on Technology, Innovation and Research and Mr Alok Nanda, Co-Chairman, CII National Committee on Technology, Innovation and Research, National Technology Mission. Advanced Materials, Critical Minerals and Metals are the key focus and priority technology frontiers under this Mission.

We would like to acknowledge the leadership and support of Dr Debashish Bhattacharjee, Chairman–CII Advanced Materials, Critical Minerals and Metals & Vice President, Technology & R&D, Tata Steel Limited for his vision, leadership and continued guidance in driving this initiative forward.

The completion of this thought leadership report has been a collaborative effort, and we are deeply grateful to the many individuals and organizations that have contributed their expertise, time, and resources.

We would like to acknowledge and express gratitude to the following experts who have been instrumental for the analysis, subsequent findings, and actional recommendations outlined in various chapters in this report.

- Prof Amol Gokhale, Professor, Department of Mechanical Engineering, IIT Bombay
- Dr Vilas Tathavadkar, Chief Technology Officer, Hindalco Industries Ltd.
- Prof B V Manoj, Professor, Department of Materials and Metallurgical Engineering, IIT Roorkee
- Dr R Ratheesh, Director & Principal Investigator, C-MET, Hyderabad
- Prof Bikramjit Basu, Professor, Materials Research Center, IISC, Bangalore
- Prof Bankim Chandra Ray, Professor, Department of Metallurgical and Materials Engineering, NIT, Rourkela
- Mr Sudipto Sen, Chief Executive Officer, Asterix Innovations Private Limited

From CII, the efforts were led by Mr S Raghupathy- Principal Adviser, Dr Ashish Mohan- Executive Director - Technology, R&D, Innovation, IPR and Design, Ms Namita Bahl- Head- Technology, R&D, Innovation and Design, and Ms Tiksha Madan- Deputy Director- Technology, R&D and Innovation.

We also wish to acknowledge the researchers, practitioners, and industry leaders who have been part of several subgroups and have generously shared their knowledge, experiences, and perspectives, providing a rich foundation of data for our analysis.

This report is a testament to the power of collaboration and the shared commitment to advancing knowledge and leadership in the field of Advanced Materials, Critical Minerals, and Metals.

Executive Summary

Life in the current twenty-first century cannot be depending on limited groups of materials and minerals, instead it is dependent on unlimited families of Advanced Materials, Critical Minerals and Metals. They are the cutting-edge of the world's technological frontiers, as they play a vital role in every aspect of our lives.

Advanced materials are new materials with enhanced properties that are intentionally designed for superior performance. Critical minerals play an essential role in modern economies and strategic sectors due to their high economic importance and growing demand. Metals are important to modern technology and are used in many aspects of our lives, and both Steel and Aluminium are two metals with enormous uses.

Together - Advanced Materials, Critical Minerals and Metals have the power to drive technological innovation and are critical as they have applications across all the technology verticals from defence to space. They are critical for national importance and are economic pillars that are integral for the growth of India, hence Investing in materials innovation is investing in India's future.

With this as a background, the Confederation of Indian Industry (CII) is on a mission to launch Advanced Materials, Critical Minerals and Metals as a movement across the nation that envisages to enable India take strategic initiatives towards technology leadership.

This report is a part of Advanced Materials, Critical Minerals and Metals initiative taken by CII. The first version of the report was released in 2022-23 and thereafter presented at multiple forums including i-CET.

The Task Force has now prepared the version 2 of the Report featuring chapters on Graphene, Titanium, Biomaterials, Recycling Materials, Composite Materials, Ceramics, Critical Minerals including Rare Earth Elements, Semiconductors, Steel and Aluminium.

This said report has been developed by an intense pool of technology experts, policy makers, eminent academicians, and industry stalwarts. Each chapter has been individually prepared by dedicated set of experts, involved in series of meetings and discussions. This report helps to identify a road map for Advanced Materials, Critical Minerals and Metals and their importance/ need for India.

This report provides an overview of the current landscape, trends, and challenges in these industries. The report also emphasizes the need for sustainable sourcing, recycling, and innovation to ensure long-term availability and minimize environmental impact. Each chapter also illustrates 2-3 successful case studies on the application of the respective material.

Graphene, a wonder material has unique properties and thus can be used in wide range of applications ranging from electronics industry to energy storage, composites, and sensors and many other areas. Chapter 1 on Graphene covers these multiple potential applications of graphene, sectoral perspectives and actionable recommendations to help India lead the Graphene ecosystem.

India has the third largest deposits of Titanium ores in the world, however, it was only in 2012 that a 500 t Ti-sponge plant came into being under funding from ISRO based on DRDO Technology. Chapter 2 on Titanium covers information and details about outstanding issues with respect to sponge and Titanium.

The ceramic industry in India is heavily dependent on imports for several of these raw materials. Thus, the supply chain issues need to be addressed adequately to achieve self-reliance. Chapter 3 on Ceramics highlights on recommendations: Seamless supply chain along with case studies.

Chapter 4 on Biomaterials and Implant examines the existing disparities within the Indian healthcare sector, specifically in the domains of biomaterials and implants. It offers a deep dive into the challenges that hinder the progress towards achieving self-reliance in manufacturing and clinical application of these critical components for patient care.

Currently, fiber reinforced polymer (FRP) composites have taken a giant leap to replace metals in numerous applications due to their superior properties and ease of manufacturing. Chapter 5 on Composites explains in details in the types and future of composites.

Recycling is the process of conversion of waste to new materials and objects out of it. The recovery of energy is also regarded as part of recycling. Recycling is a key component in the waste hierarchy. Chapter 6 on Recycling Materials focuses on promoting circular economy and ensures the sustainable development.

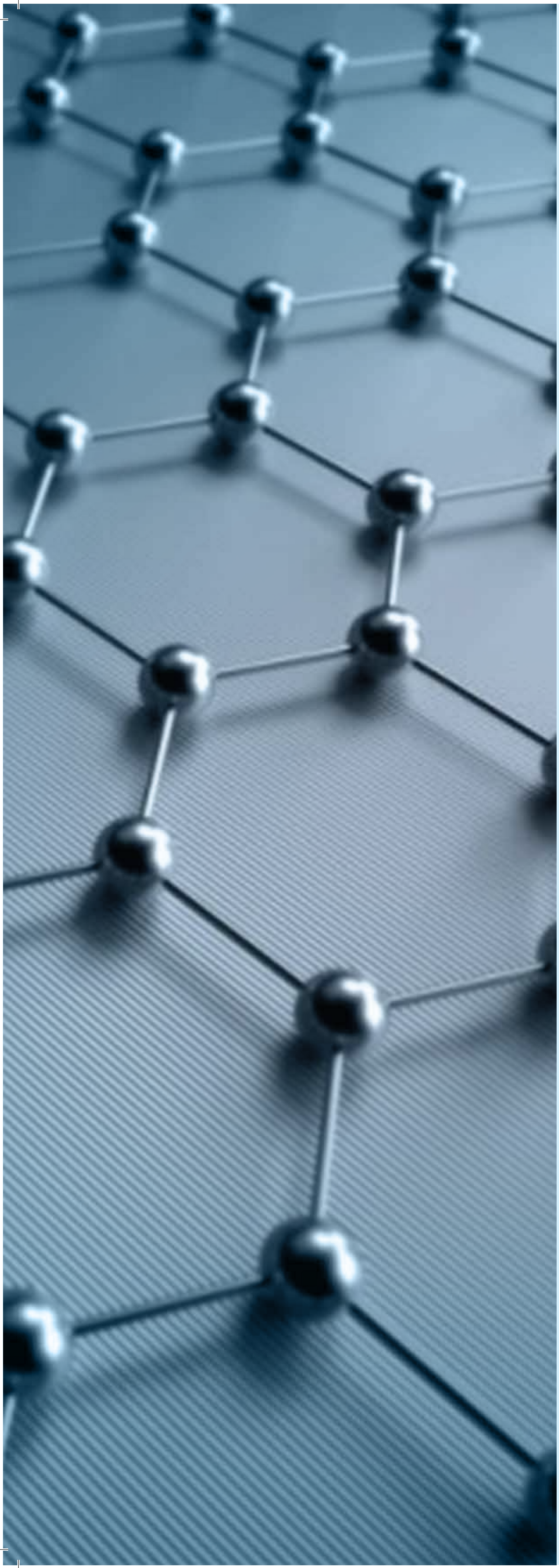
Critical minerals are those that have growing demand and high economic importance in modern economies, especially in the emerging and strategic sectors. However, these minerals typically face risks of supply chain disruptions and price volatility, chapter 7 on Critical Minerals and Rare Earth Elements highlights various aspects of the same.

An important area is the usage of high end steel grades, where substantial boost is required. The applications of advanced high strength steel (AHSS) grades in India, except Dual Phase steel, is still very limited. Chapter 8 on Steel throws light on gaps and recommendations in steel sector.

India's Semiconductors indigenous capabilities in various manufacturing process steps such as single crystal growth, edge trimming of the grown crystal, pseudo squaring of the cylindrical crystal, chamfering and polishing of edges and finally wafering, etc., are not robust and need major investment and trained manpower. Chapter 9 on Semiconductors focuses on gaps, recommendation and actionable points.

The Aluminium industry in India faces challenges such as energy-intensive production processes, environmental concerns, and fluctuating global prices of aluminium. Chapter 10 at present is an abstract on Aluminium – background and certain recommendations. Detailed version of chapter on will be released in subsequent summit.

Overall, report aims to inform decision-makers and stakeholders about the significance of these materials, minerals and metals and the opportunities they present.



CHAPTER-1:

GRAPHENE

1.1 Executive Summary

In 2004, Andre Geim and Konstantin Novoselov successfully isolated a stable single atomic layer of graphite at the University of Manchester. They conducted a series of experiments and showed remarkable electrical and thermal properties. This was a new epoch in material science! It was the first two-dimensional nano materials that was discovered. In the experiments that followed this discovery by various groups around the world, it was demonstrated to have tremendous mechanical strength, excellent electrical and optical propertiesas described in the Figure 1. What is of particular interest for practical applications is that while materials at the nanoscale are generally unstable, graphene is very stable under ambient conditions. In 2010, Geim and Novoselov were awarded the Nobel prize in physics for this breakthrough work. With all the following properties that has been reported by researchers around the world, scientists now believe that graphene can bring disruptive technologies in future[1, 2].

Figure 1: Properties of graphene and its derivatives

1. Graphene in its pristine form can be produced only in small quantities and mostly in research labs. However, its large-scale production presents unsurmountable challenges.

2. In the recent years large scale production of graphene via chemical method, such as Hummer's method and thermal exfoliation methods have been used.

3. The graphene produced, come in several variants that may be classified into three broad categories, namely as:

    - Graphene oxide
    - Reduced graphene oxide
    - Functionalized graphene

The classification shown here is limited to chemically reduced graphene. There are different type of graphene including chemically reduced graphene, thermally reduced graphene, CVD grown graphene, epitaxial graphene etc. Moreover there are different forms of graphene also like graphene ribbons, graphene quantum dots etc. which have specific application potentials.

These graphene variants have been produced around the world for specific target applications. Graphene oxide contains functional groups that can be exploited to interact with other materials for applications in coatings, composites, water filtration, and sensors etc. However, its reduced form which had good electrical properties can be used in battery applications, electrochemical sensors, etc.

Functionalized graphene's are produced by tailoring covalent bond of graphene with the attachment of different functional groups to achieve its use in a variety of different application areas. Functionalized graphene such as N-doped graphene, S-doped graphene, fluorographene etc. are used in energy storage, in (opto)electronics, nanomedicine and environmental applications. The functionalization of graphene with various chemical species is a continuously growing field having enormous potential for inter-disciplinary application development.

Graphene can be grown in the form of films but only on few selected metals such as copper and nickel. To develop applications using graphene films, transfer process has been developed which allow transfer of graphene films from metal substrates to variety of substrates such as Silicon, PET, glass etc. Efforts have been put to develop a roll-to-roll growth and transfer process of graphene films[3]. Such films can find applications in flexible display and optoelectronics.

Despite the enormous application potential, it is worth mentioning that graphene is semimetal with zero band gap, which weakens the competitive strength of graphene for applications in semiconductors fab. Recent study has shown that epitaxial graphene grown on silicon carbide substrate can exhibit band gap with mobility ten times of silicon. This semiconducting graphene is chemically, mechanically, and thermally robust, and can be patterned. This breakthrough of creating a graphene semiconductor could revolutionize semiconductor Industry[4].

Graphene is expected to contribute to many industrial sectors, as it has many extreme properties combined in one material and has the versatility to adapt to multiple potential applications. For instance, the combination of transparency, conductivity and elasticity will help graphene to find application in flexible electronics, whereas transparency, impermeability and conductivity makes it suitable for applications such as transparent protective coatings and barrier films. The list of such combinations is continuously growing every day and is expected to replace many of the currently used materials and generate new market domains. Graphene can open up its own market in the areas of microelectronic and semiconductor devices, Sensors and thin film devices, Nano electrodes for inexpensive organic electronic devices such as organic photovoltaic (OPVs), liquid-crystal devices (LCDs), organic light-emitting diodes (OLEDs), or organic field effect transistors (OFETs), Energy conversion devices like Supercapacitors, fuel cells and batteries, etc.

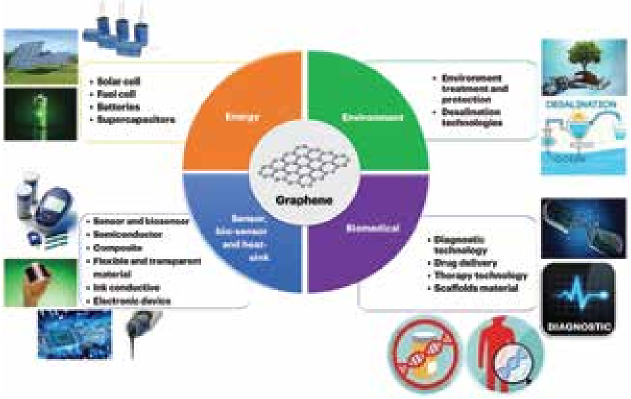


Figure 2: Potential Graphene Applications

1.2 Strategic Importance of Graphene in Indian context

For India to truly emerge as a global technological powerhouse, investment in R&D with focus on emerging material and technology is need of the day. Access to deep material technologies will enable India to propel and develop world class products for global human, social and Industrial good. IP at material level will help to define the countries potential to lead multiple product play in global economy.

- Graphene is considered as wonder material of 21st century because of its potential to create value in almost all streams of technology varying from polymers, coating, energy, structural, textile, biomedical etc.

- Graphene has enormous potential to enhance performance by doping or replace existing materials because of its range of properties such as strength, conductivity, im-permeability, bio compatibility and optical properties.

- India in past has missed the bus with regards to Solar revolution. One among many other reasons was Polysilicon manufacturing competence. Lack of technology to convert abundance of sand as potential raw material into Polysilicon, could be a great learning to take a pole position in Graphene technology with sufficient access to Graphite and other potential raw material within India.

- Successful synthesis of Graphene and developing graphene enriched products would have direct contribution to India's technology leadership position and Innovative index. The new era of "Sustainable future" would derive many values from Graphene, its variants and its use in developing cutting edge and affordable products for greener energy, health care, mobility, electronics, sustainable packaging, EV, energy storage, Water, infrastructure, Aerospace and Defence to name a few. A leadership position in graphene and its application would create a true potential opportunity for India's Research and Development competency to be harnessed by global economy.

India being one of the fastest growing economies, graphene has the potential to play in a large part of the future technologies.

Following are a few potential areas of significance

a) Research has found that graphene is a promising material for fast charging and long-lasting batteries. Looking at the future of electrical vehicle (EV), and more electronic gadgets, it is important to have batteries and energy storage devices produced in India.

b) Owing to the current scenario of depleting groundwater and scarcity of potable water, graphene can play a major role to reduce the cost of filter membranes through graphene based filtration technology with in-house graphene production in bulk.

c) India is inviting global players to setup chip making semiconductor foundry initiative. Integration of epitaxial graphene semiconductor into conventional silicon-based fabrication lines could be a promising focus, as it would allow the combination of high-performance graphene devices with established CMOS readout circuitry, with production costs as low as for conventional silicon technology[4,5]. Graphene in the form of conducting material may play critical role in wearable and flexible electronics, RF IDs antenna and biosensors.

d) India has huge presence in polymer component and packaging manufacturing through organized and unorganized sectors. Value added Graphene polymer composites can be developed with improvement in strength and functional properties such as thermal conductivity and anti-static properties. Rubber and paints are other sector wherein graphene can play significantly.

e) Graphite is abundantly available naturally in India. Graphite can be converted to graphene via top-down exfoliation processes such as liquid phase, electrochemical, thermal, and chemical exfoliation. Last decade has seen a lot of focus on development of scalable exfoliation processes. Graphene is an important material globally because of its application potential. If India focuses on graphene production using natural reserve graphite, India can become global source for supply of graphene and its variants.

f) As India will become a construction hub in the next decade, graphene can also play an important part in those fields. Mixing graphene with cements can decrease the weight of the concrete materials and decrease the water consumption with lower construction lead time.

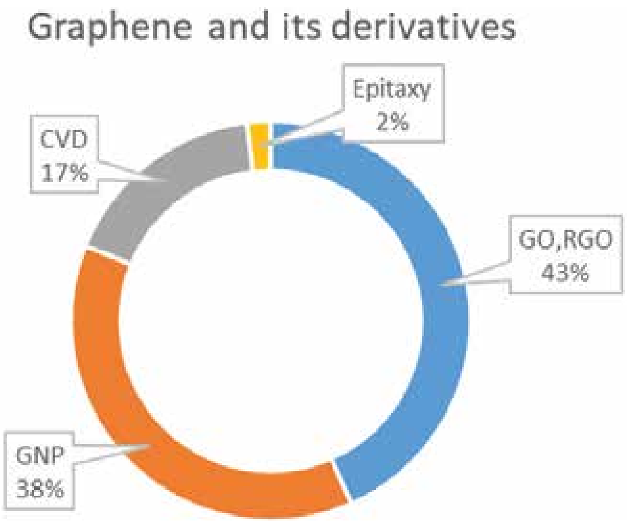


Figure 3: Graphene and its derivatives production trend globally (based on number of companies). India has one among top 10 Graphene producing industry player early with capacity exceeding 100 tonnes per year as of 2021

1.3 Global and Indian Graphene Market Analysis and Forecast

Till 2017 China was the leading producer of Graphene oxide in the world with a capacity of 710 tonnes per year. The total capacity of Europe and USA was around 10% of China's total capacity. While the graphene nano-flakes production was highest, with China having a production capacity of 1400 tonnes per year,Europe and US combinedly produced around half that figure. This scenario has changed at the beginning of this decade with US and Canada taking leading position.

Around the world graphene is produced by various routes. More than 80% of applications have used graphene oxide (GO) and reduced graphene oxide (rGO), produced by chemical methods and graphene nano-platelets (GNP) produced by thermal, liquid phase exfoliation and other methods.

Key market segments

a) Graphene is not one material, but a range of material depending on how it is functional-ized. A new variant can be developed to complement a specific application.

b) Two vectors for Graphene would define countries prominence and its ability to deliver breakthrough innovative products. The first is - Graphene material play with different variants and second is developing applications using the different graphene material delivering a range of graphene value added products.

c) Graphene and its derivatives can be widely used as an additive to polymer, rubber and paint industry globally. Graphene has also seen traction for battery anode applications such silicon batteries, conductive additive to lithium battery cathode etc.

d) Single layer graphene dispersion is most suited for R&D activities and the art to functionalize graphene offers the Industry to take lead in developing products for global good.

e) Graphene applications research so far has been focused on polymer composite, coating, energy and structural applications because of process simplicity for adaptation of graphene technology. However, effort has been put to find success in niche applications with focus on market disruption such as touch screens, chip interconnects and quantum electronics. Please find below list of graphene application focus areas (figure[3.2] and [3.3]).

Given the potential graphene holds in transforming a diverse range of technology verticals, its value chain can only grow. However, as the nascent science and technology of graphene unfolds, every stage of its value chain seems to be mired in uncertainties. At one end of the chain, the scientist is bogged down with questions of control of microstructure, residual oxygen and even with a poor understanding of interactions between graphene sheets to form self-assembled structures. At the next level, graphene manufacturers are challenged by high cost of production and the choice of the method of production. With the recent progress on standardization of graphene quality form (ISO/TS 21356-1), the user-industries are now confident about the consistency in quality of graphene that would best suit their applications.

Supplier Name	Country	Tonnes per year	Application Focus
NanoXplore	Canada	4000	Composite & Energy
Elcora Resources	Canada	2500	Energy
SuperC Technology	China	1000	Energy, Coating, Thermal, Composite
Sixth Element	China	1000	Composite, Coating, Energy, Ink, Adhesive
Global Graphene Group	USA	300	Thermal, Ink, EMI, Coating
Graphene XT	Italy	300	Lubricant, Coating, Composite, Membrane
Ningbo Morsh	China	300	Composite, Energy, Ink
Gnanomat	Spain	200	Ceramic, Energy
Tata Steel	**India**	**100**	Composite, Coating, Fabric, Energy
First Graphene	Australia	100	Composite, Concrete, Energy
Avanzare	Spain	100	Thermal, Ink, Flame retardant, Composite
Carbon Solutions	USA	100	Commercial sale
Gerdau Graphene	Brazil	100	Concrete, Composite, Lubricants, Coatings, Sensor
Graphenano	Spain	100	Concrete, Medical, Composites, Sensor, Energy
Leademano Tech	China	100	Coating, Energy, Composite, Sensor, Membrane
Talga Resources	Australia	100	Energy
Cabot	USA	80	Composites, Battery, Ink
Chengdu Organic Chemicals	China	80	Foam, Composite
Beijing Qingdajiguang Technology	China	50	Ink, sensors, Hydrogen storage, catalysis
Directa Plus	Italy	30	Textile, Tyres, composites, Membrane, oil spill, ink
DDH Advanced Materials	USA	30	Ink, Energy, Hydrogen Storage
Haydale	UK	30	Ink, Sensor, Ceramic, Energy
Garmor Inc.	USA	20	Membrane
2D Materials	Singapore	12	Textile, Energy, Lubricants, Ceramics, cement
Suzhou Gaotong Graphene-Tech	China	12	Thermal, Coating
Abalonyx	Norway	10	Sale
Applied Graphene Materials	UK	10	Coating, Composite, Lubricant, Energy

Figure 4: Key Producer and their volume (based on our own research)

Figure 5: Application Focus ranking based on research activities in listed domain

Market Size

The Graphene Market size is estimated at USD 0.79 billion in 2024, and is expected to reach USD 4.84 billion by 2029, growing at a CAGR of 43.64% during the Forecast period (2024-2029).

(Source: https://www.mordorintelligence.com/industry-reports/graphene-market)

1.4 Major Gap Areas: Indian Perspective

The Indian scenario in graphene production and its application is still in its emerging stage. Most of the players are start-ups with a few major players. As compared to China, which is one of the largest contributors to graphene productions in the world, we observe that we lack the ecology required for innovation and collaboration in industry. There is also less awareness about the possible advanced technology that could be possible by using graphene.

Global graphene market is expanding and is adapting graphene technologies in improving product performance for better consumer experiences. For example, Samsung is focusing on graphene-based touch screen development for flexible display. Huawei has used graphene to develop long-lifespan graphene-assisted Li-ion battery to withstand high temperatures. Semiconductor industry is looking into graphene and other 2D material as means for continuation of Moore's Law.

However, steps are underway to meet and exceed global play with Government committing resources and giving the opportunity to Industry and academia to collaborate to retire R&D risk quickly, help commercialize technology with scale. One such initiative is the India Innovation Centre for Graphene established by MEITY, Govt of India in collaboration with C-MET, Digital University Kerala and Tata Steel as Industrial partner. Centre aim to build graphene technologies, create human talent, engage and energise start-ups and Industry with global academic and Industrial alliance. This path-breaking initiative from government provides an opportunity for Industry to lead, leveraging their operational excellence and competence. Academia and R&D competence being augment with Industrial anchor is one of its unique features that will help India to address the eco-system ask.

India is expected to have a digital economy of USD 1 trillion by 2025, and India's electronics system design and manufacturing (ESDM) sector is expected to generate over USD 100 billion in economic value by 2025. Electrical and electronics production in India is expected to increase rapidly due to government initiatives with policies, such as Make in India, National Policy on Electronics, lowering import dependence, energizing exports, and manufacturing, like the "Make in India" program to make the country self-reliant. Graphene conducting ink technology can contribute for growth of digital economy.

India is the second largest telecommunication market in the world with a subscriber base of 1.16 billion. The Indian mobile economy is one of the fastest growing economies and it can substantially contribute to the GDP of the country (Ref: Report by GSMA and BCG). The number of internet subscribers in the country is expected to double by 2021 to 829 million and overall IP traffic is expected to grow four-fold at a CAGR of 30% by 2021. This shows the tremendous potential that our country has in the telecommunication market.

Even though we are yet to roll out 5G technologies in India, with the current pace of advancements in technology, the 5G technology will be followed by 6G without much delay. The international players in the telecom industry are expecting the 6G technology to be launched by 2030. In 5G, 6G and futuristic telecom technologies, Graphene is emerging as a game changer. Graphene can be a revolutionary material in photonics for telecommunication applications.

It can expand the potential of silicon photonics with new functionalities and can enable high speed light modulation with low energy consumption. Graphene has already cemented its place as a multifunctional material in the 5G technology, such as antenna design, 5G thermal management, EMI shielding, graphene gated OPFET devices, photodetectors, etc. There has been tremendous improvement in the properties of graphene device for 5G technologies within a very short span of time. As we have seen in the case of 5G technology, 6G technology also will roll out in the 100 to 300GHz region and later move on to more challenging 1THz region to get the ultimate response time, data capacity, data transfer, and other promised advances. This will be another focus area for graphene technology in India.

1.5 India Value Chain v/s Global Value Chain

India being home of the world's largest population, poses the unique position in terms of a large market with continuously increasing demand of the advanced technologies, and huge manpower to be employed for such technological developments. Like any global graphene value chain, large number of Indian universities and research institutions are engaged and are best suited for rigorous R&D activities furthering fundamental research on standardisation of different graphene specifications.

The emerging value of graphene technology offers industry leaders from across the sectors to come forward, collaborate and encourage R&D for a purpose then leading to large-scale production of graphene and specific applications. This approach would assist India to rapidly get out of boot-strap approach of graphene's and potential scalable applications. Large scale commercial applications are stuck as it requires scaled-up consistent graphene production, and on other hand scaled-up graphene production is stuck as scalable applications are yet to be identified or popularised for use by large population as a market.

The above chicken-egg dilemma is prevalent equally across the globe; however, sense of awareness is developing globally to enable the application of the graphene, the wonder material. Today, India rather has certain advantages compared to the other global leaders, in terms of available resources, technical competence, production capacities and to top it all market requirements. India, having a matured academic and industrial calibre if set into full motion, should be able to become the leader of graphene technologies, providing answers to the rest of the world, on what strategy should be applied for this technology development.

India, aiming to become a five-trillion dollar economy, is in an advantageous position with a supportive S&T policy (both for innovation and indigenized manufacturing), a strong materials science base, a forward-looking academia–industry nexus (with the industry eager to build on bench-scale findings and an academia that is more than eager to part with its expertise), conglomerates and start-ups willing to experiment and even take risks,

A vibrant market that pounces on anything new, a well-oiled network of services, and a distinct demographic edge (median age of Indians: 27 years). Thus, India not only has a unique opportunity to be a world leader in materials technology, but also to leverage its manufacturing strength and supply chains towards a resilient market economy.

1.6 Gap Areas and Recommendations to Fill Gaps

Technology: Graphene, unlike other materials, heavily rely on intermediate material developments and processing towards a final specific application. For example, the type of graphene required for battery applications can be very different from the graphene used for coating technologies. Also, this is a highly process dependent technology, and performance can be heavily dependent on the way graphene has been processed. This uniqueness of the graphene imposes challenges in terms of standardization of graphene and its applications. At this point, India has great opportunity to standardise graphene and setting up steady state applications of graphene. Government along with industries need to identify products relevant to India with graphene intervention. Industry should come forward to define the problem statement with focused mandate for graphene-based technology development. Industry can launch technology-oriented project with specific target to optimized graphene doping and scalable process for graphene addition to different polymer systems.

EV driven automobile industry should sponsor technology projects with mandate to make part of vehicle with ultralight using graphene and its variant. Government should join hand with industry to jointly fund such programs. We need to bring structure in graphene-based research program going on in research labs and IITs in India. Industry should lead competency gap identification, Government should fund technology development project in graphene applications across widely adoptable areas such as polymer composite, energy storage and academia should bridge intellect gap in making Graphene technology a reality.

- **Government Support:** Push for applied research and indigenous technology. Developing innovation and research ecosystem, where academia and industry can both come together to solve problems. There should be an understanding of where the market is moving and what are the needs. Government should support funding and industry should lead deployment of program with agility. IP should be effectively monetized.

- **Collaboration:** Industry and academia partnerships. Fast innovation and application development research. India Innovation Centre of Graphene is one such example which has potential to bridge this gap. For any specific technology development different work packages can be developed which can be further taken up by R&D centres individually.
- **Infrastructure:** We have sufficient lab and R&D infrastructure in India to support graphene technology development. To develop skilled manpower for mass production of graphene, universities should launch specific master programmes for nano material manufacturing with focus on graphene. Diploma courses for one year can also be considered.
- **Supply Chain:** Large scale graphene flakes can be produced through exfoliation of graphite using processes such as liquid phase exfoliation, electrochemical exfoliation and chemical exfoliations. India comes at seventh position in terms of global graphite reserves. These graphite reserves can be converted to graphene at affordable cost with development of graphite beneficiation and exfoliation technology.

Graphene is set to become the next disruptive technology material. Although we tend to imagine graphene as a perfect 2D lattice of carbon atoms, everyday samples are more often multi-layered and contain heteroatoms, most commonly oxygen in the form of edge functional groups. Fortunately, many applications can make do with less-than-perfect graphenic products. Because the product variety and their market penetration are driven by the quality and quantity of graphene manufactured, it is easy to see that the consumer will have easy and early access to products based on the lowest grade of graphenes while products that must use high-end graphene's (electronic quality and biocompatible functionalized ones) will be hard-buy and stay far from his reach. Being an evolving field, material benchmarking has not been rigid. This situation opens up mega opportunities for graphene manufacturers.

1.7 Role of the Stakeholders such as, Government, Academia, Industry and Research Institutes

Formation of an Apex dedicated governing body with members from Government, Academia, Industry and Research Institutes, such as a Graphene-council, may help significantly to speed up this process. Such council can initiate the process of identifying all possible specific application segments, such as potential usage of graphene in energy storage & harvesting applications, in electronics applications etc., with main focus to standardisation requirements of graphene. Thereafter, setting up academia-industry collaboration to establish roadmaps to achieve those targets, and initiation of futuristic projects targeting specific application domains.

Government should be able to launch program under skill India initiative to support graphene-based industries. Research institutes will provide work force to carry out the technology led research projects. For graphene quality check, industry should make standards. Government should develop process for certification of graphene and graphene enriched products.

1.8 Recommendations

Industry to lead the technology way, government should provide anchor and research funding, academia with the intellect capital and engaging the Industrial and start-up ecosystem would put India's graphene revolution in motion. In the midterm, R&D project can be executed with focus on scalable technology development under supervision of partnering industries. Government can provide soft loan to MSME and start-ups to setup manufacturing plants for production of graphene and graphene-based products. Start-up focused special call can be open for graphene based product development.

In the near-term, it is necessary that the academia and industry work in tandem to mass-produce high-quality graphene products. Taking cognizance of the technological importance of this material, Government should make policy initiatives for the long-term with emphasis on augmenting graphene manufacture and funding R&D programs to tap the vast potential this material presents. Government along with leading industries should collaboratively work together to get the best and develop products using graphene technologies. Graphene the most promising material for next generation technologies has yet to get its place in India. Thus, it is essential to put our right efforts to develop inhouse graphene applications deliver breakthrough products at an affordable cost for local and export market and further creating jobs in India.

Graphene a wonder material has unique properties and thus can be used in wide range of applications ranging from electronics industry to composite and so on. Last decade has observed that gradual improvement in graphene production globally with production cost going down. In terms of applications, value addition through graphene has impacted polymer composite, coating, cements, sensors, bio applications etc. The Global Graphene Market is expected to grow by USD 4.84 billion by 2029, with a compound annual growth rate of 43.0 percent between 2024 and 2029. Considering expert opinions and reports, the advantages of investing in the graphene technology are clear.

The graphene industry in India being in its initial stages very little work is done in terms of regulations and standards. Impetus must be given by both industry and government with supporting policies for funded research and commercialization.

1.9 Sectoral Perspectives

1.9.1 Sustainable Packaging

The properties of graphene can be exploited for various application where large quantity rather than high quality of graphene is required, such as in polymer systems. The advantage of using graphene over other carbon-based additive is that it could be produced at large scale without high temperature and metal catalysis[6] which makes this material cheaper than other nanomaterials. It also requires Lower content (<1% by weight or volume) to significantly improves the mechanical, electrical, and thermal properties of the polymers[7].

The advantages of graphene over traditional fillers and other materials stems from its combination of mechanical and transport properties, as well as chemical and thermal resistance, high surface area and low thermal expansion coefficient.

However, the polymers-based graphene composite field is still in infancy, and several challenges and open questions remain such as improvement in composite properties at large volume fractions, integration into fiber-reinforced composites, determining scaling behavior of mechanical and transport properties in nanocomposites, and how graphene–matrix interactions at the nanoscale are related to bulk composite properties.

There is immense opportunity of graphene in polymer to improve the barrier property especially in flexible packaging. Currently, Metallic layers as well as polymers having different thermal gradients are being used, which makes the packaging material non-recyclable. Graphene is known for its excellent strength, thermal conductivity, and barrier properties, making it an ideal component for enhancing the performance of packaging materials. Graphene could replace all the different polymeric layers as well as metallic part to provide single layer packaging solution. This packing materials will be recyclable and sustainable. World is also looking for the opportunities growing for biodegradable polymers as a single use plastic. A lot of polymers are being explored, but attaining the mechanical properties as compared to polymers being used currently, is a challenge. Graphene could be saviour in this area, low weight percentage of it could improve the mechanical properties without affecting its biodegradable nature.

The graphene infused packaging market is expected to witness significant growth as rising demand for sustainable packaging solutions. World's increasing environmental consciousness is one of the major factors contributing towards the market growth. The superior properties of graphene-infused packaging, make it an attractive option for various industries, including food and beverage, pharmaceutical, e-commerce and electronics. In the pharmaceutical sector, it can be used to enhance drug delivery systems and prevent contamination. In electronics and semi-conductor industries, it can improve circuit performance and durability. In the food industry, it can extend the shelf life of products and provide antimicrobial properties.

1.9.2 Coatings

The electrochemical phenomenon of corrosion leading to infrastructural damage costs up to 4% of global GDP per year and in India, it could cost an estimated 5% of GDP per year. Therefore, improving effectiveness of current corrosion protection practices along with functional and decorative objective can influence sustainability efforts in a big way. Due to excellent impermeability properties of graphene, it can open the door to many interesting types of coating, paints, inks and more.

Graphene's superb electrical and thermal conductivity can be used to make different conductive paints for EMI shielding and heat spreader; its high strength can make for durable coating that do not crack and resistant to oil or water. Apart from this, graphene also can be utilized for the development of anti-bacterial coating, anti-fog paints, non-stick coating, etc.

Recent effort is focused on use of graphene and its derivatives as an additive for different paint applications. Multifunctional Graphene Oxide (GO) nano-paint was developed by incorporating GO sheets in an alkyd resin with suitable non-toxic additives via ball milling techniques studied by Krishnamoorthy et al.[8]. The as prepared GO nano-paint showed excellent corrosion resistance behaviour in both acidic and high salt content solutions as investigated by the immersion and electrochemical corrosion study. Apart from that, the antibacterial property of the GO nanopaint coated surface was studied against three bacterial strains (Escherichia coli, Staphylococcus aureus, and Pseudomonas aeruginosa) and it was observed that the GO nanopaint inhibited the bacterial growth on the surface.

The functionalized graphene nanoplatelets used as an anticorrosion additive for spectrally selective coating investigated by Sest et al.[9]. A spectrally selective coating is a special type of coating that filters out 40–70% of the heat normally transmitted through window glass, while allowing the full amount of light to be transmitted. It was demonstrated that modified multilayer graphene nanoplatelets exhibit excellent dispersibility in many solvents suitable for the preparation of spectrally selective coating. Ding et al. developed anticorrosive coating via graphene passivation for epoxy based paint systems[10]. From the electrochemical study it was observed that the addition of 0.5 wt% of nonconductive graphene in epoxy coating system improves the barrier properties of the coating and exhibits excellent corrosion resistance compared to pure epoxy coating.

Paint industries are coming up with innovative graphene-based coating systems. Applied Graphene Materials (recently acquired by Universal Mater Inc.) has commercialized a series of graphene-based dispersion named as 'Geneble'[11]. The dispersion utilized as additives for the paint and coating system to enhance the barrier and anti-corrosion properties at lowloading. Addition of 5% - 20% w/w Genable dispersion in the paint formulation significantly improve corrosion resistance property without compromising other physical performances. Further they have developed Genable epoxy primer that can significantly extend the life of existing coatings and reduce the frequency and cost asset maintenance.

Graphenestone based in Spain, has developed conductive shielding paint with graphene, named 'Proshield Premium'[12]. The paint system is mainly designed for protection against high and low frequency electromagnetic radiation. The Proshield premium paints lowers the electromagnetic pollution, and interferences between wireless network in different spaces, enhancing effectiveness of RFID and WiFi system. The paint is recommended to use for commercial stores and warehouses, domestic use, hospital, offices, recording studios, laboratories as well as in server rooms.

'Surface Protective Solution'[13] has developed graphene based new generation protective coating named SPC Graphene Coating mainly for automotive industry. In coating solution, the graphene platelets have been dispersed in the formula to act as a strengthening agent. As developed coating exhibited high-definition gloss, excellent surface slickness, rich color depth, and remarkable hydrophobic properties. A series of sprayable transparent conductive coating based on graphene has been commercialized by TBA protective solutions[14]. The graphene has been incorporated in the two-pack epoxy system, polyurethane system, as well as in acrylic system. The two-pack epoxy graphene paint has been used in the electronic industry where electrostatic discharge is to be avoided.

On the other hand, the polyurethane graphene paints have been utilized in the application where a highly conductive surface is required on a flexible surface such as PU elastomer, PVC, rubber variants fabrics, leather etc.

Potential of graphene in paint coating systems for improvement in corrosion and other functional properties have been demonstrated by a number of research publications and commercialized products. Commercialization of graphene paint at bulk scale is slowly progressing.

1.9.3 Water

Scarcity of drinkable water is causing a serious problem around the world. Effective, environment friendly and low energy water treatment process is required for treatment of effluents from the industries and river water. Recently, Graphene oxide and its various derivatives have been shown to be promising candidate for the remedy of water problem. Graphene has a huge surface area and graphene oxide contains diverse functional groups spread over this area. Making use of these properties, graphene, graphene oxide and graphene-based materials have been used in water filtration and water purification process.

(a) Removal of dyes

The removal of dyes by graphene oxide and graphene-based materials mostly uses the process of adsorption. Large surface area and π-π interaction are mainly responsible for the efficient adsorption by these materials. Electrostatic attraction takes place between negatively charged surface due to the presence of oxygen functionalities present in GO sheet and the positive cationic dyes[15, 16].

(b) Removal of Heavy Metals

Another important aspect of water purification is the removal of heavy metals. Mainly the functional groups present in the GO nano composite participate in the complexation process with the heavy metal ions and in the process the ions get removed from the water. Heavy metals can be removed in three following ways :

(i) Functionalization with inorganic salts: GO composites are decorated with magnetic inorganic materials. With the help of these magnetic materials, several metal ions can be removed. Fe_3O_4 impregnated GO and RGO sheets are extensively used for removing some heavy metal ions. Other inorganic oxides like MnO_2, SiO_2, TiO_2 are also used to make graphene composites for removal of metal ions.

(ii) Functionalization with common organic groups: Functionalization may be also done through covalent modification and non-covalent decoration. Ethylenediaminetetraacetic acid (EDTA) is the most commonly used organic molecule to functionalize GO

Cetyltrimethylammonium bromide (CTAB) is also used. Complexation of the heavy metal ions takes place with the help of these functional groups, resulting in their removal from the solution.

(iii) Functionalization with polymers:Polymers are also considered as good reagents for functionalizing GO due to the large functional groups present in them. Polypyrrole, polyaniline, poly (amido-amine), chitosan, cellulose, epoxy resin are the most used polymers for the functionalization of GO. The aggregation between the polymer induced graphene oxide sheets is also minimized which helps in the adsorptive behavior.

Graphene-based materials have attracted significant attention in the water purification market due to their unique properties and the potential to solve complex challenges in the water treatment field. Though most of the results have been demonstrated in the lab environment, some notable players in this field have started preliminary industrial studies in the manufacture and use of graphene-based materials. Versarien Technologies uses GO membrane for water filtration, including desalination and removal of heavy metals. Ionic Industries based in Australia uses GO membrane effectively in the removal of contaminants from water including bacteria, virus and heavy metals

With its amazing properties, graphene-based materials can be considered as the most suitable for the removal of water pollutants. However, the major challenge for water purification with graphene-based materials is scale up with available engineering solutions.Graphene based materials has potential to be the best solution of the water purification problem.

1.9.4 Health

Graphene and its derivatives have attained a significant attention since a decade because of its distinctive characteristics at nanoscale. Graphene nanoplatelets, also referred as nanosheets produced through the exfoliation of graphite demonstrates biocompatibility and play great role in biomedical applications. The immense and advanced area of biomedicine have witnessed the potential role of graphene. A significant work has been done in imaging, biosensor, and personalized healthcare monitoring to move towards high technology readiness levels (TRL).

Graphene Flagship spin-off, InbrainNeuroelectronics based in Barcelona, is developing graphene-based brain implants to alleviate neurological disorder. The Catalan Institute of Nanoscience and Nanotechnology (ICN2) and the Institute of Microelectronics of Barcelona have led development of flexible brain probes made of graphene micro-transistors which can be used to record pathological brain signals associated with epilepsy with excellent fidelity and high spatial resolution. This technology is licensed to a spin off company known as InbrainNeuroelectronics.

InbrainNeuroelectronics has further developed graphene-based implantable transistors to capture high-resolution brain-computer interfaces to illustrates brain mapping for clinical function. It will empower clinicians to monitor localized activity of neurons for respective interventions and intent to elucidate and target neurological disorders including Parkinson’s disease, epilepsy, strokes. The projected market size is approx. USD 5.69 Billion by 2030[17].

Electron mobility is one of the pivotal features of graphene and making it an appropriate material for sensing applications. Paragraf, a globally leading company is in to mass manufacture of graphene-based electronic devices including biosensors and magnetic sensors for a range of applications in automotive and consumer sector. Incubated in 2017 as a spin off from Cambridge University, it has secured approximately USD 65 Million and recently in 2023 has merged with Cardea Bio, the world’s leading producer of graphene-based biocompatible chips.

In continuation, Grapheal has come up with flexible graphene-based sensor potentially able to detect bioanalytes using a smartphone. Incubated in 2019, Grapheal’s TestNpass has been awarded CES Best Innovation in 2022 under Health and wellness category. TestNpass is a very own electronic "test strip" that screens the biomarkers in the body fluids and transfers the information through smartphone. Simultaneously, they have (?) developed WoundLAB, an electronic patch that enables continuous monitoring of localized skin wounds remotely via smartphone app. This will enable doctors to have information in real time and provide treatment.

1.10 Other Two-dimensional nanomaterials

The emergence of graphene has sparked significant interest in the realm of two-dimensional materials. Variants of graphene, such as graphene oxide and functionalized graphene, find applications in various fields like composites, paints, and sensors. However, their utility in nanoelectronics remains limited due to their semi-metallic properties, necessitating chemical or physical modifications to exhibit a bandgap.

Recent years have seen notable advancements in the research of two-dimensional nano materials, notably Transition Metal Dichalcogenides (TMDCs), denoted by the formula MX2, where M represents transition metals like Ti, Mo, or W, and X denotes chalcogens such as S, Se, or Te. Layered TMDCs like MoS2 and WS2 exhibit semiconducting behaviour, making them promising candidates for electronics, optics, and spintronics applications.

Among TMDCs, MoS2 stands out with its sizable bandgap of 1.83 eV, suitable for low-power electronic devices. Its potential spans various electronics applications, including transistors, photodetectors, and memory devices, offering complementary advantages to graphene in nanoelectronics.

Furthermore, TMDCs' bandgap varies with the number of layers, enabling their use in optoelectronic devices. Phototransistors made from different layers of MoS2 demonstrate sensitivity to specific light wavelengths, while MoS2 nanosheets show potential in light-emitting diodes. Additionally, TMDCs find applications in gas sensors and energy storage systems.

TMDCs can be synthesized via bottom-up and top-down approaches, with methods like mechanical exfoliation and chemical vapor deposition (CVD) being prominent. While current applications include lubricants and powder forms, CVD holds promise for large-scale electronics production by growing MoS2 layers through sulfurization of transition metal sheets.

The potential of 2D materials extends to various emerging technologies, including semiconductor applications, memory and spintronics, 6G communication, and quantum computation, highlighting the diverse opportunities they present in shaping the technological landscape.

1.10.1 Semiconductor Applications

The semiconductor industry continually grapples with the challenge of sustaining its longstanding trajectory of rapid advancement, which has persisted for more than sixty years. This drive for innovation, often linked with Moore's law, faces scrutiny as silicon devices push into sub-5-nm technology nodes, encountering significant obstacles in dimensional scaling. Concurrently, there's a parallel trend termed "More than Moore," emphasizing the integration of diverse functionalities beyond pure digital processing, in response to the evolving landscape of technologies like 5G connectivity and IoT.

Diversifying beyond traditional silicon, particularly into the realm of two-dimensional (2D) materials, presents promising avenues for overcoming these challenges and enhancing semiconductor capabilities. The ultra-thin nature of 2D materials positions them as potential substitutes for silicon in future transistor designs, enabling continued scaling while also allowing integration with existing CMOS technology for added functionalities such as sensing and photonics.

Research suggests that transistors based on 2D van der Waals semiconductors could offer a pivotal solution, with entities like IMEC and the Graphene Flagship showcasing their potential for next-generation integrated circuits. Additionally, the exceptional mechanical properties of 2D materials make them well-suited for micro and nano electromechanical systems (MEMS/NEMS), enhancing sensitivity and efficiency in various sensing applications.

The high surface-to-volume ratio and adaptable functionalization of 2D materials render them ideal candidates for gas, chemical, and biosensing applications. Moreover, their distinct optical properties, particularly in the infrared spectrum, present advantages over conventional silicon in optoelectronic applications, potentially challenging costly III–V semiconductor technologies.

While research into the electronic applications of 2D materials has been ongoing for more than a decade, the abundance of available data and successful device demonstrations underscore their vast potential in electronics, optoelectronics, and sensing domains.

Challenges Facing Semiconductor Chip Applications of 2D Materials

1. Maintaining the high-quality, single-crystal flake-like structure of 2D materials during integration poses a significant challenge.

2. Defects in 2D materials have a profound impact on device performance due to their influence on chemical behavior. Achieving precise and stable control over "effective doping" remains a challenge, requiring deterministic replacement of two-dimensional crystal atoms.

3. Direct growth of materials on desired substrates presents another obstacle; current transfer techniques are not suitable for scaling up the process.

4. Ensuring proper adhesion of films to substrates is crucial for device fabrication.

5. Challenges at the device level include controlling dielectric and contact interfaces to 2D materials, as well as achieving low ohmic contact schemes that meet industry specifications.

Recent advancements have shown improved electrical contact resistance to MoS2 using semi-metallic Bismuth, which mitigates metal-induced gap states and spontaneous formation of degenerate states in MoS2. To foster a European ecosystem for 2D materials across the entire value chain, the 2D-Experimental Pilot Line has been established, operating on a shared-cost model between users and service providers.

On the device level, leading semiconductor manufacturers are transitioning from FinFETs to stacked nanosheet FET architectures for advanced CMOS nodes. However, further scaling of channel length necessitates thinning the channel thickness to maintain electrostatic control and suppress short channel effects. Yet, reducing Si sheet thickness increases charge scattering at interfaces, leading to a drop in carrier mobility and device performance. 2D semiconductors present a promising solution as they are self-passivated in the third dimension, minimizing the impact of surface scattering on charge carrier mobility and offering a potential replacement for thin silicon.

1.10.2 Memory Device and Neuromorphic Computing

Advancements in computing power demand highly efficient storage with low-latency memory devices. Significant strides have been made in spin-torque memory technologies (SOT MRAM) through material innovations. However, only a limited number of optimal material combinations have been identified, with CoFeB/MgO playing a prominent role for nearly two decades without a viable alternative emerging yet.

In their monolayer form, two-dimensional materials (2DMs) possess atomic thinness and exceptionally smooth interfaces, interacting weakly through Van der Waals forces and exhibiting minimal element intermixing. These characteristics, along with the versatility of 2DMs, render them highly attractive for spintronics and memory technologies reliant on ultrathin materials and precisely engineered interfaces to achieve desired functionalities.

2DMs have been explored for their potential to enhance perpendicular magnetic anisotropy (PMA), crucial for memory device architectures. Combining graphene with Co, Fe, and/or iron–palladium (FePd) shows promise in this regard, with theoretical calculations indicating up to a 100% increase in PMA compared to pure Co films when graphene is incorporated.

Furthermore, 2DMs can impede atom diffusion in magnetic tunnelling junctions (MTJs), preventing intermixing that can degrade device performance. Graphene and hexagonal boron nitride (hBN) possess dense electron cloud structures and low chemical reactivity due to their hexagonal lattice arrangements. Embedding chemical vapor deposition-based 2DMs in MTJs can address fabrication challenges, improving device morphology as tunnel barrier thickness and lateral dimensions scale down. Their atomically thin, flexible, and inert nature minimizes defects related to dangling bonds, interface states, and interfacial alloy formation. For instance, graphene can serve as both a contact and heat dissipation layer, while hBN can act as an encapsulation and insulating layer simultaneously.

1.10.3 6G Communication

6G technology is anticipated to become operational by 2030, requiring electronic devices to function at terahertz (THz) frequencies and millimeter wavelengths to facilitate 6G communication. This next-generation technology aims to fulfill the needs of a fully interconnected world, offering ubiquitous wireless connectivity and introducing promising technologies like the Internet of NanoThings, the Internet of BioNanoThings, and quantum communications, which are poised to revolutionize wireless communications significantly.

The evolution of wireless communication systems has been revolutionary in recent years, benefiting various stakeholders including commercial solution providers, academic research groups, standards bodies, and end-users, driven by the advancements of 5G technology. However, with evolving societal needs, emerging use cases are surfacing that cannot be adequately addressed with 5G. For instance, the next generation of virtual augmented reality, such as holographic teleportation, demands terabits per second (Tbps) data rates and microsecond-level latency, beyond the capabilities of current 5G millimeter wave (mmWave) frequency bands.

Furthermore, the increasing demand for industrial automation and the transition from Industry 4.0 to Industry X.0 necessitate connectivity density beyond the limits of 5G, requiring a revamp of existing network management practices. Remote healthcare solutions' success hinges on the quality and availability of connectivity, with 6G poised to introduce key enabling technologies like THz band communications and network automation to deliver the highest wireless communications quality with very-high throughput and ultra-low latency.

To realize this ambitious vision, significant technological breakthroughs are essential, particularly in high-frequency devices such as transistors and diodes. The demand for higher output power, lower phase noise, and improved receiving sensitivity in THz band transceivers has spurred advancements in device development. Gallium arsenide (GaAs) and indium phosphide (InP), known for their high electron mobility, are ideal candidates, especially for applications above 100 GHz.

Additionally, graphene, carbon nanotubes, and graphene nanoribbons are gaining attention due to their exceptionally high electron mobility, significantly surpassing silicon. Graphene-based devices have already demonstrated exceptional performance in power detectors and plasmonic antenna arrays at frequencies up to 600 GHz and 200 GHz, respectively. These devices hold promise for achieving groundbreaking performance at frequencies exceeding 1 THz, paving the way for the realization of 6G's ambitious goals.

1.10.4 Quantum Computations

Quantum computing operates on the principles of quantum theory, which describe the behaviour of matter and energy at atomic and subatomic levels. Quantum computers utilize quantum phenomena like quantum bits (qubits), superposition, and entanglement to perform complex data operations that conventional computers struggle with.

In classical computing, information is represented by bits, while quantum computing employs qubits as memory units. Qubits consist of a two-state quantum-mechanical system capable of existing in two distinguishable quantum states simultaneously. These phenomena, such as superposition and entanglement, are not experienced in the classical world.

Superposition allows an object to be in multiple states simultaneously until observed, while entanglement describes the correlation of energy and mass regardless of distance. Both phenomena play crucial roles in advancing computing and communication technologies, enabling the processing of a vast number of calculations beyond the capabilities of ordinary computers.

While classical computers process information as 1's and 0's, quantum computers leverage the laws of quantum mechanics, allowing for information to be processed as both 1's and 0's simultaneously, thanks to superposition.

To implement a quantum computer effectively, certain conditions must be met, including well-characterized and scalable qubit systems, the ability to initialize qubit states, the realization of a universal set of quantum gates, long decoherence times, and specific measurement capabilities.

Several proposed devices and materials can be utilized to construct qubit systems capable of quantum computing:

1. Graphene Quantum Dots (GQDs): Single-layer graphene and bilayer graphene (BLG) are considered promising platforms for spin qubits due to their low spin-orbit interaction and hyperfine coupling. BLG quantum dots have demonstrated long spin relaxation times (T1), suggesting graphene's potential as a host material for scalable spin qubits.

2. Transition Metal Dichalcogenide (TMDC) Quantum Dots: TMDCs, such as MoS2, exhibit direct band gaps and broken inversion symmetry, making them promising candidates for spin qubits in quantum computation.

3. Dopant Atoms in Silicon Crystals: Pure silicon crystals with dopant atoms offer potential for utilizing electron and nuclear spins for computation. Defects in wide-bandgap semiconductors like hBN serve as promising platforms for solid-state spin-active defects in quantum technology.

4. Superconducting Qubits: Google and IBM are developing quantum computing hardware with increasing qubit counts. Additionally, many 2D TMDCs exhibit superconducting properties and can be explored for qubit applications.

1.11 Case Studies

Case Study 1: Graphene Rubber Masterbatch for Elastomers

1. Executive Summary

Tata Steel has developed Graphene - a 2D carbon material that has tremendous benefits to offer in terms of enhancing mechanical properties, barrier protection, thermal conductivity, and electrical conductivity. With these properties in mind, extensive work has been carried out to understand the advantages of graphene in elastomer against other nanofillers and it has been found that Graphene fortification in elastomer has improved the mechanical benefits of rubber compounds in terms of tear strength, abrasion resistance, etc.

Graphene fortification in elastomers is done to improve the performance of products as well as make products more sustainable. Graphene Rubber masterbatch is prepared by dispersion and functionalization of Graphene in rubber in a concentrated manner to ensure easy mixing of this masterbatch in a rubber compound for use in the final product. This masterbatch is prepared by exfoliating the graphene layers and maximizing the interfacial surface area for better rubber-filler interaction. This masterbatch can be used in any elastomeric product. Tata Steel has found success in conveyor belts, and tyre treads and is in the process of creating masterbatch for other elastomeric applications such as shoe soles, hoses, etc.

2. Key challenges faced

Tata Steel has faced a significant challenge in fully benefiting from the wonder material, Graphene, due to its dispersion and functionalization issues in the final product. However, after years of iterations, Tata Steel has developed a Graphene rubber masterbatch that comes with pre-dispersed and functionalized Graphene. Customers can add this ready-to-use masterbatch to their rubber compound to achieve desired properties.

3. Benefits, including Techno-commercial benefits

Graphene rubber masterbatch in conveyor belts increase life of conveyor belt by 1.5 times by tremendously reducing abrasion loss as well as resisting wear and tear of the belt. In tyre tread, Graphene masterbatch helps in reducing the rolling resistance and wet grip of the tyre thus contributing to the reduction in fuel consumption up to 8%.

4. Figure / Illustration of the Technology/Product

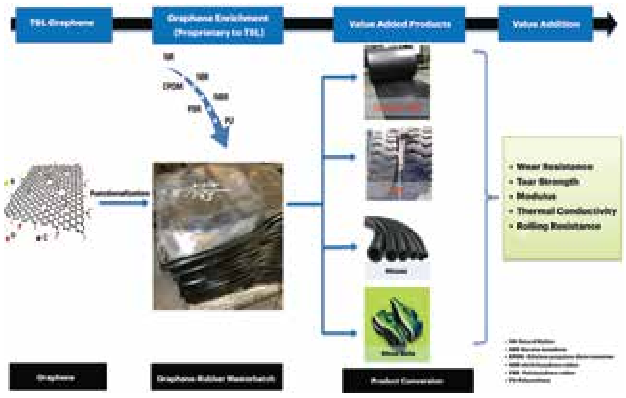


Figure 6: Graphene Rubber Masterbatch Value Play

Tata Steel started initially by selling Graphene powder to customers so that they could add it to their products and get the desired benefits that Graphene has to offer. Customers found Graphene difficult to handle and could not realize its benefits in products. Tata Steel has taken a step further to simplify the process for customers and created a Graphene rubber masterbatch where Graphene is already dispersed, allowing customers to directly add it to their compound and gain the desired benefits. This masterbatch formulation is proprietary to Tata Steel. Graphene rubber masterbatch is currently used in conveyor belts and tyre treads.

In conveyor belts, Graphene rubber masterbatch is currently used in the top layer of conveyor belts to provide a reduction in abrasion loss, improvement in tear strength, and wear resistance. All these properties have combined to improve the life of the conveyor belt by 1.5 times to 3 times based on the environment it is operating. Tata Steel has Graphene Rubber masterbatch formulations for different grades of conveyor belts.

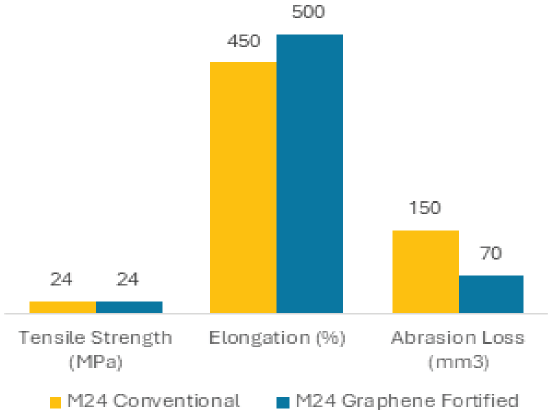


Figure 7: M24 General Purpose Grade

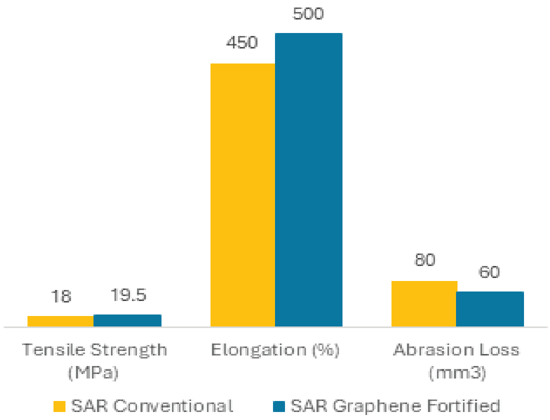


Figure 8: SAR General Purpose Grade

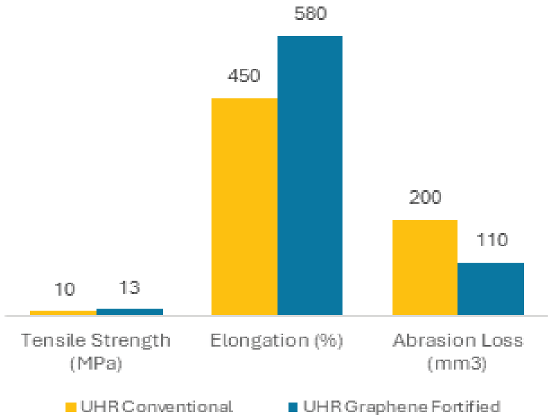


Figure 9: UHR Grade

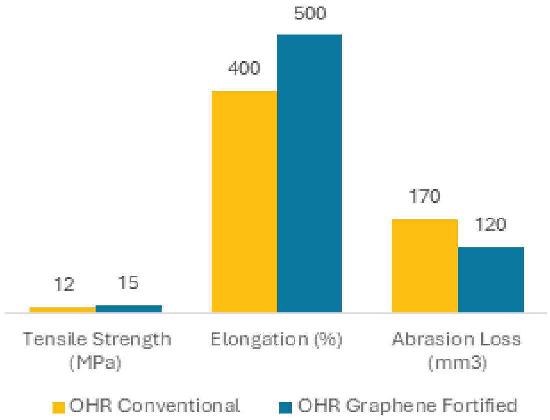


Figure 10: OHR Grade

Graphene Rubber masterbatch in tyre tread shows improvement in tear strength, tensile strength, and 300% modulus as well as a reduction in abrasion loss as shown in Figure 6. With the increase in inherent properties of the compound, the life of the tyre tread is increased to 1.5 times of conventional tread without graphene masterbatch in it. For instance, the increase in the life of tyre tread used in retreading can be seen in Figure[7]. The experiment was conducted on Normal truck tyres of size 11.00-20.

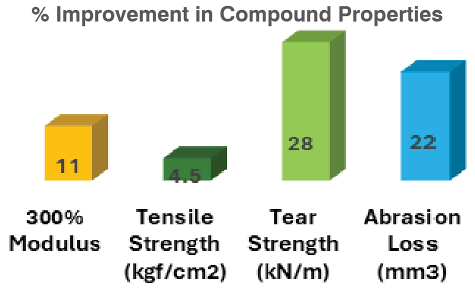


Figure 11: Percentage Improvement in Graphene fortified Compound Properties

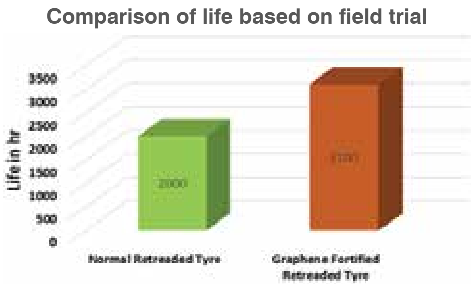


Figure 12: Life Comparison of normal vs Graphene Fortified Retreaded tyre

Tata Steel is under progress to create master batches for other rubber products such as shoe soles, hoses, etc.

Case Study 2: Graphene based Conductive Inks

1. Executive Summary of the project

Likhotronics' CP-03 is an innovative graphene-based carbon ink designed to revolutionize the field of printed electronics. With its unique formulation, CP-03 aims to address the growing demand for high-performance conductive inks in various applications. The project's objective is to develop a cost-effective and versatile ink solution that delivers superior conductivity and reliability.

2. Key challenges faced

- Achieving optimal dispersion of graphene within the ink matrix to ensure uniform conductivity and mechanical properties.
- Ensuring consistent conductivity across different substrates and printing conditions, requiring precise control over ink formulation and deposition parameters.
- Developing an ink formulation that is compatible with various printing processes, including screen printing, inkjet printing, and roll-to-roll printing, to enable scalable manufacturing of printed electronics.

3. Partners involved, if any

- National Centre for Flexible Electronics (NCFlexE), IIT Kanpur

4. Benefits, including Techno-commercial benefits (50- 75 words)

- Superior conductivity: CP-03 offers excellent electrical conductivity, enabling the printing of intricate circuits with high precision.
- Cost-effectiveness: By leveraging graphene's unique properties, CP-03 provides a cost-effective alternative to traditional conductive inks.
- Versatility: CP-03 is compatible with various printing methods and substrates, making it suitable for a wide range of applications in flexible electronics.

5. Figure / Illustration of the Technology/ Product

Figure 13: Ink and products using ink

Case Study 3: Advanced Repair Materials: Polymer Hybrid Nanomaterials

1. Executive Summary

Zara P Care is a paint and chemical manufacturer. It has developed three polymer hybrid graphene products, viz; FCR, FSR, and CRP-FLR for construction industries. The major problem the construction industry is facing is repairing the old, deteriorated concrete and maintaining the newly laid concrete. The revolutionary substance called Fast Concrete Repair (FCR) was created specifically for the repair sections to fix patchwork. FCR is a Three-component formulation with graphene and polymer hybrid, a self-levelling material, and ideal for patch repairs. The nanoplatelets' presence allows for a very high compression factor. It is not as brittle as concrete, and it has zero water permeability.

FCR does not require any sort of curing, in contrast to concrete. This makes the FCR different from other repair materials and makes it more suitable, especially for repairing floors and roadways in situations where stopping operations is not an option. Its superior abrasion resistance helps it withstand wear and tear from heavy traffic and abrupt braking. Another extremely special feature of FCR is its ability to endure temperatures between -80 and 300 degrees Celsius. It clings to the concrete with excellent strength.

However, occasionally the topping on concrete wears off at a particular age or for other reasons. Because of its consistency, applying FCR in these situations is impractical. This is when the FSR is effective. Concrete resurfacing is done by FSR fast concrete surface repair. Except for consistency, the attributes of FSR and FCR are identical due to their similar composition. FSR is more fluid-containing, which makes it workable and flowable for topping or resurfacing concrete floors.

In certain instances, serious cracks in concrete occur rather than potholes or removal of topping. There are many reasons why these cracks can occur, but insufficient and inadequate curing is the most common and significant one. Zara created CRP-FLR, a self-levelling crack filler compound, to address these cracks.

2. Key Challenges Faced

Diverse techniques are employed globally to fix concrete. The primary determinant in selecting the concrete repair technique is the expense of the material and how it is applied. In cases where bituminous material is to be used for patch repair, the following four techniques are typically used:

Throw-and-Go Patch: Although a temporary solution, this is the simplest and fastest repair option. Without compressing it, the material is used to fill in the patch or pothole. This means that the substrate won't retain stuff for very long.

Throw and Roll: This is an additional temporary technique wherein the material is filled in the pothole or repaired and then compacted using the truck's wheels. In some way, this compaction aids in the material's adhesion to the substrate. This approach is likewise fast and short-term, but it's preferable to the "through-and-go patch" approach.

Surface Preparation and Compaction: First, the potholes are cleared of any water and dust particles. The patch's edges are trimmed. After that, the material is added to the patch and compacted using a vibrator to fill in all the holes and reach the optimum density.

Injection Method: Initially, any water or dust particles are removed from the potholes. The margins of the patch are clipped. The substance is then injected using a pneumatic spray at high pressure. Since the high-pressure injection fills in all of the material's voids, compaction is not necessary.

In addition to the materials and processes listed above, several other approaches are also in use, such as filling the patches with ultra-high-performance concrete (UHPC). The strength and durability of UHPC is its advantages. Superior flexural and compressive strength are features of UHPC. It is more durable than other materials because of these qualities. In comparison to white topping, polyurethane, and epoxy grout, is also a more affordable option. Although the UHPC possesses the benefits listed above, its shrinking is by far its biggest drawback. Since the material is based on water, heat is released during the curing process, which causes shrinkage strains to form at the interface between the material and the substrate. The adherence of the material to the concrete substrate may be impacted if these stresses exceed the acceptable limits.

Utilizing epoxy grout is another widely used technique. This material is offered by numerous global corporations in the market. In 2022, the epoxy sector held a 60.4% sales share, leading the market. The epoxy material's resilience against ultraviolet light, aesthetic appeal, affordability relative to alternatives, and curing time are the main factors contributing to its commercial dominance. In contrast to concrete, it reaches its maximum strength in a single day and doesn't require a unique curing process. The application of this material is its main drawback. Workers with the necessary skills are required to apply epoxy.

In addition, applying epoxy is a slower process than applying other materials. Since the majority of epoxy on the market is sold in two or more pack systems, mixing, stirring, and applying the material within the allotted time are significant obstacles to quality control.

The market now wants the product that was finally developed after considering all of the aforementioned items' shortcomings. The industry demands a self-curing concrete repair and resurfacing solution because it might not be able to cure at every location, let alone for an extended amount of time. Many industries don't want to sacrifice quality for the sake of curing.

All currently used materials require at least 48 hours to cure, which severely limits the usual activities that were carried out before the application of the material. Therefore, the industry needs materials that can cure in a few hours or less, since this will shorten the idol time of the site and minimize losses incurred as a result.

3. Benefits, including Techno-commercial benefits

The characteristics that FCR and FSR display, like as quick setting and free curing, boost their popularity. In addition, FCR and FSR are not moisture-sensitive like polyurethanes are, and they are more flexible, abrasion-resistant, and UV-stable than epoxy coatings. One-coat solutions that dry quickly and function effectively are gradually replacing two-layer epoxy-based coat and urethane topcoat systems with FSR coating. As a result, process productivity is improving and FSR demand is growing. Because the product is highly durable, the FCR and FSR have lower lifecycle costs than the alternative solution. Despite its age, the conventional epoxy coating method is nevertheless extensively utilized in many industries because of its affordability, and ease of usage.

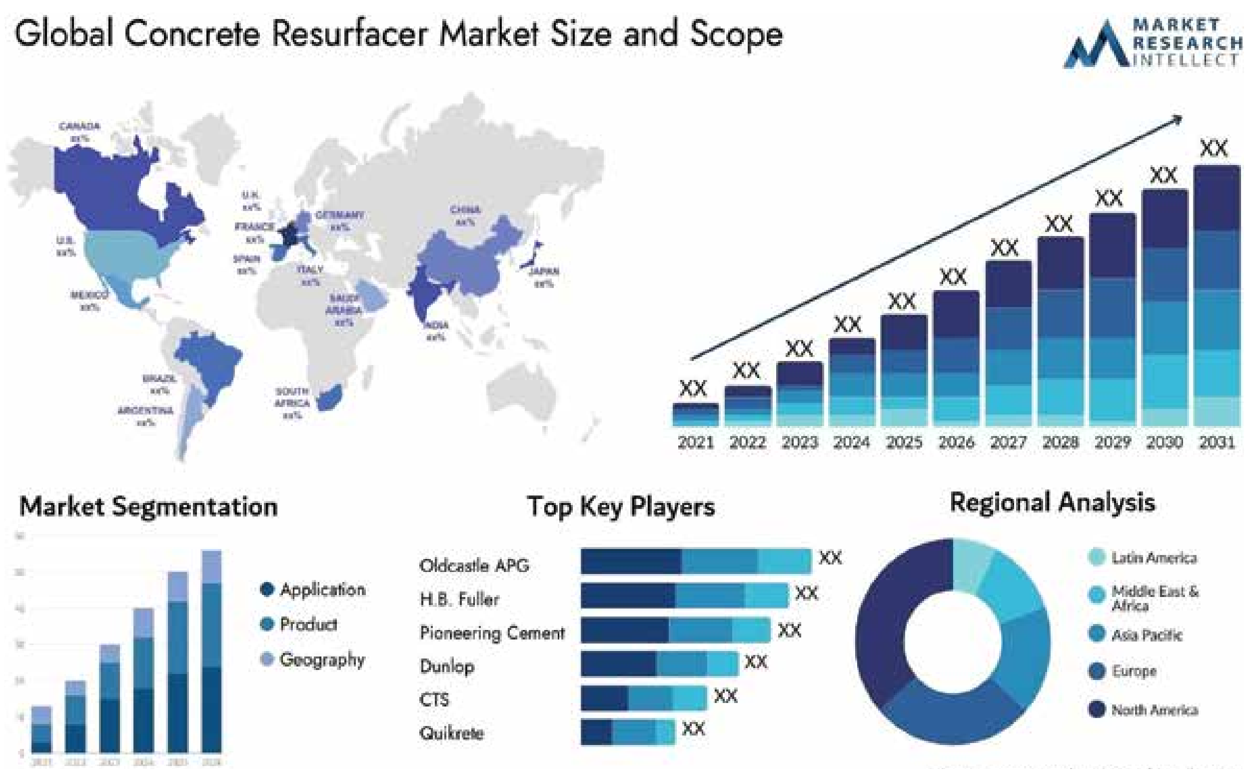


Figure 14: Global Concrete Resurfacer Market Size and Scope

(Source: www.marketsearchintellect.com)

Market Analysis

S. NO	Company	Product/Technology/ Advanced Materials Product and Solutions
1.	Tata Steel Ltd.	Graphene Rubber Masterbatch for Elastomers
2.	Likhotronics Tech Private Limited www.likhotronics.com	Graphene Based Conductive Inks
3.	Zara P Care www.zaracare.in	Advanced Repair Materials: Polymer Hybrid Nanomaterials

Chapter Contributors

On behalf of the CII National Mission for Technology, Innovation and Research, we would like to acknowledge and express gratitude to the following for their contributions in the Chapter on Graphene:

- **Dr Debashish Bhattacharjee,** Chair, CII National Task Force on Advanced Materials, Critical Minerals and Metals & Vice President, Technology & R&D, Tata Steel and Lead, Graphene Chapter
- **Mr Kamesh Gupta,** Chief Graphene Business, Innoventure and Medical Materials Technology and New Materials Business, Tata Steel
- **Dr Shyam Kumar Choudhary,** Head NPD - Graphene Applications, New Materials Business, Tata Steel Limited
- **Dr Trilochan Bagarti,** Manager Process Improvement Rolling Tech, R&D and Technology, Tata Steel Limited
- **Dr Arunabh Ghosh,** Associate Director (Cell Design),Ola Electric, Bangalore, India
- **Prof Aravind Vijayaraghavan,** Professor of Nanomaterials, Department of Materials, Head of Internationalisation, Faculty of Science & Engineering, University of Manchester, UK
- **Dr A Seema, Scientist-E,** Centre for Materials for Electronics Technology (C-MET)
- **Dr T Prem Kumar,** Senior Principal Scientist (Retired), CSIR-Central Electrochemical Research Institute
- **Prof Dipankar Chattopadhyay,** Department of Polymer Science & Technology University College of Science & Technology, University of Calcutta, Kolkata
- **Dr Rajashekhar Pujar,** Researcher Associate, New Materials Business, Tata Steel Limited
- **Dr Vimal Kumar Sharma,** Application Engineer Life Care Solutions New Materials Business, Tata Steel Limited
- **Mr Nitish Kumar,** Asst. Manager- Thermoplastic Design, New Materials Business, Tata Steel Limited
- **Dr Saptarshi Dhibar,** Researcher - Polymer Coatings & CompNew Materials Business, Tata Steel Limited
- **Dr Amartya Bhattacharya,** Researcher - Hydrogen Technology New Materials Business, Tata Steel Limited
- **Dr Sandip Ghosh,** Sr. Application Engineer- Graphene, New Materials Business, Tata Steel Limited

References

1. A. C. Ferrari, et al., Nanoscale, 7, 4598-4810(2015)
2. K. S. Novoselov, Nature, 490, 192 (2012).
3. M. M. Tavakoli, et al., Advanced Functional Materials, 30, 2001924 (2020).
4. Zhao, J., Ji, P., Li, Y. et al., Nature 625, 60–65 (2024).
5. Daniel Neumaier, et al., Nature Materials, 18, 525-529 (2019).
6. V. Palermo, Chem. Commun., 2013, 49, 2848.
7. D. A. Dikin et.al., Nature, 2007, 448, 457–460.
8. Krishnamoorthy et al., Carbon, 72 (2014) 328 – 337.
9. Sest et al., Solar Energy Materials and Solar Cells 176 (2018) 19 – 29.
10. Ding et al., Carbon, 138 (2018) 197 – 206.
11. Applied Graphene Materials, www.appliedgraphenematerials.com
12. Graphenestone, www.graphenestone.com
13. Surface Protective Solution, www.surfaceprotectivesolutions.com
14. TBA Protective Solutions, www.tbaps.com
15. Y. Yang et al. Langmuir, 29(34) (2013), 10727–10736
16. P. N Diagboya et al., Carbon, 79 (2014), 174–182
17. https://gpht-bci.eu/2024/01/09/revolutionizing-brain-comput er-interfaces-via-groundbreaking-graphene-technolo

CHAPTER-2:

TITANIUM AND ITS ALLOYS

2.1 Executive Summary

Titanium alloys have a relatively low density, high corrosion resistance, ability to develop high strength and good creep resistance up to about 550^{0}c. As a result, they are widely used in air frames and aeroengines. Their usage in other sectors is limited to biomedical implants, chemical processing equipment, sports goods and to a small extent, armour. A large proportion of Ti alloys are used as forgings, plates, sheets, tubes and, to a small extent, castings [Lutjering 2007].

The initial applications of titanium alloys in aerospace were in the compressor section of the aero-engine, where their high temperature capability was primarily the reason for their selection. However, the introduction of Ti-alloys in the air frame of Boeing 787 saw a major shift in the material distribution in that application (Figure 1). They replaced aluminum alloys in the air frame, in spite of their higher density. This was possibly because Boeing had decided to use CFRP (Carbon Fiber Reinforced Polymers) in the air frames due to their higher strength to weight ratio and the fact that aluminum is not galvanically compatible with CFRPs [Hakansson 2016].

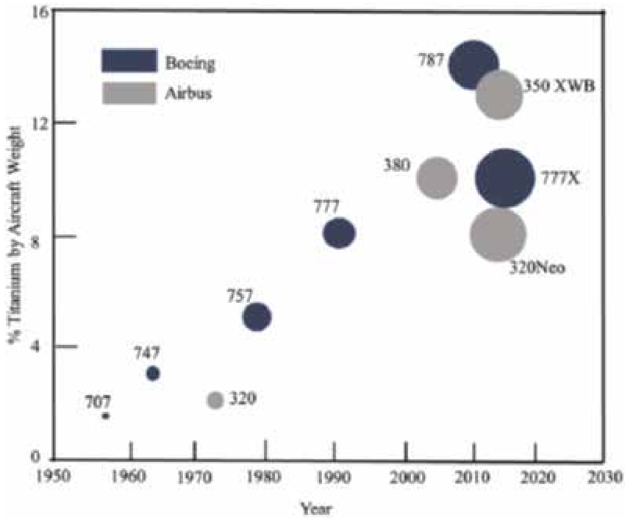


Figure 1: Usage of Ti-alloys in commercial airplanes [Sankaran 2017]

Parts of the landing gear of Boeing 777 and 787 are now made of Ti-alloys, which were earlier made of high strength steels, resulting in weight saving [Lutjering 2007]. Table 1 shows the gradual increase in the titanium content used in the air frames of various Boeing and Airbus passenger aircraft.

Future higher supersonic aircraft such as the Advanced Medium Combat Aircraft (AMCA) will perhaps see increased usage of titanium sheet components in near-engine locations due to service temperatures expected to be beyond the capability of currently used Al-alloys.

The other application where titanium could partially replace nickel is the aeroengine, where titanium aluminide intermetallic alloys could replace Ni base superalloys for High Pressure Compressor (HPC) blades and Low-Pressure Turbine (LPT) Blades [Lutjering 2007]. Some of these applications have already been realized in GE's recent engines [Bewlay 2016].

Table 1: Distribution of various materials used in the air frame of passenger and fighter aircraft [Sankaran 2017]

Materials Distribution (wt%)							
Material	Boeing					Airbus	
	747	757	767	777	787	A380	A350
Aluminum	81	78	80	70	20	61	19
Titanium	4	6	2	7	15	10 (Ti and steel)	14
Steel	13	12	14	11	10		6
Composites	1	3	3	11	50	22	53
Other	1	1	1	1	5	7	8

2.2 India Value Chain v/s Global Value Chain

As elaborated above, with 593.5 Mt of ilmenite and 31.3 Mt of rutile, India has the third largest deposits of titanium ores in the world [Nagesh 2017]. However, it was only in 2012 that a 500 t Ti-sponge plant came into being under funding from ISRO based on DRDO Technology. This plant is hosted and operated by Kerala Minerals and Metals Limited, a state PSU. It uses ilmenite ore mined at the Chavara coast, converted in stages to TiO2 and then to aerospace grade TiCl4. The technology is based on the time-tested Kroll's process which is basically a magnesiothermic reduction process. It may be mentioned that the indigenous Ti-sponge has been certified by airworthiness agencies.

The outstanding issues with respect to sponge are high price (about $22 per kg) compared to the international price (about $9 per kg in 2019). This is partly related to the facts that: (a) grades other than the top grade, which are not suitable for aerospace use, are difficult to sell, thus adding to the overall price of the sponge and (b) recycling of magnesium which is used as the reductant in the Kroll's process has not yet taken place, although the recycling plant is under installation, based on DMRL knowhow.

There have been several instances where state governments with foreign collaborations have expressed interest in exploiting ilmenite resources of their states to produce Ti-sponge, but none has materialised. Mishra Dhatu Nigam (Midhani), a Defence PSU has most facilities such as Vacuum Arc Remelting (for making ingots out of Ti-sponge), Forging press (for break down- and shape forging), rolling mill (for flat products), heat treatment etc, required to produce various mill forms mentioned in the introduction. The installed capacity of Midhani is 300 t mill products, which is projected to increase to 500 t initially, but can go up to 1000 tpa. There are no known firms other than Midhani who have similar capabilities, either in terms of infrastructure or in terms of technology.

The following are the known users of titanium and its alloys in India:

Indian Space Research Organization (ISRO), HAL, Defence Research and Development Organisation (DRDO), Brahmos Aerospace Pvt Limited (an Indo-Russian Joint Venture), and Midhani, all being for aerospace structural and engine applications.

Combat aircraft programmes of the country typically use alloys in bar, plate, sheet, tube, wire and forging forms, involving various processing operations such as melting, casting, forging, extrusion, rolling, ring rolling, cladding, heat treatment, fabrication, and machining. The most common alloys used are Ti-6Al-4V (normal and ELI, i.e., extra low interstitials grade), Ti-5Al-2.5Sn-ELI, VT-14 (Ti-5.4Al-3Mo-1V), Ti-3Al-2.5V and Ti-15V-3Al-Sn-3Cr alloy. Another area of interest is Ti-alloys for demanding environments, such as for hypersonic thermal protection systems, for impact absorbing applications etc. Applications of electron-beam-welded hemispherical caps to make air bottles (pressure vessels) are being realised in ISRO (see Fig. 2.5.1) [Gupta 2015].

Applications of smart alloys based on Ti such as Nitinol have been realised in hydraulic couplings used in fighter aircrafts. Programmes aimed at higher supersonic aircrafts will further increase proportion of titanium used in the airframe.

The current indigenous efforts of manufacture of aeroengine discs for the licensed production of an aeroengine, using near-isothermal forging process, will culminate during this period. Also, the industrial capability to make beta alloy forgings for landing gear and beta alloy sheets for higher supersonic fighters will mature during the same period. Apart

Figure 2: Forged & Machined Hemisphere (inset: pressure vessel made out of hemispheres) [Gupta 2015]

from industrial capability development, the airworthiness certification is also expected to be completed.

In the near future, one can expect launch of development of newer Ti-alloys equivalent to Ti-5553 for landing gear applications in place of Ti-10-2-3 alloy. In Ti-5553, the rate of change of β volume fraction with temperature (below β transus) is low, making it easier to control it within 5-10% for the purpose of optimising between creep and fatigue resistance. Similarly, development of Ti-alloy sheets of compositions equivalent to Beta21S is likely to reach industrial level production to cater to higher supersonic aircraft skin as well as hypersonic applications. Liquid hydrogen tanks made of EB-welded Ti-alloy are suitable for cryogenic engines for satellite launch vehicles. Thus, complete transition to cryogenic propulsion will drive up the requirement of super alpha Ti-alloys, which have good properties at cryogenic temperatures (20K). In terms of processing, hot isostatic pressing of powder Ti-alloys, isothermal forging for complex products will see further growth, apart from EB welding. The other generic areas which will gain importance in the near future are production technologies which are cost competitive for commercial uses, products with higher buy-to-fly ratio to reduce scraps and green processing technologies due to stringent environmental regulations.

The high strength beta titanium alloy similar to Ti-10V-2Fe-3Al (Ti-1023) has been indigenously developed by DRDO with Midhani. This alloy is for closed die forging application as it has low flow stress at the hot forging temperatures and therefore complex shapes can be manufactured for aircraft structural applications. 100 mm dia forged bars and 60 mm dia hot rolled bars of the alloy has been type certified for aircraft applications and it will be used in future aircraft structural forgings, replacing the Ni-Cr-Mo steels and resulting in about 40% saving in weight on similar size basis.

An alloy similar to Ti-5Al-5Mo-5V-3Cr in terms of properties is presently under industrial scale development by DRDO in collaboration with Midhani. It is a high strength beta titanium alloy that has higher hardenability in comparison to Ti-10-2-3 and will be used for higher section size thickness forged components for aircraft structural applications.

The medium temperature capable, oxidation resistant alloy for aircraft sheet and formability application similar to Timet21S is also under industrial scale development. Thick plates (120 to 150 mm thick) of Ti-6Al-4V has also been developed along with type certification for aircraft structural application. Several compositions of intermetallic titanium alloys, γ-TiAl alloys for aero-engine applications are also in various stages of development for high temperature applications. These alloys extend the application temperatures of conventional high temperature titanium alloys that is below 600°C, beyond 750°C and can replace nickel base superalloys and result in considerable weight saving as has been proven in case of GE GenX-1B engine. Besides this DRDO has also established thick plate titanium welding by two pass auto-TIG process with its industrial partners. This enables the manufacture of large size titanium alloy bulk head frames for future aircraft applications

2.3 Gap Areas and Recommendations

Ti spong making technology

The technology to make Ti sponge exists in India at the Titanium sponge plant (TSP), KMML. However, KMML has been operating at a capacity of 150-200 MT/year against the installed capacity of 500 MT/year due to various reasons Technical/expert recommendations are put in place for improving economics and increasing the operating capacity to 500 MT/year. KMML has also been asked to work out the details for capacity expansion to 1000 MT/year. Capacity expansion beyond that however, may need technology for producing titanium sponge in bigger size batches of 6-8 MT/batch whereas the current batch size is 3.0-3.5 MT.

The $MgCl_2$ (by-product in the Ti sponge plant) recycling technology is under pilot scale testing. Two pilot projects of 70 MT/year of Mg metal are being implemented at Zirconium complex, Tuticorin and TSP, KMML, Chavara, Kerala. Based on the results of the pilot plants, there is scope for expansion of the facilities.

The technologyi to make Ti based aeroengine forgings also exists in India, although it has not been implemented at large industrial scale. Currently Government is considering establishing large scale forge facility for the purpose. The crucial challenge here is to generate enough work to keep the press engaged to justify the purchase. Larger width rolling mills are required to produce plates of adequate width for ISRO as well as Brahmos programmes. Titanium alloy investment casting technology capability has been fully established in several industries like PTC, Lucknow, Midhani and HAL. DRDO has partnered with industry to develop a few components. The manufacture of investment cast titanium alloy parts invariable requires HIP (hot isostatic pressing) that has also been established in private (PTC, Lucknow-has a big HIP furnace) as well at a few govt. organisations. Therefore, this technology is fully mature and even aircraft structural parts have been manufactured and type certified by DRDO.

Development of Aluminium based Masteralloys

Titanium alloy melting requires Aluminium based masteralloys for carrying out addition of denser and higher melting beta stablisers like V, Nb, Mo etc. These are always imported and are costly. Their supply is also ransom to international geo-political scenario and also other vagaries of supply chain issues. Therefore DRDO is in the initial stages of industrial scale development of industrial partners for production of these Aluminium based masteralloys that are normally produced by thermit process.

Recycling of Titanium alloys

As the titanium alloy production picks up in India, there will be lot of scrap generated; hence DRDO has just started work on recycling of titanium alloy scrap along with industrial partners. There are two issues that is planned to be addressed. Firstly, titanium sponge production results in various grades of it. Titanium sponge of grade-1 quality is used for alloy production by compaction of electrodes and melting. The other grades of titanium sponge are not very compactable and hence it is difficult to form electrodes for melting. PTC, Lucknow industries have planned to have a Electron Beam Cold Hearth Remelting furnace (EBCHR) along with Vacuum Arc remelting and other facilities. DRDO along with its industrial partners is therefore planning to use the other grades of sponge for melting and also is planning for establishing Titanium alloy scrap melting and usage as soon as the facilities become operational at various industries. High temperature carbo-chlorination can be adopted to recycle highly oxidized titanium scrap to produce $TiCl_4$ with associated value addition.

2.4 CASE STUDY

Case Study 1: Development of thick Titanium forgings at L&T for Submersible – Deep Ocean mission

Project Description

The project involves manufacturing of 4 types of thick titanium alloy forgings for personnel sphere of manned submersible system , capable of going up to 6000 metre depth in Indian ocean for deep sea exploration. The project encompasses development and establishment of forging technology & duplex annealing heat treatment parameters for manufacturing of Titanium alloy forgings (Dia. 2.1 m class & ~125mm wall thickness) with critical mechanical properties requirements including fracture toughness (77 MPa.m$^{1/2}$ min.) and Ultrasonic Class A as per AMS2631

Project Objectives

1. Design of tools and dies for forging Ti alloy components to near net shape of finished components.
2. Develop forging technology for converting VAR Ti alloy ingot to shaped forgings to near net shape.
3. Establish intermediate and final thermo-mechanical processing cycles to achieve desired mechanical properties
4. Simulate the forming process through simulation software (Simufact) for studying the material flow and stress on dies
5. Shaping of components to near net shape in the form of profiled ring and dome shaped forgings

Key Challenges Faced

1. Ti6Al4V alloy has a very narrow forging temperature range thereby require multiple reheats to realize the near-net shape components.
2. Temperature and strain rate dependent flow stress also pose forging challenges and thereby requires careful selection and control of the process parameters.
3. Loss of material due to multiple stages of bloom conditioning by grinding/ machining to remove the surface openings at intermediate stages
4. Close control on dimensions in hot condition with specially designed tools to address the issue of material availability
5. Achieving uniform mechanical properties and realizing ultrasonically sound forgings meeting AMS2630 Class A1.

Partners Involved

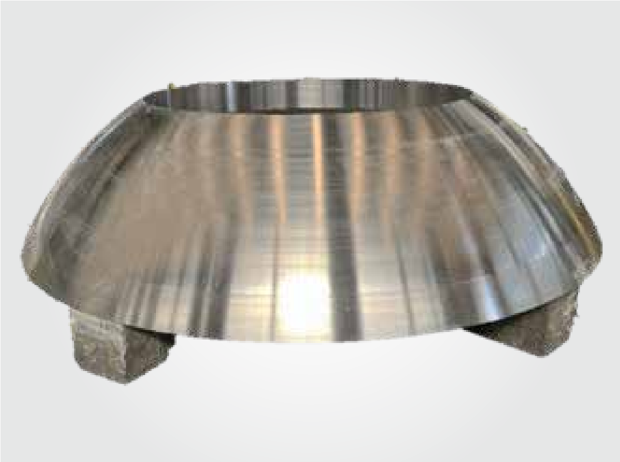
- Forgings processed at L&T Special Steels and Heavy Forgings in collaboration with Materials and Mechanical Entity-VSSC/ ISRO, Trivandrum.
- Ti6Al4V-ELI Ingots of 5.5MT indigenously made at Midhani using melt over melt techniques (largest made in the country till date)

Benefits

- **Fulfilling the Aim of India's Deep Ocean Manned Mission:** With success of manned submersible sustaining pressures at a depth of 6000m below sea level. India will be joining the elite group of four other countries who have acquired these capabilities.
- **Advancement in Forging Capabilities:** L&T Special Steels and Heavy Forgings achieved a milestone by manufacturing India's heaviest Titanium alloy shaped forgings (Dia. 2.1m class and 125mm wall thickness), showcasing L&T's capability to produce titanium forgings.

Figure / Illustration of the Technology/ Product

Processing



Final product

Case Study 2: Development of Metastable Beta Heat Treated Alloy Sheet

Project Description: High strength metastable beta titanium alloy Titan44A meeting the specification AMS4897 is required for hot zone structural parts of indigenous combat aircraft programmes. Typical size of the sheets is 1.2 mm thick x 1000 mm width x 2000 mm length. The material is required to be hot formed followed by age hardening.

Project Objectives

1. The alloy composition to be achieved is Ti-15Mo-3Al-2.7Nb-0.25Si
2. The typical Young's Modulus is 103 GPa.
3. YS = 938 MPa at R.T. and 517 MPa at 482 °C
4. The sheets should be flat, without scratches (since it has to satisfy fatigue properties) and the surface should be free of oxidation

Key Challenges Faced

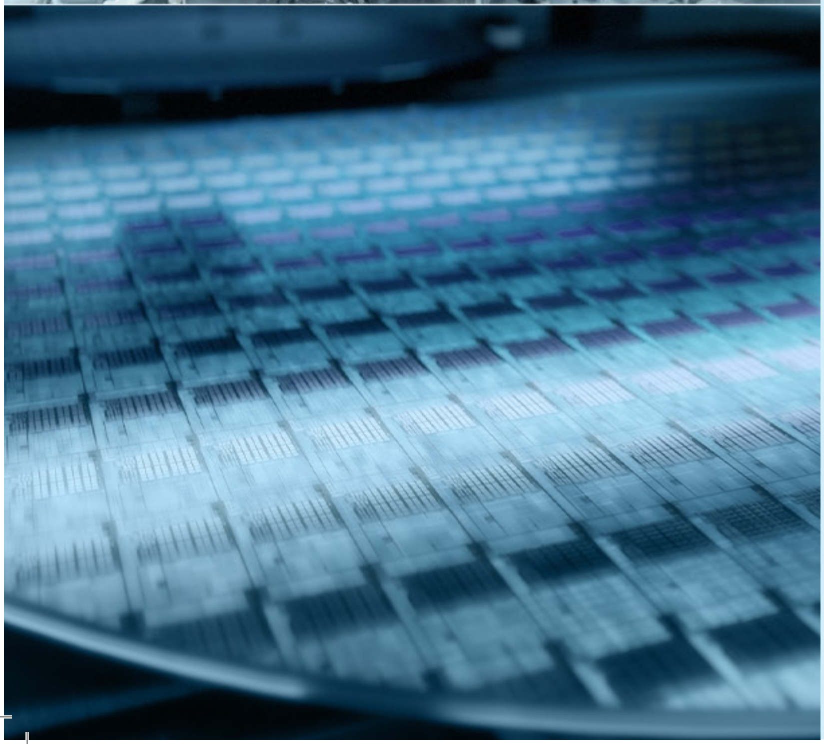
- Mo-containing master alloys are required for alloy making by vacuum arc remelting. These are not produced in India nor easily importable
- Lack of suitable cold rolling mill infrastructure which allows coil-to-coil rolling under applied tension to ensure flatness of the sheet
- The heat treatment requires a vacuum furnace with inert gas quenching facility. This is not available in India.
- **Partners involved if any:** ADA (leading), DMRL (development partner), Mishra Dhatu Nigam (Industry)
- **Benefits:** The Titan44A alloy sheets are required to be used in hot zone of combat aircraft. Developing indigenous source help in reducing import dependency and material procurement times.

Chapter Contributors

On behalf of the CII National Mission for Technology, Innovation and Research, we would like to acknowledge and express gratitude to the following for their contributions in the Chapter on Titanium and Its Alloys:

- **Prof Amol Gokhale** Professor, Mechanical Engineering, Indian Institute of Technology Bombay and Lead, Titanium Chapter
- **Dr Amit Bhattacharjee,** Director of Management Studies & Head, Titanium Alloy Group, DMRL, Hyderabad
- **Dr Ch RVS Nagesh,** Scientist G, Head Ti and Mg Group, DMRL Hyderabad
- **Mr Sanjay Sharma,** New Products Business, L&T, Mumbai
- **Dr R K Rayudu,** ADA





CHAPTER-3:

CERAMICS

3.1 Executive Summary

In India, a large number of research groups in IITs, IISc, NITs and universities have been pursuing cutting edge research in the field of engineering ceramics. Ceramic engineering as an independent discipline at the undergraduate level has been taught in few institutes across India including IIT BHU, NIT Rourkela, Govt. College of Engineering and Ceramic Technology, Kolkata, HKE Society's PDA College of Engineering, Gulbarga, University College of Engineering and Technology Bikaner, Bikaner Technical University, Bikaner, Rajasthan Technical University, Kota, Asian International University, Manipur and Anna University, Chennai. A large number of CSIR labs (CGCRI, Kolkata, NML, Jamshedpur, NAL Bangalore, NIIST Trivandrum), DRDO labs (DMRL, Hyderabad, ASL Hyderabad), BARC Mumbai, and VSSC-ISRO, Trivandrum, have been developing different technologies related to manufacturing and deployment of ceramics for emerging applications spanning from traditional sectors (pottery, refractories) to more advanced and strategic sectors (electronics, communications, energy, space, biomedical, environmental). A number of MSMEs and large multinational corporates (MNCs) have been manufacturing and commercializing various ceramic products. However, the growth of ceramic industries in India has not been significant over last several decades in terms of meeting the domestic market demand or to exploit the opportunities in translating early-stage technologies from national labs. In the above perspective, this report presents a status and recommendations for the national ecosystem in ceramics. A team of 6 expert members comprising senior academicians, research scientists and industry leader provided a persuasive report on major enablers that help bridging the gap between Indian and global situations. The authoritative perspective towards developing techno-entrepreneurship, capacity building, complementary ecosystem and policy making for the ceramics growth in Indian context is presented. The application domains ranging from traditional ceramics and refractories to advanced ceramics, glasses and coatings in frontier sectors are discussed with major focus in the Indian context. The increasing involvement of advanced ceramics and future demands in energy, aerospace, and defense sectors is highlighted. Considering the vulnerable supply chain and energy-intensive and pollution-prone production routes, the report also suggests pertinent steps in achieving sustainability while maintaining techno-commercial benefits. The report closes with a few example studies of recent technology and product developments in the Indian ceramic sectors.

3.2 Materials and Market

Ceramics and glass have shaped the history of human civilization over millennia. From ancient footprints of developments in ceramics and glass in archaeologically excavated sites in Egypt, Mesopotamia, India, and China to modern times, there has been a distinct transition from the craft of making ceramic pottery, jewellery, and decorative artwork to engineering ceramics for a variety of advanced technological applications. In most developed and developing economies, the usage of engineering ceramics encompasses a wide gamut of applications, such as structural, environmental, energy generation, healthcare, automotive, aerospace, sensors & actuators, electronics & telecommunication, defense, and so on. Ceramics, a class of inorganic materials with ionic and/or covalent bonding, have unique advantages with respect to other material classes (metals and polymers) in terms of superior thermal properties (thermal shock resistance), mechanical properties (higher hardness and compressive strength), tribological properties (lower wear rate) and high temperature properties (strength retention, oxidation resistance).

According to a report of the Grand View Research, the advanced ceramics and composites market is divided into several key segments. The largest segment of the advanced ceramics market is electronics & electrical, followed by chemical, transportation, and industrial. A smaller share of the market segment is claimed by medical, defense & security, and others [1]. The global market size for advanced ceramics and composites is estimated at $103.44 billion in 2021 and is expected to grow at compound annual growth rate (CAGR) of 4.1% to reach $148.5 billion by 2030 [2]. The US market for advanced ceramics is estimated at $16 billion which has grown almost 200% in the last decade and a half. The European market for advanced ceramics is estimated at €28 billion. The Japanese growth of sophisticated, high-quality, high-performance, and innovative ceramics, coined "fine ceramics" is expected to reach ¥2 trillion in near future [3]. With a global market of $100 billion, the ceramic industry demands a great deal of attention and focus in the Indian context, especially, as it has risen to the fifth largest economy in the world surpassing the UK, as per the recent report from the International Monetary Fund (IMF). The growth in the Indian ceramic market is accelerated as the country pitches for infrastructure (metallurgical, cement, roads & bridges, buildings, etc.), energy generation (thermal power plants, hydrogen energy, solar energy, etc.), transportation (automotive, aerospace and railways) and strategic initiatives (indigenous production of defense and aerospace equipment) which require technical and industrial ceramic components at large scale. Majority of the Indian export of ceramic products are to the Middle East and Europe, with Saudi Arabia accounting for up to 20% of the total ceramic exports. Indian ceramic industry is growing at 9% CAGR and has become a €7.5 billion industry in 2022 [4]. The rising demands in the domestic and export market need to be accomplished by suitable initiatives by the Indian industries for which a clear roadmap is essential. As ceramics play pivotal role in advanced engineering and the development of a sustainable society, developed counties have adapted best practices to ensure high-quality production, cost effectiveness and, sustainability. The United States government initiated Materials Genome Initiative (2011) to accelerate advanced materials development by integrating high-throughput experimentation, computational tools, and data analytics. The European Union identified Key Enabling Technologies (KETs) to drive innovation, competitiveness and sustainable growth to maintain leadership in strategic sectors. Strategic Priorities for Advanced Materials Technology Program (2008) is one of the programs of Saudi Arabia to achieve sustainable development via advanced materials technology. Despite growing demand for advanced ceramics in frontier sectors, India's progress is limited due to issues related to raw materials availability, supply chain, processing, machining & finishing, equipment manufacturing, testing, certification, trained manpower, etc.

3.3 Gap Areas and Recommendations

3.3.1 Raw materials

India has rich mineral reserves of basic raw materials (viz. quartz, bauxite, talc, limestone) that can be used for preparing traditional ceramics. However, the unavailability of high purity powders and precursors for manufacturing advanced ceramics (viz. electronic grade SiC, Si_3N_4) remains an issue of major concern.

The ceramic industry in India is heavily dependent on imports for several of these raw materials. Thus, the supply chain issues need to be addressed adequately to achieve self-reliance.

Recommendations: Seamless supply chain

Developing sustainable industries and industry clusters in various application domains of ceramics is instrumental in driving the supply chain. Industry clusters are located in limited places like Morbi, Thangadh, Khurja, Vriddhachalam, etc. A national level nodal agency is recommended to coordinate with ceramic industry clusters. The agency shall have a mechanism to provide a timely supply of required raw materials by taking care of the import permissions, taxation and other related issues. A regular survey shall help in obtaining the domestic demand information with respect to newer applications.

Recommendations: Mineral processing

Private companies and R & D organizations need to be encouraged for the extraction, purification, beneficiation and other steps of processing of available minerals to obtain high quality ceramic powders to meet the demands of Indian ceramic industry.

Recommendations: Fiber synthesis

India faces technology denial or embargo for ceramic fibers (such as high purity silica fibers, high-strength carbon fibers, SiC fibers, etc.). It is high time that Indian academia and R & D to focus on producing high purity ceramic fibers in collaboration with industry for their use in frontier sectors.

3.3.2 Manufacturing

In addition to raw materials unavailability and supply chain vulnerability, ceramic industries experience a large degree of negative externality in terms of the highly polluting and energy-intensive nature of manufacturing processes. The lack of skilled manpower and process equipment manufacturers are also major concerns. Furthermore, performance testing facilities and certification agencies are limited.

Recommendations

Ceramic industries shall adapt non-aqueous, less effluent and less energy-intensive synthesis routes considering the environmental and energy concerns. Advanced techniques like atomization, microwave sintering, additive manufacturing, etc. can be adapted. Incentives need to be provided for the domestic manufacturers of equipment for processing and testing. Indian industry shall adapt advanced technologies in manufacturing equipment for ceramic processing, characterization and performance assessment to meet the diversified and stringent demands in frontier applications. For example, high-temperature furnaces (graphite furnaces, hot press, etc.) and advanced fabrication equipment (3D printers, LSI, Sputtering, HVOF coating, CVI, etc.) are required for the development of advanced ceramics and coatings. Furthermore, characterizing these ceramic materials in simulated application conditions for performance assessment requires specific testing facilities like high-temperature UTM, indentation testers, tribo-test rigs, physical property measurement system (PPMS), etc.). Cluster-specific certification organizations need to be established to obtain hassle-free permissions for product qualifications.

Computational data science approaches are essential to understand and predict the processing-property relationships. Such approaches can be explored to address the related materials questions, saving significant time and cost when compared with conducting numerous physical experiments. It is important that artificial intelligence, machine learning, etc. need to be adapted to solve problems related to ceramic materials and manufacturing.

3.3.3. Consortium and capacity building

India is currently the second largest manufacturer of ceramic products and deserves the first position with respect to the largest domestic and international market. However, the domestic industry players are few and lack coordination with academia to meet market demands. The expertise in developing advanced ceramic materials to meet the demands in strategic and other frontier sectors is rather limited.

Recommendations: Complementary ecosystem

Efforts should be made to increase the number of participants to develop a competitive as well as a mutually complementing ecosystem. Government support should focus on facilitating the establishment of manufacturing bases in the domain. Collaborations form an important route for complementing the ecosystem. Networking with academic and R&D institutions in India and abroad, leveraging the strength of bilateral and multilateral international cooperation programs and promoting participative science and technology development with industrial partners should be explored and implemented.

Recommendations

Techno-entrepreneurship and capacity-building in new ceramic materials development synergized through R&D and technology inputs from national laboratories, academic institutions, etc. could prove to be an important driver in sustaining a vibrant industrial base. Such an effort should act as a feeder line for the development of start-ups and indigenous manufacturing hubs in the country.

Centres of Excellence (CoE) are to be set up at premier national institutes with a proven track record of delivering products and solutions related to advanced ceramics, composites and coatings. Such Centres should be equipped with the necessary infrastructure for innovative product and process development along with necessary training programs for industry professionals from MSMEs/ Corporates.

Encouraging academic institutes for ceramic undergraduate programs is necessary to prepare skilled manpower to meet large demands from the industry/research. Efforts shall be made towards increasing the skilled female workforce and maintaining gender equality.

Setting up national Centres for ceramics testing and characterization, setting up skill Centres, implementing new curricula for university science and engineering programs, inculcating trans-disciplinary skills in management, entrepreneurship, etc. could form important components in capacity building for the sector.

3.3.4 Government Support

Recent extreme changes in supply chains forced the global ceramic players in the US and Europe to shift their dependence for ceramic supplies from China to India. The policy makers in the Government need to support the Indian ceramic industry to grab the opportunity to become a reliable supplier in the global market. Recently initiated programs/schemes like Micro and Small Enterprises - Cluster Development Program (MSE - CDP), Industrial Infrastructure Upgradation Scheme (IIUS), Credit Linked Capital Subsidy Scheme (CLCSS), etc. to some extent support the ceramic industries development and technology upgradation towards enhancing the productivity.

Recommendations

It is high time that a national-level advanced ceramics program be implemented with a major emphasis on the indigenous development of raw materials and precursors for advanced ceramics. Government support should be provided towards enhancing extraction, exploration, manufacturing, and production in the country.

This should be synergized with support to the private establishments to set up suitable infrastructure for technological development and promote innovation and entrepreneurship.

Recent efforts of the Gujarat state government in collaboration with the United Nations Industrial Development Organisation (UNIDO) to support the Morbi ceramic clusters modernization are to be adapted by other state governments for their local ceramic clusters [5]. Import duties and FDI need to be rationalized as the current duty for finished products happens to be lower than that of raw materials, thereby impeding manufacturing. The imposition of anti-dumping duty on ceramic products imported from China is one of the major ways to prevent dumping in Indian markets. Incentives such as lowering of Goods and Service Tax (GST) produced by Indian manufacturers (which is already in practice) are to be continued.

Several international bodies developed certifications or standards like ISO 13006, EU 14411, ANSI A137.1, etc. to meet the quality and safety benchmarks for ceramic products at the global level. Japanese Industrial Standards, Guobiao Standards (China) and Bureau of Indian Standards are rather general and do not effectively address issues specific to ceramic materials, manufacturing and testing. In order to ensure the quality of Indian ceramic products at the domestic and international levels, immediate efforts are to be made to draft an Indian Certification of Ceramics similar to the Indian Certification of Medical Devices. The certification organizations should function at the cluster level to facilitate small or medium scale ceramic industries.

Besides policies and guidelines that encourage setting up incubators and innovation Centres in research/academic institutions, seamless mechanisms for technology transfers and protocols would be strong enablers in driving the ceramic innovation ecosystem in the country.

3.4 Traditional and Advanced Ceramics

In view of the Indian perspective towards becoming the 4th largest economy and in line with the Make in India initiative, the contribution of ceramic materials development and engineering will be predominant. The present section deliberates on major categories of ceramics with respect to their use as traditional ceramics and advanced ceramics.

3.4.1 Traditional Ceramics

The traditional ceramics comprise tiles, bricks, sanitarywares, tablewares, ornaments, glasswares, ceramic insulators, cement, and refractory bricks. India is the second largest global producer of ceramic tiles, sanitaryware, and tableware accounting for 7% of the global production, with ₹26,500 crore market set to grow at 9% in the current decade. A dominant share of the Indian ceramic market is captured by the ceramic tile industry (market size €3.8 billion). With rapid urbanization in India and the emphasis on Smart Cities by the Government, the demand for ceramic tiles and sanitaryware is anticipated to grow rapidly till 2030. Morbi, a small town in Gujarat, traditionally made tiles way back in the 1930s, houses more than 1000 ceramic manufacturing units at present, and is known as the Ceramic Capital of India. The traditional ceramics domain faces several challenges, such as stringent environmental norms, the rising cost of production, high-energy intensive and low-efficiency processing, etc. Modern kiln design, increased efficiency in firing, and energy-saving innovations and materials technology are being adapted worldwide to meet these challenges.

The availability of raw materials typifies the challenges for the refractories sector. Naturally occurring minerals like fire clay, kyanite, bauxite, sillimanite, magnesite, etc., and synthetic raw materials like alumina, mullite, magnesia, etc. are being routinely used. The non-availability of raw materials makes the Indian industry heavily dependent on foreign sources, particularly China. Magnesite is one such example and so is alumina-silicate, which has a high content of alumina. Beach sand minerals like sillimanite and zircon are used for the production of refractories. Graphite and non-oxide materials will be largely the future refractory materials for iron and steel plants. Monolithic refractories (castables, gunning mix, and plasticiser) are being increasingly used to enhance performance.

3.4.2 Advanced Ceramics

Advanced ceramics and ceramic composites constitute an important segment of ceramic materials. Owing to the unique combination of physical, mechanical, thermal, electronic, tribological and corrosion properties, advanced ceramic and ceramic composites are preferred over currently used metallic alloys for various applications. In the advanced ceramics family, carbides & nitrides of silicon, aluminium, tungsten, etc., borides of titanium, zirconium, hafnium, etc., oxycarbides, carbonitrides and oxynitrides (such as silicon oxycarbides, silicon carbonitrides, SiAlON, etc.), fibers of silicon carbide, silicon nitride, and composites made of carbon/SiC/ZrC/Si3N4 fiber reinforcement and SiC/Si3N4 matrix are of immense strategic importance for the country.

Continuous carbon fiber reinforced ceramic matrix composites are desirable for several high-end applications like heat exchangers, nuclear reactor components (e.g. control rod sheath & fuel constituents, fusion energy (first wall materials), receiver materials of concentrated solar power systems, high temperature thermoelectric devices and static components in gas turbines and aero engines, etc [6]. CSIR-NAL successfully developed complex-shaped carbon fiber or SiC fiber reinforced SiC composite products by isothermal isobaric chemical vapour infiltration (ICVI) process. As the matrix/fibre interface plays a pivotal role to achieve required properties, interfacial engineering needs to be investigated for the development of these composites. Considerable research has been done in the manufacturing of carbon fibres, whereas extensive efforts are needed to manufacture other fibres such as ZrC, SiC, etc. for their use as reinforcement to obtain composites with superior mechanical, tribological and high-temperature oxidation resistance properties. A study at IIT Roorkee illustrated the development of dual phase SiC/Si3N4 nanowires/fibres/threads by a suitable heat treatment of milled nanosize SiC particles [7].

Alumina, titania, zirconia, silicon carbide, or some glassy materials are used as membranes for water purification purposes such as industrial effluents, oil-water separations, removal of heavy metals, gas separation, etc. The Indian & Middle East ceramic membrane market is estimated to surpass US$ 1,687.20 million in terms of revenue by the end of 2028, exhibiting a CAGR of 10.20% during the forecast period (2021 to 2028) [8].

As the largest consumer of glass in construction around the globe, India is rapidly expanding on account of emerging industrial infrastructure, automotive and construction sectors. It is estimated that the Indian commercial glass market will grow at a CAGR of around 12% over the forecast period of 2019-2027. Specialty glasses with high mechanical strength, chemical resistance and optical transmission find applications in different fields such as electronics, optics, ophthalmic lenses, glass-ceramics, etc. High performance glass fibers with superior corrosion resistance, temperature resilience, and operating spectrum are essential for frontier applications. The global market for fiber optics is projected to grow at a CAGR of 10.9% during the period of 2022-2027, and is expected to reach $8.9 billion. India currently has almost 28 lakh kilometers of an optical fiber network that is slated to rise to 50 lakh kilometers by 2024, with an annual deployment rate of around 4 lakh kilometers. Despite this, only two Indian companies Sterlite Technologies Ltd., Aurangabad, and Aksh Optifibre Ltd, Hyderabad are involved in making standard communication fiber for optical fiber cabling. Indian manufacturers produce 100 million kilometers of optical fiber annually, which falls short of the national requirement by almost 50%. Apart from telecom, the Indian defense sector procures fiber-based laser components and high power fibers for gyroscopes, light detection and ranging (LiDAR) application, metal cutting, marking engraving, etc.

With regards to healthcare applications, bioceramics occupy a special place (compared to metals, polymers, and their composites) due to their unique characteristics and properties. Globally, the bioceramics market is expected to grow at a CAGR of 6.5% during (2021-2030) [9]. Hydroxyapatite bioceramic is considered for hard tissue replacement, while bioinert ceramics such as Al2O3, and ZrO2 are popular for total hip replacement and dental implants. The successful endeavor of indigenous manufacturing of phase pure beta-tricalcium phosphate (β-TCP) together with clinical validation is presented in Annexure-2.

In the present scenario, the communication, defence, aerospace, medical and healthcare industries move towards high dielectric ceramics for diverse applications. Electronic ceramics include piezoelectric materials, ferrites, solid electrolytes, multi-ferroics, and ferroelectrics. Metal oxide semiconductors (MOS) are used for gas sensor applications. The scientists at CSIR-NAL indigenously developed oxygen and NOx sensors for their use in automobiles. Electro-magneto ceramic materials development is ubiquitous to meet new applications in electronic packaging and miniaturised RF systems.

Globally, limited manufacturers (Maruwa, Exxelia, Kyocera, etc.) for electronic ceramics are available, and in India, technical ceramics manufacturing is very limited due to several challenges. Technical ceramics production requirements demand clean environment and ultra-high pure raw material. Ceramic machining & finishing by ultrasonic or diamond-coated tools is inevitable to realise custom-designed products having different contours for specific applications. But, the component sizes are small and quantum is less compared to conventional ceramics. Yet, the cost is high due to imported raw materials of electronic grade purity, stringent processing conditions, test & evaluation procedure etc. It is necessary to set-up dedicated pilot-scale plants for technical ceramics production including machining to meet domestic requirements of aerospace and defence sectors. Currently, initiatives have been made by ISRO with seed activities involving M/s. CUMI, Hosur, M/s. COSMO Ferrites, Parwanoo, M/s. Bhukanwala Industries, Navsari, M/s. VCB Electronics, Pune, etc. The recent announcement of Tata Electronics to build a state-of-the-art semiconductor assembly and test facility in Assam is a significant step towards developing the semiconductor manufacturing ecosystem.

Several ceramics and glasses are used as coatings for components subjected to extreme conditions of chemical attack, high wear and high temperature as they transform the surface of the substrate into chemically inert, friction resistant, abrasion resistant, and oxidation resistant over a range of temperatures. The applications of ceramic coatings are many including engine components, insulating tiles, space shuttles, rocket exhaust cones, prosthetic parts, surgical instruments, etc. The value of ceramic coating global market was USD 9.75 billion in 2021 and is estimated to grow at a CAGR of 7.8% during 2022-2030 [10]. Several techniques like chemical vapour deposition, physical vapour deposition, dip coating, electrophoretic deposition, thermal spray techniques (HVOF spray, plasma spray, detonation gun spray), etc. are employed to coat variety of ceramics including oxides, silicides, borides, nitrides, oxides and carbides on metallic substrates. One example study of the fabrication of detonation spray machine and its capability of ceramic coating technology is presented as Annexure-3. Thermal sprayed zirconia coating on metal substrate is used for moving parts of the engine where oxidation and wear are major concerns. WC-Co-Cr coating is useful for paper-rolling mill where corrosion by acidic or basic pulp is of concern in addition to the abrasion.

Glass coatings are applied using spraying or dipping technique for space heaters, radiators, and exhaust ducts of engines. Yttria-stabilized zirconia, rare earth oxides or rare earth zirconates are preferred as ceramic topcoats in thermal barrier coatings (TBCs) for gas turbine combustors, aero engine components, and heat exchangers to provide heat insulation and improve efficiency at elevated temperatures. Transparent conductive ceramic coatings are used for solar panel applications. Another example of indigenous technology development of eco-friendly graphene oxide based solar absorber coating is presented in Annexure-4.

In summary, there is a rising demand for the usage of ceramics for wide variety of applications ranging from domestic sector to frontier regimes. In particular, strategic applications such as high-speed missile radomes, bulletproof vehicular armor, nuclear power generation systems, etc. essentially need advanced ceramics, glasses and coatings. As the technologies for processing these are strictly controlled by established foreign powers and many products are under embargo, it is imperative to develop indigenous technologies, preferably with indigenous raw materials for processing and fabrication of these materials and components thereof.

3.5 Sector-Specific Aspects

The present section draws attention to the selected sectors where ceramics are essential for the sustainable development. An overview of ceramics used in the energy, aerospace, and defense sectors are highlighted in the Indian context.

3.5.1 Energy Sector

Ceramics and glass are key materials for the safe generation of nonconventional forms of energy. Affordable hydrogen generation is the basic pillar of the hydrogen economy, especially for the developing world. In 2021, the Government of India announced the National Hydrogen Energy Mission (NHEM). In this context, the production of hydrogen using a high temperature solid oxide electrolyzer cell (SOEC) has high potential due to its high efficiency and economy of scale. It is important to develop SOEC for the sustainable power generation with solid oxide fuel cells (SOFC). Indigenous development of such materials and components is essential to align with the global demand for cutting-edge technologies related to non-conventional energy generation and storage. In this regard, CSIR-NAL has indigenously developed SOFC single cells and small stacks and successfully tested them in SOFC and SOEC modes. Another national lab, ARCI jointly with CSIR-CGCRI and HPCL, in a consortium project, is establishing a pilot scale facility for the development of SOFC systems and fabricating indigenous solid oxide fuel cells.

In terms of materials related to Li-ion battery technology, the primary raw materials required for cathode powder manufacturing, which makes 35% of a cell cost and 10% of total electrical vehicle cost, are manganese, nickel, and lithium. The cathode materials are typically either 'layered' Li- transition metal (Ni, Mn, Co etc.) oxides, which possess a cation ordered rock salt structure, or olivine structured Li- transition metal (Fe, Mn etc.) phosphates. Spinel structured Li-Mn/Ni-oxides are also being developed. Their synthesis usually involves co-precipitation or solid state reaction; both of which are scalable processes.

For electrode powder manufacturing, access to appropriate mines for lithium, nickel, manganese, etc. is thus required. Lithium is mainly controlled by three countries in the world: Australia, Chile, and Argentina. India has recently found Lithium reserves in Jammu & Kashmir. Nickel is not produced from primary sources in the country and the entire demand is met through imports. Fortunately, India has manganese ore deposits that occur mainly as metamorphosed bedded sedimentary deposits at several places [11].

As an alternative to Li-ion batteries, Na-ion based batteries are being aggressively pursued. The cathode materials in sodium-ion based batteries are typically ‘layered’ Na- transition metal oxides (which are Co-free; and can be based on Ni, Mn, Fe, Ti; some of which are available in India) or Na- transition metal phosphates. The hygroscopic nature of ‘layered’ Na- transition metal (TM) oxide-based cathode materials not only renders handling/storage an issue, but also mandates the usage of toxic/hazardous/expensive N-Methyl-2-pyrrolidone (NMP) as the solvent for preparing the electrode slurry. In this regard, a recent study at IIT Bombay has demonstrated a strategy to facilitate the development of highly water-stable ‘layered’ Na-TM-oxide cathode materials for Na-ion batteries [12]. In addition to the cathodes, for transitioning from liquid electrolyte containing battery cells to solid electrolyte containing ones, Li-ion or Na-ion conductors as solid electrolytes are being pursued and are deemed to have immense significance shortly.

Using thermal barrier coatings (TBCs) in aircraft propulsion, power generation, and marine

propulsion reduces fuel consumption and green-house gas emissions. TBCs are generally low thermal conductivity ceramic materials used to protect metallic components in high operating temperature conditions. TBCs are also being used in diesel engines, where higher operating tempera-tures translate into increased fuel economy and cleaner exhaust.

3.5.2 Aerospace Sector

Ceramics and glasses find wide applications in the aerospace sector because of their unique combination of properties including light weight, ablation resistance, electrical insulation, corrosion resistance, and wear resistance. Satellites use various types of glasses for sensor applications. Glass ceramics like zerodur and silicon carbide are preferred for space mirrors, astronomical telescopes and laser gyroscopes. ARCI has indigenously established a facility to fabricate lithium aluminosilicate based low expansion glass ceramics of size 380mm x 350mm x 150mm. Optical solar reflectors are widely used for spacecraft thermal management.

Glasses like silica and aluminosilicate are also used as viewports for human space programs. Many electronic ceramics are used from ultra-high frequency to millimeter band of frequencies. Various dielectrics are used in patch antennas, filters and resonators. Alumina is widely used as a substrate for electronic circuit packaging applications. An example study of indigenous development of alumina and zirconia substrates for SOFCs is presented as Annexure-5. Ferrites are preferred for electromagnetic suppressions. Boron nitride and silica are used as liner materials for electric propulsion systems. Porous tungsten impregnated with oxides are used as thermionic material for electric propulsion systems.

Ceramics are largely recommended for critical components of space vehicles due to their high temperature capability. Porous silica tiles are used in the windward, flexible insulation in the leeward and carbon - carbon composites with silicon carbide coating are used in the leading edges. Hypersonic vehicles (Mach >5) or space missions, including launching from Earth to entry into the planetary atmosphere, experience extreme conditions of temperatures due to aerodynamic friction heating. ZrB_2, HfB_2, or TaC based composites are being considered for the ultra-high temperature applications such as thermal protection systems, leading edges, nose caps and rocket nozzles of hypersonic space vehicles. Besides, thermal barrier coatings are required in the thrust chamber of space vehicle engines.

In civil aviation, the use of ceramic matrix composites (CMCs) is increased in the last few decades to improve engine efficiency and reduce weight and CO_2 emissions. Using CMCs in the combustor and turbine parts improved fuel burn improvements and emission reduction. Furthermore, the use of CMC (C/C or C/SiC) in aeroplane brakes to passenger car brake systems has been witnessed in the last few decades.

3.5.3 Defense Sector

Owing to the attractive combination of less density, hardness, wear resistance, heat and corrosion resistance, wide variety of ceramics are used in defense sector. Alumina, titanium boride, silicon carbide, boron carbide, etc. are preferred for the armor systems and lightweight combat vehicles. Fused silica and silicon nitride are used for radomes of advanced tactical missiles due to their capability of retaining high strength in high velocity and high temperature conditions [13]. Also, ceramics find applications in infrared sensors, piezoelectric sensors, antennas, waveguides for communication system, laser windows, etc.

Yb-doped high-power fiber laser of multi-kilowatt power is explored for directed energy applications to clear space debris. Tm-doped glass is an important component to develop directional infrared counter measure (DIRCM) suitable for the anti-missile system, La-doped glass for making night vision goggles. Nd-doped bulk laser glass is critical in guidance system for the development of LiDAR system. Er-doped glass is used for the fiber-based system for data transmission in a nuclear environment, Sm-doped system to make permanent magnet suitable for high temperature operation, high-resolution telescope for use in space research, high-end electronics gadgets (smartphones, electronic panels), efficient LEDs, etc. Besides, all of these applications, when combined with other strategically important materials, advanced lasers could be used to build highly efficient batteries, electrical cars for the next generation, and so on. Another area of current research interest in terms of strategic application is the requirement of blue-green lasers for underwater strategic areas to detect submersed substances, navigation, coastal security, etc.

3.6 Sustainability

The increased competitiveness in the frontier sectors demands greater utilization of indigenous resources and development of sustainable ceramics technology. The ceramic industries are high energy and capital intensive. A significant amount of the cost of manufacturing ceramic items goes in the form of capital expenditure (CapEx) and operational expenditure (OpEx) for comminution of lumps into powders, colloidal processing of slurries, high-temperature sintering, cutting, grinding, and machining of ceramic blanks to shaped components, pollution mitigation measures and so on. Developed economies (such as European Union) have laid a great deal of emphasis on improving the techno-economics of ceramic production in the form of energy-efficient and sustainable technologies that are environmentally benign. Upscaling technologies from the laboratory level to the operational level constitutes a critical sustainability challenge that needs to be addressed. In a study by the European Union on emission sources from ceramic industries, 64% seem to come from fuel combustion, and process emissions and indirect emissions account for 17% and 19%, respectively [14]. India intends to attain the status of a carbon-neutral economy within 2075. This target has been envisaged in fixing and revising intended nationally derived contribution (INDC) that focuses among others, on nurturing sustainable processes in industries. Ceramic industries, with particular reference to pottery and tiles, unfortunately, represent among the most polluting industries in terms of carbon emissions. It is therefore pertinent to ensure that the Indian ceramic industry adopts ways to reduce combustion-related emissions along with others. The European Union has adopted such technologies e.g. microwave-assisted drying, heat pumps, use of biomass, biogas, syngas, green hydrogen, and electrification; to name a few. Indian ceramic clusters and industries have not yet enabled similar technologies and processes. Technological development that adapt

(i) less use of carbon-containing additives

(ii) use of optimized clay mixes in terms of carbon content and

(iii) use of advanced techniques like additive manufacturing to reduce consumption/ wastage of carbon-rich raw materials, shall be encouraged to attain carbon neutrality in processing. Post-processing operations like shaping using rapid and low cost machining techniques like electrical discharge machining, ultrasonic machining, air /water jet machining, etc. shall be adapted to achieve sustainable ceramic product development.

3.7 Case Studies

Case Study 1: Nuclear/ Defense/Aerospace Sector

Non-Oxide Ceramic Powder Synthesis and Densification

1. Executive Summary

In view of the challenges in importing high quality non-oxide powders for ceramic product manufacturing for the use in frontier sectors, indigenous development of powder synthesis technique is highly essential. BARC developed indigenous solid-state technique for synthesis of boron carbide (B4C), titanium boride (TiB2) and zirconium boride (ZrB2) powders and their subsequent densification by hot pressing.

2. Key Challenges

The production process for B4C powder involves a graphite resistance furnace with water-cooled terminals, developed by BARC, capable of producing abrasive-grade powder at a capacity of 3 tons per annum. Key challenges include maintaining consistent quality in B4C production, optimizing the efficiency of the graphite resistance furnace, and managing the high current requirements for the power supply. Additionally, ensuring the quality of the obtained product with uniform stoichiometry and free carbon levels. safety of the water-cooled terminals and addressing any potential environmental concerns during the production process are also some of the challenges.

Key challenges include optimizing the synthesis and densification processes of TiB2 to ensure consistent quality and performance. Additionally, managing the high temperatures and 0.001 Pa vacuum required for the production of TiB2 poses technical hurdles [13]. Addressing cost-effectiveness and scalability issues while maintaining the desired properties of TiB2-based materials presents another significant challenge.

Key challenges include optimizing the solid-state reaction technique for ZrB2 powder synthesis to ensure uniform particle size and purity. Additionally, achieving high-density ZrB2 shapes via hot pressing while maintaining structural integrity and desired properties poses technical hurdles. Addressing cost-effectiveness and scalability issues in production processes are also significant challenges.

3. Partners

BARC has shared the expertise of the technology with the following:

B4C technology: M/s. Bhukhanvala Industries Pvt. Ltd., M/s. Central Electronics Ltd., M/s. Saru Smelting Pvt. Ltd., M/s. CS Zircon Products Pvt. Ltd., M/s. Adonis Avero, M/s. Brahamastra Defence Techno Products Ltd.

TiB2 technology: M/s Bhukhanvala Industries Pvt. Ltd.

ZrB2 technology: M/s Bhukhanvala Industries Pvt. Ltd.

4. Techno-commercial Benefits

The utilization of these important ceramics offers numerous benefits, both technical and commercial. Their exceptional properties make them ideal for many nuclear, defense, and aerospace applications. The widespread applications contribute to market competitiveness, innovation, and economic growth, while availability ensures cost-effective solutions industrial needs.

5. Figures / Illustration of the Technology/ Product

B4C powder

TiB2 dense shapes of different sizes

Case Study 2: Healthcare Sector

Beta Tricalcium Phosphate Products for Healthcare

1. Executive Summary

Calcium phosphate (CaP) based bioceramics have garnered significant attention in the field of regenerative medicine and tissue engineering due to their biocompatibility, osteoconductivity, and bioactivity. Among the various forms of calcium phosphate, beta-tricalcium phosphate (β-TCP) with its chemical formula Ca3(PO4)2 stands out as a material that offers excellent biodegradability and resorbability, making it ideal for bone regeneration/ growth. The strategic utilization of wet chemical synthesis route results in synthesis of phase pure β-TCP. The process involves meticulous mixing of calcium (Ca) and phosphorous (P) precursors in a highly stoichiometric Ca/P molar ratio of 1.50, with pH regulation by controlled addition of ammonia. The final precipitate undergoes a series of well-defined processes involving, filtration, drying and heat treatment before benchmarking the product against commercially available β-TCP powder. The β-TCP granules are currently being supplied to the Paradigm Innomed as raw material for the bone graft substitutes. These granules are further sterilized and the bone granules have been clinically validated in a large number of orthopedic surgeries in patients across Indiautilized independently (without any antibiotics) as bone fillers. Post-operative, β-TCP granules suppressed the puss formation (lack of infection). These bone granules were clinically used together with calcium sulfate hemihydrate (CaSO4.1.5H2O), clinically acceptable bone cement.

2. Key Challenges

The synthesis of CaP products is intricately linked to stoichiometric precision and pH control during the production process. Even minor deviations in the calcium-to-phosphorus (Ca/P) ratio can significantly impact the properties. Additionally, scaling up the synthesis process presents challenges related to the increased quantity of ammonia, necessitating sophisticated process engineering to ensure safety during the process.

3. Partner

IISc, Bangalore and R&D division of Tata Steel Ltd.

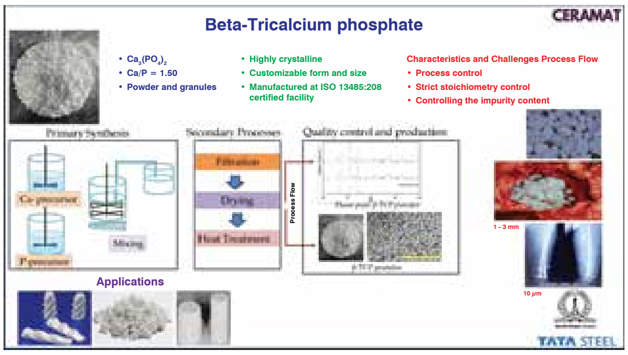
4. Customers

Paradign Innmoed Pvt. Ltd., Varanasi

5. Techno-Commercial Benefits

β-TCP offers high end biocompatibility, facilitating cell adhesion and bone regeneration, and is an alternative to the expensive allografts. Further, its bioresorbability aids in seamless tissue integration over time. With optimal mechanical support and cost-effectiveness, β-TCP's customizable synthesis empowers tailored solutions for diverse clinical applications.

6. Figures / Illustration of the Technology/ Product



Case Study 3: Energy Sector

Detonation Spray Coating Technology

1. Executive Summary

Detonation spray coating (DSC) technology is a premier, versatile and unique thermal spray family member technology, capable of depositing ceramic, cermet, metallic, alloy and composite coatings on a variety of substrate materials for enhancing wear, friction, corrosion, thermal, electrical, oxidation resistances. ARCI has indigenously developed detonation spray coating (DSC) technology for reaping the potential benefits of enhanced component service life and the associated techno-economic benefits to the Indian industry.

2. Key Challenges

The global technological resources are limited as the technology has been primarily developed nearly simultaneously by Linde Air Products Division of Union Carbide and scientists in the erstwhile Soviet Union. The process was mostly available as SERVICE ONLY from the Coatings Service Division of Union Carbide (now Praxair Surface Technologies) and therefore were the single-sourcing concerns and supply chain issues. Unlike most other thermal spray variants, the DSC technology is a pulsed process, therefore realizing an economically viable technology in the competing market is essential for its commercial sustenance and industrial adoption.

3. Partners

ARCI Hyderabad and Institute of Problems for Materials Sciences (IPMS), Ukraine.

4. Techno-commercial Benefits

The electrical power required is very minimum and operating gas pressures are low compared to other techniques. The coating system is economical for depositing coatings on low to medium size range components. Variety of coatings can be deposited on various industrial components using DSC technique. For example, ARCI has successfully deposited carbide coating on the pump shaft of nuclear power plant using the indigenously developed DSC technique.

5. Figure / Illustration of the Technology/ Product

Prototype advance DSC

Detonation spray coated pump shaft of nuclear power plant

Case Study 4: Energy Sector

Eco-friendly Graphene Oxide Based Solar Absorber Coating

1. Executive Summary

CSIR-NAL developed an eco-friendly graphene oxide based solar absorber coating as an alternative to existing NALSUN technology. A simple wet chemical method was used to prepare the graphene oxide powders with tailored optical properties. A sprayable formulation was prepared to deposit directly on metal substrates without any pre-treatment. The spectrally selective coating consists of two layers: an absorber layer and an inorganic protective layer. The coating can be sprayed on metal and non-metal substrates at a substrate temperature of 150 C. These coatings exhibit a high solar absorptance in the range of 0.91-0.93 and thermal emittance in the range of 0.25 - 0.30 at 82 C. The coating displays good thermal stability up to 175 C in air for longer durations. The coating has qualified stringent environmental tests such as humidity, condensation, accelerated aging, UV, and corrosion resistance as per the ASTM and International Energy Standards. Based on the test results, the service life of the coating is expected to be more than 20 years.

2. Key Challenges

Eco-friendly synthesis of graphene oxide powders with required optical properties (i.e., high absorptance and low emittance). The as-prepared powder should be RoHS and REACH compliant. No volatile organic compounds should be used in the synthesis process.

3. Partners

CSIR-NAL Bangalore transferred the technology to M/s. Supreme Solar Pvt. Ltd., Bangalore for manufacturing and commercialization of eco-friendly graphene oxide coatings for solar thermal applications.

4. Techno-Commercial Benefits

In general, spectrally selective coatings on evacuated tubes were deposited by sputtering process, which is a cost-intensive. The technology developed by CSIR-NAL is cost effective and the process is eco-friendly. In addition, the raw materials used in this process are abundant in nature and is cheap. The chemical disposal needs minimal effluent treatment process, because of the usage of environment-friendly materials.

5. Figure/Illustration of the Technology/Product

Patents

Indian Patent 0053NF2023, Application No.: 202311022581, Filed on March 28, 2023

International Patent, Application No.: PCT/IN2024/050296, Filed on March 22, 2024

Case Study 5: Aerospace Sector

Ceramic Substrates for Space Electronics and Consumer Products

1. Executive Summary

Ceramic substrates (ceramic printed boards) are the most ingenious and economical materials used in consumer electronics products and space electronics. The predominant ceramic materials that are used as electronic substrates and packages for space electronics include alumina and aluminium nitride. Alumina is the most widely used ceramic substrate as it is inexpensive, exhibits high resistivity, good mechanical and dielectric strength, superior thermal and corrosion stability and additionally provides hermetic sealing. There is a huge demand for alumina substrates for industrial and strategic applications. However, to date, all the requirements of alumina substrates are met by import. Realizing the great potential of alumina substrates, M/s. Carborundum Universal Ltd. (CUMI), Hosur sponsored a project to CSIR-NAL for the development of alumina (96 and 99.6%) and zirconia substrates for solid oxide fuel cells. CSIR-NAL has successfully developed the products and transferred the technology to CUMI in June 2018 and CUMI has set up a state-of-the-art tapecasting facility and has commenced the commercialization of sintered alumina products.

2. Key Challenges

To achieve perfectly flat substrates with camber <50 μm

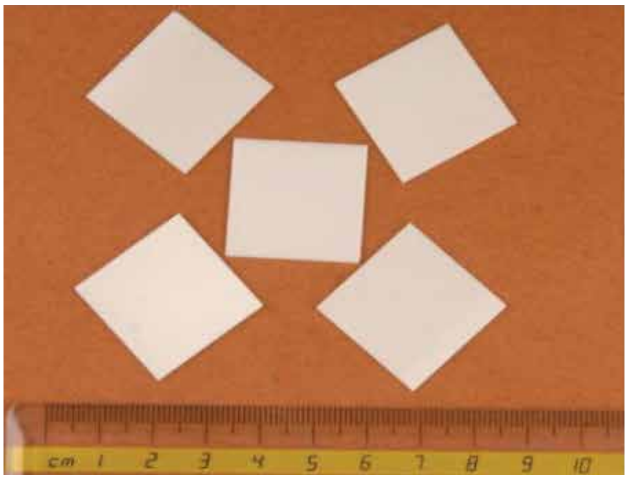
3. Partners Involved

CSIR-NAL Bangalore and M/s. Carborundum Universal Ltd. (CUMI), Hosur

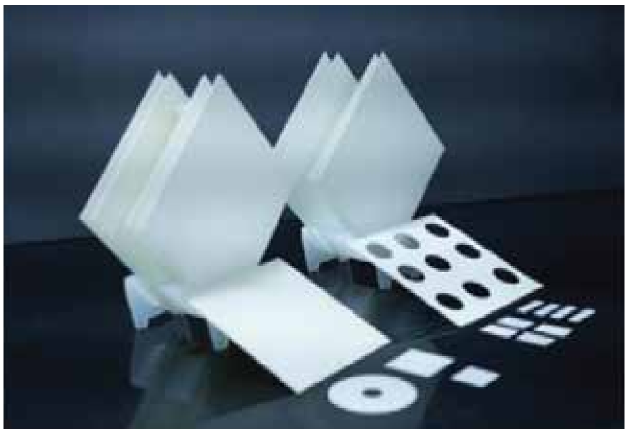
4. Techno-commercial benefits

These substrates are presently imported and are expensive. CUMI is trying to utilize locally available raw materials and manufacture at a lower cost. CUMI can now supply thick and thin film substrates for microelectronics application with the thickness ranging from 250 microns to 3 mm.

5. Figure/illustration of the Technology/ Product



Polished alumina substrate for microwave integrated circuits



Alumina substrates manufactured at CUMI

Chapter Contributors

- **Prof B Venkata Manoj Kumar,** Indian Institute of Technology Roorkee, Roorkee
- **Dr Harish C Barshilia,** CSIR-NAL, Bangalore
- **Dr L Rama Krishna,** ARCI, Hyderabad
- **Prof Amartya Mukhopadhyay,** Indian Institute of Technology Bombay, Mumbai
- **Dr Tammana S R Ch Murthy,** BARC, Mumbai
- **Dr M R Ajith, VSSC-ISRO,** Thiruvanthapuram
- **Dr Shyam S Rao,** CUMI, Bangalore

References

1. Advanced Ceramics Market Size, Share, Growth Report 2030 https://www.grandviewresearch.com/industry-analysis/advanced-ceramics-market (Accessed on May 09, 2024)

2. Advanced Ceramics Market Size, Share & Analysis Report, 2030 https://www.polarismarketresearch.com/industry-analysis/advanced-ceramics-market (Accessed on May 09, 2024)

3. TIFAC Report on Technology Roadmap Materials 2035 (2015)

4. Indian Ceramic Industry: Status Quo and Outlook, Messe Muenchen India and EAC International Consulting (2022)

5. R. P. Gupta and B Biswas. Trends and Growth in Ceramics Industry: A Comparative Study between India and China. Business Studies, Volume XLI, Nos. 1 & 2 (2020)

6. J. Binner and T. S. R. C. Murthy, Structural and Thermostructural Ceramics," in Encyclopedia of

7. R. Muthaiah, B. V. M. Kumar, Indian Patent No. 362136 (2017)

8. India & Middle East Ceramic Membrane Market Size by 2028 https://www.coherentmarketinsights.com/market-insight/india-and-middle-east-ceramic-membrane-market-4850 (Accessed on May 09, 2024)

9. https://dataintelo.com/report/bioceramics-and-hydroxyapatite-market (Accessed on May 09, 2024)

10. Ceramic Coating Market Size & Share Report, 2030 https://www.grandviewresearch.com/industry-analysis/ceramic-coatings-market#:~:text=The%20global%20ceramic%20coatings%20market%20size%20was%20estimated%20at%20USD,USD%2010.42%20billion%20in%202022 (Accessed on May 09, 2024)

11. Indian Minerals Yearbook 2020 https://ibm.gov.in/writereaddata/files/04272022163406Manganese_2020.pdf (Accessed on May 09, 2024)

12. B. S. Kumar, A. Pradeep, V. Srihari, H. K. Poswal, R. Kumar, A. Amardeep, A. Chatterjee, A. Mukhopadhyay, Cation–Oxygen Bond Covalency: A Common Thread and a Major Influence toward Air/Water-Stability and Electrochemical Behavior of "Layered" Na–Transition-Metal-Oxide-Based Cathode Materials. Advanced Energy Materials 2023, 13, 2204407

13. M. S. Heydari, J. Ghezavati, M. Abbasgholipour, B. M. Alasti, Various types of ceramics used in radome: A review, Scientia Iranica B 24(3), 1136-1147 (2017)

14. Ceramic Roadmap to 2050 https://cerameunie.eu/media/ambd23os/ceramic-roadmap-to-2050.pdf (Accessed on May 09, 2024)

CHAPTER-4:

BIO-MATERIALS AND IMPLANTS

4.1 Executive Summary

This detailed report examines the existing disparities within the Indian healthcare sector, specifically in the domains of biomaterials and implants. It offers a deep dive into the challenges that hinder the progress towards achieving self-reliance in manufacturing and clinical application of these critical components for patient care. Highlighting the strategic launch of the Medical Materials business by TATA Steel as a pioneering step towards innovation, this report, based on the intense deliberations in a 14-member team comprising senior leaders and young researchers from Indian industries, also provides specific recommendations for the policymakers as well as seeks to inspire and guide the formulation of a robust, indigenous ecosystem for producing high-quality medical materials and devices. By identifying specific gap areas, the report provides targeted recommendations for policymakers, aiming to foster a conducive environment for the growth of Make-in-India initiatives in this field. This document closes with illustrative examples (Refer Annexure I) of a few successful technology developments in this advanced materials sector, to demonstrate the impact of Industry-Institute collaborations, to manufacture medical implants or biomaterials in India.

4.2 Background

The realm of biomaterials is vast, encompassing both natural and synthetic substances engineered to interact with biological systems for therapeutic or diagnostic purposes. Biomaterials constitute a vital class of materials crucial for various medical applications, encompassing the replacement or regeneration of damaged tissues or organs or for the support or enhancement of their biological functions. These materials span a spectrum from natural to synthetic, including metallic, polymeric, and ceramic-based products. Recognizing the significance of advanced materials in this domain, several noteworthy options have been identified.

At the forefront are well-established materials such as Ultra-High Molecular Weight Polyethylene (UHMWPE), Stainless Steel, Cobalt-Chromium (Co-Cr) alloy, Titanium (Ti) alloy, and Zirconia, which collectively command a substantial share of the implant market. Additionally, there exist several other materials, albeit less commonly utilized in comparison, yet of considerable importance. These include β-TCP (beta-tricalcium phosphate), Hydroxyapatite(HAp), Gelatin, Collagen, PLLA (poly-L-lactic acid), PLGA (poly(lactic-co-glycolic acid)), and PEEK (polyether ether ketone).

Hydroxyapatite, for instance, finds extensive application across various industries, including the biomedical sector, food and fodder industry, pharmaceuticals, cosmetics, as well as in basic and advanced research laboratories. Given the broad utility and potential of these materials, it is imperative to focus national efforts on their development and utilization as biomaterials for indigenous biomaterial and implant development. The proposed national task force will diligently harness the diverse capabilities of these advanced materials, ensuring their inclusion and comprehensive exploration to drive innovative biomaterial and implant solutions.

Advanced materials: Phase pure and Thermal sprayed hydroxyapatite, β- TCP, Gelatin &

Collagen, UHMWPE, PLA, PGA, PMMA, PEEK, Bioactive glass (45S5), Poticon (Potassium Titanate), Zirconia, Alumina, Zirconia toughened alumina (ZTA)

Metallic biomaterials: Stainless steel (different variations); Titanium alloy; Co-Cr-Mo alloy (F-75 grade), Nitinol (Ni-Ti shape memory alloy); Magnesium alloys.

4.3 Gap Areas and Recommendations

I. Lack of Coordinated Translational Programs with Mandatory Industry Involvement Recommendations

1. **Initiating Collaborative Projects:** Industries should initiate projects in collaboration with end users (clinicians) to align with market requirements. Academic partners should contribute scientific evaluations to address academic, clinical, and industrial needs effectively. The final outcome, including patents or technology transfer, should rest with the industrial partner.

2. **Comprehensive Project Catalogue:** Compile a comprehensive catalogue of projects from the top 50 institutions (NIRF ranking) to facilitate effective collaboration between industrial partners, clinicians, and academicians.

3. **Delineating Desired Outcomes:** All stakeholders must collaboratively delineate desired outcomes to meet the needs of clinicians, academicians, and industry. This includes conducting clinical trials, publishing research, and achieving translational milestones.

II. Inadequate Collaboration with Clinicians during Early Stage of Academic Research Recommendations

1. **Integration of Clinicians in Translational Research:** Translational research initiatives must integrate clinicians as key opinion leaders to provide precise clinical requirements, guiding collaborative efforts from the early stages.

III. Shortage of Globally Accepted Certified Testing Centres and Innovation Hubs

Recommendations

1. **Establishment of Robust Testing Framework:** Collaborate with industries to establish regulatory-compliant testing facilities adhering to international standards. NABL-accredited testing facilities should be established at key manufacturing hubs, facilitating affordable testing for startups and MSMEs.

2. **Adherence to Well-Defined Protocols:** Test centers must adhere to well-defined protocols aligned with international standards, ensuring authenticity and reliability through regular audits by interested industrial partners.

IV. Inadequate Innovation in Implant Design and Development

Recommendations

1. **Establishment of Consortia:** Form consortia between medical institutions and industrial partners to facilitate seamless data exchange for in-depth research and development of innovative implant products.

2. **Government Support for Data Sharing:** Government should establish online portals for sharing clinical data in a secure manner for R&D activities. Facilitating clinical trials for innovative implants is also recommended.

V. Shortfall of Skilled Manpower in Medical Implant Manufacturing Industries

Recommendations

1. **Enhanced Technical Education:** Integrate practical training into technical education programs to enhance the quality of skilled manpower. Establish skill development centers specific to medical device manufacturing and encourage summer training for technology students in core engineering industries

2. **Encouraging Independent Research:** Encourage independent research in larger organizations with established R&D facilities to facilitate the translation of academic research into practical applications

VI. Absence of National Regulatory Bodies with Well-Defined Regulations and Understanding of Regulatory Compliance

Recommendations

1. **Establishment of Robust Regulatory Body:** Establish a strong government regulatory body equivalent to US-FDA or European-CE or MDR 2017 guidelines to streamline regulatory processes and develop clear and transparent regulatory frameworks. Integrate topics related to regulatory compliance into academic course curricula and promote workshops focused on regulatory frameworks for industry and academic participants

2. **Streamlining Regulatory Processes:** Provide guidance to manufacturers to ensure compliance with quality standards and regulations, thereby fostering a stable and predictable business environment.

4.4 Government Support

4.4.1 Special Focus on Advancing Biomaterials and Implants to Market

1. **Funding Mechanism for Higher TRL Projects:** Research projects at higher Technology Readiness Levels (TRL 6-7) demand dedicated attention, especially in biomaterials and implants transitioning from lab to market. The primary barrier, cost-intensive clinical studies, necessitates significant funding allocation through a separate mechanism. Review panels for such projects should consist of governing bodies, medical experts, Clinical Trials Registry-India (CTRI) personnel, and industrial stakeholders.

2. **Support for Certification Processes:** The government's support for certification processes relevant to innovative medical devices is crucial. This assistance ensures that regulatory requirements are met efficiently, facilitating the market entry of indigenous technologies.

3. **Periodic Updating of Regulatory Guidelines:** Regular updates to regulatory guidelines, incorporating insights from research and academic experts, are essential. This iterative process ensures that new materials or techniques are appropriately regulated, potentially reducing entry barriers for indigenous technologies. Quality standards can be upheld through benchmarking against standard products, with guidance from government-certified medical experts.

4.4.2 Revising DSIR Certification Rules for MSME Sector

4.5 **Streamlining DSIR Certification Processes:** Revising Department of Scientific and Industrial Research (DSIR) certification rules to better suit the Micro, Small, and Medium Enterprises (MSME) sector is imperative. The National Research Foundation (NRF) could reassess DSIR requirements in the Indian context, aiming to simplify certification procedures, minimize documentation requirements, and eliminate intermediaries.

4.6 **Reinstate Higher Tax Benefits for R&D Expenditure:** Reinstating higher tax benefits for industry research and development (R&D) expenditure, previously reduced from 200% to 100%, is warranted. Additionally, offering special rebates for expenditure on skilled manpower, such as PhDs in the medical sector, is essential to prevent brain drain and foster talent retention, a strategy previously implemented in the United States, mitigating significant brain drain from Asian countries.

4.4.3 Promotion of Indigenous Medical Device Manufacturers

1. **Implementation of Differential Import Duties:** The government should implement higher import duties for finished medical devices while providing subsidized import duties for raw materials or semi-finished products used by manufacturing industries in India. This approach incentivizes indigenous developers to increase investments and strengthens the Make-in-India initiative.

2. **Facilitating Technology Transfer and Restricting Duplicate Efforts:** Government facilitation of technology transfer from academic and national laboratories to startups or MSMEs is vital. Implementing policies to curb duplicate efforts in academia and industrial R&D further optimizes resource utilization and fosters innovation.

4.5 Collaboration Challenges

1. **Complexity and Specialization:** The intricate nature of advanced materials and biomedical research demands specialized knowledge and expertise. Industry professionals often face challenges in comprehending these complexities without collaboration with academic researchers. Facilitating more collaborative projects, supported by government funding, is essential to bridge this knowledge gap.

2. **Long-Term Investment vs. Short-Term Goals:** Academic research primarily focuses on long-term goals, such as fundamental understanding and scientific discovery, diverging from the short-term, profit-driven objectives of the industry. Aligning these divergent objectives through strategic planning between academia and industry can foster productive collaboration. Establishing forums for industry-academia interaction enables discussion on project needs and requirements

3. **Intellectual Property Concerns:** Translational research in medical materials and implants often leads to innovative technologies, raising concerns about ownership, patent rights, and commercialization strategies. To overcome these obstacles, fostering mutual understanding between academia and industry is imperative. Agreements should delineate ownership, patent rights, and commercialization strategies to protect the interests of both parties, with an emphasis on expediting the patent evaluation and granting process.

4. **Risk Aversion:** Industries may hesitate to invest in biomedical device projects due to perceived risks, including uncertain outcomes, technical challenges, and market viability. Addressing these barriers is crucial for successful collaboration. Investing in preliminary feasibility studies and forming partnerships with academic institutions can mitigate risks by leveraging technical expertise and support.

4.6. Stakeholder Empowerment for Indigenous Industry Ecosystem

Government's Role in Indigenous Industry Growth

The government plays a pivotal role in shaping policies and providing support for indigenous industry growth. Establishing strategic policy centers for comprehensive market research on biomaterials and implants is essential for informed decision-making, while incentivizing new industries addresses critical shortages

Academia's Contribution to Industry Innovation

Academic institutions serve as vital hubs for innovation, collaborating with industry to drive translational research and technology transfer. Tailored management training programs for biomedical entrepreneurs and industry-focused curriculum integration bolster academia's contribution to industry growth and skilled manpower development.

Industry's Role in Commercialization

Industries are instrumental in translating research outcomes into commercially viable products. Collaboration with academia and government bodies is crucial for identifying market needs and developing innovative solutions. Active participation of industry experts as adjunct faculty in professional education programs enriches academia with insights into market opportunities and effective commercialization strategies.

Leveraging Research Institutes for Innovation

Research institutes drive innovation and technology development. Collaborating with academia, industry, and government agencies, they establish strategic innovation centers. These facilitate transferring clinically validated technologies to industries, focusing on commercial-scale production of biomedical-grade materials, addressing raw material gaps.

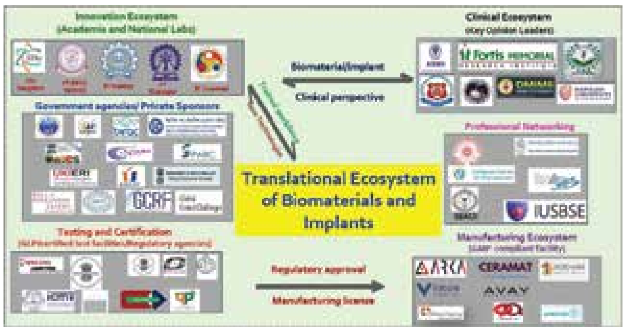


Figure 1: Interdisciplinary and Translational Ecosystem in India

4.7 Recommendations for Short, Medium, and Long-Term Growth

4.7.1 First Three (3) Years

1. **Establish Strategic Policy Centres for Market Research:** Set up dedicated centers for comprehensive market research on biomaterials and implants to inform industry decisions.

2. **Address Raw Material Shortage:** Formulate policies to establish new industries for raw material and resin manufacturing (polymers, ceramics, metal and alloys), reducing dependence on imports.

3. **Strengthen and Expand Innovation Centres:** Enhance existing innovation centers LIKE KIHT/AMTZ to facilitate technology transfer and commercial-scale production of biomedical-grade materials.

4. **Maintain National Registry of MedTech Innovations:** Ensure KIHT/AMTZ institutions maintain a national registry to expedite market entry of promising technologies.

5. **Advance Make in India Initiative in Bio Convergence Manufacturing:** Stimulate industry engagement in translational research, particularly in Bio 3D printers, ensuring tangible outcomes beyond publications, thereby bolstering India's prowess in bio convergence manufacturing.

6. **Government Investment in Healthcare Sector:** Increase funding for biomedical manufacturing and establish a robust regulatory framework to ensure quality standards.

7. **Promote Industry-Focused Clinical Excellence:** Encourage industry participation in translational research from the TRL-1 outset, while conceiving translational research programs at strategic innovation centers fostering impactful outcomes beyond publications.

8. **Mandatory Management Training for Entrepreneurs:** Implement training programs to equip biomedical entrepreneurs with essential business skills.

9. **Industry Experts in Education:** Engage industry experts as adjunct faculty to enrich educational programs and bridge academia-industry gap.

10. **Incentives for Indigenous Entrepreneurs:** Create incentives to attract indigenous entrepreneurs and boost start-up growth.

11. **IP Training Certification for Innovators:** Introduce IP training certification to enhance understanding of IP-related procedures and valuation.

12. **Establish National Translational Research Institute:** Establishing a specialized institute focusing on orthopaedic, liver, skin, and cancer biomaterials, which serve various purposes such as diagnosis, therapy, and monitoring through drug delivery systems, tissue engineering, diagnostic devices, implants, and scaffolds, would offer innovative solutions to enhance implant quality and patient care outcomes, thereby driving innovation and collaboration.

4.7.2 First Five (5) Years

Fostering Innovation Ecosystem

1. **Enhanced Collaboration:** Strengthening the innovation ecosystem involves promoting standardized contract agreements between industry and academia, expediting engagement with universities. Introducing optional tenures for biomedical researchers in industry and allowing academia to act as part-time consultants facilitates knowledge exchange vital for innovation and competitiveness.

2. **Empowering MSMEs:** Facilitating Indian MSMEs to evolve into viable contract manufacturers with robust market strategies is crucial. Targeting established companies such as Meril Healthcare, Stryker, Smith and Nephew, and Zimmer opens avenues for growth. The burgeoning demand, especially in the orthopedic and dental sectors, underscores the need for local manufacturing.

3. **Knowledge Enhancement:** Enhancing the country's understanding of manufacturing processes is imperative. Courses focusing on automation, sensor data utilization, and leveraging Industry 4.0 principles are essential. Additionally, emphasis on minimizing environmental impact aligns with sustainable manufacturing practices.

4. **Research Infrastructure Development:** Establishing research parks at premier institutions like NITs and renowned research hubs fosters the incubation of startups. These centers equipped with state-of-the-art facilities, particularly in advanced manufacturing like biomedical prototyping, catalyze innovation and technological advancements.

5. **Promoting Technological Advancement:** Accelerating technological advancement is paramount. Investing in cutting-edge research and development facilities and incentivizing innovation hubs will propel advancements in bio-convergence manufacturing. This emphasis on technological progress ensures India's competitiveness in the global market and drives economic growth.

6. **Fostering International Collaboration:** Strengthening partnerships with leading global institutions and industry players fosters knowledge exchange and enhances India's position in the global bio-convergence manufacturing landscape. This collaboration facilitates access to advanced technologies, fosters innovation, and opens avenues for market expansion, ensuring India's prominence on the global stage.

Short- and long-term plans for advanced biomaterials and implants (Figure 2) involve establishing strategic policy centers, fostering industry-academia collaborations, enhancing manufacturing knowledge, and creating research hubs, aiming to bolster indigenous innovation and global competitiveness

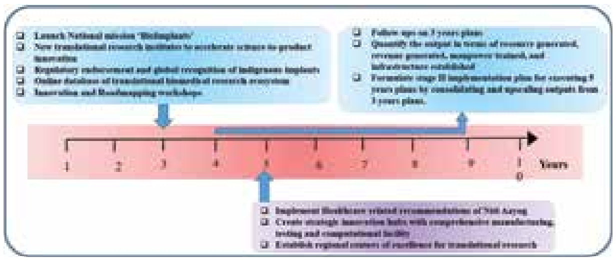


Figure 2: Short- and long-term plan suggested for advanced materials for biomaterials and implants

Nurturing industry collaborations and capabilities (Figure 3) while fostering the growth and sustainability of incubators and start-ups is crucial for driving innovation and economic growth in the biomedical sector, propelling advancements in healthcare solutions and fostering entrepreneurial success

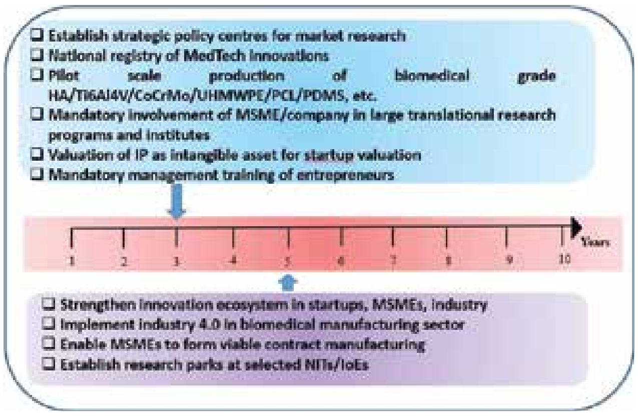


Figure 3: Strengthen industry ties, enhance capabilities, and support incubator and startup growth.

While, the translational ecosystem for biomaterials and implant development (Figure 4) aims to cultivate industry-academia partnerships, enhance manufacturing capabilities, and establish research hubs, fostering innovation to ensure healthier outcomes and bolster India's healthcare infrastructure.

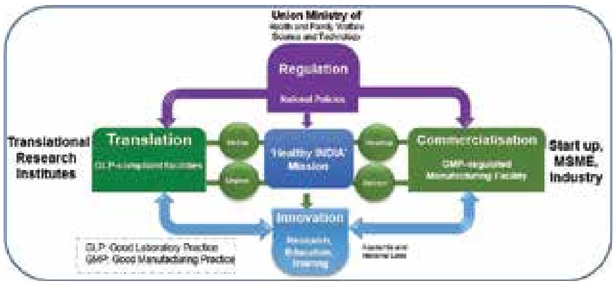


Figure 4: Translational ecosystem for biomaterials and implant development for healthy India

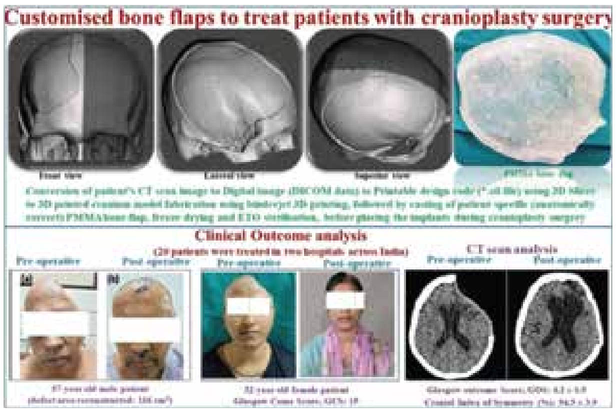
Timeline depiction for three year (3) and five year(5) development plan under the CII national task force for biomaterials and implants

Milestone	Tentative Timeline								
	0-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48	48-60
Establishing and formulation of task force for advance materials for biomaterials and implants									
Laying out strategies to encounter the raw material needs and policy level changes for Indian industries									
Formulation and launch of national mission on 'BioImplants'									
Evaluation of milestones under advanced materials by quantifying the resources produced									
Formulation of consortium of industries and academic partners for Indian implant requirements									
Recommendations for policy level changes to NITI ayog for improving indigenous development of raw materials an implants									
Creating strategic innovation hub with manufacturing and testing facility available to all the Indian partners									
Creating of a data bank for al the resource and information generated									
Establishing regional centres of excellence									
Evaluation of milestones and laying out future action plans									

4.8 CASE STUDIES

Case Study 1: 'FlapIn': Bone Flaps for Cranioplasty Surgery

Annexure I



Technology Know-How:

- 'Patient-specific 3D printed clinical models for bone flaps with consistent clinical outcomes in cranioplasty', Intellectual Property and Technology Licensing, Indian Institute of Science, Bangalore, Feb., 2020.

Clinical study approval:

- Clinical Trial Registry of India (CTRI, approved by Indian Council of Medical Research, ICMR- National Institute of Medical Statistics):

- CTRI/2018/09/015680, registered on 11/09/2018 – Ramaiah Medical College

- CTRI/2021/08/035575, registered on 11/08/2021 – DMIHER, Wardha

Lead Neurosurgeons (Collaborators):

1. Dr. Manish Baldia, Wockhardt Hospital, Mumbai and Nais Brian, Mumbai

2. Dr. Anirudh T J, Professor, Institute of Neurosurgery, Ramaiah Memorial Hospital, Bangalore, India

3. Dr. Sandeep Iratwar, Professor, Department of Neurosurgery, Datta Meghe Institute of Higher Education & Research, Sawangi (Meghe), Wardha, Maharashtra, India.

Academic Institute (Scientific Establishment) - Principal Investigator: Professor Bikramjit Basu, Laboratory for Biomaterials Science and Translational Research, Materials Research Centre, Indian Institute of Science, Bangalore, Karnataka, India.

Manufacturing company in India: Nais Brain, Mumbai, India and AVAY Biosciences, Bangalore, India

Executive Summary:

Based on a multicentric pilot clinical study, IISc researchers utilized the 'Design-to- Manufacturing' approach to develop a technology, starting from patient's CT scan data to anatomically correct bone flap and validated using a cohort study on 20 human subjects during 2017-23, following the human ethics committee approvals from the participating institutes as well as from the Indian Council of Medical Research (ICMR) through CTRI. Most of the patients had undergone decompressive craniectomy after traumatic brain injury, while a few had spontaneous intracranial hemorrhage due to other causes. 3D printing-based patient-specific design and fabrication of acrylic cranioplasty achieves acceptable cosmetic and clinical outcomes in patients with decompressive craniectomy, with less manual intervention and shorter intraoperative time. While using a PMMA-based 'FlapIn' device with clinically acceptable structural properties, the technology uses a low-cost 3D printer-mediated patient-specific design of customized PMMA flap, an affordable implant option for cranioplasty surgery in resource-constrained settings.

Challenges:

- Physiological remodeling of cranial bones in younger patients

- Medical registry of patients undergone cranioplasty surgery in India and clinical outcomes

- Direct 3D printing of patient-specific bone flaps, without using cranium model to cast flaps

Acknowledgment: Department of Biotechnology (DBT), Government of India for the financial support.

Case Study 2: UHip: Injection Molded Acetabular Liners

Invention disclosures:

- **Technology patent:**

a) Ultra-High Molecular Weight Polyethylene Polymer Blends for Manufacturing of Injection Moldable Orthopedic Implants; Indian Patent Application No 202441019944.

b) Polymer-Ceramic Hybrid Composite Material for Orthopedic Prostheses and Method of Producing the Same; Indian patent granted in 2021 (3011/CHE/2015).

Design Patent: Injection moldable cemented acetabular liner (Design registration no: 365979-001, granted on June 13, 2022)

Academic Institute (Scientific Establishment) – Principal Investigator: Professor Bikramjit Basu, Laboratory for Biomaterials Science and Translational Research, Materials Research Centre, Indian Institute of Science, Bangalore 560012, Karnataka, India.

Manufacturing Partner: INDO MIM Limited, KIADB Industrial Area Doddaballapur, Bengaluru 561203, India

Clinician Collaborator:

Dr. D. C. Sundaresh, Director, Sathya Sai Institute of Higher Medical Sciences, Bangalore, India

Executive summary:

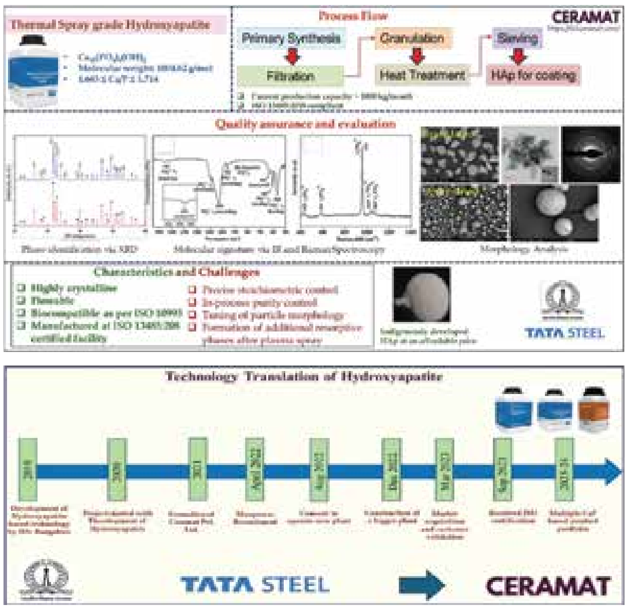
This technology development involves the polymer flow-related thermophysical property assessment, mold design, polymer flow analysis under simulated injection molding parameters, component manufacturing at optimized molding conditions, product quality assessment using 3D X-ray imaging, hip simulator studies, in silico analysis (static and dynamic biomechanical response) and clinical outcome analysis. The critical influence of the UHMWPE modification and injection molding process parameters on the manufacturing of defect-free acetabular liner components with clinically acceptable dimensional tolerance, surface roughness, fatigue wear resistance and strength properties was established.

Challenges:

- UHMWPE modification without compromising strength and ductility
- Injection moldability-relevant viscoelastic properties and shrinkage of medical-grade UHMWPE
- ISO-certified orthopedic implant testing facility in India
- Supply of medical-grade UHMWPE in India

Acknowledgment: Department of Biotechnology (DBT), Government of India and IMPRINT Project of the DST-SERB, Government of India, for the financial support.

Case Study 3: Thermal Spray Grade Hydroxyapatite for Medical Implants



Technology Know-How:

- ‘Scalable manufacturing of bioceramics, and a process thereof’, transferred from Intellectual Property and Technology Licensing, Indian Institute of Science, Bangalore, 2019.

Academic Institute and Scientific Establishment: Professor Bikramjit Basu, Laboratory for Biomaterials Science and Translational Research, Materials Research Centre, Indian Institute of Science, Bangalore, Karnataka, India and Dr. Subrata Mukherjee, TATA Steel R &D, Jamshedpur, India

Manufacturing company: Ceramat Pvt. Ltd. (TATA Steel Enterprise), Vasai, Mumbai, India

Executive Summary:

Hydroxyapatite (HA) is widely esteemed as a ceramic biomaterial owing to its superior osteoconductive and bioactive attributes, mirroring the mineral phase of bone. HA is extensive utilized for coatings on metallic implants, demonstrating notable advantages such as enhanced biocompatibility, sustained osseointegration a6midst implant motion, and mitigated post-operative discomfort. Ceramat manufactures thermal spray grade HA, specifically tailored for thermal spray coating applications on orthopedic implants. Ceramat is currently manufacturing thermal spray grade HA with a current capacity of 200 kg per month and is working on production scale-up of >1000 kg per month, in ISO 13485:2016 certified plant.

Challenges:

Hydroxyapatite (HA) experiences incongruent melting within plasma, leading to the formation of additional phases that augment the resorption properties of the coating. Consequently, to mitigate these challenges, stringent control over the stoichiometry of HA, precise management of particle size, and meticulous adjustment of coating parameters are essential.

Case Study 4: T² Dent: Endosseous Dental Implant

Invention disclosure:

- Design registration: A hybrid threaded dental implant system (set) with hexagonal anti-rotational feature(Design registration no: 366803-001, granted on June 27, 2022)
- Technology patent: A dental implant assembly for dental prosthesis (Indian Patent Application No. 201841032295, granted on Jan 24, 2024 and filed for US patent – currently under scrutiny)
- Regulatory approval from CDSCO, Ministry of Health and Family Welfare
- Manufacturing medical devices under Medical Device Rule, MDR-2017-Test License Number (MMFG/TL/MD/2022/000471, Dt. 14/10/2022)

Clinical study approval:

- Clinical Trial Registry of India (CTRI, approved by ICMR):

- CTRI/2022/01/039353, registered on 12/01/2022 – KGMU, Lucknow;
- CTRI/2022/06/043437, registered on 22/06/2022–DMIMS, Wardha;
- CTRI/2023/04/051641, registered on 17/04/2023 –RUAS, Bangalore.

Executive Summary:

In summary, the technology development provides a concise roadmap and lessons learnt, from the design and lab-scale development phases, extending to pilot scale manufacturing to post-manufacturing quality validation and pre-clinical studies in animal models, and finally to human clinical studies. The industry-academia collaborative efforts showcase the development of end-to-end high-quality dental implants for the socio-economically challenged population of various developing nations, and it boosts the idea of 'Atma Nirbhar Bharat (self-reliant India)' initiative by the Government of India.

Challenges:

- Closer and regular interactions with the clinicians
- Number of regulatory-compliant certified testing facilities in India for Implant quality validation
- Supply of medical-grade raw materials for implant manufacturing

Scientific Establishment: Laboratory for Biomaterials Science and Translational Research, Materials Research Centre, Indian Institute of Science, Bangalore, Karnataka, India.

Manufacturing Partner: ARKA Medical Devices Pvt Ltd, Medical Device Park, Sultanpur, Hyderabad, Telangana, India

Clinician Collaborators:

1. Dr. Vibha Shetty, Professor and Prosthodontist, Faculty of Dental Sciences, Ramaiah University of Applied Science, Bangalore, Karnataka, India
2. Dr. Balendra Pratap Singh, Professor and Prosthodontist, Department of Prosthodontics, King George Medical University, Lucknow, Uttar Pradesh, India
3. Dr. Priyanka Banode, Professor and Periodontist, Department of Periodontology, Sharad Pawar Dental College, DMIMS DU, Sawangi (Meghe), Wardha, Maharashtra, India.

Acknowledgment: Department of Biotechnology (DBT) Government of India, Abdul Kalam National Innovation Fellowship by the Indian National Academy of Engineering, for the financial support.

Chapter Contributors

On behalf of the CII National Mission for Technology, Innovation and Research, we would like to acknowledge and express gratitude to the following for their contributions in the Chapter on Biomaterials and Implants:

- **Prof (Dr.) Bikramjit Basu,** Professor, Indian Institute of Science (IISc) and Lead, Biomaterials Chapter
- **Dr Manish Baldia,** CEO & Founder, NAIS BRAIN, Mumbai
- **Dr Vishwas P R,** CEO, Amace Systems Pvt. Ltd., Bangalore
- **Dr Sabyasachi Roy**, CEO, Ceramat Pvt. Ltd. (TATA Enterprise) Mumbai
- **Dr Shiv T,** Vice President, Indo MIM Private Limited, Bangalore
- **Dr Subrata Mukherjee,** Head Advanced Materials and Characterization Research Group, R&D Tata Steel
- **Dr Nilay Lakhar,** CEO, Synthera Biomedical, Pune
- **Dr P T Reddy,** CEO & Founder, Arka medical Devices Pvt. Ltd., Hyderabad
- **Mr Debashish Pradhan,** GM (R&D), Head, Innovations & General Manager, Biorad Medisys Pvt. Ltd., Pune
- **Mr Bejou Krishna,** Sr. Vice President, AVAY Biosciences Private Limited
- **Mr Sushant Banerji,** CEO & Founder, Orthotech Indi Pvt. Ltd., Valsad, Gujarat
- **Dr R Vignesh,** Associate Researcher, Tata Steel
- **Dr Lubna Sheikh,** Researcher Healthcare Solutions, Tata Steel
- **Dr Venkata Sundeep Seesala,** Research Associate Tata Steel

CHAPTER-5:

COMPOSITES

5.1 Executive Summary

Composites are defined as the mixture of two or more materials to achieve properties better than the individual component. They are formed through dispersion of a discontinuous or reinforcing phase within a continuous phase or matrix. Currently, fiber reinforced polymer (FRP) composites have taken a giant leap to replace metals in numerous applications due to their superior properties and ease of manufacturing. FRP composites are superior in terms of versatility, corrosion and weather resistance, high strength to weight ratio, light weight, and cost efficiency. Therefore, implementation of FRP composites is enhancing day by day in several sectors such as construction and civil engineering, aerospace and defense, automobiles, railways, marine, sports, energy, and many more. Global FRP Market size is projected to reach $172.2 billion by 2026, with a CAGR of 4.2% during 2021-2026. Figure 1 shows the market share of different application sectors, where automobiles and construction sectors dominate.

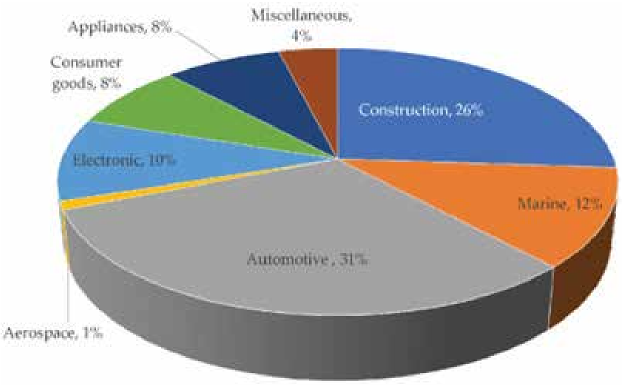


Figure 1. Sector wise market share of FRP composites

Construction and civil engineering application of FRP dominate the market growing at a CAGR of 5.4%. The main structural applications of FRP composites are buildings materials, bridges, repair and rehabilitation, railway platforms, construction of road, cooling towers, portable office, etc. FRP products like pultruded profiles and rebars are produced for structural components in construction industries. A variety of glass fiber grades along with epoxy, vinyl ester and unsaturated polyester matrixes are used in these products depending on required performance and cost. High-performance carbon fibers are used for high modulus and strength requirement. Different pultruded FRP profiles are used in building and bridge superstructure construction applications.

On the other hand, automotive sector holds the largest share of FRP application. High strength to weight ratio is the main factor to utilize FRP in the automotive industry for reduction of cost and fuel consumption. FRP components are mainly used in vehicle bodies, frameworks, and containers. Glass fibers are commonly used in most of the common structural applications of FRP. Therefore, glass fiber holds the largest share (38%) among all the fibers in FRP products. Carbon fiber and aramid fiber based FRP composites dominate in aerospace, defence, and sports sectors. Due to the higher strength with lower density carbon fiber FRP are preferentially used in aircraft primary structure, as well as in several military aircraft, marine or navy ship, submersibles, bullet proof and ballistics application and other different marine and defence technologies. FRP composites are also widely considering in several emerging areas including wind energy, structural component of battery, sports, bio-medical, and other different new fields.

In India, the estimated market value (around 1500 Cr. per year) and expected CAGR (>10%) is very high. However, the consumption of FRP material per capita is very low (<0.5 kg) compared to other countries like in China 3 kg and in USA 12 kg. Therefore, for aggressive growth of FRP in India, requires advanced technologies with advanced research, awareness, government support, and collaboration.

5.2 Global and Indian Market Analysis and Forecast

Several factors contribute to the ongoing expansion of the global FRP composites market, notably heightened demand from the aerospace sector, the integration of composites in the manufacturing of lightweight automotive components, and the scaling up of wind turbine blades to enhance energy generation in both onshore and offshore wind power installations. According to the "Fiber-Reinforced Composites Market" report by Straits Research, global FRP composites market size was valued at USD 93,254.56 million in 2023, with projections indicating it will escalate to USD 133,053.11 million by 2032, showcasing a compound annual growth rate (CAGR) of 5.9% over the forecast period. Throughout this period, the Asia-Pacific region is anticipated to wield the greatest influence over the composites market, experiencing a notable CAGR of 7.8%. Fuelled by rapid urbanization and infrastructure development, countries such as China, India, and Japan are actively channelling investments into composites for diverse applications spanning transportation, water management, and building construction, with a key emphasis on ensuring long-term durability and resilience.

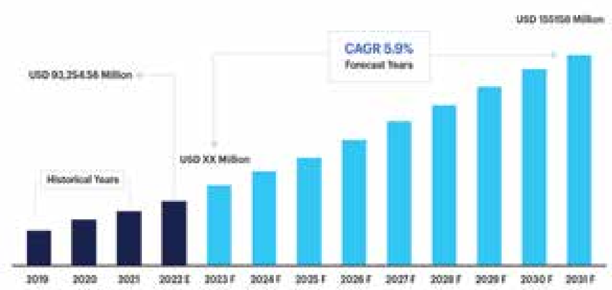


Figure 2. Global fiber-reinforced composites market size (2019-2031) (source: Straits Research)

Currently, application wise marine sector contributes around 10-15% of the market share of FRP composites. As per recent report India is the world's top arms importer. Russia, USA and France are the three major suppliers of arms to India. In terms of market share among various other applications, FRP composite found highest requirement in the automotive market. As of March 2024, Indian Railway Finance has a market cap of $22.85 Billion. Indian Aerospace and Defense Market value is USD 27.1 Billion in 2024 and is expected to reach USD 54.4 Billion by 2033, at a CAGR of 6.99% during the forecast period 2024 – 2033.

According to the latest report by Businesswire titled "India Composites Market Report 2022", the Indian composites market is poised for remarkable growth, with an estimated value of $1.9 billion by 2026, demonstrating a notable CAGR of 16.3% from 2021 to 2026. This surge in market value is primarily attributed to the growing emphasis among manufacturers on materials offering superior strength, durability, and weight savings. As India undergoes a profound transformation in its industries and infrastructure, the demand for advanced composites continues to escalate, positioning this market as a pivotal contributor to the nation's economic growth.

Furthermore, the Indian Government's ambitious carbon emissions reduction target and its concerted efforts toward renewable energy, including eco-friendly energy generation initiatives, are fuelling demand for applications such as wind energy and solar panels. The report indicates that wind energy remains the largest end-user segment in terms of both value and volume, with projections pointing towards substantial growth in the foreseeable future.

Despite the promising outlook, the composite market in India faces several challenges, including raw material costs, manufacturing complexity, and stringent quality control requirements. Balancing the need for desired strength, weight, and performance characteristics while managing costs poses significant challenges. Additionally, the industry grapples with the demand for skilled labour in composites manufacturing and the imperative to maintain consistency in production processes to meet quality standards. Environmental regulations and the growing preference for sustainable composites also exert a notable influence on market dynamics.

The COVID-19 pandemic presented unprecedented challenges to the composites market in India, with sectors such as construction and automotive experiencing slowdowns, while aerospace and defense sectors witnessed increased interest in lightweight and high-strength composites. However, post-pandemic recovery efforts are expected to drive renewed growth as industries invest in advanced composites for applications such as aircraft manufacturing and infrastructure development.

In the global context, the composite market is fiercely competitive, with key players continuously striving to assert dominance. Major companies deploy strategic initiatives such as mergers, acquisitions, and partnerships to enhance their market presence and diversify their product portfolios. Additionally, these industry leaders prioritize technological innovation and research development endeavours to enhance the performance of their FRP composites offerings.

The prominent players in the global FRP composite market are American Fiberglass Rebar, American Grating, LLC, Avient Corporation, B&B FRP Manufacturing Inc., DowAksa, Engineered Composites Ltd, FRP Composites Inc., Hexcel Corporation, Hyosung Corporation, Mitsubishi Chemical Holdings, Plasan Carbon Composites, Rochling Group, SABIC, SGL Group, Solvay SA, Ten Cate NV, Toray Industries Inc., TUF-BAR, TPI Composites Inc., Zoltek Companies Inc., Owens Corning, Jushi Group, Toray Industries, Hexion, etc.

In India, leading companies in the composites market include Reliance composites, Tata Steel, Arvind, Suzlon, Kineco, Mahindra CEI Automotive, Tata AutoComp Systems, and Patil Rail Infrastructure. These companies are at the forefront of driving innovation and shaping the future of the composites industry in India.

5.3 International Best Practices

International best practices in the FRP composite industry encompass a range of strategies and methodologies aimed at optimizing product quality, safety, efficiency, and sustainability.

Quality Assurance and Standards Compliance: In addition to adhering to international standards like ISO, ASTM, and EN, companies in the FRP composite industry establish comprehensive quality assurance systems. This involves rigorous testing protocols, documentation of processes/SOP, and adherence to specific quality benchmarks to ensure consistent product quality and safety.

Material Selection and Testing: Extensive research and testing are conducted to select the most suitable fiber types, resin systems, and additives for specific applications. This includes testing for mechanical properties, such as tensile strength and modulus, as well as durability factors like resistance to corrosion, UV degradation, and chemical exposure.

Design and Engineering: Advanced design methodologies, such as finite element analysis (FEA), are employed to optimize the structural integrity and performance of FRP components. Engineers utilize computer-aided design (CAD) software to model complex geometries and simulate various loading conditions, resulting in designs that maximize strength-to-weight ratios while minimizing material usage.

Manufacturing Processes: Companies implement state-of-the-art manufacturing techniques such as vacuum infusion, resin transfer molding (RTM), filament winding, 3D printing, automated fiber placement, as well as digital manufacturing process to produce FRP components with high precision and consistency. These processes are carefully controlled to minimize defects, ensure resin impregnation, and achieve uniform fiber distribution throughout the part.

Health, Safety, and Environment (HSE): Worker safety is paramount in FRP composite manufacturing facilities, with strict adherence to Occupational Safety and Health Administration (OSHA) regulations and industry best practices. Waste management systems are implemented to minimize environmental impact, and sustainable practices are integrated into operations to reduce energy consumption and emissions.

Training and Certification: Employees receive comprehensive training on safe handling practices, equipment operation, and quality control procedures. Certification programs ensure that personnel are competent in their roles and understand the importance of adhering to industry standards and regulations.

Lifecycle Assessment and Sustainability: Lifecycle assessments are conducted to evaluate the environmental footprint of FRP products from raw material extraction to end-of-life disposal. Companies prioritize sustainable practices such as material recycling, waste reduction, and energy efficiency to minimize environmental impact and meet sustainability goals.

Quality Control and Inspection: Robust quality control measures are implemented at every stage of the production process, including incoming raw materials inspection, in-process monitoring, and final product testing. This ensures that components meet stringent quality standards (e.g., ISO9001:2015) and customer specifications before being released for use.

Research and Development: Significant investments are made in research and development to drive innovation in FRP materials, processes, and applications. This includes exploring new fiber reinforcements, resin formulations, and manufacturing techniques to improve performance, reduce costs, and expand market opportunities.

Industry Collaboration and Knowledge Sharing: Companies actively participate in industry associations, conferences, and collaborative research projects to share best practices, exchange technical knowledge, and stay abreast of emerging trends and technologies. This collaborative approach fosters innovation and continuous improvement within the FRP composite industry.

5.4 Gap Areas

The major gap areas in composite materials are broadly classified into the following three categories.

5.4.1 Technology

i. Unavailability of Raw Materials and its manufacturing technology

Some of the major raw materials used in FRP composites like polymers and fibers are mostly imported from other countries. There is no manufacturing facility for carbon fiber, basalt fiber and aramid fiber available in India. Govt. should take initiative and allocate budget to promote "Make in India" manufacturing of resin and fiber.

ii. Unavailability of advanced composite manufacturing technology

In India, most of the composite manufacturers are small companies and they use mostly manual or semi-automatic process for the manufacturing of composite parts. The companies are still following the old and traditional manufacturing processes. There could be several reasons behind these practices, (i) lack of knowledge about the latest development in composite product manufacturing technology, (ii) lack of govt. support, (iii) lack of budget for implementing the new process, (iv) lack of technical skill of the employees, (v) lack of awareness among the management and employees about the benefits of the new technology. To address these issues, Govt. of India and the company top management should organize more workshops, conferences, and technical talk to become familiar with the advanced technologies.

iii. Unavailability of efficient and large-scale composite recycling technology

Around 53% market of FRP composite materials used in different applications are made of thermoset polymer which are non-recyclable. Average lifespan of normal FRP composite is around 20-30 years depending on the constituent polymer and surrounding atmosphere. After the end-of-life, FRP composites are either grinded or burnt or landfill. In all the three cases it causes environmental pollution and/or health hazards. At present, there is no commercially available recycling technique which can recycle thermoset FRP in large scale. Research is going on all over the world to develop an efficient recycling technique for recycling thermoset FRP composites. Current research also focuses on the development of reprocessable thermoset resin, which behaves like thermoset at normal temperature and can be reprocessed like thermoplastic at higher temperature.

iv. Lack of understanding of regulatory compliances

Regulatory compliances are essential to meet international requirements and maintain product quality. Premiere educational institutes should integrate courses on regulatory compliance and requirements into their study frameworks to equip students with prior knowledge for industry absorption.

The government should promote workshops focused on the regulatory framework, benefiting both industrial and academic participants, and Industry should consider hiring interns (MTech and PhDs) periodically to provide training on regulatory requirements.

v. Unavailability of skilled manpower

The skill level for semi-skilled or skilled manpower can be enhanced by incorporating more practical training at the grassroots level. It is recommended to have an amalgamation of industry and academics for periodic seminars and practical workshops. It is also recommended to have a compulsory industrial training for the technology students to keep them at par with the industrial developments. Further, need to encourage independent research in larger organizations with established R&D facilities. This will boost the translation of academic research into practical applications.

5.4.2 Government Support

Research projects involving higher Technology Readiness Levels (TRL 6-7), particularly in composite hydrogen storage tank and others, require special focus. The critical barrier to this project is the unavailability of in-house testing and validation facility, which must be addressed by allocating significantly greater funding through a separate funding mechanism. The review panel for such projects should comprise governing/allocating bodies, and industrial stakeholders.

Regulatory guidelines should be periodically updated with input from research and academic experts. This ensures that new materials or techniques are appropriately regulated, potentially easing entry barriers for indigenous technologies.

Quality standards can be maintained through benchmarking against standard products with consultation from government-certified composite experts.

Government should consider reinstating higher tax benefits for industry R&D expenditure, which was recently reduced from 200% to 100%. Additionally, special rebates should be provided for expenditure on skilled manpower, such as PhDs in polymer composite sector, to prevent brain drain and encourage talent retention.

5.4.3 Collaboration

To some extent lack of collaboration between industry and academic institutions affects the progress on advanced research of FRP composites. The lack of collaboration can stem from several factors, few are discussed below:

- Academic research is typically focused on attainment of long-term goals, such as fundamental understanding and scientific discovery. This approach frequently diverges from the short-term, profit-driven objectives prevalent within the industrial partners. This disparity could potentially discourage industry from investing in collaborative research. Strategic planning between academia and industrial stakeholders could bridge the gap and align their objectives in mutually beneficial way.
- Advanced materials research often culminates in the creation of innovative technologies and intellectual property. The concerns surrounding ownership, patent rights, and commercialization strategies can pose obstacles to collaboration as both academia and industry strive to safeguard their interests. It is imperative to foster mutual understanding between the two parties, and such agreements should outline the ownership, patent rights, and commercialization strategies in a manner that protects the interests of both parties.

5.4.4 Additional factors

i. Lack of awareness

The use of composite materials for structural applications was started in 1980s. Whereas, metal is being used since long before, around 1800 BC. So, in comparison to metals like iron, steel, aluminum etc. composite material is quite young. People have limited knowledge about the benefits of the material. Hence, acceptance level of the composite products among the people is low as compared to steel and other metals.

ii. Unavailability of globally accepted certified testing and validation center.

The Indian industries are currently outsourcing various testing and validation of FRP composite products from USA and European countries because of the inadequate testing and validation facilities in India. For example, testing and validation of FRP pressure vessels and Type-IV/ Type-V hydrogen storage tank. Such testing & validations are costly and time consuming. To address this challenge, it is essential to establish a robust framework of testing laboratories, in collaboration with industries, that strictly adhere to international standards. To expedite testing processes, it is recommended to establish testing and accreditation centers at key manufacturing hubs throughout the country.

iii. Unavailability of Indian testing standard

Composite materials are used in a number of applications like railway, construction, aerospace, pressure vessels, defense, mobility etc. Each of these application follows separate standard and regulatory compliances. Indian testing standards are available for some of these applications while for others it is missing. For example, Indian standard for testing and validation of low- and high-pressure composite vessels used in water storage, wastewater treatment plant, Type-IV and Type-V tank for H2 storage and transportation, FRP rebar testing are missing. Govt. agencies must be proactive enough in this case.

5.5 Recommendation and Conclusion

One of the biggest challenges of FRP composites is that they are not recyclable as most of the used matrixes are thermoset polymers. As per the growing market size there is a huge demand of FRP composites in several sectors, whereas environmental legislation is becoming restrictive day-by-day due to the non-recyclability and traditional waste managements (like landfill, incineration, etc). Though there are few alternative solutions like pyrolysis, mechanical recycling, chemical degradation, etc. for partial recovering of FRP composite products after their end use.

However, these approaches suffer from several drawbacks such as being less cost-effective, requiring high-energy, posing environmental hazards, downgrade applications, and so on. Therefore, a great attention must be conferred on advanced recycling technologies of FRP composites to achieve sustainable and economic benefits. There is a massive demand on development of high performance, cost-effective, re-processable or recyclable polymer matrix through either developing re-processable/recyclable thermoset matrix or by developing high performance thermoplastic matrix.

Low toughness or brittleness nature with inherent inhomogeneity of FRP is another issue. Development of high-performance engineering thermoplastics like PEAK, PPS, polyamides, etc. based FRP composites those are not only recyclable but display superior mechanical properties including high toughness and fatigue.

Another drawback of FRP composites (GFRP) used in general purpose applications is it's low elastic modulus. Generally, carbon and aramid fibers exhibit comparative modulus values with steel. However, attribute of their high-cost values restricts their use in general structural applications. Whereas glass fibers are cost effective to utilize in most of the structural applications. But the lower modulus value (one fourth of steel) of GFRP limits it's structural applications compared to conventional materials. Thus, further development is required in this area to develop high modulus GFRP either by incorporating fillers into the system or modifying fiber without much effecting the cost and other properties.

Most importantly, to aggressively grow FRP market in India, advanced technologies with advanced research, awareness, government support, and collaboration is needed.

5.6 Sectoral Perspectives

5.6.1 FRP Composites in Construction and Infrastructural Sector

Introduction

The construction and infrastructure sector extensively employs a wide range of traditional materials, renowned for their long-standing history of proven strength and reliability.

However, these conventional materials possess inherent limitations and are typically produced by energy-intensive processes. Additionally, this sector contributes approximately 40% of global carbon emissions, exacerbating the climate emergency and necessitating urgent action to promote the adoption of sustainable and eco-friendly alternatives.

To address these challenges, the construction and infrastructure sector has embarked on a journey to embrace fiber-reinforced polymer composites (FRPs) since the mid-90s. FRP composites, comprising fibers embedded within a polymer matrix, exhibit remarkable mechanical properties. The fibers impart strength and stiffness, while the matrix functions as an adhesive, facilitating the efficient transfer of forces between the fibers. FRP composites offer a numerous of advantages over traditional materials, including lightweight construction, superior specific strength, long durability, reduced installation time, and lower operational and maintenance costs. FRPs have found widespread application across various sectors, including load-bearing structures, infill panels, pressure pipes, tank liners, and roofing systems. Recent advancements have led to the development of complete FRP structures, encompassing insulated panels, floor gratings, stairways with handrails, working platforms, as well as bridge structures. Furthermore, FRPs serve aesthetic purposes and can be employed for linings, fittings, and cladding, enhancing their versatility in architectural and design applications.

This section is structured into five parts to provide a comprehensive understanding of FRP materials in construction and infrastructure applications. The first part establishes the context and background of FRP material usage. The second part explains into the constituent materials and design/quality standards of FRP products. The third part explores the national and international market scenario, offering insights into the product portfolios of different composite industries. The fourth part focuses on challenges and future prospects associated with FRP implementation. Finally, the fifth part presents case studies illustrating the successful integration of FRP materials in various projects.

Key Product Components

FRP composites offer a versatile solution for construction and infrastructure projects, providing durability, strength, and corrosion resistance. Figure 3 featuring FRP composites major product portfolio in construction and infrastructure sector.

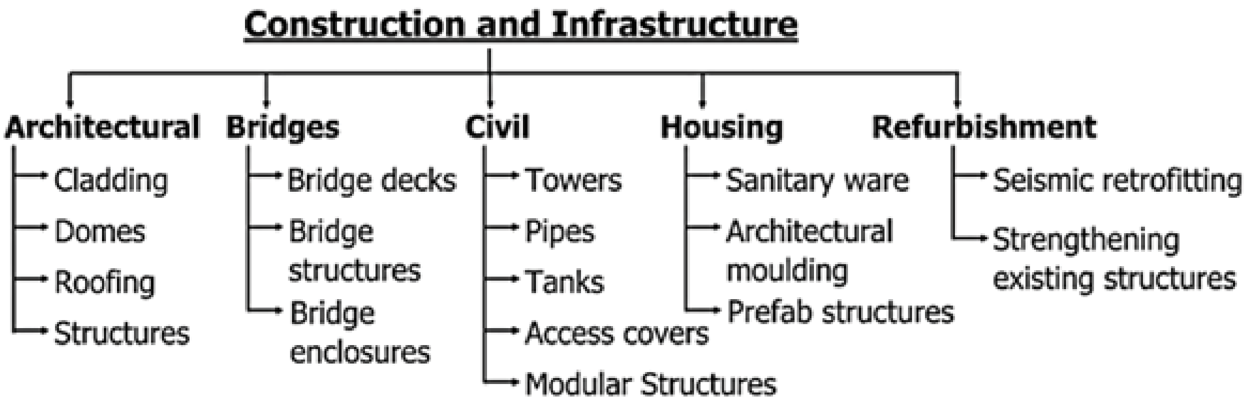


Figure 3. Major product component in construction and infrastructural application

Composite Served	Materials Used	Design/Quality Standards
 GFRP Pipes	**Polymer:** Polyester Vinyl Ester Epoxy Isophthalic **Reinforcement:** Glass fiber Silica Sand	• BIS: IS 12709 & IS 14402 • AWWA: AWWA C 950 • ISO: ISO 10639 & 10467 • ASTM D 2996: • High Pressure Applications • API 15 LR: • For Oil & Petroleum Sector • DIN 16965 For Thermoplastic Liner with GFRP
 FRP Lighting Poles	**Polymer:** Polyester **Reinforcement:** Glass fiber	• As per ANSI C 136.20 - 1990 • BS EN 40 - 7:200 • AASHTO LTS-2 1985
 FRP Pultruded Walkways & Railings	**Polymer:** Polyester **Reinforcement:** Glass fiber	• ASTM D 3917-96 • As per customer need

 FRP PRE - FAB	**Polymer:** Polyester Reinforcement: Glass fiber **Customization:** • FRP-FRP Sandwich Panel • FRP-PPGI Panel • FRP-Pultruded Sandwich Panel	• IS 875(Wind) • IS 1893(Earthquake) • IS 6746 • IS 11551 • As per customer need
 FRP Roofing Panels	**Polymer:** Customized **Reinforcement:** Glass fiber **Special:** Anti-Aging film	• ASTM D3841 • ASTM E108 • IS 12866 • As per customer need
 FRP Storage Tanks	**Polymer:** Polyester Vinyl Ester Epoxy Isophthalic **Reinforcement:** Glass fiber **Customization:** PP/FRP PVC/FRP ECTFE/FRP	• BS 4994 • ASME RTP-1 • ASME Section X
 FRP Bridges	**Polymer:** Polyester, Vinyl Ester **Epoxy Reinforcement:** Glass/Carbon/Basalt fiber	EN 13706-1:2018 ASTM D801M-16 ISO 10406-1:2019 AASHTO LFRD ACMA

 FRP Moulded Gratings	**Polymer:** Polyester Epoxy **Reinforcement:** Glass fiber	• ASTM E-84 • ASTM D-635

National and International Market Scenario

In the national context, the acceptance of FRP composites in infrastructure projects has shown a consistent upward trajectory. Both public sector entities and private organizations are actively investing in research and development initiatives to exploit the inherent advantages of FRP composites in construction and infrastructure applications. Projections suggest a notable surge in the market for FRP composites within the construction and infrastructure sectors, with an anticipated Compound Annual Growth Rate (CAGR) ranging between 12-15% by 2025. This growth is driven by an increasingly nuanced understanding among industry stakeholders regarding the superior performance attributes of FRP structural elements, including rebars, grids, skin panels, and roof sheets, particularly in contexts characterized by seismic vulnerabilities or heightened susceptibility to corrosion.

Company Name	Product Portfolio
EPP Composites Pvt. Ltd. (Rajkot, India)	FRP Pipes, Cooling Towers, Storage Tanks, various FRP Pultruded Products, Cable Trays, Electrical Boxes, Electrical Poles, FRP Doors, Roofing Sheets, FRP Fittings & Liners.
Arvind Composites (Gandhinagar, India)	FRP Cable Trays, Ladders, Gratings, Poles, Gratings, Platform with Handrails, Staircases, Walkways, Scaffolding, Fencing, and Modular infrastructure.
Everest Composite Pvt. Ltd. (Vadodara, India)	Gel coated FRP Panels, Moulded Gratings, Skylight FRP Panels, Cooling Tower Cladding Panels, Industrial Roofing and Cladding Solutions, FRP rebars, Prefab Solutions.
Reliance Composites (Vadodara, India)	Modular Houses, Gratings, Manhole Cover, Light Poles, Walkway Bridges, Ladder, Canopy, Doors, Cooling Tower Structures, Pipes, Cable Tray, Jio Pole, Prepreg, Reinforcing Bar, Storage Tanks, Structural Fittings.
Fibro Plastichem (Vadodara, India)	FRP Poles, Pipes & Fittings, GRP Tank, GRP Equipment, Railway Coach fabrication.
Aradhana Technologies (Bangalore, India)	Moulded Products, Tanks, Gratings, Sheets, Exhaust systems, FRP security cabins.
Jindal Advanced Materials (Gurugram, Haryana)	Cable Master Trays, Sentinel Manhole Plates, Rebar, Staircases.
TATA Steel Composites (Kolkata, India)	FRP Pipes, Bridges, Poles, Pressure Vessels, Tanks, Modular Toilets, Customized FRP Products, Security & Isolation cabins.

On the global scale, the FRP composites market within the constructions & infrastructure sector is experiencing robust growth, driven by advancements in technology, infrastructure development projects, and sustainability initiatives.

North America: The United States and Canada serve as prominent markets for FRP composites, particularly in applications such as bridge rehabilitation, pipeline systems, and aerospace engineering.

Europe: European countries are increasingly integrating FRP composites into infrastructure projects to enhance sustainability and reduce life cycle costs. Notable applications include bridge strengthening, underground structures, and marine construction.

Middle East and Africa: Escalating investments in infrastructure, coupled with the demand for corrosion resistant materials in harsh environmental conditions, are stimulating the uptake of FRP composites in sectors like oil and gas, utilities, and transportation.

Asia-Pacific: With rapid urbanization and infrastructure development, countries like China, India, and Japan are actively investing in FRP composites for transportation, water management, and building construction, prioritizing long-term durability and resilience.

Table Few international composite industries and their product portfolio

Company Name	Product Portfolio
Creative Composite Group (United States)	Cooling Towers, Bridge Decking, Boardwalks, Structural Profiles, Utility Poles, Industrial Tanks & Processing Equipment.
Tencom Limited (United States)	Pultrusion Profiles, Fiber Glass Rod, Poles, Angels, Bars & Channels.
Composite Tech (Austria)	FRP Rebar, Pipes, Tanks, Silo, Mesh, Structural Profiles
Horse Construction Ltd. (China)	FRP Bridge Bearing System, Crack Repair System, Steel Bonding System, Anchoring System.
RPS Composites (Alabama, United States)	FRP Pipes, Fittings, Tanks, Vessels, Structural Profiles.
GRP Industries (UAE)	FRP Enclosures, Kiosks, Roofing & Customized Products
Ferro Grate (Ajman, UAE)	FRP Gratings, Flatforms, Ladders, Access Cover, Cable Trays
Grating FRP (Australia)	FRP Sandwich Plates, Pultruded Structures, Moulded Gratings, Pultruded Gratings, Manhole Covers, Gratemates 4 Wheel Drive Non-Slip Mates, Staircase, Handrail, Roofing System.

Challenges & Future Prospectives

The World Green Building Council reported that the construction sector is major responsible for global energy related carbon emissions. Substantial efforts have been dedicated to mitigating these emissions through the development of building materials with reduced environmental impacts, including recycled or bio-based alternatives. Nevertheless, these sustainable options often incur higher costs compared to conventional materials. In recent years, researchers have turned their attention to advanced composite materials engineered to sequester more CO2 during their production processes than they emit, thereby offering a "carbon-negative" solution that not only meets stringent building standards but also presents cost efficiencies relative to standard structures.

Examples:

Example 1: FRP Bridges

FRPs are pioneering a transformative shift within the construction sector, witnessing widespread integration across various bridge components. Notably, the average weight of an FRP bridge is approximately half that of a steel bridge. Furthermore, while conventional steel bridges typically offer a lifespan of up to 50 years, FRP bridges are engineered to endure for a century. However, in the contemporary construction landscape, sustainability takes precedence, necessitating adherence to rigorous environmental, social, and economic criteria. Environmental considerations encompass minimizing energy consumption, waste generation, and ensuring recyclability. Social imperatives mandate optimal workplace safety, reducing noise and dust emissions. From an economic standpoint, comprehensive evaluations are conducted on material costs, fabrication efficiency, installation timelines, transportation logistics, as well as long term maintenance, repair, and rehabilitation expenditures.

Each FRP component demands a specialized manufacturing approach, contingent upon a nuanced interplay of material characteristics, production rate, and cost considerations. The hand-layup method, favoured for its suitability in crafting sizable components, is nonetheless beset by labour intensive workflows and inherent variability in product quality. Vacuum Assisted Resin Transfer moulding (VARTM) emerges as an apt solution for fabricating smaller to medium-sized intricacies at intermediate production scales, but this process requiring substantial investments in tooling and consumables. In contrast, the pultrusion process offers unparalleled consistency in product quality while effectively minimizing solvent evaporation. Additionally, the advent of 3D printing presents a revolutionary method, enabling rapid prototyping of complex geometries, particularly advantageous in challenging environmental contexts. However, its adoption mandates access to high-grade materials and specialized equipment. **Figure 4** provides a comprehensive illustration of the diverse manufacturing methodologies and commonly employed materials in the realm of FRP bridge construction.

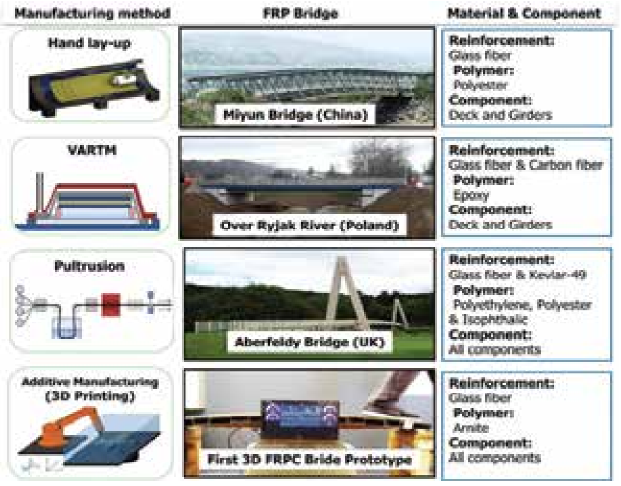


Figure 4. Manufacturing methods and commonly used materials in FRP bridges

Life cycle cost (LCC) assessment stands as a critical determinant in the comprehensive cost analysis of composite structures. LCC encompasses initial, maintenance, and rehabilitation expenditures. From the literature various studies have empirically demonstrated that the fabrication cost associated with FRP structures is typically 40-50% higher compared to conventional counterparts like prestressed concrete and steel. Figure 5, illustrates the anticipated LCC savings achievable with FRP bridges relative to conventional equivalents. Notably, Figure 5b elucidates that while FRP bridges exhibit higher initial costs. However, their superior resilience to harsh environmental conditions translates into lower LCCs, necessitating only routine cleaning to ensure operational functionality. Additionally, Figure 6 provides a detailed breakdown of the constituent components and their configurations within the bridge structure.

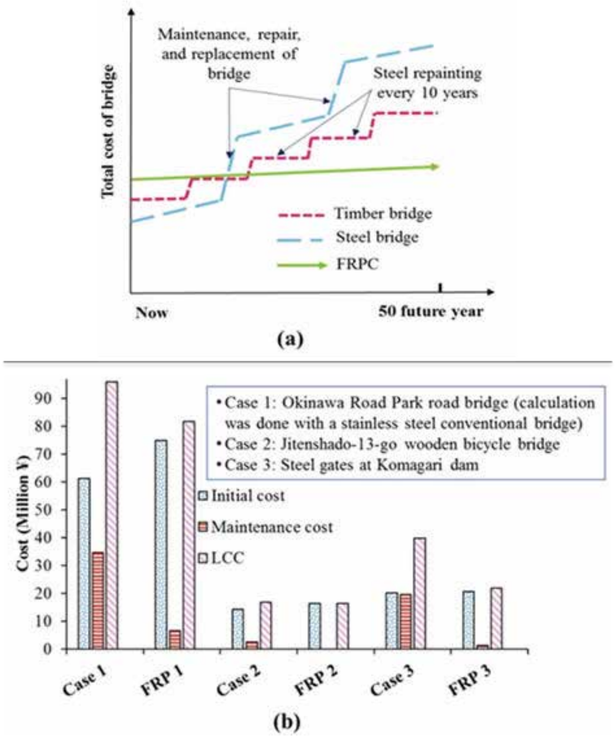


Figure 5. (a) Schematic of LCC of different bridge types and (b) comparing the initial, maintenance and LCCs of 3 conventional bridges with FRP substitutions

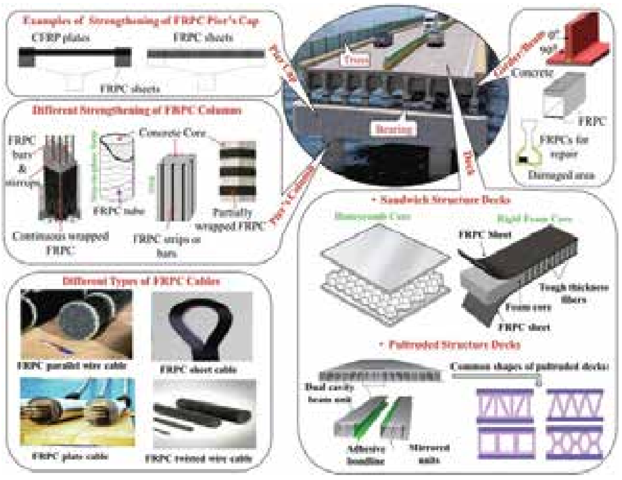


Figure 6. FRPs usage in bridge industry

1. Carbon negative composite decking system

The Heldebrant group, based at the Pacific Northwest National Laboratory (PNNL), has led the development of an insnovative composite decking system with the aim of mitigating the environmental impact of conventional building materials. This pioneering system incorporates low-grade brown coal and lignin as fillers within the decking composites, subjected to meticulous chemical functionalization processes to optimize their performance characteristics. Subsequent blending of various ratios of lignin and coal particles with high-density polyethylene (HDPE) yields brownish-black composites, whose material properties underwent thorough investigation. Results revealed highly favourable physical properties inherent in the novel composite material. Notably, it was observed that this composite material has a cost advantage, being 18% more economical than standard decking composite boards. Furthermore, the research elucidated the material's capacity to sequester more CO2 during both its manufacturing process and operational lifespan than is emitted. They have also stated that replacing 3.55 billion feet of conventional decking systems with the novel composite decking system could potentially sequester 2,50,000 tons of CO2 annually, equivalent to the yearly emissions from 54,000 cars.

Figure 7. Composite decking material (Source: Shutterstock)

2. Carbon fibre tie rods for the long-span space structures

Carbon fiber tie rods are increasingly favoured in coastal regions due to their superior corrosion resistance and extended lifespan. These tie rods serve as viable alternatives to high-strength steel tie rods, particularly in critical spatial structures. The Zhongfu Shenying group has pioneered the development of carbon fiber tie rods, utilizing 48K large tow carbon fiber (carbon core) through a pultrusion process. Test results demonstrated a significant 95% improvement in anchoring efficiency. Notably, these carbon fiber tie rods have been successfully deployed at Xiamen Xiang'an Airport, marking a significant milestone as the first large-scale application in the domain of long-span spatial structures.

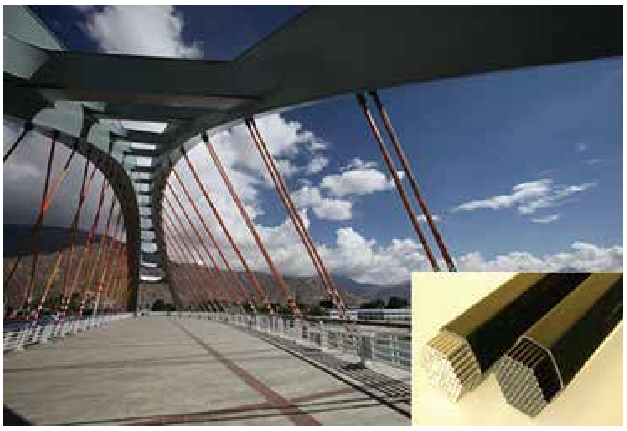


Figure 8. Carbon fibre tie rod

3. Revolutionizing fireproof protection and sustainability for FRP products

The unique combination of fireproof safety and sustainable materials offers a compelling solution for various industries seeking to support their circular and sustainable composite material requirements. These advanced fireproof materials find applications in the construction and infrastructure sectors, particularly for fireproofing and acoustic insulation purposes.

WT&C, in collaboration with ARIS Inc., has developed the ARIS Lightweight Eco Ceramic Composite (ALEC²). ALEC² stands out as a fire and corrosion-proof ceramic composite characterized by its exceptionally low thermal conductivity, lightweight nature, and 100% recyclability at the end of its product life cycle. This ground-breaking fireproof material, distinct from any other FRP composite material available in the market, provides unparalleled protection for FRP products against heat and fire incidents. Such fireproofing capabilities pave the way for a significantly safer and more sustainable future across a myriad of FRP applications and industries.

Figure 9. Lightweight Eco Ceramic Composite

4. FRP rebar

FRP rebar serves as an increasingly prominent substitute for conventional steel reinforcement in civil infrastructure projects such as roads and bridges. Owing to their superior attributes including high tensile strength, enhanced resistance to corrosion, prolonged service life, and reduced density, FRP rebar offers significant advantages over its steel counterparts. However, it exhibits few challenges in terms of lower tensile modulus and limited on-site manipulability (welding and bending) compared to traditional rebar materials.

To addresses these issues, the American Concrete Institute (ACI, U.S.) released the comprehensive building standards ACI CODE-440.11-22 in December 2022, delineating the specifications for FRP rebar usage in structural concrete applications. This encompasses various connection methodologies, spanning cast-in-place, precast, and non-prestressed construction techniques. Simultaneously, ASTM International's composite materials committee D30 introduced the new standard specification D8505 in 2023, tailored specifically for the latest generation of FRP rebar, incorporating both Glass Fiber Reinforced Polymer (GFRP) and Basalt Fiber Reinforced Polymer variants.

In a recent development, a strategic alliance has been formed in between ExxonMobil subsidiary Materia (Pasadena, Calif., U.S.), NEG-US (Shelby, N.C., U.S.), and GatorBar (Ahmeek, Mich., U.S.), to tackle the increasing global demand for composite rebar in the concrete reinforcement sector. This collaborative effort has ensued in the development of a novel rebar material, featuring a composition comprising polyolefin thermoset resin and NEG-US fiberglass. These entities report significant enhancements, with the new rebar material exhibiting 2-4 times the strength and weighing 4-7 times less than traditional steel.

Figure 10. FRP Rebar (Source: Mateenbar)

5. FRP utility poles

Fiberglass composite poles represent a highly corrosion-resistant and durable solution, boasting a lifespan of up to 75 years. They serve as viable alternatives to traditional wooden and metal utility poles. Furthermore, these composite poles exhibit superior fire resistance due to the incorporation of fire-resistant resins, additives, and other specialized solutions.

In a recent development, Creative Composites Group (CCG) based in Alum Bank, Pa., U.S., has introduced its pultruded StormStrong utility poles. Engineered for enhanced resilience, these poles are specifically designed to withstand extreme weather events such as hurricane-force winds, blizzards, and deep freezes. Additionally, CCG now offers FireStrong utility poles, which have been classified as self-extinguishing according to UL94 with a V0 rating. These poles are equipped with a self-monitoring system that continuously monitors structural performance, ensuring optimal safety and reliability.

Figure 11. Storm Strong composite utility poles

6. Repair, strengthening and retrofitting

The evolving landscape of social demands, advancing design specifications, stringent safety regulations, and structural degradation necessitate the reinforcement of existing reinforced concrete and steel structures, encompassing a wide range of infrastructure such as bridges, jetties, buildings, and pipelines. Common methodologies for strengthening include the application of external reinforced concrete or shotcrete jackets, epoxy bonding of steel plates, or external post-tensioning techniques.

An alternative and increasingly popular approach involves the utilization of FRP materials, typically in the form of thin laminates or fabrics. FRP composite strengthening exhibits exceptional performance characteristics, rendering it highly versatile in reinforcing various structural elements including slabs, beams, reinforced concrete, pre-stressed/post-tensioned concrete, steel, and timber structures. Notably, the application of FRP fiber wrapping directly onto existing substrates circumvents the need for extensive demolition and reconstruction, thereby minimizing disruption during repairs and significantly reducing installation time and associated costs.

In recent years, an expansion of companies has emerged offering a wide spectrum of modular FRP repair solutions tailored for infrastructure applications. These solutions often feature prefabricated panels renowned for their lightweight properties, boasting an 80% reduction in weight compared to traditional reinforced concrete panels. Noteworthy examples include QuakeWrap (Tucson, Ariz., U.S.), specializing in Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP) products tailored for strengthening pipes, walls, and other structures. Similarly, in India, the Reliance Composites Solution Division provides a comprehensive suite of carbon and glass fiber reinforced polymer products designed for strengthening diverse structural members, all adhering to stringent international standards.

The effective implementation of fiber reinforced systems stands to significantly extend the service life of structures while concurrently minimizing maintenance demands. These solutions not only repair deteriorated structures but also safeguard them against seismic events and corrosion, contributing to overall structural resilience and longevity.

Figure 12. Structural retrofitting

5.6.2 FRP Composites in Automobile Sector

Background

Fiber reinforced polymer (FRP) composites are widely being accepted in the automotive industry due to its enhanced properties, such as easy moldability, improved aesthetics, reduced weight, and impact strength, as compared to other conventional automotive components. With coming time FRP composites utilization will notice significant increase due to its ability to exhibit maximum mass reduction of automobile and carbon emission reduction potential by reducing the overall weight of the vehicle. In various structural, interior, exterior and alternative powertrain applications, FRP composites found its applications. In terms of market share among various other applications, FRP composite found highest requirement in the automotive market.

In 2022, the International Organization of Motor Vehicle Manufacturers (OICA) reported a global production of approximately 85.01 million vehicles, marking a 5.99% increase from the 2021 figure of 80.20 million vehicles. This upsurge underscores a heightened demand for fiber reinforced polymer (FRP) composites within the automotive sector.

Notably, the industry's expansion correlates with the escalating adoption of electric vehicles (EVs). The World Economic Forum (WEF) documented a sales volume of nearly 4.3 million battery powered EVs (BEVs) and plug-in hybrid electric vehicles (PHEVs) during the first half of 2022, further bolstering the demand for FRP composites. Meanwhile, the Indian automotive market has exhibited remarkable growth across diverse vehicle categories. Passenger vehicle sales soared from 30.7 million to 38.9 million units in the fiscal year 2022-23, while the commercial vehicle segment witnessed a significant uptick, with total sales escalating from 7.2 million to 9.6 million units. India's EV market is undergoing a transformative phase, with EVs accounting for approximately 5% of total vehicle sales between October 2022 and September 2023, signifying an escalating need for FRP composites.

Key products/components

FRP composites are utilized for applications such as chassis, body panels, structural reinforcements, dashboards, door panels, seat structures, bumpers, fenders, hoods, battery enclosures, electric motors, and power electronics. Few of these major applications are described below.

S. No.	Product/component	Description
1	Chassis, body panels, and structural reinforcements  	FRPs are increasingly used in various structural components of vehicles; critical parts that are responsible for bearing the load and impact forces during normal operation and collision events, such as chassis, body panels, and structural reinforcements, benefit from the high strength and stiffness of these materials. This not only enhances safety standards but also contributes to the overall performance of vehicles.
2	Interior components  	Characteristics of FRP composite, such as easy molding, shaping, and tailoring to fit specific requirements and applications, enabled automotive engineers to create functional designs that can improve the appearance of the interior parts, such as dashboards, door panels, and seat structures.

3	Battery enclosures 	FRP composite find applicability in alternative powertrain components like battery enclosures. They contribute to weight reduction, enhance thermal management, and provide protection against mechanical and electrical stresses. By using FRPs, electric and hybrid vehicles can increase their energy efficiency and extend their driving range, as well as reduce the environmental impact of battery production and disposal.

Current scenario (National and International markets)

India

In India, automotive applications of FRP contribute to 31% of the total FRP industry market share.

S. No.	Name	Description	Automotive Products
1	Mahindra CIE, India.	Mahindra CIE Ltd. (Amalgamated) was incorporated in the year 1982. Mahindra and Mahindra Group decided to set up Siro Plast Ltd., a company slated to provide quality products in engineered plastic composites.	Commercial Truck Front Panel, NVH Cover, Fender, Engine Hood, Front Bumper, Rickshaw Fender, Base Panel, Back Panel, Head Lamp Reflector, SMC And DMC Components, EV Covers, Composite Components.
2	Tata AutoComp Systems, India	Started in year 2000 as ACSI, a JV with Owens Corning India Technology, provides products in the automotive industry to Indian and global customers, including Ashok Leyland, John Deere, Tata Motors, International Tractors, Man Force Trucks, New Holland, Daimler.	Front Panel, Bumper, Fender, Door Add-on, Body Side Add-on, Trim Pillars, Aero Corner, Wiper Cover, Hood.
3	Reliance Composites (RELX Composites), India	Reliance industries entered the composite business in 2017 through Reliance Composites Solutions (RCS). Reliance composites are made at the world's most integrated FRP/GRP (glass reinforced polymers) composite manufacturing facility.	Front Fascia, Dash board, Seat Pan & Structure, Roof Panels, Floor Module with flooring, Wheel for LMV, Steering, Interior Side Window Panels, Partition Panel, Bonnet Covers.

International

S. No.	Name	Description	Automotive Products
1	Toray Composite Materials America, US	Toray Composite Materials America, Inc. began producing advanced composite materials in 1992.	Carbon fiber and prepreg material
2	Teijin Automotive Technologies, Japan	Prior to 2017, Teijin supplied some low-volume carbon fiber reinforced plastic (CFRP) components to automakers. However, With the acquisition of Continental Structural Plastics (now Teijin Automotive Technologies), Teijin became a Tier 1 supplier.	Side Panels, Body Components, Liftgates, Removable Hardtop Assemblies and Modular Roofing Systems, Tonneau Covers, Trunk and Decklid Assemblies, Fender Assemblies, Pickup Box, Pickup Box Tailgate Closeout, Electric Vehicle Battery Covers and Complete Enclosures, Radiator Support Assemblies, Bumper Beams, Structural Members, Sunshade Substrate, Spare Tire Hub and Locator Assemblies, Fuel Tank Heat Shields, Splash & Underbody Shields, Access Covers, Engine Shrouds, Engine Cover Assembly, Engine Sump Pan
3	HEXCEL, US	Founded in 1948, HEXCEL is an integrated composite solutions provider in the industry.	Structural parts, leaf springs, Car bodies and interiors
4	Mitsubishi Chemical Carbon Fiber and Composites, Inc., Japan	The composites division of MCCFC, was formed in 1978 and its Carbon Fiber Division has been producing standard modulus carbon fibers since 1984.	PAN-based carbon fiber, PITCH-based carbon fiber, Carbon Fiber composites, Film adhesive, Prepreg, Towpreg.

Challenges and future prospectives

Key obstacles hindering the extensive utilization of composites in the automotive sector encompass limited industry familiarity with polymer- and aluminum-based composite materials, constrained production rates stemming from underdeveloped processes, the necessity for novel joining techniques, insufficient understanding of material behaviors within automotive environments, inadequate recycling technologies, limited supplier availability, and absence of comprehensive crash models. Furthermore, the comparatively high cost of carbon fiber in contrast to other structural materials presents a significant impediment to its widespread integration. Despite these challenges, composites find application in various components of modern automobiles. The potential of lightweight composites in the automotive industry is substantial, yet further research is imperative. It is noteworthy that costs are inversely proportional to a vehicle's mass, underscoring the economic implications of material selection.

Figure 13. (a) The 2022 BMW iX battery-electric sports activity vehicle (SAV) features a multi-material combination of metals and composites in its innovative Carbon Cage. (b) Rassini's 1+C hybrid leaf spring features a single steel parabolic main plate and a flat glass fiber composite helper plate to provide suspension on the rear wheels of the Ford F-150 pickup truck

The electric vehicle (EV) battery enclosures represent a pivotal area for composite utilization in the automotive sector, driven by the imperative for original equipment manufacturers (OEMs) to diminish the mass of the overall battery pack.

In 2022, battery enclosures for EVs garnered significant attention in automotive composite discussions, yet internal combustion engine (ICE) vehicles remain relevant. OEMs persistently integrate composite structural components into both EVs and ICE vehicles where practical, alongside transitioning towards more efficient, automated processes to accommodate higher production volumes. Notably, BMW Group introduced its latest battery-electric sports activity vehicle (SAV), the iX, in 2022, featuring a "Carbon Cage" body frame that amalgamates various manufacturing techniques, including resin transfer molding (RTM) braided preforming, fiber-reinforced thermoplastic injection molding, compression molding, and metallic elements, building upon BMW's prior composite strategies for models such as the i3, i8, and 7-Series (Figure 13 (a)).

Composite leaf springs and leaf spring components remain at the forefront of composite applications in automotive (Figure 13 (b)). For instance, the recipient of the Grand Award at the 2022 SPE Automotive Innovation Awards was an all-composite leaf spring developed by Mubea for General Motors Co., promising substantial mass reduction compared to conventional steel leaf springs.

Moreover, the automotive industry continues to pursue sustainable material solutions across various components, embracing innovations ranging from natural fiber composites to bio-based resins and recyclable materials. Some noteworthy developments in sustainability reported in 2022 include BMW's investment in flax fiber materials supplier Bcomp, Toyoda Gosei Co. Ltd.'s successful application of bio-derived cellulose nanofiber reinforced plastic for automotive components, Faurecia's establishment of a Sustainable Materials division focused on developing eco-friendly materials, and Porcher Industries' launch of automotive-grade thermoplastic composite stiffeners primarily composed of flax fibers, tailored for use in automotive interiors and decorative components.

5.7 Case studies

Case study 1: FRP Composite material for Railway Applications

1. Executive Summary

In 1950, glass fiber reinforced polymer (GFRP) composites were extensively used in the fabrication train carriages interiors, luggage racks, and sanitary facilities, enhancing performance and reducing noise and vibration. They become prominent in high-speed trains like the TGV, which travels at speeds exceeding 300 kmph. Subsequently, South Korea developed the KTX II train in 2010, capable of attaining speeds up to 400 kmph. Notably, specific sections of the high-speed train structure including the nose were constructed using high strength FRP composites to withstand the pressure waves and aerodynamics shocks encounter during passage through tunnel apertures. Therefore, in terms of cost effectiveness and various aspects of railway vehicles, the use of FRP composites offers potential benefits. Further, to expand the use of FRPs and increase confidence in the railway sector, further research efforts are required. Moreover, as of April 2024, Indian Railway Finance has a market cap of $22.71 Billion. This makes Indian Railway Finance the world's 840th most valuable company by market cap. Indian Railways operates over 13000 passenger trains and over 8000 freight trains daily covering over 7000 stations across India. Therefore, there is a huge demand of FRP composite materials for developing structures and equipment in railway sector.

2. Key challenges

Challenges in FRP composite application in railways encompass standardization, material certification, fire safety, integration complexities, cost considerations and providing durability. Overcoming these challenges require developing precise standards, rigorous certification procedures, and advanced fire-resistant formulations. collaborative efforts are vital to ensuring seamless integration of FRP composites, enhancing railway infrastructure efficiency and longevity.

3. Partners involved

National Composite Industry partners:

S. No.	Name	Railway products
1	Fibro Plastichem Pvt Ltd, Dankuni, India	Railway Coach Fabrication: FRP Partition Wall, Composite Berth, FRP Windows, Panels, and Modular Toilets for Various Types of Coaches.
2	Arvind Composite Gujarat, India	Major Products Include. • Interior/Exterior Parts of Rail & Metro Coach • Honeycomb/Foam Sandwich Panels • Ceiling Panels • Modular Toilets • Front Mask /Nose Cone

3	MSL: Mobility Solutions Limited Punjab, India	MSL produces of railway parts and components with a broad spectrum of FRP and Sheet Metal solutions along with a variety of railway interior solutions. • Major Products Include. • Interior Panels • Toilet Modules • Front and Rear End • Bogie Frame, • Side Wall, Roof & Doors
4	S.V. Composites & Engg. Pvt. Ltd. Maharashtra, India	FRP Interiors, Exteriors, Toilet modules, Seat Tool Products for Metros and Railways.
5	Pramod Fibre Plast Pvt. Ltd. Nashik, India	Manufactures railway seating, FRP modular Toilets, Fire Retardant Grade Side and Ceiling Panels.
6	Reliance composite Vadodara, India	Manufacture products catering the emerging needs of Rail & Metro Rail segment. • Interior / Exterior of Rail & Metro Rail Coach • Sidewall, End-wall, Partition Panel • Electrical Cubical Panel • Ceiling & Window Panel • Seats • Modular Drop-down / Bio-digester Toilet • Front Mask / Aerodynamic Front End

International Composite Industry partners:

S. No.	Name	Railway products
1	BGL Technology International Inc. Dubai, UAE	FRP components in railway construction, like, FRP platforms and stairs, GRP railings, bridge covers, track crossings and service routes.
2	Creative Composites Group. United States	Railway platform and transit, coverboards, stairs, fire resistance tunnel, etc.
3	Evergrip Limited United Kingdom	GRP Rail Access Platforms and Railway Ramps.
4	Space Evolution Industry Technology Co., Ltd., China	Special in the part marking for Train and Metro.
5	Suzhou East Railway Co., Ltd., China	Rail Vehicle, Wagon Bogie, Body Parts, Rail Parts, etc.

4. Benefits, including Techno-commercial benefits

FRP composites present a compelling proposition in the railway sector due to their inherent technical advantages. FRPs lightweight nature minimises energy consumption and enhances locomotive efficiency. Additionally, their corrosion resistance ensures prolonged service life for railway infrastructure, reducing maintenance costs. The durability of FRP composites translates to fewer replacement cycles, offering substantial life cycle savings. Moreover, FRPs design flexibility allows for customised solutions, optimising performance. From a techno-commercial perspective FRP composite offer superior long-term return on investment, regulatory compliance, and a competitive edge in the market.

5. Figure / Illustration of the Technology/ Product

S. No.	Product/component	Description
1	Coach/Bogies/wagon and wheelset 	Bogies are multi-component structures that serve a variety of purposes in the railway transportation systems. These structures support the weight of the train and connect it to the rails.
2	Panels of rail 	Sidewall and ceiling panels of rail body

3	Toiletries  	FRP based modular toiletries
4	Windows 	Different types of windows in rail coaches are made of sheet moulding GFRP
5	Seating 	GFRP based passenger seats for different types of train coaches, like passenger, AC, Metro, etc.
6	Rail lines 	FRP composites are also employed in the railway industry for structural purposes in rail lines.
7	Platform and ramps 	FRP platforms, bridges, overbridges and stairs, large number of GRP railings, bridge covers, track crossings and service routes are utilized for safe access in railway station and rolling stock.

Case Study 2: FRP Composite Material for Pressure Vessels Applications

1. Executive Summary

FRP composite pressure vessels (PV), employing fibre reinforcement within a polymer matrix, represent a significant advancement in storage technology. Their inception stems from the need to overcome limitations of traditional metallic cylinders, such as susceptibility to corrosion and weight inefficiencies. FRP cylinders offer a compelling range of benefits, including exceptional strength to weight ratios, corrosion resistance, and design versatility, rendering them pivotal across various industries. However, the quest for futuristic development in storage applications, notably in sectors like CNG and hydrogen, necessitates ongoing research and innovation. Addressing challenges improving material properties, enhancing manufacturing processes, and refining safety standards is paramount. Advancements in composite formulations such as nanocomposites, hold promise for enhancing mechanical properties and reducing permeability, thus optimising storage efficiency and safety. Moreover, exploring novel manufacturing techniques like, automated fiber placement, automated filament winding, and resin infusion can further streamline production and enhance product consistency. Overall, sustained research efforts are pivotal for unlocking the full potential of FRP composite PVs in addressing evolving storage needs and advancing industrial capabilities.

2. Key challenges

The development of FRP hydrogen storage tanks, encompassing Type-IV and Type-V variants, confronts challenges ranging from ensuring hydrogen permeability to managing high pressure demands and addressing impact and fatigue resistance. Critical aspects include sealing, regulatory compliance, cost of effectiveness, testing, validation, and thermal stability of composite PV. Overcoming these hurdles mandates interdisciplinary expertise and stringent testing for safety, efficiency and regulatory adherence.

3. Partners involved

National Composite Industry partners:

S. No.	Name	Features
1	Supreme Industries Ltd. Mumbai, India	Annual Capacity: 5,00,000 Composite LPG cylinders. Expected Durability: 20 years. KAVACH variants (Global certifications): 8 KAVACH Type IV composite LPG cylinders are manufactured using the highest quality raw materials sourced from global suppliers.
2	Indoruss Synergy Pvt. Ltd. New Delhi, India	Major Products Include. • Type-IV CNG Cylinder • CNG Cylinder Cascade • Composite LPG Cylinder
3	Litesafe cylinders Mumbai, India	Lifesafe is a new generation of composite cylinders for filling LPG has gained huge interest and appreciation across the globe due to its various striking features. • 100% explosion proof • Translucent Body • Rust free • Light & Efficient • Aesthetically Appealing • Reduced Maintenance

4	Fibro Plastichem Kolkata, India	Fibro Plastichem, manufacturer of FRP Pressure Vessel. • Capacity up to 2500 Gallo • Outstanding performance • Long Durability • Can with stand harsh chemical environment • Better Corrosion resistant • Low maintenance • Maximum Operating Pressure - 150 psi

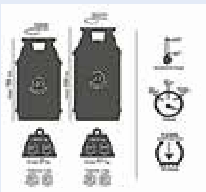
International Composite Industry partners:

1	Aburi Composites England, UK	Aburi Composites supplies the widest range of 'Type IV' composite LPG cylinders. • Low maintenance & Logistical Cost • Easy to Handle • Non-Explosive
2	Advanced Material Systems (AMS) Taiwan	AMS hydrogen cylinders are accredited for use worldwide and are produced to recognised global standards including ISO 11119-2, UN-TPED Pi, DOT (USA) and TC (Canada) certification. • Durable, with excellent flame and impact resistance

4. Benefits, including Techno-commercial benefits

FRP composite PVs offer technical superiority with high strength to weight ratios and corrosion resistance, ideal for aerospace and automotive applications. Commercially, reduced material costs and minimal maintenance enhance cost effectiveness. Enhanced efficiency and safety features bolster market competitiveness, positioning FRP PVs as preferred solutions across industries.

5. Figure / Illustration of the Technology/ Product

S. No.	Product/component	Description
1	Type-IV LPG Cylinders 	Composite LPG Cylinders are systematically tested by international institutions and certificated to international standards and regulations including ISO 11119-3, EN 12245, ADR/RID 2015 and Dir2010/35/EU.
2	Pressure Vessels 	FRP PVs are designed as a replacement to conventional water storage tanks which are to provide better facility of Water Storage and Filtration as composites provide Corrosion Resistance and Higher Service Life.

5.8 Advanced Materials Market Company Analysis

S. No.	Company	Product/Technology/ Advanced Materials Product and Solutions
1	EPP Composites Pvt. Ltd., Rajkot, India	FRP Pipes, Cooling Towers, Storage Tanks, various FRP Pultruded Products, Cable Trays, Electrical Boxes, Electrical Poles, FRP Doors, Roofing Sheets, FRP Fittings & Liners.
2	Arvind Composites, Gandhinagar, India	FRP Cable Trays, Ladders, Gratings, Poles, Gratings, Platform with Handrails, Staircases, Walkways, Scaffolding, Fencing, Monkey ladders, and Modular infrastructure.
3	Everest Composite Pvt. Ltd., Vadodara, India.	Gel coated FRP Panels, Moulded Gratings, Skylight FRP Panels, Cooling Tower Cladding Panels, Industrial Roofing and Cladding Solutions, FRP rebars, Prefab Solutions.
4	Reliance Composite, Vadodara, India	Modular Houses, Gratings, Manhole Cover, Light Poles, Walkway Bridges, Ladder, Canopy, Doors, Cooling Tower Structures, Pipes, Cable Tray, Jio Pole, Prepreg, Reinforcing Bar, Storage Tanks, Structural Fittings.
5	Fibro Plastichem, Vadodara, India	FRP Poles, Pipes & Fittings, Pressure Vessel, GRP Tank, GRP Equipment, Railway Coach fabrication.
6	Aradhana Fiber glass Technologies,Bangal ore, India	Moulded Products, Tanks, Gratings, Sheets, Exhaust systems, FRP security cabins.
7	Jindal Advanced Materials Gurugram, Haryana	Cable Master Trays, Sentinel Manhole Plates, Rebar, Staircases.
8	TATA Steel Composites, Kolkata, India	FRP Pipes, Bridges, Poles, Pressure Vessels, Tanks, Modular Toilets, Customized FRP Products, Security & Isolation cabins.
9	Creative Composite Group, United States	Cooling Towers, Bridge Decking, Boardwalks, Structural Profiles, Utility Poles, Industrial Tanks & Processing Equipment.
10	Tencom Limited, United States.	Pultrusion Profiles, Fiber Glass Rod, Poles, Angels, Bars & Channels.

S. No.	Company	Product/Technology/ Advanced Materials Product and Solutions
11	Composite Tech Austria	FRP Rebar, Pipes, Tanks, Silo, Mesh, Structural Profiles
12	Horse Construction Ltd., China	FRP Bridge Bearing System, Crack Repair System, Steel Bonding System, Anchoring System.
13	RPS Composites, Alabama, United States	FRP Pipes, Fittings, Tanks, Vessels, Structural Profiles.
14	GRP Industries, UAE	FRP Enclosures, Kiosks, Roofing & Customized Products
15	Ferro Grate, Ajman, UAE	FRP Gratings, Flatforms, Ladders, Access Cover, Cable Trays
16	Grating FRP, Australia	FRP Sandwich Plates, Pultruded Structures, Moulded Gratings, Pultruded Gratings, Manhole Covers, Gratemates 4 Wheel Drive Non-Slip Mates, Staircase, Handrail, Roofing System.
17	SHM Shipcare, Mumbai, India.	FRP Boat manufacturing and repair: building, repair, maintenance, and dry-docking services for FRP boats.
18	Kineco Kaman Composites India (KKCI), Goa, India	Sonar Dome
19	Suvarna Fibrotech Pvt. Ltd., Pune, India.	Branded boat manufacturer in India. Manufacturer of marine grade FRP with high quality decks, hulls, and extensive range of FRP boats.
20	Prolong Composites India Private Limited, Mumbai, India	FRP boats, offshores, and other marine secondary architecture
21	SEASAFE, INC, Lafayette, Louisiana, USA	GF-FRP products such as cable trays, handrails, ladder systems, grating, and pultruded profiles for offshore platforms and ships.
22	Qingdao Grandsea Boat Co Ltd., China	FRP boats

S. No.	Company	Product/Technology/ Advanced Materials Product and Solutions
23	Unicomposite, Nanjing, China.	FRP docks and other secondary marine components.
24	FGS Composites, Oakhurst, Australia.	Marine vessels and superstructure including interior, cold rooms, engine bay and water systems. Also, manufacturer of custom small ships and boats.
25	MSL: Mobility Solutions Limited, Punjab, India	MSL produces of railway parts and components with a broad spectrum of FRP and Sheet Metal solutions along with a variety of railway interior solutions. Products include wide range of FRP/GRP composite solutions like Nose cone/Front end, Interior panelling and toilet modules; sheet metal solutions like sheet metal/fabricated products such as Front Mask/Nose, Front and Rear End, Under Frame, Bogie Frame, Side Wall, Roof and Doors; interior solutions like frames and components.
26	S.V. Composites and Engineering Private Limited, Pune, India	FRP Interiors, Exteriors, Toilet modules and Seat Tools and Products for Metros and Railways. FRP GRP Railway Parts include metro vestibules GRP tool, CAR window panel, metro seat and much more.
27	Pramod Fibre Plast Pvt. Ltd., Nashik, India	Manufactures railway seating, FRP modular toilets, side and ceiling panels in fire retardant grade material.
28	Reliance composite (RelX™), Vadodara, India	Manufacture products catering the emerging needs of Rail & Metro Rail segment. • Interior / Exterior of Rail & Metro Rail Coach • Sidewall, End-wall, Partition Panel • Electrical Cubical Panel • Ceiling & Window Panel • Seats • Modular Drop-down / Bio-digester Toilet • Front Mask / Aerodynamic Front End Driver Cab Interior of Rail, Metro Rail & Locomotives
29	BGL Technology International Inc., Dubai, UAE	FRP components in railway construction, like, FRP platforms and stairs, GRP railings, bridge covers, track crossings and service routes.

S. No.	Company	Product/Technology/ Advanced Materials Product and Solutions
30	Creative Composites Group, US	Railway platform and transit, coverboards, stairs, fire resistance tunnel, etc.
31	Evergrip, UK	GRP Rail Access Platforms and Railway Ramps.
32	Space Evolution Industry Technology Co., Ltd., China	Special in the part marking for Train and Metro.
33	Suzhou East Railway Co., Ltd., China	Rail vehicle, wagon bogie, body parts, rail parts, etc.
34	Kineco Ltd., Goa, India	Sonar domes, ballistic proof bunker, portable bridges, high pressure pyrogen ignitor cases for GSLV and PSLV launch vehicles.
35	Suvarna Fibrotech Pvt. Ltd., Pimpri-Chinchwad, Maharashtra, India	Bunkers, FRP shelters for high altitude, defense instrument carrying box, biodigesters, cabins etc.
36	Pramod Fiber Plast Pvt ltd., Maharashtra, India	Shelters and containers used in defence applications
37	Starwin Industries, Dayton, USA	Supplies 75 types of radomes and other components that support various military aircraft and weapons systems like F-Series fighter jets, AWACS, and the RIM-7 Sea Sparrow.
38	Collins Aerospace, USA	Manufacturer of large composite structure for US and Canadian navies like submarine bow domes, surface ship sonar domes, composite sonar keel domes and submarine high-frequency acoustic windows.
39	ACP Composites, California, USA	Manufacturer of a wide range of military and defense composite parts and systems, including UAV frameworks, accessories for vertical take-off and landing (VOTL) aircrafts, body and vehicle armor, and satellite and antenna mponents.
40	Piran Advanced Composites, UK	Produces lightweighting military vehicles and components, armour/ballistics protection and fairings for various defence and military vehicles.

S. No.	Company	Product/Technology/ Advanced Materials Product and Solutions
41	Impact Materials, Hangzhou, China	Aramid fiber-based products include radomes, bulletproof vests, helmets, military vehicles, aircraft, missiles, nose cone and body of ballistic missiles. Aramid fiber-reinforced composite materials are used in aircraft components such as wings, fuselage, and landing gear.
42	Mahindra CIE, India.	Commercial Truck Front Panel, NVH Cover, Fender, Engine Hood, Front Bumper, Rickshaw Fender, Base Panel, Back Panel, Head Lamp Reflector, SMC And DMC Components, EV Covers, Composite Components.
43	Tata AutoComp Systems, India	Front Panel, Bumper, Fender, Door Add-on, Body Side Add-on, Trim Pillars, Aero Corner, Wiper Cover, Hood.
44	Toray Composite Materials America, US	Carbon fiber and prepreg material
45	Teijin Automotive Technologies, Japan	Side Panels, Body Components, Liftgates, Removable Hardtop Assemblies and Modular Roofing Systems, Tonneau Covers, Trunk and Decklid Assemblies, Fender Assemblies, Pickup Box, Pickup Box Tailgate Closeout, Electric Vehicle Battery Covers and Complete Enclosures, Radiator Support Assemblies, Bumper Beams, Structural Members, Sunshade Substrate, Spare Tire Hub and Locator Assemblies, Fuel Tank Heat Shields, Splash & Underbody Shields, Access Covers, Engine Shrouds, Engine Cover Assembly, Engine Sump Pan
46	HEXCEL, US	Structural parts, leaf springs, Car bodies and interiors
47	Mitsubishi Chemical Carbon Fiber and Composites, Inc., Japan	PAN-based carbon fiber, PITCH-based carbon fiber, Carbon Fiber composites, Film adhesive, Prepreg, Towpreg.
48	Suzlon, India	Wind Turbines Generators, Operations, Maintenance and Services.
49	TPI composites, US	Wind turbine and related services
50	Siemens Gamesa Renewable Energy, Spain	Wind turbine and related services
51	Strohm, Neatherland	Thermoplastic Composite Pipe
52	EconCore, Netherlands	Wind turbine gondola casing and Solar Structures / Solar Panel Mountings

Chapter Contributors

On behalf of the CII National Mission for Technology, Innovation and Research, we would like to acknowledge and express gratitude to the following for their contributions in the Chapter on Composites:

1. Dr Bankim Chandra Ray, Professor, NIT and Lead, Composites Chapter
2. Mr N Sainathan, Chief NMB, Tata Steel Ltd., and Managing Director, Tata Steel TABB Ltd.
3. Prof M Gupta, CEO & MD and Ms Jyoti Chaudhari, COO, Ecoearth Solutions Pvt Ltd
4. Mr Ravi Chidambar, Chief Executive Officer, Tata AutoComp Systems.
5. Mr Vijay Rajpurohit, Managing Director, Chemical Process Piping Pvt. Ltd
6. Mr Sumit Datta, Managing Director, Fibroplastichem India Pvt Ltd.
7. Mr Pawan Tyagi, COO, Reliance Composites, Reliance Composites Polymers
8. Dr Tanmay Bhattacharyya, Chief Khapoli Project, Technology & New Materials Business, Tata Steel Limited
9. Mr Sanjeev Kumar Biswas, Chief M&S and Supply Chain Composites,New Materials Business, Tata Steel Limited
10. Dr Subrata Mukherjee, Head, Advanced Materials & Characterization Research Group, R&D, Tata Steel Limited, Jamshedpur

References

1. https://www.industryarc.com/Report/19582/fiber-reinforced-plastic-frp-market.html.
2. Qureshi J. A review of fibre reinforced polymer structures. Fibers. 2022 Mar 8;10(3):27.
3. Alin Diniță, Razvan George Ripeanu, Costin Nicolae Ilincă, Diana Cursaru, Dănuța Matei, Ramadan Ibrahim Naim, Maria Tănase and Alexandra Ileana Portoacă. Advancements in Fiber-Reinforced Polymer Composites: A Comprehensive Analysis. Polymers 2024, 16, 2. https://doi.org/10.3390/polym16010002.
4. Fiber-Reinforced Composites Market (https://straitsresearch.com/report/fiber-reinforced-composites)
5. Fiber Reinforced Polymer Market – Global Industry Assessment & Forecast (https://www.vantagemarketresearch.com/industry-report/fiber-reinforced-polymer-market-0901)
6. India Composites Market Report 2022: A $1.9 Billion Market by 2026 - Trends, Opportunities and Competitive Analysis - ResearchAndMarkets.com (https://www.businesswire.com/news/home/20220815005401/en/India-Composites-Market-Report-2022-A-1.9-Billion-Market-by-2026---Trends-Opportunities-and-Competitive-Analysis---ResearchAndMarkets.com)
7. Composites end markets: Energy (2024) (https://www.compositesworld.com/articles/composites-end-markets-energy-(2024))
8. Kossakowski, Paweł Grzegorz, and Wiktor Wciślik. "Fiber-reinforced polymer composites in the construction of bridges: Opportunities, problems and challenges." Fibers 10.4 (2022): 37.
9. Qureshi, Jawed. "Fibre-Reinforced Polymer (FRP) in Civil Engineering." IntechOpen, 2022.
10. Mallick, P. K. Processing of polymer matrix composites. CRC Press, 2017.
11. Liang, Ruifeng R., and GangaRao VS Hota. "Infrastructure Applications of Fiber-Reinforced Polymer Composites." Applied Plastics Engineering Handbook. William Andrew Publishing, 2024. 749-781.
12. Mallick, Pankar K. Fiber-reinforced composites: materials, manufacturing, and design. CRC press, 2007.
13. Joseph, Kuruvilla, et al., eds. Fiber reinforced composites: constituents, compatibility, perspectives and applications. Woodhead Publishing, 2021.
14. https://www.eppcomposites.com/index.html#firstPage
15. https://www.everestcomposites.com/
16. https://www.compositesworld.com/articles/composites-end-markets-infrastructure-and-construction-(2024)
17. https://arvindcomposites.com/
18. https://www.reliancecomposites.com/
19. https://www.fibroplastichem.com/
20. https://www.aradhanafrp.com/

21. https://www.jindaladvancedmaterials.com/

22. https://www.tatasteelnmb.com/

23. https://www.creativecompositesgroup.com/products

24. https://www.tencom.com/all-products

25. https://composite-tech.com/

26. https://www.horseen.com/

27. https://rpscomposites.com/

28. https://www.grpindustries.com/

29. https://ferrograte.com/index.php

30. https://gratingfrpaustralia.com.au/

31. https://worldgbc.org/

32. Kharissova, Alena B., et al. "Carbon negative footprint materials: A review." Nano-Structures & Nano-Objects 37 (2024): 101100.

33. Murphy, Neil. "Feasibility Analysis of a Fiber Reinforced Polymer Bridge." (2013).

34. Telang, Niket M. Field inspection of in-service FRP bridge decks. Vol. 564. Transportation Research Board, 2006.

35. Smits, Joris. "Fiber-reinforced polymer bridge design in the Netherlands: Architectural challenges toward innovative, sustainable, and durable bridges." Engineering 2.4 (2016): 518-527.

36. https://www.jeccomposites.com/news/spotted-by-jec/new-composite-decking-could-reduce-global-warming-effects-of-building-materials/

37. https://www.jeccomposites.com/news/zhongfu-carbon-core-facilitates-the-first-large-scale-application-of-48k-carbon-fibre-tie-rod-system-

38. https://alec2.com/

39. Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars—Code and Commentary

40. ASTM D8505/D8505M-23: Standard Specification for Basalt and Glass Fiber Reinforced Polymer (FRP) Bars for Concrete Reinforcement

41. https://www.compositesworld.com/news/gatorbar-neg-materia-join-forces-for-composite-rebar

42. Wazeer A., Das A., Abeykoon C., Sinha A., Karmakar A., Composites for electric vehicles and automotive sector: A review, Green Energy and Intelligent Transportation, Volume 2, Issue 1, 2023, 100043, ISSN 2773-1537, https://doi.org/10.1016/j.geits.2022.100043.

43. Alin Diniță, Razvan George Ripeanu, Costin Nicolae Ilincă, Diana Cursaru, Dănuța Matei, Ramadan Ibrahim Naim, Maria Tănase and Alexandra Ileana Portoacă. Advancements in Fiber-Reinforced Polymer Composites: A Comprehensive Analysis. Polymers 2024, 16, 2. https://doi.org/10.3390/polym16010002.

44. Fiber Reinforced Polymer Market - FRP Composites - Industry Trends & Growth (mordorintelligence.com)

45. https://www.weforum.org/agenda/2022/10/ev-sales-charging-infrastructure-transport-sector-sustainable/

46. https://www.siam.in/statistics.aspx?mpgid=8&pgidtrail=9

47. https://www.bain.com/insights/india-electric-vehicle-report-2023/

48. https://www.cie-india.com/index.html

49. https://tataautocomp.com/composites/

50. https://www.reliancecomposites.com/automobile-EV.html

51. https://www.toraycma.com/products/

52. https://teijinautomotive.com/materials/

53. https://hexcel.com/Products/

54. https://mccfc.com/composite-material/

55. Puran Singh, V. Raghavender, Sudhir Joshi, Nikale Pooja Vasant, Ankita Awasthi, Amandeep Nagpal, Alaa jasim Abd al-saheb, Composite material: A review over current development and automotive application, Materials Today: Proceedings, 2023, ,ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2023.11.012.

56. Jin Zhang, Gang Lin, Uday Vaidya, Hao Wang, Past, present and future prospective of global carbon fibre composite developments and applications, Composites Part B: Engineering, Volume 250, 2023, 110463, ISSN 1359-8368, https://doi.org/10.1016/j.compositesb.2022.110463.

57. https://www.compositesworld.com/articles/composites-end-markets-automotive-2023.

CHAPTER-6:

RECYCLING MATERIALS

6.1 Executive Summary

The primary resources are fast depleting due to over-usage and never ending global demand. In order to address this issue, critical minerals have been identified by Ministry of Mines, Govt. of India based on economic importance and supply chain risks. Many of these critical materials are used for strategically important products and the adversity has further worsened since embargo has been enforced on some of these materials such as Gallium and Germanium. Resource efficiency and circular economy are the key approaches to circumvent the scarcity of these critical minerals. The critical materials for which the primary resources are not available in the country, recycling is the only option for the self-reliance. This underlies the need for the "Seventh Resource" by means of urban mining.

Recycling is the process of conversion of waste to new materials and objects out of it. The recovery of energy is also regarded as part of recycling. Recycling is a key component in the waste hierarchy. The following paragraphs list the major recyclable materials. Recycling promotes circular economy and ensures the sustainable development.

6.2 E-Waste

The Central Pollution Control Board (CPCB) under Ministry of Environment, Forest and Climate Change (MoEF& CC), Government of India defines e-waste under E-waste Management Rules 2022 as electronic and electrical equipment (EEE) which are obsolete, broken, or discarded by the consumer (individual or bulk) as well as process rejects from manufacturing, refurbishment, and repair processes. Any end-of life equipment which is intended to discard for the purposes of dismantling and recycling will fall under the category of e-waste.

Importance of e-waste recycling: E-waste recycling is of paramount importance due to various factors such as environmental protection, resource conservation, energy saving, carbon reduction, prevention of land fill, green jobs etc.

Environmental Protection: Electronic waste contains hazardous elements like lead, mercury, cadmium, and flame retardants. Improper disposal of the e-waste will lead to leaching of these hazardous elements into the soil and water, causing pollution and posing serious health risks to humans and wildlife. Recycling of e-waste prevents entering these toxic materials in to the environment.

Resource Conservation: Electronics contain valuable materials such as gold, silver, copper, critical and rare earth metals. Recycling of these materials reduces the need for extracting and processing virgin resources, conserving energy and reducing environmental degradation associated with mining activities.

Energy Saving: Recycling e-waste requires less energy compared to mining and refining primary raw materials. For instance, recycling aluminium from electronics uses only about 5% of the energy needed to produce it from ores. In the same note, using recycled materials from spent lithium ion batteries has potential to decrease energy use by ~82 %, water usage by ~77% and SOx emissions by ~91%. This helps in reducing greenhouse gas emissions and mitigating climate change.

Prevention of Landfill Overflow: Electronic devices are one of the fastest-growing waste streams globally. Landfills are already overflowing with waste, and e-waste adds to this burden. By recycling end of life electronic devices, landfills can be reduced and extend the useful life of these gadgets through reusing or refurbishing.

Creation of Green Jobs: The e-waste recycling industry provides employment opportunities in various stages of the recycling process, including collection, sorting, dismantling, refurbishing, and recycling. These jobs not only contribute to the economy but also promote sustainable practices.

Market size: The amount of e-waste generated across the globe[2] is increasing at an alarming high rate: In 2019, 53.6 million tons of e-waste was generated. This was estimated as 21 % raise compared to last five years[3], and the Asia Pacific region alone is responsible generation of 24.9 million tons. This increasing rate is 3 times faster than the world population rate. With this rate the global e-waste is expected to exceed 70 million tons in 2030[4]. Figure 1 presents the expected generation of global e-waste[5].

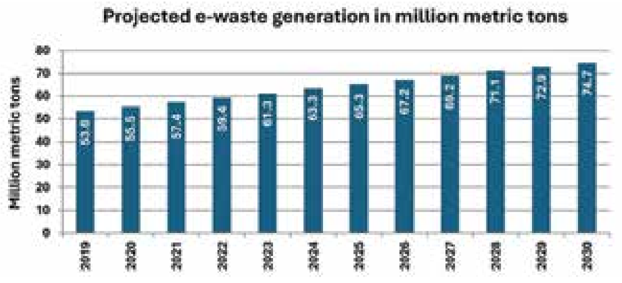


Figure 1: Global e-waste generation forecast till 2030

E-waste management in the world: Figure 2 demonstrates the e-waste management system in a few countries such as Switzerland, Italy, and Japan wherein it can be observed that the collection methods are streamlined properly with proper legislation. Also, the producers are held responsible for collecting and recycling the e-waste.

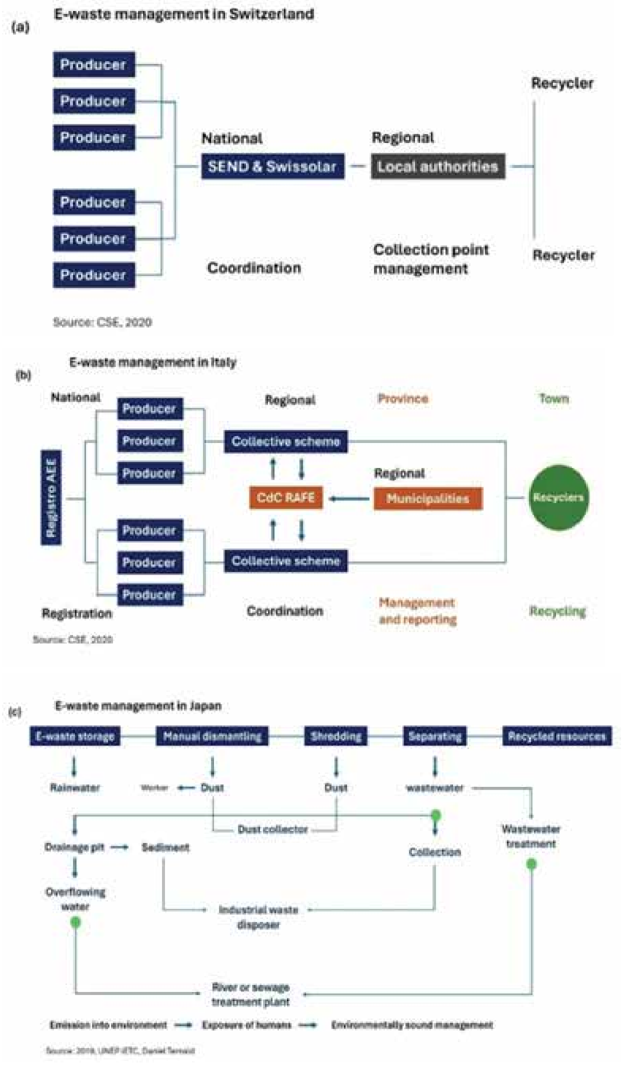


Figure 2: E-waste collection management chain in a) Switzerland, b) Italy and c) Japan[8]

Indian scenario

India is the third largest producers of electronic waste globally, with 3.23 million metric tons of e-waste annually which is equivalent to 2.4 kg per capita [8]. It is forecasted that the e-waste will touch 25.8 million metric tons by 2035 (Figure 3). The proliferation of smartphones, laptops, tablets, and other electronic gadgets contributes significantly to this volume. Collecting E-waste is the first step toward bridging consumption and the reclamation processes. Currently, collection is a major challenge, and the statistics depict that e-waste is collected at the rate of 1% for recycling (Table 1) which is very low when compared with other countries.

E-waste generation is particularly concentrated in urban areas, where population density and consumerism are higher. Cities like Mumbai, Delhi, Bangalore, Chennai, and Kolkata are among the major contributors to e-waste due to their large populations and economic activities. Among the total e-waste generated, Maharashtra alone contributes for 13.9 % which is followed by Tamil Nadu, Andra Pradesh, Uttar Pradesh, and others (Figure 4). The generated wastes are collected and processed for e-waste recycling. The ideal collection flow of e-waste is shown in the figure 5 with leakages superimposed on it. A significant portion of e-waste in India is managed by the informal sector, which consists of small-scale recyclers and scrap dealers. These informal recyclers often work in hazardous conditions, dismantling electronic devices manually to recover valuable materials such as metals, plastics, and rare earth elements. The major challenges in formal collection of e-waste are the poor reach out of the recyclers and the unwillingness of consumers to take ownership of the waste produced by them.

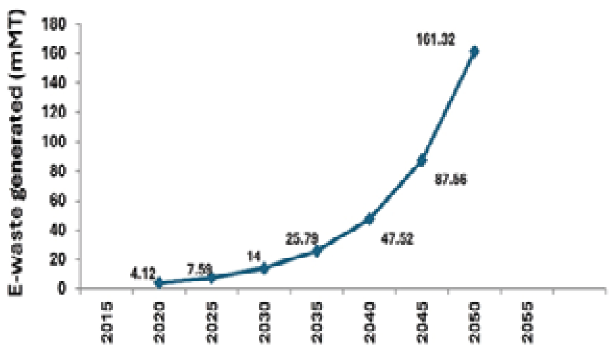
In general, the processing of e-waste is carried out in two stages (Figure 6 (a)) which includes (1) pre-processing, and (2) end processing. Pre-processing of e-waste involves several steps to ensure its safe and environmentally sustainable management. The first step in e-waste processing is the collection of electronic devices from various sources, including households, businesses, institutions, and collection centers. After collection, e-waste is segregated based on factors such as type, condition, and material composition. This step involves separating different types of electronic devices (e.g., computers, mobile phones, televisions) and sorting them into categories based on their components and materials. Once segregated, e-waste undergoes dismantling, during which it is disassembled into its individual components and parts.

In end processing stage, metallurgical processes are being applied. As an example, for PCBs either combination of pyro cum hydrometallurgical (Figure 6 (b)) processes are applied or only hydrometallurgical (Figure 6 (c)) process is applied. Among these processes, hydrometallurgical process alone is found cost-effective. However, the low recovery rate, and large volume of effluent and residue generation in the process possess are the major limitations. In case of pyro-metallurgical combined with hydrometallurgical processing of PCBs, the route is found highly effective at recovering metals from PCBs, including copper, gold, silver, and other valuable metals. High temperatures facilitate the separation of metals from non-metallic components, allowing efficient recovery. Pyrometallurgical processing effectively treat hazardous materials present in PCBs, such as brominated flame retardants and other pollutants. High temperatures can decompose or render these substances inert, mitigating environmental and health risks associated with electronic waste. However, pyrometallurgical processes generate various gases, including volatile organic compounds (VOCs), particulate matter, heavy metals, and other pollutants. Without proper gas cleaning systems, these emissions can lead to air pollution and environmental degradation, violating regulatory standards; hence a gas cleaning system is essential in pyrometallurgical processing of e-Waste.

Table 1: Top five countries in e-waste generation with its collection rate in 2019[8]

Sl. No	Rank in e-waste generation	Market (kg/capita)	Generation (kg/capita)	Collection rate (per cent)
1	China	13.3	7.2	16
2	USA	25.3	21	15
3	India	5.8	2.4	1
4	Japan	21.3	20.4	22
5	Germany	18.2	19.4	52

Figure 3: Projected e-waste generation in India[8] (source: CSE 2020)



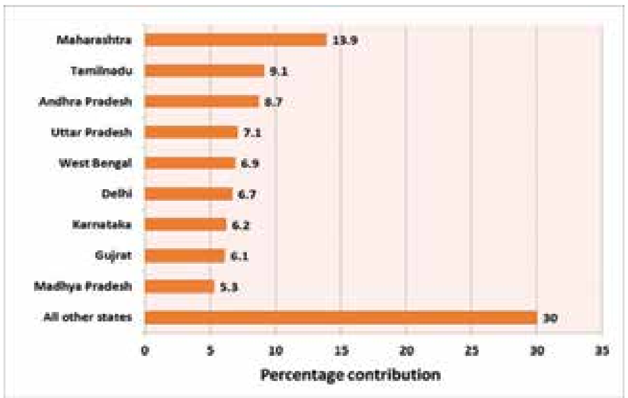


Figure 4: Annual e-waste generation by Indian states in 2018[8] (source: CSE 2020)

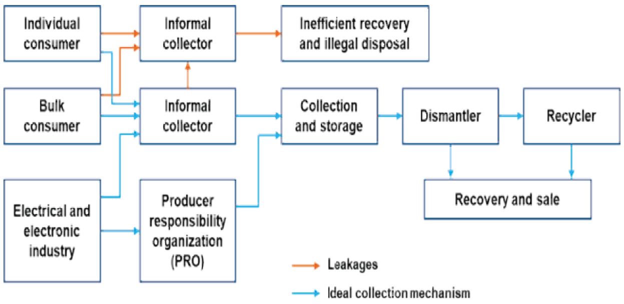


Figure 5: Ideal collection flow of e-waste materials for recycling with leakages represented from individual and bulk customers to informal sectors[8] (source: CSE 2020)

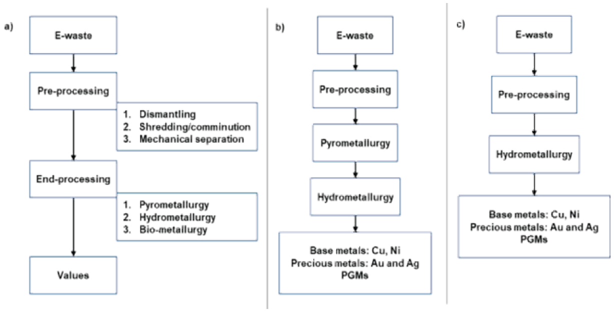


Figure 6: Stages involved in the e-waste processing (a)[9], pyro cum hydro route is a globally followed method by well-known companies across the world for PCBs (b), and hydrometallurgy route followed for PCBs (c)

Table 2: Practises followed by formal and informal sectors [8]

Parameter	Informal sector	Formal sector
Percentage of e-waste processed	90	10
General practice of e-waste processing	Rudimentary methods: Incineration, breaking, dismantling, dumping, etc.	Industrial recycling and dismantling using technically advanced methods
Current stakeholders	Dealers or retailers, unorganized recycling sector (local pawn shops, recyclers, dismantlers, etc., contractual labour, localized vendors (ksbsdis)	Government, consumers, retailers, industries or organizations, registered processing units, NGOs and manufactures
Binding laws	Not bound by any laws or regulations	Environmental laws, E-waste (Management) rules, labour laws, etc.
Major functions	Collection, disassembly, extraction and dumping	Not bound by any laws or regulations

Challenges and way-forward for e-waste recycling in India

E-waste recycling in India faces several challenges, but there are also potential solutions and strategies for moving forward:

Challenges:

Informal Recycling Sector: A significant portion of e-waste in India is processed by the informal sector, often under unsafe and environmentally harmful conditions. Table 2 shows the practices being followed by informal sectors compared to formal sector recycling. Informal sector lacks proper infrastructure, training, and regulatory oversight, leading to health hazards for workers and environmental pollution.

Lack of Awareness and Enforcement: Many consumers and businesses in India are not fully aware of the hazards associated with improper disposal of e-waste or the benefits of recycling. Additionally, enforcement of e-waste management regulations is often weak, allowing non-compliance to persist.

Complexity of E-waste Streams: E-waste comprises a wide variety of electronic devices with different materials and components, making recycling challenging. Effective separation, collection, and recycling of these diverse e-waste streams require specialized technologies and infrastructure.

Limited Infrastructure: India lacks adequate infrastructure for e-waste collection, transportation, and recycling, particularly in rural and remote areas. Existing recycling facilities may be insufficient in terms of capacity and technological capabilities to handle the growing volumes of e-waste.

Inadequate Financing Mechanisms: The cost of establishing and operating e-waste recycling facilities is significant, and financing options for such projects are limited. This poses a barrier to investment in e-waste management infrastructure and technology.

Supply Chain Complexity: E-waste management involves multiple stakeholders, including manufacturers, consumers, recyclers, and regulatory agencies. Coordinating these stakeholders and ensuring accountability throughout the e-waste supply chain can be challenging.

Way Forward:

Awareness and Education: E-waste awareness is essential to address the problem of electronic waste in India. Increasing awareness among consumers, businesses, and policymakers about the importance of responsible e-waste management are crucial. Education campaigns can highlight the environmental and health impacts of improper e-waste disposal and promote recycling as a sustainable solution. Individuals and organizations can take action by supporting e-waste awareness campaigns and adopting environmentally responsible processing in recycling electronic devices. Several successful e-waste awareness campaigns have been implemented in other countries. In the United States, for example, the Environmental Protection Agency launched a campaign called "Plug-In To eCycling" to promote the recycling of electronic devices. In Japan, there is a national e-waste recycling campaign that includes educational programs and public outreach. In Australia, the government launched an e-waste education program in schools to teach students about the importance of e-waste recycling. It is time to raise e-waste awareness in India and create a more sustainable future for all.

Strengthening Regulations: India has enacted e-waste management rules, but effective enforcement and monitoring are needed to ensure compliance. Strengthening regulatory frameworks, enhancing penalties for non-compliance, and improving enforcement mechanisms can encourage adherence to e-waste management regulations.

Formalization of Recycling Sector: Encouraging the formalization of the e-waste recycling sector through incentives, capacity building, and support for technology upgrades can improve environmental and occupational safety standards. Formal recyclers can also contribute to the development of circular economy by recovering valuable materials from e-waste.

Investment in Infrastructure: Increasing investment in e-waste management infrastructure, including collection centers, recycling facilities, and e-waste treatment technologies, is essential. Public-private partnerships and incentives for private sector investment can help addressing financing challenges and expand e-waste recycling capacity.

Innovation and Research: Promoting research and innovation in e-waste recycling technologies can lead to more efficient and environmentally sustainable recycling processes. Developing low-cost, scalable technologies for e-waste separation, dismantling, and material recovery can improve the viability of e-waste recycling operations.

Extended Producer Responsibility (EPR): Implementing and enforcing EPR policies envisaged in "E-Waste Management Rules 2022" can hold manufacturers accountable for the end-of-life management of their products. EPR mandates require manufacturers to take responsibility for collecting and recycling their products, incentivizing eco-design and product longevity.

Addressing these challenges and implementing effective strategies for e-waste recycling in India requires coordinated efforts from government, industry, civil society, and other stakeholders. By adopting a holistic approach that integrates policy interventions, technology advancements, and stakeholder engagement, India can work towards a more sustainable and circular economy model for e-waste management.

Discarded Printed circuit boards (PCBs)

Printed circuit board is an integral part of every EEE (Electrical and Electronic Equipment) product, which accounts for around 3 - 6 wt% of total e-waste generated globally. The main sources for generating discarded/waste PCBs are the PCB manufacturers, EEE manufacturers and dismantlers. The basic structure of PCB comprises laminated layered assembly composed of insulating substrate (polymer based), metal foils and electronic components attached over the board. Based on the substrate material, PCB are classified into FR-4 (flame retardant high valued PCB, composed of glass-reinforced epoxy resin) type and FR-2 type (flame retardant low valued PCB, composed of phenolic-based polymeric substance) (Li et al., 2010, (Farzana et al., 2019; Khaliq et al., 2014). Also, PCBs constitute various components attached through soldering, which are resistor, inductor, diode, transistor, capacitor, integrated circuits, processors etc. In addition to flame retardant PCBs, there are PCBs with advanced dielectrics and polymers for specific applications.

PCBs hold most valuable components of e-waste, which contains precious metals (Ag, Au, Pd), base metals (Cu, Pb, Al, Ni, Sn), rare earth metals (Nd, Gd, Dy) etc. Recovery of these metals from WPCB could be an add-on approach to reach the market demand for various metals and reduces the dependency on natural resources/ores. It is reported that, the high concentrations of the precious metals and base metals in WPCBs describe the potential value that can equalize the recycling cost. Figure 7 shows the materials which can be retrieved from discarded PCBs. Also, in comparison to primary ores, the concentration of precious metals in discarded PCBs is high. In terms of production value, the Au, Ag, Cu, Al, and steel can be produced from PCB recycling process with 14 % of original mining cost (Zhou et al., 2020). In general, discarded PCBs are classified in various grades and classified based on the precious metal content, such as low grade (<100 ppm Au), medium grade (100–400 ppm), and high grade (>400 ppm) PCBs (Hagelueken, 2006; Kaya, 2016).

The rapid increase in generating electronic waste and availability of limited metal ores drives for efficient and environmentally friendly recycling of waste printed circuit boards. Direct combustion of PCB is the informal way of recycling and not environmentally friendly, which generates CO2, HBr, particulate matters, dioxins, furans and persistent organic pollutants. Therefore, many formal technologies such as pyrometallurgy, hydrometallurgy, bioleaching, have been developed. Pyrometallurgy technology is a high temperature heat-treatment approach, offers significant reduction in the volume of waste and substantial recovery (Figure 8a). However, it causes secondary pollution and require high temperatures to proceed. Whereas hydrometallurgy is a chemical approach to work at low temperatures but generate a huge quantity of effluents and require lots of chemicals (Figure 8b).

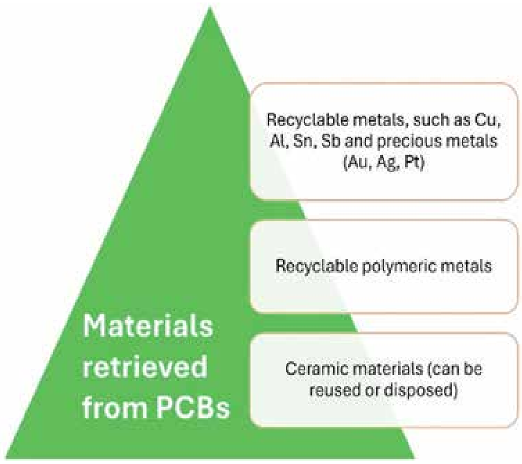


Figure 7: Materials retrieved from PCBs

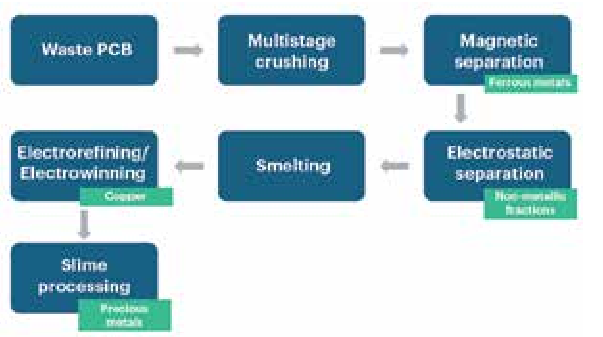


Figure 8a: Schematic flowchart of discarded PCB recycling through Pyrometallurgical process

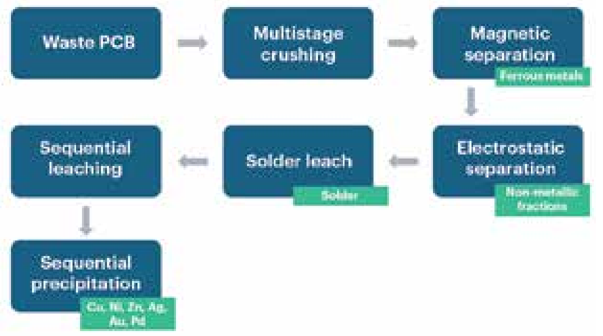


Figure 8b: Schematic flowchart of discarded PCB recycling through hydrometallurgical process

Spent permanent magnets

Permanent magnets are hard ferromagnetic materials which exhibit the retentivity or remanence and coercivity behaviour. Alnico magnets (aluminium, nickel, and cobalt), Ceramic magnets (barium or strontium ferrite), Neodymium magnets (neodymium, iron, and boron), Samarium cobalt (SmCo), etc. are well reported permanent magnets. Neodymium magnets (NdFeB) fall into rare earth elements (REE) group and hold the two-thirds of market share of permanent magnets. These rare earth elements have become the subject of concern due to their crucial role in the development of clean energy systems and green economy. NdFeB magnets contain Nd and Dy, which are very crucial elements in RE group. The market trends of NdFeB magnets indicate that the demand for these RE elements increase exponentially. Currently, China is the market leader in supplying these RE elements from primary mining (holds more than 90% share in global production from primary mining). However, the amendments to China's export policy tightened the supply of REEs and these REEs were labelled as critical raw materials by European Commission and the U.S. Department of Energy.

The essential role of REEs based permanent magnets in high-tech products and their inclusion into the list of critical raw materials by various agencies directed to find the alternative approaches to produce REEs from secondary sources. The well reported recycling processes available are pyrometallurgical, hydrometallurgical, electrometallurgical and Hydrogen Processing of Magnetic Scrap (HPMS) to recycle REEs from NdFeB magnets. Out of all these methods, hydrometallurgical route has gained more attention which follows with the chemical leaching process. Figure 9 shows a schematic process flow of permanent magnets recycling.

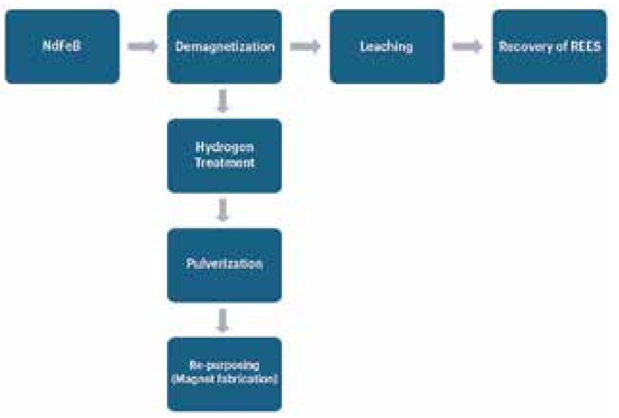


Figure 9: Schematic flowchart of permanent magnets recycling

6.3 Battery waste

Battery usage globally has been steadily increasing over the years due to several factors including the proliferation of electronic devices, the rise of electric vehicles (EVs), and the growing demand for energy storage solutions in renewable energy systems. The global demand for batteries is expected to continue growing as technological advancements drive innovation and new applications emerge. India has been actively promoting the deployment of renewable energy sources as part of its efforts to reduce carbon emissions, increase energy security, and achieve sustainable development. As the deployment of renewable energy continues to grow, so does the demand for battery storage solutions. While batteries offer significant benefits in terms of energy storage and efficiency, their increased usage can have environmental consequences if not managed sustainably throughout their lifecycle, therefore it is important to address challenges related to battery waste and recycling to minimize the environmental impact of increased battery usage.

Types of batteries

There are several types of batteries, each with its own characteristics, applications, and advantages such as lead-acid batteries, lithium-ion batteries, nickel-cadmium batteries, nickel-metal hydride batteries, alkaline batteries etc. There are different chemistries associated with each type of batteries with varying stoichiometry of the cathode compositions such as lithium cobalt oxide (LCO), lithium iron phosphate or $LiFePO_4$ (LFP), lithium manganese oxide (LMO), lithium manganese nickel cobalt oxide (NMC) and lithium nickel cobalt aluminium oxide or $LiNiCoAlO_2$ (NCA) batteries. Advances in battery technology continue to drive innovation, leading to improvements in energy density, efficiency, safety, and environmental sustainability.

Importance of battery waste recycling

30 elements in the periodic table have been identified as critical minerals by Ministry of Mines, Government of India based on the economic importance and risk in supply chain. Among them lithium (Li), cobalt (Co) and nickel (Ni) are most common critical elements found in batteries. Some types of batteries, such as nickel-metal hydride (NiMH) batteries, contain rare earth elements such as lanthanum (La), cerium (Ce), and neodymium (Nd). These elements are used in the production of battery materials and are critical for certain battery chemistries.

About 70 % of the world's lithium comes from brine, and recovery of Li from it is water and energy intensive process. Lithium repositories are concentrated mostly in Bolivia, Argentina, Australia, USA, Chile and China. In case of cobalt, DR Congo houses ~47 % of cobalt reserves worldwide, ~23 % in Australia, ~10 % in Indonesia and ~20% in rest of the world. The total global nickel reserves amounted to approximately 100 million metric tons with Indonesia and Australia possess world's largest shares, at 21 million metric tons each. For each of the critical raw material required for battery manufacturing, India is heavily dependent on other countries for its supply. On the other hand, the Indian EV market is expected to grow from 0.38 billion USD in 2021 to 152 billion USD in 2030.While India's EV battery market is estimated to expand by $300 billion till 2030. While India has no reserves for cobalt, lithium and nickel, an efficient recycling seems to be the only solution to get these minerals. It is estimated that as much as 125,000 tonnes of lithium carbonate, 35,000 tonnes of cobalt and 86,000 tonnes of nickel could be recovered by 2027 from waste batteries. The recycling of Li-Ion batteries market is going to hit by $6 billion by 2027. In India, Li-Ion battery recycling market will witness a significant exponential boost in the sector, complemented by an exponential growth in demand & supply side.

Challenges and way-forward for battery waste management

Battery waste management presents several challenges, but there are ways to address them and move forward towards a more sustainable approach. Some of major challenges faced in battery waste management are;

- **Collection of end-of-life (EoL) batteries:** Collecting EoL batteries is the first step toward bridging batteries consumption and the reclamation process. For example, Li-Ion battery (LIB) usage is traditionally been dominated in the consumer electronics (CE) market, which is the leading cause for low collection rates of LIBs. Therefore, collecting CE LIB is a challenging process compared to the batteries being used in electrical vehicles (EV) and battery electric stationary storage (BESS) LIBs. With the rapid growth of both EV and BESS sectors, a shift in the relative contributions of these market segments to EOL LIBs is forthcoming. The total volume of collectible domestic EoL EV and BESS are expected to exceed the volume of collectible EoL CE batteries in 2027 and exceed 1MM tons by 2030 (LaMotte and Clare, 2022).
- **Sorting of EoL batteries:** Battery sorting is a critical component of the battery recovery process, allowing for better aggregation of similar batteries, more efficient transportation, and the development of more effective processes for battery recycling. Collectors, especially for CE LIBs, will send collected mixed battery waste streams to sorters for further processing. An example of process flow for battery sorting is shown in figure 10.
- **Complexity of battery Types:** Batteries come in various chemistries, each with its own composition, properties, and recycling requirements. Common battery chemistries include lithium-ion, lead-acid, nickel-metal hydride, and alkaline. Managing the diverse chemistries adds complexity to recycling processes as each chemistry requires specific handling and processing techniques. Some battery chemistries pose safety risks during recycling operations due to the potential for

thermal runaway, fires, and chemical reactions. For example, LIBs are prone to thermal runaway if damaged or mishandled, posing safety hazards for recycling workers and facilities. Implementing safety protocols and technologies is essential to mitigate these risks.

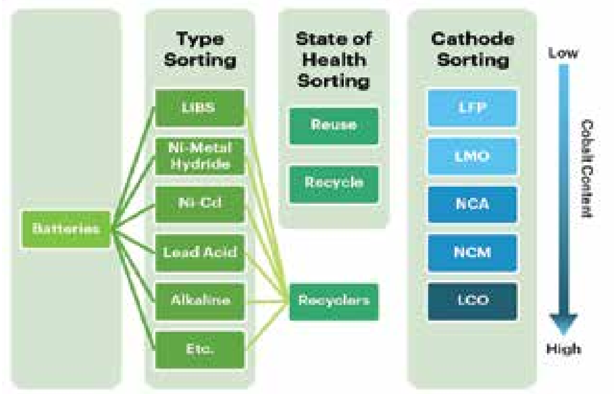


Figure 10: Process flow- LIBs sorting (ref)

- **Technological Challenges:** Developing efficient and cost-effective recycling technologies for diverse battery types is a significant challenge. Some battery chemistries, such as LIBs, require advanced metallurgical processes and purification techniques to recover valuable materials. These processes involve leaching, precipitation, solvent extraction, and electrolysis to extract pure metals from recycled battery materials. Ensuring high recovery rates and product purity while minimizing energy consumption and environmental impacts is a major technological challenge.

Way Forward:

In India, the battery usage in EV Automobiles & Consumer goods is around 40% each while for Commercial and Industrial sector it is 20% (Figure 11). China controls 90 % of battery waste market, and controls the recycle market by owning 65% of the market share (Figure 3). The battery recycling sector in India is still in its initial stages, however it holds immense potential. With the right policies and infrastructure, battery recycling can become a significant industry, contributing to India's economy while helping to address environmental challenges. The key way forwards to enhance battery recycling in India are as:

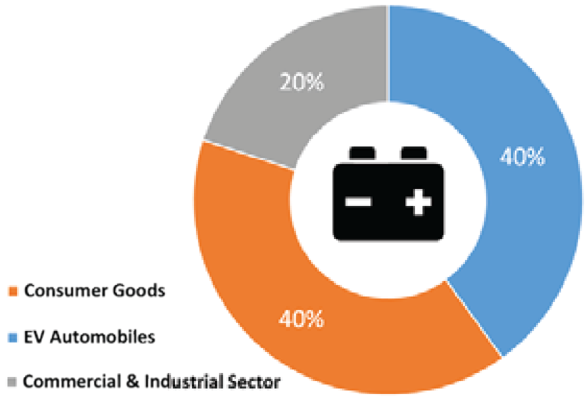


Figure 11: Battery uses in different sectors

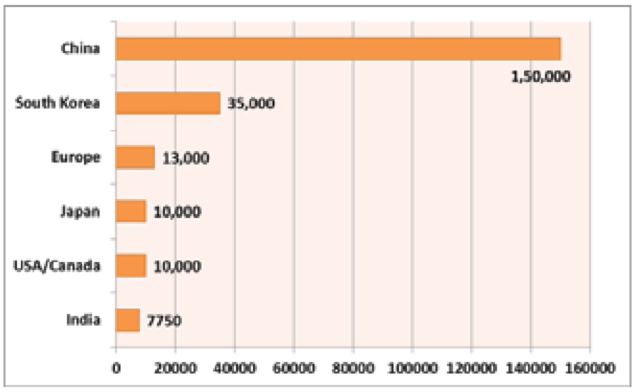


Figure 12: Recycling of batteries by geography (Metric tonnes)

- Circular Economy Approach: Embracing a circular economy approach in battery management can promote resource efficiency and value retention by maximizing the reuse, remanufacturing, and recycling of batteries and their components. The implementation of circular economy involves designing systems that maximize resource efficiency, minimize waste generation, and promote the reuse, recycling, and recovery (3R) of materials throughout the lifecycle of batteries. For example; battery manufacturers can design batteries with recycling in mind by using materials that are easier to separate and recover during the recycling process.

- Extended Producer Responsibility (EPR): Implementing EPR policies holds battery manufacturers responsible for managing their products throughout their lifecycle, including collection, recycling, and disposal. EPR encourages manufacturers to design more sustainable products, invest in recycling infrastructure, and take responsibility for the environmental impact of their products. Battery Waste Management (BWM) Rules, 2022 have been notified by Ministry of Environment, Forest and Climate Change on 22 Aug., 2022. These rules are applicable to all types of batteries regardless of chemistry, shape, volume, weight, material composition and use. As per these Rules, Producer (manufacturers, importers) shall have the obligation of Extended Producer Responsibility for the battery they introduce in the market and the Producer shall meet the collection and recycling targets as given in the rules to ensure the attainment of EPR obligations. Such initiatives from the Government and their implantation encouraged producers to continuously improve their recycling programs, invest in innovation, and collaborate with stakeholders to achieve better environmental outcomes. This in turn helps in creating a more circular and resource-efficient battery industry while reducing environmental impacts and promoting a sustainable economy.

6.4 Aluminium

As per International Aluminum Institute (IAI), nearly 75 % of the produced aluminum since 1880 has been in the service now. Till now, 900 million tons of aluminum has been produced[9]. Aluminum is an ideal metal that can be recycled many times without losing its quality. All aluminum used in cars, buildings, aircraft, etc. can be recycled. Also, the aluminum beverage cans are being recycled at far higher rates than the materials such as glass, plastic bottles, other composite containers.

The role of aluminium sector will be critical, as India advances to meet its economic growth targets. With India's growing economic might, it should be able to produce enough high-quality metal to ensure self-reliance in its defence and critical infrastructure needs to avoid global volatility in supply and prices.

Globally Aluminium is produced through two routes: (1) the primary route which involved conversion of ores to aluminium, and (2) the secondary route which is a recycling route involves aluminium production from its scrap (machining swarf, dross, end-of-life aluminium products, etc).

Advantage of aluminium recycling[9]:

a. To produce 1 tonne of aluminium through the primary route requires 4 tonnes of bauxite, 0.415 tonnes of carbon, and 13460 kWh of energy. However, to produce aluminium through secondary route, 95 % of energy required is saved which makes this route advantageous over primary route. This varies based on the type of scrap, fluxes requirement, and recycling technology.

b. In addition to the energy savings, nearly 94 % savings on CO2 equivalent can be achieved for aluminium recycling.

c. Capital cost involved for this steel recycling units is 1/10th of capital cost requirement for primary aluminium production.

d. And the produced aluminium through this recycling route can be sold 10-15 % cheaper than the aluminium produced through the primary route.

The production of Al through the secondary route is shown Figure 7 (a). Aluminium recycling which at present holds for one third of aluminium consumption has been in place since commercialization of primary aluminium products. During this recycling, aluminium quality will not be deteriorated which enables recycling aluminium for more than one time. 100 % of the scrap arising from the manufacturing of aluminium products can be recycled.

Importance of Al recycling:

In parallel to the economic growth, the Indian aluminium industry is expected to grow in both primary metal, and downstream sectors. Aluminium consumption in India was 3.3 million tonnes in 2015-16 has grown to 5.3 million tonnes in 2020-21. Aluminium consumption per capita which is 2.4 kg for India is much lesser than the global average of 11 kg per capita (Figure 8). This shows the potential demand that is highly likely in the future. Also, the government initiatives such as Make in India, smart cities, housing for all, rural electrification, freight corridors, bullet trains, EVs (Electric Vehicles), etc will have heavy requirement of aluminium. Another crucial point that needs to be noted here is only 2-5 % of loss was noticed during secondary aluminium production. This is as per a study that was carried out by Delft University, The Netherlands. Further aluminium recycling industry is categorized into two (Figure 7 (a) & (b)): (1) re-melters and (2) refiners. Here, re-melters produce wrought alloys by carefully choosing the scrap grades. Refiners primarily use scrap produced through primary aluminium production to dilute impurities.

Global scenario on secondary aluminium production: This secondary aluminium alloys produced is categorized into to which are wrought alloys and cast alloys[10]. The global secondary aluminium alloy market is estimated to garner a revenue of USD 63245 Million by the end of 2030 by growing at a CAGR (Compound Annual Growth Rate) of 4.90% over the forecast period, i.e., 2021 – 2030. Moreover, in the year 2020, the market registered a revenue of USD 39198.54 Million. As per International Aluminium Institute (IAI), in 2016, 17 million tonnes of the aluminium scrap were accrued worldwide. This number was expected to touch 21 million tonnes in 2020 which is more than 1/3rd of primary aluminium production. At present, around 20 % of aluminium demand is covered through old scrap.

According to estimates by the International Aluminium Institute (IAI), in 2016 around 17 million tons of aluminium old scrap were accrued worldwide. This number will increase to around 21 million tons in 2020, according to IAI. This corresponds to a share of more than a third of today's global output of primary aluminium. Today, around 20 % of our aluminium demand worldwide is covered by old scrap. Table: 4 shows the global secondary aluminium produced from the countries/continent like China, Japan, US, and Europe.

Table 3: Production of secondary aluminium (in kT) in China, Japan, US, and Europe[9]

Global secondary aluminium production (in '000 tons)

	Country	2011	2012	2013	2014	2015	2016	2017	2018
1	China	4400	4830	5270	5650	5780	6200	6200	6250
2	Japan	142	137	143	143	149	151	159	156
3	US	3110	3370	3420	3560	3560	3580	3640	3700
4	Europe	2591	2543	2543	2640	2637	2645	2859	2855

Following are the prominent industry leaders in the secondary aluminium alloy market[10]:

a. Century Metal Recycling Limited,
b. Kawashima Co., Ltd.,
c. Daiki Aluminium Industry Co., Ltd.,
d. Allocco Recycling, Ltd.,
e. Superior Aluminium Alloys,
f. LLC,
g. Metal Exchange Corporation,
h. Keiaisha Co., Ltd.,
i. Shin Wen Ching Metal Enterprise., Ltd.,
j. Namo Alloys Pvt. Ltd.,
k. Sunalco Industries Pvt. Ltd.

Aluminium recycling treats all category of aluminium scrap collected or imported from end-to-end products and process scrap. Globally Recyling rates are higher in transport cum building sectors and beverage sectors which are 90 and 70 %, respectively. Transportation is the major field of application worldwide due to its low density and reducing greenhouse gas emission.

Among the various countries currently do aluminium recycling, US is the world most resource abundant secondary recovery site because of its long history of aluminium production and consumption.

Indian scenario: Figures 9 & 10 (a) shows the secondary aluminium production quantities since 2015. Between 2015 and 2020 secondary aluminium demand has grown to 1.3 million tonnes from 0.86 million tonnes with CAGR of 9-10 %. The secondary aluminium which will be expected to in 2 million tonnes demand in the year 2023, accounts for 30 % of India's overall aluminium consumption of 3.7 million tonnes. Figure 10 (b) shows the major sector that consumes secondary aluminium in India. Auto sector is major sector that drives secondary aluminium market between 2015 and 2020 with contribution of ~57 and ~40%, respectively. As the scrap generation is extremely limited in India, more than 3/4th of the scrap falls into the imported category (Figure 12, and 13 (a)). Few leading producers of secondary aluminium products in India are as follows[11]:

a. Associated Aluminium India Pvt Ltd,
b. Century Metal Recycling Ltd,
c. Century N F Castings,
d. Indo Alusys Industries,
e. Minex Metallurgical Company,
f. Namo Alloys Pvt Ltd and
g. Sunalco Alloys

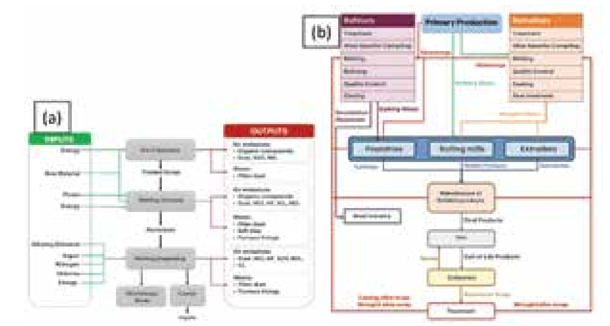


Figure 10 (a): Secondary aluminium production route, and (b) Overall process flow of Aluminium from primary processing to secondary processing

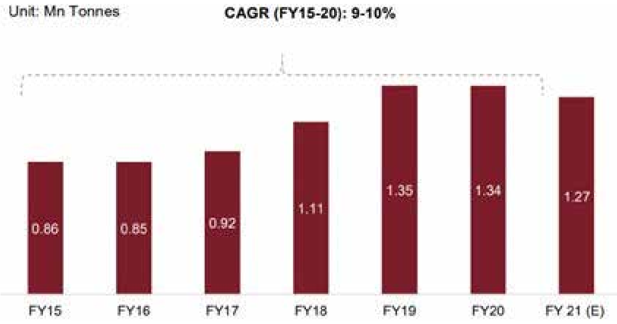


Figure 11: Per capita consumption of aluminium in 2017

Figure 12: Secondary aluminium processing till 2020[12]

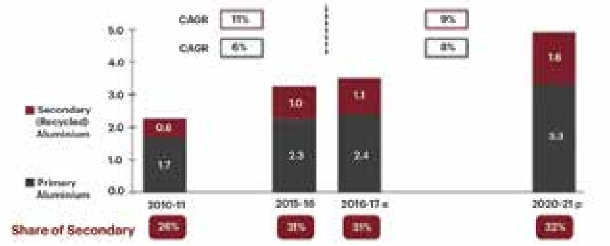


Figure 13: Share of primary and secondary aluminium in India[13]

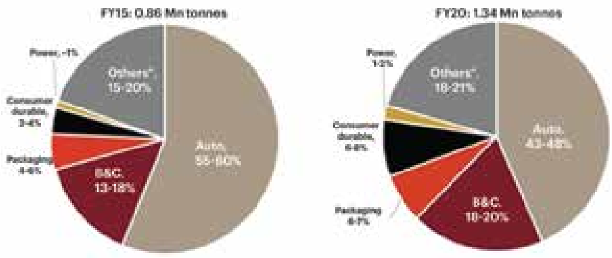


Figure 14: Application of secondary aluminium in various sectors[12]

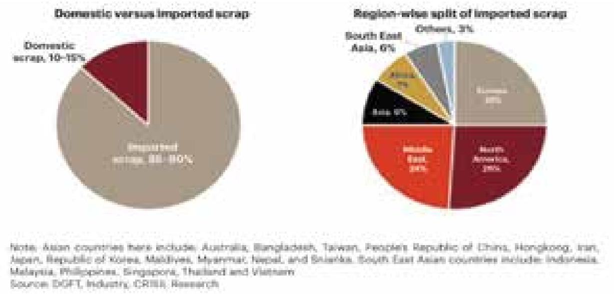


Figure 15: Aluminium scrap imports from 2015 to 2019 in india[14]

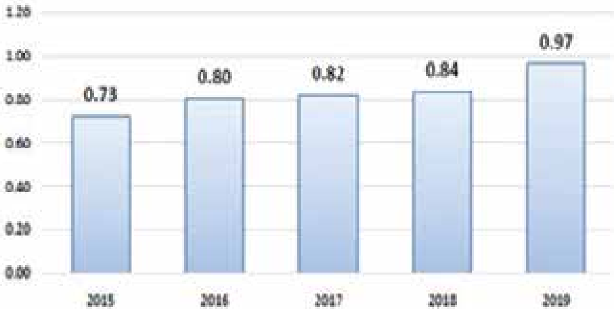


Figure 16: Imported aluminium scrap in india (a), and regionwide in the world (b)[12]

Gaps and Concerns:

In overall, Figure 14 compares the Indian scenario with global scenario on the aluminum recycling.
Scrap sorting and processing need to be carried out efficiently; otherwise, unwanted impurities may find a path to reach recycled aluminum Additional efforts need to be taken to separate aluminum scrap from the end-of-life products. To achieve this, for achieving this, proper collection and separation system should be in place As mentioned earlier, more than 3/4th of the scrap is imported – this is again due to lack of collection, segregation, and processing facilities in India. Also, higher end-of-life items from electrical sector is expected to be causing this.

Mechanization of aluminum sorting process and, adding beneficiation techniques such as eddy current separator, magnetic separator, shaking table, gravity separator, heavy media separation etc. would make the scrap recycling are major steps
Post-consumer scrap recycling must be done separately and carefully as it carries impurities and coatings on the scrap.

Development of standards for sustainability and environment are crucial for recycling as it reduces the environmental footprint compared with primary aluminum production. Also, guidelines from competitive authorities need to be setup for equipment for complying with pollution norms.

In India, quality standards for recycled aluminum need to be established as few re-melters are expected to be selling their products with lower standards[9]. In the aluminum scrap recycling sector, only 10 % of the market is unorganized. This includes utensil manufacturers and some extruders.

Figure 17: Comparison between global and Indian secondaryscrap recycling processes[9]

6.5 Concrete or Construction & Demolition (C&D) Waste

Importance: The construction sector, which is one of the top contributors to the GDP, is consistently increasing the inflow of investment. The real estate industry is expected to grow with the CAGR of 6.6 % between 2019 and 2028[16]. The construction sector is expected to account for 15 % in the GDP of 2025[17]. Building material requirement for the new building and infrastructure projects have been so high when compared to the past and is expected to rise soon. So, the building material sector itself is an enormous economy. The National Skill Development Corporation (NSDC) estimates the share of construction cost in any project is around 40-60 %[18].A crisis for building raw material in future is inevitable in near future. Table 11 talks about the criticality of availability of the building materials.

Parameter / Resources	Scarcity	Cost	Environmental impact	Embodied energy	Supply risk	Lack of recyclability	Conflict of use
Soil	**	*	***	***	**	***	***
Iron	*	***	***	***	*	*	*
Limestone	*	**	***	***	*	***	**
Sand	***	**	***	**	***	***	*
Stone (aggregate)	**	**	***	***	**	***	**
Copper	*	**	***	***	*	*	*
Bauxite (aluminium)	*	**	***	***	*	*	*
Petroleum (PVC)	*	**	***	***	*	*	*
Silica (glass)	*	**	***	**	*	*	*
Wood	**	***	***	**	**	*	*

(Legend: * is Low, ** is Medium, *** is High)

A rise in housing crisis in the country leads to the scarcity for availability of the construction materials. Rise in demand coupled with shortage of aggregates will end up in raising of the cost of construction of the building. A study by Venkatesh M. Paranthaman, a construction industry expert, found that resources like hu- man power and materials make the highest contribution—about 24 per cent—to delays in construction projects[19].

In addition to these, there are environmental problems associated with waste that are occupying ground or open space which are as follows: (1) Urban flooding, (2) Destruction of waterbodies, (3) Groundwater pollution, (4) Clogging landfills, (5) Hindering municipal waste management, (6) Degradation of open spaces, (7) Obstructing mobility, and (8) Dust pollution. So, the strong requirement for recycling of C&D is expected. With this, importance of recycling of C&D wastes can be explained.

World scenario: Globally, 2.01 billion tons of solid waste is generated. Half of these quantity is attributed to C&D waste material according to the report of world bank[20]. It is estimated that C&D waste generated in Europe is more than 850 million tonnes[21] and 530 million tonnes in the United States in 2014[18]. China had generated about 1000 million tons of C&D waste in 2013[22]. As per the research, it has been set up that reusing C&D waste as a practical alternative to naturally sourced building material. The developed countries such as EU and Singapore have reported C&D waste recycling over 90 %[23]. Following are aggregate making companies using recycled concrete in USA: (1) Lehigh Cement, (2) Vulcan Materials Company, (European Union) and USA have already capitalized this opportunity.

Their recycling rates falls somewhere between 70 and 80 %. Some EU members and Singapore have reported C&D waste recycling over 90 %[23]. Following are aggregate making companies using recycled concrete in USA: (1) Lehigh Cement, (2) Vulcan Materials Company, (3) FERMA CORP, (4) LafargeHolcim, (5) Top Grade Site Management, LLC, (6) Delta Sand & Gravel Co., (7) CEMEX S.A.B. de C.V., (8) Southern Crushed Concrete, (9) Big City Crushed Concrete and (10) Independence Recycling of Florida. Figure 18 explains about the process flow followed in Taiwan C&D waste recycling process. And this process flow may be expected to follow in the worldwide.

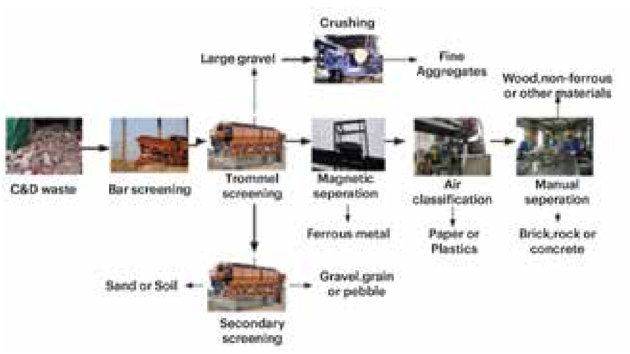


Figure 18: Process flow for C&D waste recycling in Taiwan

Indian scenario:

a. As per estimation, India generates around 150 million tonnes (Table 12) of C&D wastes, annually. However, this may be 3 to 5 times more. The composition of C&D waste is shown in the Table 13

b. India has recycling capacity for about 6,500 tonnes per day which is 1.3 % of total C&D waste generated

c. Till 2017, 53 cities were expected to install recycling facility; however, only 13 cities met the expectation (Table 14)

d. Technical ability on what and how to segregate different category of C&D waste is still question mark. Also, inconsistencies seen on characterisation methods and quantification of generated C&D waste. In addition to these, methods have not been upgraded to advent the new-age construction materials

e. Delhi 4th phase is the only good practice in the country

f. Architects design for waste mitigate handles 33 % of the waste generation

g. The government scheme, "Swachh Survekshan 2021" gives more prominence and scoring points to action on C&D waste. However, this needs to push right design for segregation, collection, recycling, and reuse.

h. Role of informal sector: Existence of a fast-growing informal economy in and around C&D waste in cities. C&D waste is an easily available material at al- most zero cost is informally used for multiple purposes, many of which have multiple environmentally associated problems. Table 15 shows how the C&D waste is processed by informal sector situated in the cities.

Table 5: C&D waste generation quantity in India since 2000

Year	Authority/Institute	Estimate (million tonnes)
2000	Ministry of Urban Development	10-12
2001	Technology Information, Forecasting and Assessment Council, Department of Science and Technology	12-15
2010	Ministry of Environment and Forest	10-12
2013	Centre for Science and Environment	530
2014	Ministry of Urban Development	No estimates
2015	Ministry of Urban Development	10-12
2015	Development Alternative and GIZ	750
2016	Ministry of Environment, Forest and Climate Change	530
2017	Building Material and Technology Promotion Council	150

Source: Compiled by CSE

Table 5: Composition of C&D waste

Waste sub-streams	As per Technology Information Forecasting and Assessment Council (TIFAC), 2001 (India)	As per MCD survey, 2004 (Delhi)	As per survey by Infrastructure Leasing & Financial Services (IL&FS) Ecosmart, 2005 (Delhi)	As per study by University of Florida, 2009 (India)	As per Coimbatore City Municipal Corporation survey, 2015 (Coimbatore)
Soil/sand, gravel	36	43	31	35	49
Bitumen	2	0	0	2	0
Metals	5	0	0.4	5	4
Masonry/brick	31	15	59	30	19
Concrete	23	35	0	25	23
Wood	2	0	1.5	2	2
Others	1	7	7.6	1	3

Source: Compiled by CSE

Table 6: India C&D waste re cycling plants

City	Place	Capacity (TPD)	Operation status
Delhi	Burari	2,000	Operational
	Mundka	150	Operational
	Shastri Park	500	Operational
Noida	Sector 80	150	Operational
Gurugram	Basai	300	Operational
Ghaziabad	Ghaziabad	150	Operational
Thane	Daighar	300	Operational
Indore	Devguradia	100	Operational
Hyderabad	Jeetimedla	300	Operational
Bengaluru	Chikkajala*	1,000	Operational
	Kannur	750	Operational
Ahmedawbad	Gyaspur Pirana	1,000	Operational
Tirupati	Tukivakam village	150	Operational
Vijayawada	Vijayawada	200	Operational
Chandigarh	Industrial Area Phase 1	150	Operational
Surat	Surat	300	Operational

Note: * Privately owned and operated
Source: Compiled by CSE

Table 6: C&D waste processing through informal sector

Recovered building material	Process	End product, economics and recycling hotspots
Steel rebars	Hammering during demolition renders some steel bars deformed and twisted, converting them into scrap	**Used for:** Steel scrap is melted down in foundries (furnaces) and cast into blocks of iron and steel **Where:** Foundries in Ghaziabad and Sikandrabad in UP, and Gobindgarh in Punjab **Rate:** Sold at Rs 22-23 per kg by the contractor
	Steel bars that can be retrieved relatively straight and without deformation are rolled into new shapes	**Used for:** In rolling mills, rebars of adequate length are passed between two rolling cylinders to give them a new shape, e.g. iron railings and steel hinges for doors can be made from rebars **Where:** Rolling mills in Ghaziabad, Muzaffarnagar, Badaun, Bareilly and Bijnor **Rate:** Bars of diameters of 10 mm, 12 mm, 16 mm, 20 mm, 25 mm and 32 mm, and lengths greater than 1.2 m or 1.5 m are sold at Rs 25-26 per kg
	Steel bars that can be retrieved relatively straight and without deformation are also utilized in construction	**Used for:** Steel bars with diameters of 8 mm, 10 mm and 12 mm, and lengths of about 1.2 m or 3 m are used in construction by lower income groups **Where:** In Ghaziabad, the market is in Jassipura. In Delhi, the markets are in Ghazipur and Seema Vihar **Rate:** Sold at Rs 30 per kg
Doors and windows	Door, windows and frames are taken out before the actual demolition takes place	**Used for:** Doors, windows and frames are bought by merchants, refurbished and sold **Where:** The markets are in Kalindi Kunj (Delhi), Khoda colony (Noida), Shahberi (Ghaziabad), Muradnagar (Ghaziabad) and Hapur **Rate:** Based on the type of wood (or steel), size and quality, doors are sold for Rs 2,000-3,500 per unit. Windows prices are Rs 1,000-2,000 per unit
Red bricks	Approximately 50 per cent of the bricks can be salvaged and reused	**Used for:** Salvaged bricks are utilized in construction by lower-income groups **Where:** These bricks are usually transported directly from a demolition site to a construction site **Rate:** Demolition contractors sell them at Rs 2-2.50 per unit
Bathroom fittings	Bathroom fitting are dismantled before the demolition begins	**Used for:** Bathroom fittings are usually made up of brass (> 70 per cent), an alloy of copper and zinc, and various other metals and alloys. They are melted down in foundries and cast into brass or copper blocks **Where:** Mandoli in Delhi has foundries that melt copper **Rate:** Bulk rate of Rs 200 per kg, copper sells at Rs 300-350 per kg and brass at Rs 380 per kg
Electric fixtures and wirings	Electric fixtures and wirings are dismantled before the demolition begins	**Used for:** Electric fixtures usually contain copper, brass, aluminium and some other metals. Wires are recycled for copper and plastic. Metals are salvaged and sent to foundries **Where:** Merchants dealing with electric fixtures and wires set shop in Chawri Bazar and Jama Masjid areas. Wires are recycled in Yamuna Pushta in Delhi **Rate:** Copper: Rs 300-350 and PVC: Rs 10-15 per kg
Glass	Glass from buildings is salvaged and sold in the second-hand market	**Used for:** Most common types of glass are clear glass and toughened glass. Clear glass can be reshaped and fetches more money. Toughened glass, on the other hand, cannot be resized easily and sells at lower rates **Where:** Merchants in Paharganj, Delhi **Rate:** Clear glass: Rs 12-16 per kg and toughened glass at Rs 4-5 per kg
Debris	Demolition of a building generates a lot of debris, composed of roller-compacted concrete (RCC), bricks, plaster, tiles, glass, etc.	**Used for:** Debris management is generally assigned by demolishers to transporters. There is a lot of demand for debris in backfilling, elevation improvement and road construction. Debris is also dumped illegally on roadsides, and in drains, waterbodies, municipal solid waste dhalaos, etc. **Where:** Across the city as per the demand **Rates:** Transporters charge Rs 600-700 per pickup by a trolley of 2-3 cu. m capacity and Rs 1,500 per pickup by a dumper of 15-20 cu. m. Dumping charges are Rs 500-1,000 per turn
	Pure RCC from demolition is diverted to crushing	**Used for:** Pure RCC waste is obtained free of charge by merchants, crushed and mixed with sand **Where:** Crushers are located in Noida and Gurugram **Rates:** Pickup is free of cost. Some demolition contractors prefer this type of waste as they do not have to spend anything on transportation

Gap identification and way forward:

a. Need robust estimation of C&D waste:

b. Characterization of the C&D waste is necessary for the management plan.

c. Land identification for collection and recycling

d. Set up transportation system for collection and transfer of C&D waste

e. Strengthen the governance framework

f. Responsibility of the construction Industry

g. Learn from global practices

h. Build confidence in recycled products for quicker uptake

i. Integrate Informal sector in C&D waste management and disposal

j. Mandatory adoption of demolition management strategies

k. Mandate on-site construction waste management during construction phase

l. Advance application of tools for end-of-life waste recovery, recycling, and circularity

m. Waste management in infrastructure projects

n. Dust control in construction projects

6.2.5 Steel Recycling

Importance: The production steel from primary sources or ore requires multiple steps involves cumulative energy input of 15-24 GJ/t. Major part of this requirement is satisfied through coal as a major reducer/fuel. In contrast with this, the steel recycling requires only 1.3-6.0 GJ/t[24]. Entire energy requirement for this can be satisfied through the electricity which can be produced through renewable energy. At present, nearly 40 % of the total steel produced is through secondary steel making or steel scrap recycling. The production of steel through secondary steel making not only saves energy but also it paves way for reduction in CO2 emission[25].

Though iron is the sixth abundant element, very less fraction of it is available concentrated fit for beneficiation and extraction. Ultimately recoverable resource (URR) is 346 GT iron ore with the demand of 3.0 Gt/year in 2011. This requirement is keep raising and it will reach the peak value of 4.5 Gt/year in the mid of the century[26]. Also, the steel recycling having the following purposes; (1) it promotes circular economy in the steel sector, (2) it decongests Indian cities

Global scenario: The global steel recycling market size was calculated to be around USD 353.30 billion in 2020. And this value is estimated to reach USD 563.92 billion by 2026[27]. The global market for steel scrap recycling was 574.1 million metric tons in the year 2020, and it is expected to grow to 784.8 million metric tons by 2027 with a CAGR of 4.6 % between 2020 and 2027.

Scraps usually split into three categories: (1) home scrap, (2) old or end of life scrap, (2) industrial scrap. Scrap recycling process follows the following steps worldwide: (1) collection and sorting, (2) separation using magnetic, eddy current, and heavy media, (3) dezincing and detinning, and (4) shredding or balling, (5) EAF (Electric Arc Furnace) melting, (6) casting, (7) forming, (8) final product.Based on the requirement and type of scrap, this procedure can be varied. For e.g., galvanised steel requires dezincing process, other normal steel scrap do not require this step.

Indian Scenario: At present, India's scrap market is unorganised and most of it are manual operation with safety and environmental concerns. In general, apart from usage of scrap in the primary route of steel making in BOFs (Basic Oxygen Furnace) (Basic Oxygen Furnace), scrap is used to produce long product through EAF/IFs. As on 2019, March, Indian was having 47 EAFs and 1128 Induction furnaces.

All these furnaces were depending upon the scrap as a raw material feed. In 2019, 32 million metric tons of steel scrap was used, and it was 11.5 % higher than 2018. Among these quantities, 25 million metric tons of the steel scrap was sourced through local scrap dealers and remaining were imported from China, United States, UAE, Saudi Arabia, Iraq, and other markets.

There is an enough potential to harness this 7 MT of scrap from domestic markets itself. This requires adequate collection centres, dismantling centres shall work in a hub-spoke model and feed to the scrap processing centres. For achieving this target 70 scrap processing centre are needed with 300 collections and dismantling centres with the presumption that 4 collecting and dismantling centres cater to a scrap processing centre. Handling capacity of each of these 70 scrap processing centre is 1 lakh tonnes. This will encourage full-service recycling companies and scrap traders to explore potential export opportunities to the Indian market. In 2020, the UAE and US are the first and second scrap suppliers to India with the market share of 12.4 % and 12.5 %, respectively.

As the Indian government works towards its ambitious plan such as Self-Reliant India or “world’s largest steel producer,” the requirement of ferrous scrap will increase to 50 to 75 million tons per annum by 2030 (Figure 19). when the production of steel rises to 250 MT, as is envisaged in the National Steel In 2030, when steel production reach 250 – 300 million tons per annum, the requirement of scrap shall rise to 70-80 million tonnes per annum. To achieve this target, India needs about 700 scrap processing centres which will be fed by 2800-3000 collections and dismantling centres spread all over the country.

In addition to these requirements, Zn on the galvannealed steel may affect the EAF/IF processes. This will be avoided by dezincing processes during the recycling stage itself just before feeding into furnaces. Also, a similar process needs to be carried out for tin coating on the steal too. These de-zincing and detinning processes are never being carried out in India, however, other steel recyclers in the world is carrying these processes to remove Zn and Sn from the steel scrap coatings. In addition, Waelz kiln process can be adopted to process Zn in EAF (Electric Arc Furnace) dust.

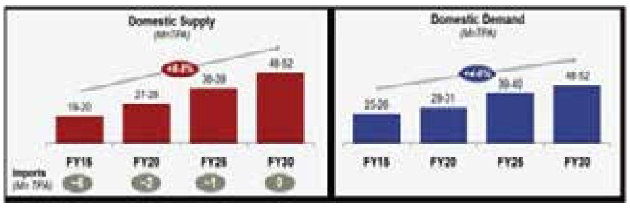


Figure 19: Steel scrap demand and supply projected till 2030[28]

6.7 Copper

Global supply chain – Key recycling agencies: Copper Scrap market size is estimated to be worth USD 65950 million in 2022 and is forecast to a readjusted size of USD 84900 million by 2028 with a CAGR of 4.3% during 2022-2028.

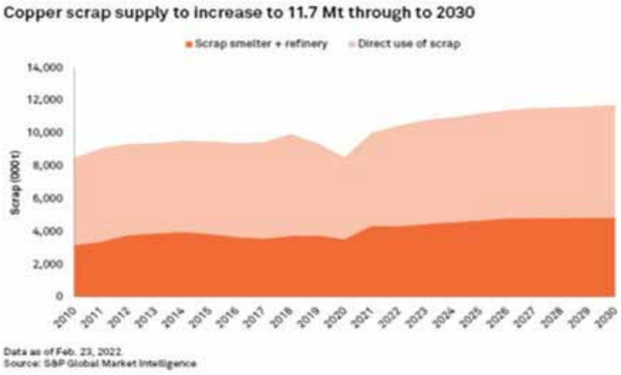


Figure 20: Copper scrap supply - global - with forecast up till 2030 [15]

It is forecast global copper scrap supply - including smelter and refinery feed and directly melted scrap - to rise to 11.7 Mt in 2030 from 10.0 Mt in 2021. Despite the projected increase, the scrap recycling sector faces several challenges that affect both the supply and demand sides of the market and will need to be addressed. China has been the main importer of copper scrap, responsible for around half of the global imports in gross weight. The latest Chinese scrap import rule, set up in 2020, has set the minimum copper content at 94%. This helped boost Chinese imports in 2021, with the gross weight of copper scrap entering China surging 79.5% year over year to 1.7 Mt. Europe exported 2.3 Mt of copper scrap in gross content in 2021. U.S. has been a major exporter of low- grade copper scrap, exporting approximately 919,000 tonnes of copper in gross weight in 2021.

World over forecasted copper demand in 2008.

Area	% demand	Area	% demand
United States	13.4	Oceania	1.0
Western Europe	21.7	Japan	7.1
Africa	0.8	Korean republic	6.3
Other North America	4.2	Taiwan	4.2
Central and South America	2.9	China	22.8
Eastern Europe and CIS	5.7	Other Asia	9.8

Indian scenario

1. It is estimated that between 30% and 40% of the domestic demand in India is met by recycled copper[26]

2. Thus approximately 90,000 MT of copper scrap is imported, and another 60,000 MT is generated from the rejects coming out of the existing copper consuming units[31]

3. India today has a copper smelting capacity of 477,000 tpa with an overpowering contribution from the private sector such as Sterlite Industries Limited (SIL) and Hindalco Industries Limited (the copper business division is known as Birla Copper).

4. Hindalco Industries is doubling the capacity of its Dahej smelter in Gujarat to 500,000 tpa. Sterlite is expanding its Tuticorin smelter in Tamil Nadu from the present 180,000 tpa to 300,000 tpa.

5. By 2020, copper production capacity in India is projected to rise to 1600,000–1800,000 tpa, going by the growth in domestic demand, from 400,000 tonnes in 2003, copper demand are estimated to grow at 8% annually, much higher than world demand growth of 3%.

6. The intensity of copper consumption in India will continue to increase until 2050. Below table (Table 17) shows distribution of copper usage and Table 18 shows generation rates of diverse types of copper scrap in India.[31].

Table 7: Copper usage in India at various sector

Distribution of copper usage in India.

Sectors	% Consumption[a]	% Consumption[b]
Electrical and telecom	57	32
Transport	7	11
Building and construction	7	35
Consumer durables	6	10
Engineering	9	12
Others	14	-

Technology for copper scrap recycling: Based on copper scrap quality, the processing route is adopted. For contaminated copper with quality of 88-99 %, the fire refining cum electrorefining route is chosen. For high quality alloys, induction melting route is chosen, to make the same alloys. For high quality copper, hearth furnace is chosen along with continuous casting to produce pipes and copper sheets.

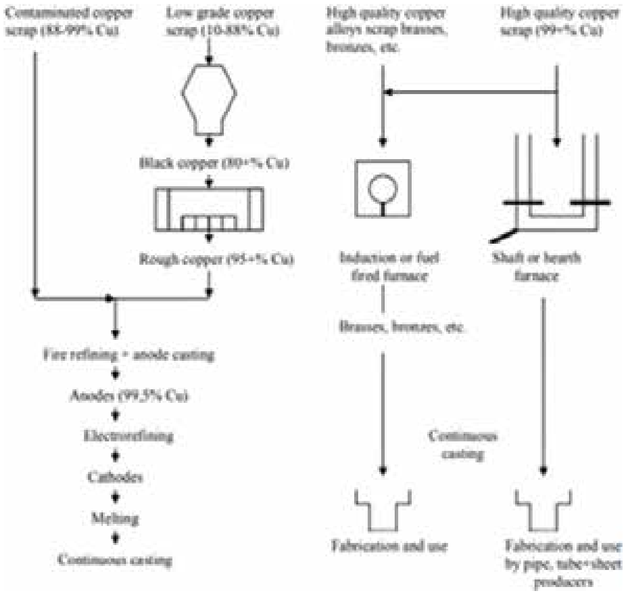


Figure 21: Flow sheet of processes for the recovery of copper and copper alloys from scrap. Low grade scrap is usually smelted in shaft furnaces but also in other furnaces, e.g. electric[33].

Supply side risk: Monopoly in copper supply makes the market prone for political risk such as domestic political unrest within the mining countries and issues on security and transport accessibility. A 15-day mines closure in Peru and Chile would wipe out 1.5 % global annual Cu supply. India is relying on imported Cu concentrate for their smelters which will be deciding factor for the sustenance of existing capacity and future projects[32]. Steps involved in mitigating the supply-side risk:

a. Reducing import dependency by finding out other available mines for Cu concentrate supply. As per the Ministry or Mines's annual report, KABIL has signed an MoU with three stat-owned organisations in Argentina, the Fat East Investment and Export agency in Russia. Major industries like Birla group have plans to shift from conventional imports to acquire the mining rights abroad for the raw material and they have already acquired mining rights in two copper mines in Australia.

b. Incorporating sustainability in midstream and downstream sectors

c. Investing in R&D initiatives and alternative interventions: For minerals with limited reserves in India such as copper, R&D in mineral processing technologies, and alternative interventions such as advancement in recycling processes are critical.

Technology gap and corrections:

a. Raise in low grade Cu scrap importing: Many countries have revised their policies and guidelines in copper scrap quality; i.e., imposed higher standards on copper content and purity of the scrap.

b. Constraints on the demand side of the scrap market: Technical limitations on maximum (17 %) amount of copper scrap used in the copper smelters. To overcome this, an important technological change is necessary to allow more scrap in the smelters. New capacities for secondary smelting can be added to facilitate processing higher processing of copper scrap. E-scrap is used at specialist operations like Boliden AB (publ)'s Ronnskar smelter in Sweden, which has the technology to recover metals, including gold, from mobile phones and circuit boards. U.S.-based Prime Materials Recovery Inc. and Spain's Cunext Group launched a joint venture in February 2021 - produces copper anodes from copper scrap and copper fines. Furthermore, Aurubis will also start construction of a multimetal recycling smelter in Augusta, Ga in August. This has been planned to commission in 2024. The location of new recycling capacity should be strategically determined, with secondary smelters built close to where scrap is generated — urban areas, major cities, and tech valleys — to minimize transport and reduce the carbon footprint of the process chain.

Scrap quality is also a factor influencing demand: Low-grade scrap is typically used in smelters. There are some specialist secondary smelters, but most of the scrap goes to primary smelters where it is charged with the concentrate. High-grade scrap is used in refineries, where it is cast into anodes and then refined. Most wire rod makers need a very-high-quality copper product, with 99% contained copper. Most of the scrap, however, has a lower contained copper content of 94%-96%, which trades at a discount and cannot be used by many wire rod producers. Direct-use scrap is the biggest demand component of copper scrap usage and is supplied by cut-offs from rod producers, including cuttings, borings, shavings, and turnings.

Government issues and remedies

a. Taking advantage of higher quality of copper import policy's in other countries, India can allow imports of secondary Cu materials with lower metallic content. To attract more copper resources, the Indian government cut import duties on copper scrap by half in February 2021, to 2.5 % from 5.0 %.

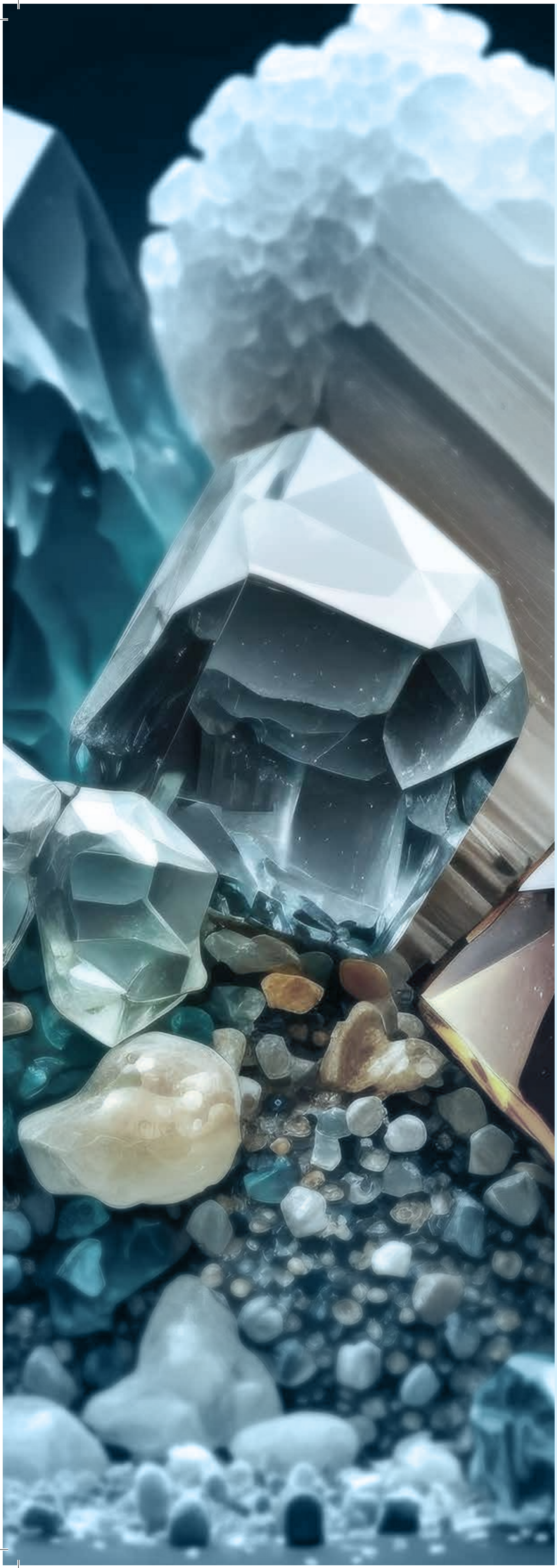
b. Most of the companies in India have not been registered due to environmental concerns and tax liabilities. So, Government of India needed to develop a strategy for collection of end-of-life copper and promote recycling industries in the country for efficient recycling and recovery of copper.

c. Lack of an established collection system copper industry in India, which utilizes diverse types of old copper scrap, is highly unorganized and is dominated by small and medium enterprises in handicrafts, utensils, art ware etc. Thus, organised sector for collection needs to come in place.

Role of the stakeholders: Future growth in the copper recycling industry boasts the potential to enable decarbonization, although scrap will need to be part of a much broader low- carbon energy transition drive. The copper scrap sector faces many challenges, some of which can be addressed by increased investment in capital equipment and technology. An active role by governments will be crucial to the copper sector's impact on decarbonization, through promotion of green policies, incentives to accelerate investment and fostering conditions for wider circularity. Restrictions on global trade of copper scrap, triggered by new trade guidelines, could push domestic industries to invest in the copper secondary market while also creating new recycling hubs. In contrast with the steel industry, however, where a comparatively greater abundance of scrap supply could accelerate decarbonization, the constraints on copper scrap supply are expected to have a more muted impact, thus keeping primary copper ore as the major player in the copper market for the near future.

Chapter Contributors

- Dr R Ratheesh, Director, C-MET Hyderabad
- Dr K. K. Pant, Director IIT Roorkee
- Dr U. Kamachi Mudali, Vice Chancellor, HBNI, DAE
- Dr Sandip Chatterjee, GC and Director, MeitY, Govt. of India
- Dr P Rambabu, Chief Sustainability Officer, M/s Greenko Group
- Dr K. Srinivas, Vice President - Re Sustainability Limited, Hyderabad
- Dr S. Rajesh Kumar, Scientist, C-MET Hyderabad
- Dr Ajay Kaushal, Scientist, C-MET Hyderabad



CHAPTER-7:

CRITICAL MINERALS AND RARE EARTH ELEMENTS

7.1 Executive Summary

Critical minerals are those that have growing demand and high economic importance in modern economies, especially in the emerging and strategic sectors. However, these minerals typically face risks of supply chain disruptions and price volatility. They often have no substitutes and have reserves and processing/refining capacities located only in a few countries. Many of these minerals are produced only in very small quantities, often as minor or companion minerals with primary minerals or as by-products of other mining activities.

From smartphones and laptops to medical devices and consumer electronics and from electric vehicles (EVs) to wind turbines, critical minerals play an increasingly important role in almost every part of modern life. The battery industry requires lithium, cobalt, nickel (as cathode materials) and graphite (as the anode material); the electronics industry relies on silicon, tin, and gallium; and motors in EVs and wind turbines need rare earth elements, such as neodymium. Copper, the cornerstone for electrification and finding applications across industries, is considered a critical mineral in many countries. As the world moves towards a Net Zero future, the demand for materials for electric mobility and renewables is increasing sharply. Aside from these energy transition minerals, some critical minerals find applications in strategic sectors, such as defence and space, and could be essential for national security.

Major economies are planning to develop resilient and diverse supply chains to insulate themselves from geopolitical disruptions and market shocks. Raw materials are a significant element in the cost structure of many technologies required in energy transitions, and the viability of many energy transition technologies and emerging technologies depends on the availability of these critical minerals at the right price. So, the urgency surrounding critical minerals is escalating as major economies aim for self-reliance and material security. The global demand for these minerals is rising faster than ever. In 2040, the world will need four times as many critical minerals for clean energy technologies as it does today. It is often said that the world is now witnessing the beginning of a new supercycle for strategic commodities, especially critical minerals.

The rising demand for critical minerals is driving investments in building resilient, diverse, and responsible value chains for critical minerals. These value chains often span many geographies and require a long time and substantial investment to build. Moreover, many areas of the value chains require special skills, expertise, and technical know-how. Typically, the critical minerals value chains comprise the following:

- **Upstream:** Mineral prospectivity analysis using geoscience and geophysics, and exploration and extraction of minerals.
- **Midstream:** Intermediate processing and manufacturing of components.
- **Downstream:** Assembly of components and manufacture of final products such as electric vehicles, smartphones, and electronic devices.
- **Recycling:** Reusing, recovering, and recycling critical minerals (also called urban or secondary mining) from end-of-life equipment.

Amongst the various critical minerals, this section primarily focuses on energy transition minerals such as lithium, nickel, cobalt, and graphite.

7.2 Strategic Importance of Critical Minerals for India

India's future mobility, renewable energy, defence, and electronics industries are poised for significant growth, driven by rising demand and a supportive policy framework, including the Production Linked Incentive (PLI) schemes introduced by the Government of India (GoI). To accelerate to a Net Zero future, key enablers are industrial decarbonisation through several measures, including using renewable energy and a low-carbon transportation sector by replacing internal combustion engine vehicles with electric vehicles. However, India has a high import dependency for most of the key minerals needed for these industries and some of the strategic sectors.

India's very high import dependency for certain elements is listed below:

The Net Import Reliance for Critical Minerals of India (2020)

Critical Minerals	Percentage (2020)	Primary Import Sources (2020)
Lithium	100	Chile, Russia, China, Ireland, Belgium
Cobalt	100	China, Belgium, Netherlands, US, Japan
Nickel	100	Sweden, China, Indonesia, Japan, Philippines
Vanadium	100	Kuwait, Germany, South Africa, Brazil, Thailand
Niobium	100	Brazil, Australia, Canada, South Africa, Indonesia
Germanium	100	China, South Africa, Australia, France, US
Rhenium	100	Russia, UK, Netherlands, South Africa, China
Beryllium	100	Russia, UK, Netherlands, South Africa, China
Tantalum	100	Australia, Indonesia, South Africa, Malaysia, US
Strontium	100	China, the US, Russia, Estonia, Slovenia
Zirconium (zircon)	100	Australia, Indonesia, South Africa, Malaysia, US
Graphite (natural)	100	China, Madagascar, Mozambique, Vietnam, Tanzania
Manganese	100	South Africa, Gabon, Australia, Brazil, China
Chromium	100	South Africa, Mozambique, Oman, Switzerland, Turkey
Silicon	100	China, Malaysia, Norway, Bhutan, Netherlands

Like most countries, India has assessed the criticality of minerals based on two key factors: economic importance (need for minerals in various end-user industries and impact of the sectors when minerals become unavailable in supply chains) and supply risk . The Centre for Social and Economic Progress (CSEP), a non-profit public policy think tank in India, and GoI's Department of Mines have identified critical minerals for India using the EU methodology. The first stage of assessment was to study the critical minerals strategies of various countries to determine key criteria for assessing criticality and develop a set of minerals for identification as critical minerals.

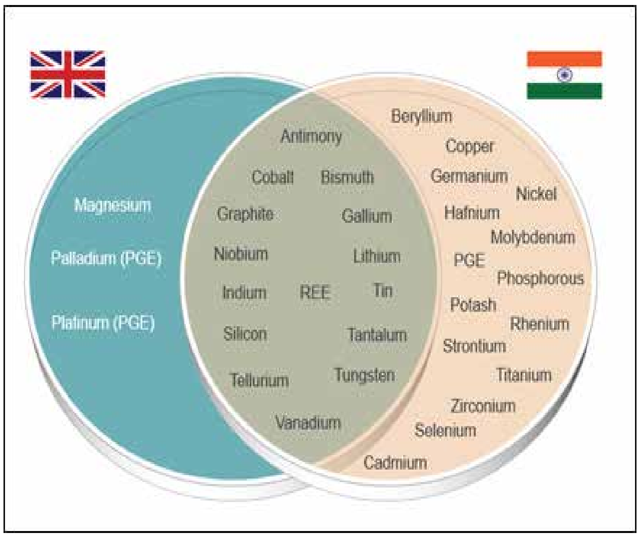
[a] Source: A report on 'Unlocking Australia-India Critical Minerals Partnership Potential' by Australian Trade and Investment Commission, July 2021

[b] Supply Risk takes into account the country's reserves and production compared to the global reserves and production and issues that might affect supply, such as the governance of supplier countries, environmental aspects, the contribution of recycling (i.e., secondary raw materials), substitution, import reliance, and trade barriers such as export restriction by key producing countries.

In the second stage of assessment, an inter-ministerial consultation was carried out to identify minerals critical to the sectors concerned. The third stage assessment was to derive and use an empirical formula to determine the list of critical minerals. The empirical formula considered factors like disruption potential, substitutability, cross-cutting usages, import reliance, and recycling rates. Following the assessment, the Ministry of Mines identified a set of 30 critical minerals in its report, published on 28 June 2023.

The Final Set of 30 Minerals Critical to India		
Antimony	Lithium	Strontium
Beryllium	Molybdenum	Tellurium
Bismuth	Niobium	Tellurium
Cobalt	Nickel	Tin
Copper	PGE	Titanium
Gallium	Phosphorous	Tungsten
Germanium	Potash	Vanadium
Graphite	REE	Zirconium
Hafnium	Rhenium	Selenium
Indium	Silicon	Cadmium

Like India, many large economies worldwide have identified their respective sets of critical minerals depending on demand from their domestic industries, growth plans of key end-user industries, existing in-country reserves and manufacturing capabilities, and the degree of import dependence. Due to the geographical concentration of mineral reserves and the nature of the global supply chains, there is considerable overlap between the elements that various countries have identified as critical minerals. For example, the diagram below shows a high degree of overlap between critical minerals identified by the UK and India. The 'critical' aspect of some minerals might change with time as new reserves are discovered, adequate extraction and processing facilities are built up, technological advances affect their demand or substitute materials are developed.

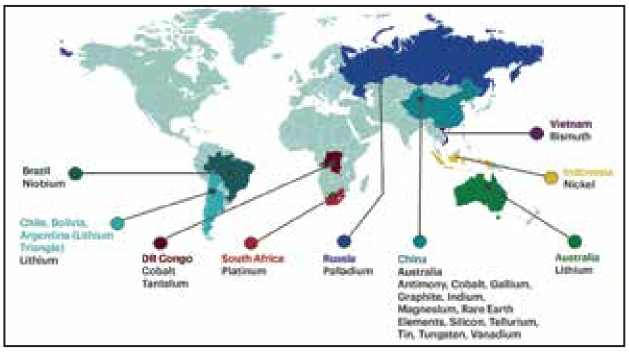


[c] The platinum-group elements (PGEs)—platinum, palladium, rhodium, ruthenium, iridium, and osmium.

[d] Rare earth elements (REE) are a group of 17 elements, including 15 elemnts of the lanthanide series in the periodic table of elements, together with scandium and yttrium.

7.3 Global Value Chain

Most critical minerals are concentrated only in a few countries. These have extensive supply chains as minerals extracted often travel thousands of kilometres to reach processing or refining facilities and are then transported to end-user industries such as battery gigafactories, which supply batteries to EV majors. The supply ecosystem comprises companies operating only in a specific area (such as mining or refining) of the value chain, as well as fully vertically integrated companies running mines-to-battery materials operations. Key reserves of some of the critical minerals are shown and discussed below.



7.3.1 Lithium

Lithium, the third element of the periodic table and the lightest metal offers unparalleled energy density and is a cornerstone of EV battery chemistry. While there are vast resources (~98 million tonnes) of lithium on earth, only about one-third of the reserves are deemed economically viable for extraction. Lithium is found in brine in the vast salt lakes/flats (Salars) such as Salar de Atacama in Chile and Salar De Uyuni in Bolivia in the lithium triangle of South America (Bolivia, Argentina, and Chile), and also in China. Lithium salts are processed into lithium carbonate and lithium hydroxide as precursors to cathode active materials for battery manufacturing units. Lithium is also found in ore form in lithium-bearing minerals, such as spodumene and petalite, primarily extracted from pegmatites in Australia, Zimbabwe and Brazil. Chile, Argentina and China are the world's largest producers of lithium. Aside from domestic sources, China has strategically acquired lithium mining assets in Chile, Canada, and Africa and plays a key role in the global lithium supply chain with nearly 60-70 per cent of global refining capacities. Africa has fast-growing lithium production capacities. The continent accounted for about 4 per cent of the worldwide lithium production in 2023 but is expected to contribute 10 per cent of global supply in 2024, boosted by increased Chinese investment. Most of this increased production in Africa is likely to come from Zimbabwe.

7.3.2 Nickel

Nickel is found in laterites (nickeliferous limonite and garnierite) and in magmatic sulphide deposits (pentlandite). While laterite ores are found near the earth's surface and extracted by surface mining operations, sulphide ores are primarily found in greater depth and extracted from underground mines. Indonesia is the largest nickel producer, amounting to about 30 per cent of the global production, followed by the Philippines, New Caledonia, Russia, Canada, and Australia. Russia supplies about 10 per cent of the world's nickel, but Nornickel in Russia is one the world's largest suppliers of battery-grade nickel (aside from being the world's largest palladium producer), contributing about 15 – 20 per cent of the global supply. Aside from the top-producing countries, a few nickel projects are being developed in other geographies. For example, in the USA, the Tamarack nickel project is being developed in a joint venture between Talcon Metals and Rio Tinto, which will supply 75,000 tonnes of nickel concentrate to Tesla over six years once commercial production is commenced.

About 65 per cent of nickel is used in the stainless industry and in producing superalloys and high-performance special alloys, but the growing EV industry is driving a rapid demand for nickel. Nickel is the key component in the nickel manganese cobalt (NMC) and nickel cobalt aluminium (NCA) cathodes, accounting for the largest material intensity (about 40 kg in an average electric vehicle) amongst the cathode materials. The battery industry is estimated to account for about 14 per cent of global nickel demand.

The vulnerability of the nickel supply chain was demonstrated during the sudden and almost overnight spike in the nickel price at the beginning of the Russia-Ukriane conflict. Uncertainty about supply and possible sanctions against Russian commodities led to an unprecedented surge in the nickel price, forcing the suspension of nickel trade at the London Metal Exchange for a few days in March 2022.

7.3.3 Cobalt

Cobalt contributes to EV batteries' high energy density and thermal stability and is an essential element in most current battery chemistries. According to a report by the Cobalt Institute, EV is the most significant end-user sector for cobalt, accounting for 40 per cent of the global cobalt market and 86 per cent of the annual growth in demand in 2023. Nickel cobalt manganese chemistries are the most significant driver of the cobalt demand. The Democratic Republic of Congo (DRC) is the largest supplier of global cobalt production, with a share of about 70 per cent. Indonesia became the second largest producer in 2022, supported by the rapid development of domestic nickel-cobalt mines and the installation of High-Pressure Acid Leaching units, which produce mixed nickel-cobalt hydroxides.

While battery manufacturers are looking at various cobalt-free battery chemistries, such as Lithium iron phosphate (LFP) and lithium manganese iron phosphate (LMFP), it is estimated that some of the cobalt-based and cobalt-free battery chemistries will coexist in the medium-term, and the demand for cobalt is likely to double by 2030.

7.3.4 Graphite

Accounting for the largest material density (about 70 kg in an average EV battery), graphite is another critical mineral that is witnessing a steep demand from the EV industry. The EV industry currently uses both natural and synthetic graphite. Both offer some advantages and disadvantages. In natural graphite, the crystallisation of magmatic carbon produces unique flake graphite, which supports higher energy density. However, natural graphite often has impurities that might impact the performance of anodes. Though more expensive than natural graphite, synthetic graphite has more uniform properties and offers higher cyclability (the number of times a battery can be charged and discharged). Synthetic graphite also offers more speed to the market as natural graphite resources are finite, and exploration and mine development take many years.

With 60 per cent of the world's natural graphite production and nearly half of the world's synthetic graphite production, China is the largest graphite producer and refines almost 90 per cent of graphite used in EV batteries. China controls nearly the entire global production of uncoated spherical graphite, the precursor to natural graphite anode material. While some large natural graphite mining capacities being developed in Canada, Sweden, and Africa will partially address the supply concerns surrounding over-dependence on China, there is ongoing research on alternative anode materials such as cubic titanium-monoxide (TiOx) and spinel lithium-titanate (LTO) and the use of silicon alongside graphite in battery anodes.

7.3.5 Copper

Another key energy transition metal is copper. It is one of the first metals that humans discovered and used (since the Chalcolithic age 4,500-3,600 BC). The early months of 2024 have seen a boom in the copper price due to some mine closures and strong demand from energy transition industries, growing electrification, and the fast-growing electronics and artificial intelligence sectors. Electric vehicles need 2.5 to 4 times more copper than internal combustion engine cars and account for about 55 per cent of the global copper demand. Data centres that power AI servers will need an additional one million tonnes of copper in the next three years. Copper demand is expected to increase by 53 per cent by 2040, but supply is likely to grow only by 16 per cent. EV producers aim to improve material and cost efficiency by using less copper in electric vehicles through improved designs of wire harness systems, compact battery cells, and alternative materials.

7.3.6 Rare Earth Elements

China has the largest reserves of rare earth minerals, at 44 million tonnes, and was the largest producer of rare earth elements (REE) in 2023, with an output of about 240,000 tonnes. Vietnam, Brazil, Russia, India, Australia, and Canada have large REE deposits. Though China produces about 60 per cent of REE globally, it processes more than 90 per cent. China also focuses on moving up the value chain and creating value-added products such as permanent magnets. In view of China's ban on exports of REE processing technologies in December 2023 , many countries are fast-tracking projects on REE processing.

There are ongoing projects by US, Canadian and UK companies in various areas of the REE value chain.

Pensana Plc of the UK is developing one of the world's largest and highest-grade magnet metal rare earth deposits in Longonjo, Angola, near the Lobito corridor, which will provide easy connectivity to the Lobito Port. The operation will extract, concentrate, calcine and chemically refine the extracted materials to produce a high-value mixed rare earth carbonate for exports. The company has another REE exploration license in Angola. Pensana is setting up a REE separation and processing facility in Saltend at the Zero Carbon Humber cluster in Humber, Yorkshire.

The Saskatchewan Research Council (SRC) in Canada launched its REE processing project in 2020. The facility would use Canadian technology to convert REE ore to individual REE products in two stages. The first is the concentration of ore to mixed REE Carbonate. The second is the more complex separation stage that converts the mixed REE Carbonate to commercial pure-grade REEs. This vertically integrated Rare Earth Processing Facility is scheduled to be commissioned by the end of 2024. SRC expects to produce 400 tonnes of Rare Earth Metals per year beginning in 2025. Recently, SRC signed a five-year agreement in principle with Hung Thinh Group (HTG) from Vietnam to import rare earth carbonate to this facility. Under the agreement, HTG will supply SRC with up to 3,000 tonnes of rare earth carbonate annually for five years beginning in June 2025.

7.4 Indian Scenario

India produces 95 minerals, including four fuel, ten metallics, 23 non-metallic, three atomic, and 55 minor minerals. Globally, India is amongst the top five producers of bulk minerals, such as coal, bauxite, iron ore, chromite, and zinc. India has a geological potential similar to mineral-rich Southern and Eastern Africa and Western Australia. However, historically, India focused on mining conventional minerals and exploring critical minerals like lithium, cobalt, and rare earth elements was not prioritised. The emphasis of the mining sector has been on meeting the domestic demand for minerals for industries such as iron and steel and thermal power, reducing dependence on imports through the setting up of state-owned mining enterprises and the nationalisation of mineral resources. As a result, most investments in the mining sector were made in conventional minerals such as iron ore, coal, bauxite, and limestone, which were essential for industrialisation and infrastructure development. India could not capture the value addition through processing and refining critical minerals for high-tech applications without adequate proven reserves and exploration efforts.

India's key priorities are now to secure access to resilient global supply chains, invest in or co-own overseas critical minerals assets at various stages, from early prospecting and exploration blocks to shovel-ready mines, initiate focused exploration efforts to identify and assess new reserves of critical minerals and build a robust recycling ecosystem through urban or secondary mining. In addition, India must actively engage in bilateral and multilateral arrangements to develop and benefit from assured critical mineral supply chains in friendly countries and close allies and deepen collaboration on emerging technologies in various parts of the value chain.

India’s ongoing exploration programmes have recently identified a few lithium reserves, but the mine planning, development, and commencement of commercial-scale production will take several years. The Geological Survey of India discovered 5.9 million tonnes of inferred lithium resources in the Salal-Haimana area of Reasi district, Jammu & Kashmir, in February 2023. The term ‘inferred’ refers to the ‘preliminary exploration stage’, the second of a four-step process. So, a full assessment of the reserve size and commercial viability of mining has not yet been ascertained.

The Ministry of Mines has taken several steps aiming at developing a globally competitive critical minerals sector in India:

1. GoI has amended the Mines and Minerals (Development and Regulation (MMDR) Act, 1957, through the MMDR Amendment Act, 2023, to include 24 minerals identified as critical and strategic for the country under the Act. The amended Act has also empowered the Central Government to auction blocks of these minerals. GoI has removed six critical minerals (lithium, beryllium, titanium, niobium, tantalum and zirconium) from the list of atomic minerals and placed them with other minerals to be auctioned by the GoI.

2. In November 2023, India launched the first round of its critical minerals auction for 20 blocks, out of a planned 100 blocks, in eight Indian states for a range of minerals such as lithium, potash, vanadium, graphite, and rare earth elements (REE)., GoI planned to check monopolies in critical minerals by allowing one applicant to submit only a single bid in an auction of a mineral block. The second tranche of the auction of critical mining blocks was launched on 1 March 2024. This second round of auctions included minerals such as graphite, tungsten, vanadium, rare earth elements, nickel, potash, and cobalt. The Ministry of Mines launched the third tranche of auctions for seven critical mineral blocks on 14 March 2024. The blocks up for auction include minerals such as glauconite, graphite, nickel, PGE, potash, lithium, and titanium, spanning across Bihar, Jharkhand, Tamil Nadu, Uttar Pradesh, and the Union Territory of Jammu and Kashmir. The outcomes of the first three rounds of auctions are expected to be announced around June 2024. The subsequent tranches of the critical minerals auctions are likely to be announced following the General Election in India in June 2024. Key details of the mineral blocks being auctioned in the first three tranches are given in the Annexure.

3. GoI aims to expedite the critical minerals mine development process so that the mines can enter the production phase within four years. Moreover, to boost private sector participation and support Notified Private Exploration Agencies for critical and strategic mineral exploration, incentives up to 25-30 per cent of the exploration cost would be funded by the National Mineral Exploration Trust (NMET).

4. GoI promoted Khanij Bidesh India Ltd (KABIL), which focuses on having overseas mining assets for two prime critical and strategic minerals, lithium and cobalt. KABIL has actively engaged with Australia on a G2G basis and initiated due diligence for two lithium and three cobalt mines in Australia. In January 20204, KABIL entered into an agreement with the state-owned enterprise of Catamarca province of Argentina, Catamarca Minera Y Energética Sociedad Del Estado (Camyen Se), to start exploration and development of five lithium brine blocks in the Catamarca province at a project cost of INR 2 billion. KABIL plans to open an office in Catamarca, Argentina, to support this project.

5. The Inter-ministerial Committee, set up by GoI to identify key critical minerals for India, recommended creating a Centre of Excellence for Critical Minerals (CECM) in the Ministry of Mines. The centre will collaborate with international agencies/ KABIL to strategically acquire foreign assets of critical minerals. The Centre of Excellence will periodically update the list of critical minerals for India, notify the critical mineral strategy from time to time, and work on developing an effective value chain of critical minerals in the country.

6. Major manufacturing economies worldwide are building international partnerships on critical minerals. These cooperations are happening bilaterally and multilaterally in groups such as the US-convened Minerals Security Partnership (MSP) of 14 developed countries. India joined this US-led alliance in June 2023 during Indian Prime Minister Narendra Modi's visit to the USA.

7. India has been working with several countries to build close cooperation in the critical minerals sector. In March 2023, India and Australia entered into a Critical Mineral Investment Partnership, mainly focused on lithium and cobalt. According to the Australia-India Economic Cooperation Trade Agreement, tariffs on the import of essential minerals like zirconium, titanium, cobalt, and nickel from Australia have been eliminated. India and the UK have held several events focused on various aspects of the critical minerals sector, including exploration, extraction, and recycling, and supported an Indian trade mission to the UK in 2022. Earlier this year, a UK-India workshop on critical minerals was held in Bhubaneswar in February 2024. It was attended by several companies, R&D bodies, and government departments in the two countries.

8. Aside from critical and deep-seated minerals within India's landmass, India is aiming to build expertise in deep-sea mining exploration and became a member of the UN's International Seabed Authority (ISA) in 2016. This led to the launch of India's Deep Ocean Mission (DOM) through the Ministry of Earth Sciences (MoES) in 2021, with a budget of INR 40.7 billion over five years. This initiative, a part of India's Blue Economy agenda, aims to develop deep-sea mining technologies and is expected to support the Critical Minerals strategy. DOM is one of nine missions under the Prime Minister's Science, Technology, and Innovation Advisory Council (PMSTIAC). Two key focus areas of this initiative are the Central Mid-Ocean Ridge (exploring hydrothermal sulphide deposits that contain multi-metals such as gold, platinum, and other minerals) and the Central Indian Ocean (exploring poly-metallic nodules.). India is developing 'Matsya6000', a deep-ocean submersible (expected to be completed by FY24) designed to accommodate a three-member crew to reach a depth of 6,000 m to the ocean bed in the central Indian Ocean. India has also developed a deep-sea mining machine called VARAH-1, which successfully completed a field test at a depth of 5,270 meters in the Central Indian Ocean., In January 2024, India submitted applications to the International Seabed Authority for approval of plans of work for rights to explore polymetallic sulphides in the Indian Ocean Ridge (Carlsberg Ridge) located away from India's western shores and for exploration of a cobalt-rich ferromanganese crust in deep seabed region, Afanasy-Nikitin Seamount (ANS), located away from the eastern shores, in the Central Indian Ocean.

Alongside GoI's policy initiatives, the Critical Minerals sector in India is also witnessing growing interest amongst Indian companies in investing in the industry and forming domestic and global partnerships.

[e] Further details suggests that four out of 20 blocks are auctioned for a Mining Licence (ML), allowing the licensee to begin mining operations after obtaining necessary clearances. The remaining 16 blocks are auctioned for a Composite Licence (CL), allowing further geological exploration to determine mineral content. Once sufficient information is collected on mineral deposits, the licensee can apply to the state government to convert their CL to an ML for mining operations. The licensee has three to five years to complete the exploration level, failing which, the license will be withdrawn.

[f] KABIL is a joint venture company of three Central Public Sector Enterprises under the Ministry of Mines, Government of India, namely, National Aluminium Company Ltd. (NALCO), Hindustan Copper Ltd. (HCL) and Mineral Exploration and Consultancy Ltd (MECL).

Some notable projects are mentioned below:

1. Reliance New Energy Limited, a wholly-owned subsidiary of Reliance Industries Limited, acquired Sheffield and Oxford-based sodium-ion battery technology company Faradion in January 2022 at £100 million and planned to invest £25 million as growth capital further to accelerate the commercial rollout. Reliance will use Faradion's technology at its proposed fully integrated energy storage factory at The Dhirubhai Ambani Green Energy Giga Complex in Gujarat. In March 2022, Reliance New Energy Limited acquired Lithium Werks BV for a total transaction value of US$ 61 million, including funding for future growth. Headquartered in the Netherlands, Lithium Werks has offices and R&D and production facilities in the USA, Europe, and China. Lithium Werks is a leading cobalt-free and high-performance lithium iron phosphate (LFP) battery provider.

2. In February 2024, the Tata Group's global battery business entity, Agratas, announced a £4 billion investment to build a 40GwH battery plant in Somerset, UK. Once completed, this will be one of the largest battery gigafactories in Europe. The project will be implemented in phases, and commercial production is likely to commence in 2026. Agratas will have battery innovation centres in India and the UK.

3. Tata Chemical has established a process of recovering valuable materials from used Lithium-ion batteries. Their InsperiCoTM is the world's first branded recycled cobalt. The technology can be used for various types of lithium-ion batteries, including those based on lithium cobalt oxide, nickel manganese cobalt oxide and nickel cobalt aluminium oxide..

4. Having already achieved the capabilities of manufacturing fine-quality battery foils for EV batteries at its Mouda unit in Maharashtra, Hindalco Industries has announced an investment of INR 8 billion to build a new plant near Sambalpur in Odisha to manufacture 25,000 tonnes of fine-quality aluminium foils for EV batteries. In July 2022, Hindalco Industries signed an MoU with Phinergy, a leading Israel-based pioneer in metal-air battery technology, and IOC Phinergy Private Limited (IOP) - a joint venture between Phinergy and India's leading oil PSU Indian Oil Corporation on R&D and pilot production of aluminium plates for aluminium-air batteries and recycling of aluminium after usage in these batteries. Hindalo Industries has also shown interest in exploring and extracting battery minerals such as lithium and nickel through the ongoing auction of critical minerals.

5. In October 2023, Birla Carbon, one of India's leading manufacturers and suppliers of high-quality carbon solutions, completed the acquisition of Nanocyl SA, a worldwide leader in multi-wall carbon nanotubes based in Belgium. The acquisition enables Birla Carbon's presence in materials critical to lithium-ion battery performance and other conductive applications in the energy systems market. In 2019, Birla Carbon announced a collaboration with CHASM Advanced Materials Inc., a leading developer and manufacturer of printed electronics materials and battery materials based on proprietary carbon nanotube and ink/coating technologies to accelerate the discovery and development of novel nanomaterials to benefit various market segments including high-performance tyres, novel coatings, and next-generation batteries.

6. In 2018, Exide Industries, India's leading battery manufacturer, set up Exide Energy Private Limited (Nexcharge), a joint venture with Switzerland-based Leclanché SA, to develop lithium-ion modules and packs with battery management systems for electric vehicles and stationary applications. In March 2022, Exide Industries announced its plan to invest INR 60 billion to establish a lithium-ion cell manufacturing plant in collaboration with China's SVOLT Energy Technology. In April 2024, South Korean automotive majors Hyundai Motor Company and Kia Corporation announced a partnership with Exide Energy Solutions (EESL), a subsidiary of Exide Industries, to localise EV battery production, primarily lithium iron phosphate (LFP) cells in India.

7. Indian battery major Amara Raja invested in the European EV battery company InoBat in December 2021. InoBat has a Li-ion battery R&D facility and production line in Slovakia. The company is backed by a consortium of partners, including CEZ, one of the major European Utilities, and Rio Tinto. Amara Raja also invested in the Bengaluru-based battery technology start-up Log9, which works on LTO and LFP lithium-ion battery technologies. In May 2024, Amara Raja announced that the company would invest INR 95 billion over the next ten years in R&D and manufacture of lithium-ion batteries. The gigafactory in Telangana will have the capacity to produce 16 GwH of lithium cells and 5 GwH of battery cell packs.

8. The Chatterjee Group (TCG) is setting up a battery

research laboratory in Kolkata at its Research Institute for Sustainable Energy under the TCG Centre for Research, Education, Science, and Technology (TCG Crest).

9. Ola Electric is setting up a 20GwH EV battery gigafactory at its EV hub, which is being developed in the Krishnagiri district in Tamil Nadu. The gigafactory will have an initial capacity of 5 GwH. Ola has also shown interest in participating in the ongoing critical minerals auction round to bid for lithium mining assets in India.

10. In May 2023, Kolkata-based Himadri Speciality Chemical announced an investment of AUD 10.32 million (about INR 5.8 million) in Syndney-based Sicona Battery Technologies Pty Ltd for a 12.79 per cent stake. Sicona specialises in silicon anode technology to enhance the energy density of lithium-ion batteries.

11. In November 2023, PCBL Limited, a company in the RP-Sanjeev Goenka Group and a leading global manufacturer of carbon black, announced a joint venture with Australia's Kinaltek Pty in nano silicon technology for EV battery applications. PCBL will own 51 per cent of the joint venture and infuse US$16 million into the JV, with a commitment to infuse up to US$28 million in stages for setting up a manufacturing facility.

12. Epsilon Advanced Materials Pvt Ltd produces anode materials, including natural and synthetic graphites and silicon carbon composites for battery manufacturers. In January 2024, Epsilon Group announced an investment of INR 100 billion to set up an integrated carbon complex in Orisha comprising manufacturing facilities for advanced carbon materials, speciality carbon products, and carbon black. Epsilon Advanced Materials is also building a US$650 million, 50,000 TPA anode plant in North Carolina, USA.

13. KPIT Technologies, an independent software integration partner to the automotive and mobility ecosystem, launched its Sodium (Na)-ion battery technology in December 2023. KPIT has been working on software development, integration and validation for electrification programmes for global automotive leaders. The project demonstrated a synergetic industry-academia collaboration between KPIT and the Indian Institute of Science Education and Research (IISER), Pune. The IISER Pune team led by Dr. Satishchandra Ogale contributed to material synthesis, characterisation and battery testing.

14. TACC Limited, a subsidiary of HEG Limited, a leading manufacturer of graphite electrodes for electric arc furnaces, is setting up a 20,000-tonne EV battery graphite anode plant.

15. In February 2024, JSW Group signed an agreement with the Odisha government to establish an integrated EV vehicle and battery manufacturing facility in Cuttack and Paradip with an investment of INR 400 billion. JSW Group has also shown interest in participating in the ongoing auction of critical minerals.

16. In March 2024, Panasonic Group and Indian Oil Corporation signed a binding term sheet to initiate discussions to draw a framework for forming a joint venture to manufacture cylindrical lithium-ion batteries in India. The key aspects of the joint venture are likely to be firmed up soon.

17. In December 2021, Vedanta Resources acquired Nicomet, a leading Nickel and Cobalt producer based in Goa. With this acquisition, Vedanta became India's sole producer of nickel. Nicomet produces high-quality battery-grade nickel sulphate crystals that are used to manufacture batteries for electric vehicles globally. In 2023, the company, now integrated into Malco Energy of the Vedanta Group, started producing nickel metal and cobalt sulphate, and plans to diversify its product portfolio to include nickel nitrate, nickel chloride and nickel carbonate.

18. The world's largest coal producer, Coal India Limited, plans to develop a non-coal portfolio. Coal India might consider overseas acquisitions of critical minerals mining assets, especially lithium, cobalt, and graphite. It is also participating in the ongoing critical mining auctions in India.

19. Tirupati Graphite has a presence in the UK, India, and Madagascar. The company is engaged in flake graphite mining and processing in Madagascar and the manufacture of high-purity, expandable, micronised, and spherical graphite at Patalganga in Gujarat. It also has a graphene research facility in India.

20. National Mineral Development Corporation (NMDC)'s subsidiary in Australia, Legacy Iron Ore Ltd, announced that by the first quarter of 2024, they plan to commence their first gold mining operation in the Mount Celia Gold Project in Western Australia. It will also commence pre-feasibility studies for lithium reserves in the Mount Bevan region later this year. The company is in discussion with Australia's Hancock Prospecting Pty Limited for lithium exploration and mining.

21. Hindustan Copper Limited is implementing a plan to increase its mining capacity from its current level of ore production to 12.2 million tonnes per annum (MTPA) in Phase I in the next six to seven years. Expanding the Malnjkhand Copper Complex in Madhya Pradesh will increase the ore production capacity from 2.5 to 5.0 MTPA by developing an underground mine below the existing open pit mine. The proposed expansion of mines in the western sector, Khetri and Kolihan in Rajasthan, will increase ore production capacity to 3 MTPA, and the proposed expansion and reopening of Surda Mine in Jharkhand will increase its production capacity from 0.4 MTPA to 0.9 MTPA. The expansion projects will boost domestic production of copper metal to reduce India's dependence on imports.

22. National Thermal Power Corporation (NTPC), India's largest power producer, is considering lithium acquisitions in Australia. NTPC Mining is also considering uranium mining within India and exploring options for sourcing critical minerals like lithium, cobalt, graphite, and nickel from resource-rich nations such as Argentina and Chile.

23. Neyveli Lignite Corporation India Limited (NLC India), currently engaged in coal and lignite mining and power generation, has expressed interest in mining lithium and is likely to participate in the critical minerals auction.
In addition to GoI's initiatives and investment and collaboration plans for the industry, Indian academia and research and innovation ecosystems are working on several technology areas, with the support of the private sector as well as various ministries and departments of GoI, including the Ministry of Mines, Department of Science and Technology (DST), and the Ministry of Electronics and Information Technology (MeitY). Some key initiatives are discussed below:

- Amongst the various laboratories and research centres under the Council of Scientific and Industrial Research (CSIR), the CSIR-Central Electrochemical Research, based in Karaikudi in Tamil Nadu, is working on a range of areas, such as advanced lead-acid batteries, lithium batteries, flow and metal-air batteries, sodium-ion batteries, lithium-sulfur batteries, and supercapacitors and Bhubaneswar-based CSIR – Institute of Minerals and Materials Technologies undertakes research in many areas ranging from materials chemistry to mineral processing and from hydro and electro-metallurgy to advanced materials technologies.

- DST is supporting the development of indigenous technology for batteries. Science and Engineering Research Board (SERB), a body under DST, has funded 42 projects, including a few national and international conferences/workshops to disseminate the knowledge of advancement in future energy materials in general and in aluminium ion batteries, sodium-ion batteries, polymer batteries and graphene-based batteries in specific. DST has also supported a project on graphene-protected Si nano-spheres for developing high-energy density Li-ion batteries.

- The International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), an autonomous R&D Centre of DST, is working on materials and devices for super-capacitor and Na-ion (Sodium ion) batteries as future technologies. ARCI has been developing indigenous technologies to produce electrode materials (cathode and anode) in large quantities for Li-ion batteries for electric vehicles. ARCI has also successfully demonstrated lithium-ion phosphate (LFP) and lithium titanate (LTO) technologies.

- IIT- BHU has developed Na-NMC (sodium nickel manganese cobalt oxide) and NFM (sodium nickel manganese iron oxide) cathode materials and novel sodium superionic conducting solid-state electrolytes designed specifically for sodium-ion batteries. It has also developed cylindrical cells and the resultant battery pack, supported by the Ministry of Higher Education (MHE) and SERB, DST. IIT Bombay, too, has worked on sodium-ion battery chemistries, and IIT Madras has been working on zinc-air batteries. Bangalore-based Indian Institute of Science (IISc) has been working on improving the performance of solid-state battery technologies.

- Some alternative battery chemistries that the Indian research bodies are working on are summarised below.

Energy Storage: Alternative Material Platforms

Battery Type	Cathode Material	Anode Material
Li-Air, Mg-Air, Al-Air, Fe-Air, Zn-Air, Lead flow batteries, Vanadium flow batteries, Na-S, Li-S, Thermal batteries, Na-NiCl2 (Zebra batteries), Ag-Zn, Mg-AgCl reserve batteries, Ultra lead-acid Batteries, Lead – Carbon, Li-Carbon, dual carbon	Lithium Nickel Cobalt Manganese Oxide (LiNiCoMnO2), Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO2), Lithium Cobalt Oxide (LiCoO2), Lithium Manganese Oxide (LiMn2O4), Lithium Iron Phosphate (LiFePO4/C), Lithium Titanium Oxide, NiMn-Co-Al cathode materials, amorphous carbon, hard carbon, graphite (natural, synthetic graphite, Krish carbon), Metal, Organic Frameworks - cathode & composite cathodes	Si–Graphite composite anodes, Tin composite anodes, Li metal anodes, Metal-Organic Frameworks - anode

7.5 Gap Areas

With its attractive geology, large unexplored areas, dedicated exploration funding, and strong government and corporate support, India is well-placed to be an ideal exploration destination for domestic and international companies. However, only about 10 per cent of India's large acreage of Obvious Geological Potential (OGP) has been explored effectively, and there are some key gaps in the exploration area:

1. India does not have an early-stage (junior) exploration industry, which accounts for more than 80 per cent of new and world-class mineral discoveries internationally.

2. While a lot of geoscience data is available in the country, several qualitative and quantitative roadblocks exist in the availability and analysis of these exploration datasets.

GoI is aware of the challenges in this sector in India and has taken several robust and effective steps to clear the numerous bottlenecks. However, the complex nature of the challenges requires practical and sustained participation from all the concerned stakeholders, including, but not limited to, mining corporate houses, different mining states, government and private research institutions, and policy think tanks.

A few suggested steps are given below as an initiative to kick-start the early-stage exploration of critical and deep-seated minerals in India.

1. Reprocessing, integration, and analysis of existing exploration data through the application of technologies based on Artificial Intelligence (AI) and Machine Learning (ML) to generate exploration targets for national and international explorers.

2. Marketing the “Atmanirbhar Exploration” concept (including technical marketing of the above datasets) in key international markets.

3. Application of new and disruptive exploration technologies over the OGP areas. Working with government and private clients to optimise the value of geoscience data

4. Customised commercial packages/incentives for early-stage explorers of deep-seated and critical minerals in India to attract national/international junior exploration companies.

5. Active participation of the mining corporates in India to develop the junior mining sector in the country for mutual benefit.

Besides mineral exploration and mining, India needs mineral processing and refining technologies. Despite having one of the world's largest deposits of titanium-bearing minerals and large deposits of rare earths, India depends on imports because it lacks suitable commercial-scale technologies for refining and value addition. So, aside from exploration, India will urgently need mineral beneficiation, processing, and refining technologies for critical minerals.

Policy Initiatives in many countries are helping onshore battery minerals mining and processing facilities through substantial incentives. For example, the USA's Inflation Reduction Act (IRA), signed into law in August 2022, provides US$392.5 billion to boost the financing and development of projects for the energy transition. EU and its member countries are working towards creating funds to support the critical minerals industry. India has NMET to support exploration activities and the PLI scheme for the advanced chemistry cell manufacturing sector, but some soft funding and incentives for the midstream sector will help quickly build domestic capabilities and competitiveness,

Indian academia, research bodies, and corporate R&D teams must address any knowledge gap in the critical minerals sector through technology transfer, training, and upskilling.

India needs to quickly build domestic capabilities to recover and recycle critical minerals. While the Centre for Materials for Electronics Technology (C-MET) under MeitY is working on E-waste processing facilities and some projects are being implemented in the private sector, the recovery and recycling activities need a rapid scaling up. Secondary or urban mining could help India reduce import dependency and create a domestic supply chain to support end-user industries.

Mining and processing of critical minerals can have negative environmental consequences. Hence, sustainable mining practices and robust environmental regulations will be crucial. Ensuring fair compensation and working conditions for those employed in the critical minerals sector is vital for social responsibility. Community development initiatives in mining areas will also be an important aspect.

7.6 Role of the Stakeholders such as Government, Academia, Industry and Research Institutes

The earlier sections have outlined recent policy measures initiated and the roles being played by the Ministry of Mines and the Ministry of Earth Science, various research and innovation projects being supported by the Department of Science and Technology, and investment and technology collaboration plans and projects by leading companies in the private and public sectors. A symbiotic relationship between industry, academia, and research bodies will help build on this positive momentum. As India has very few domestic resources and urgently needs access to mineral resources and technologies for exploration, mining, beneficiation and processing, and component manufacturing, a joined-up and concerted effort in scaling up research and development and piloting and deployment of technologies in key areas of the critical mineral value chain is very much needed.

7.7 Recommendations and Conclusion

As key economies in the world are keen to insulate themselves from supply chain disruptions, market shocks, and price volatility, the business and investment landscape in the critical minerals is changing fast as the cross-border flow of trade, investment, and technology transfers gather momentum. Several countries and global majors are drawing up their critical minerals strategy with a sense of urgency. India must develop self-reliance in critical minerals by launching an extensive exploration programme to locate new reserves and fast-tracking mining assets to the shovel-ready stage through streamlining policies, accessing global mining assets, and building resilient and geographically diverse supply chains.

A secure and diversified supply chain will make India less susceptible to price volatility and supply disruptions. Developing domestic capabilities in exploration, processing, and refining will create a more self-reliant India in the critical minerals sector with the vision of "Atmanibhar Bharat". Stabilising a robust domestic critical minerals industry ecosystem will support the growth of advanced manufacturing sectors like electric vehicles and renewable energy technologies. Finally, securing critical minerals will be crucial for India's technological advancement and its position in the global clean energy transition.

Here are some recommendations that would help India progress towards self-reliance by building domestic capabilities and addressing supply chain vulnerabilities in the critical minerals sector.

Upstream

1. Intensified efforts by the Geological Survey of India (GSI) and private exploration companies to locate and assess domestic critical mineral reserves. Utilising advanced technologies like geophysical surveys and remote sensing and employing various AI tools can expedite this process.
2. Attract international junior mining companies to India to support and speed up exploration projects.
3. Offer high-quality and reliable geological and geophysical data to attract juniors and global and domestic exploration companies.
4. Build additional domestic capabilities in the latest exploration technologies, geoscience, and geophysics, including geological data interpretation and analysis capabilities.
5. Aim to build a domestic junior mining start-up ecosystem.
6. Build a geographically diversified critical materials supply chain.
7. Secure a stake in/acquire global critical mining assets through KABIL and other public-sector and private companies.

Midstream

1. Capacity building in ore processing and refining for preparing battery-grade anode or cathode materials and processing technologies for rare earth minerals to manufacture permanent magnets.
2. Aim to invest in global processing facilities to manufacture battery-ready anode and cathode active materials and play an increasingly important role in the global value chain.
3. R&D and innovation in mineral beneficiation and processing (especially from low-grade ores).
4. Scale up R&D and innovation in emerging battery chemistries with deeper and stronger links between academia, R&D and innovation bodies, and industry partners.
5. Develop battery chemistries independent of critical minerals such as nickel and cobalt and replace rare-earth-based permanent magnets with new magnetic materials and new technologies.

Downstream

1. Encourage urban/secondary mining and increase the recovery, reuse, and recycling of critical minerals from end-of-life batteries and electronic waste to complement primary mining activities and reduce import dependency.
2. Set up large-scale domestic hydrometallurgical battery minerals recycling facilities.
3. Develop advanced smelting technologies for batteries and other e-waste.

Policy

1. Build stronger international links through the Mineral Security Partnership and various bilateral co-operations and create links between the proposed Centre of Excellence for Critical Minerals in India and similar organisations globally for benchmarking and accessing global best practices.
2. Secure the interests of global mining majors by ensuring a conducive and supportive policy framework.
3. Develop incentive schemes for producing intermediate materials (cathode active and anode active materials) to help larger domestic and foreign investments in this area.

Skill Development

1 . Promote skill development in exploration, mining, beneficiation and processing of critical minerals and material science/battery chemistries. Building a skilled workforce is essential for the growth of the critical minerals sector. This includes training geologists, mining engineers, and processing specialists to meet the growing demand for expertise.

Annexure

Details of Critical Mineral Blocks in the First Three Traches of Auction in 2024

E-Auction	Launch Date	Last date of bid submission	Number of Blocks Bid (Out of 100)	Key Mineral	Key States
1st Tranche	29 November 2023	26 February 2024	20	Glauconite, Chromium, Nickel, Copper, Potash, Manganese, Graphite, Molybdenum, Titanium, Bauxite, Phosphorite, Rare Earth Elements	Bihar, Gujarat, Jharkhand, Odisha, Tamil Nadu, Uttar Pradesh, Jammu and Kashmir, Chhattisgarh
2nd Tranche	29 February 2024	23 April 2024	18	Tungsten, Vanadium, Graphite, Rare Earth Elements, Glauconite, Phosphorite, Nickel, Platinum Group of Minerals, Cobalt, Potash	Andhra Pradesh, Arunachal Pradesh, Chattisgarh, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan and Tamil Nadu.
3rd Tranche	20 March 2024	14 May 2024	7	Glauconite, Graphite, Nickel, PGE, Potash, Lithium, and Titanium	Bihar, Jharkhand, Tamil Nadu, Uttar Pradesh and Union Territory of Jammu and Kashmir

Chapter Contributors

On behalf of the CII National Mission for Technology, Innovation and Research, we would like to acknowledge and express gratitude to the following for their contributions in the Chapter on Critical Minerals and Rare Earth Elements:

- Mr Sudipto Sen, Chief Executive Officer, Asterix Innovations Private Limited
- Prof Dr Sakthi Saravanan Chinnasamy, Associate Professor of Economic Geology, Department of Earth Sciences, Indian Institute of Technology Bombay
- Prof Satishchandra Ogale, Director, Research Institute for Sustainable Energy (RISE), TCG-CREST, Kolkata, India and Emeritus Professor, Indian Institutes of Science Education and Research, Pune.
- Mr Sudipto Mukerji, Chief Executive Officer, Natural Resources Consulting Limited, UK
- Mr Tim Archer, Chief Technology Officer, Natural Resources Consulting Limited, UK
- Mr Saibal Ghosh, Former Trade Commissioner at the High Commission of Canada to New Delhi, India.
- Ms Ankita Chakraborty, Research Associate, Asterix Innovations Private Limited.
- Ms Anusha Kumar, Research Associate, Asterix Innovations Private Limited

References

1. https://www.mining.com/africas-lithium-supply-to-triple-this-year-benchmark-minerals/

2. https://talonmetals.com/im-looking-to-capitalize-on-the-coming-ev-boom-by-investing-in-nickel-mining-and-processing/

3. https://www.cobaltinstitute.org/wp-content/uploads/2023/05/Cobalt-Market-Report-2022_final-1.pdf

4. https://economictimes.indiatimes.com/tech/technology/innovation-in-evs-seen-denting-copper-demand-growth-potential/articleshow/101625039.cms?from=mdr

5. https://www.csis.org/analysis/what-chinas-ban-rare-earths-processing-technology-exports-means#:~:text=At%20present%20China%20produces%2060,given%20China%20a%20near%20monopoly.

6. https://www.ft.com/content/5b031db7-23dd-43d3-afe1-cef14817296f

7. www.pensana.co.uk

8. https://indianexpress.com/article/explained/explained-economics/critical-minerals-auction-process-9056726/

9. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1983066

10. https://energy.economictimes.indiatimes.com/news/coal/govt-launches-2nd-round-of-critical-mineral-blocks-estimated-at-30-trillion/108121955#:~:text=This%20second%20round%20of%20auctions,time%2C%20benefiting%20our%20farmers.%22

11. https://energy.economictimes.indiatimes.com/news/coal/mines-ministry-launches-third-e-auction-tranche-for-seven-critical-mineral-blocks/108508987#:~:text=1%20min%20read-,Mines%20ministry%20launches%20third%20e%2Dauction%20tranche%20for%20seven%20critical,Territory%20of%20Jammu%20and%20Kashmir.

12. https://www.business-standard.com/india-news/critical-minerals-production-to-start-in-4-yrs-govt-to-soon-start-auction-123121500819_1.html

13. https://www.livemint.com/news/india/govt-to-pay-30-upfront-in-critical-mineral-exploration-11702663133761.html

14. https://www.thehindubusinessline.com/markets/commodities/india-eyes-strategic-alliances-with-australia-for-lithium-and-vanadium-supplies/article67645048.ece

15. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1996380

16. https://mines.gov.in/admin/storage/app/uploads/649d4212cceb01688027666.pdf
17. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1946416
18. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1905863
19. https://cmlre.gov.in/research-programs/deep-ocean-mission-dom
20. https://www.isa.org.jm/secretary-general-annual-report-2023/
21. https://www.thehindu.com/sci-tech/science/deep-ocean-mission-matsya6000-seabed-mining-blue-economy/article67457379.ece
22. https://www.newindianexpress.com/nation/2023/Jul/25/india-a-pioneer-in-technology-for-deep-sea-exploration-2598287.html
23. https://www.fortuneindia.com/enterprise/indigenous-deep-sea-mining-vessel-set-for-mid-2024-trials/111510
24. https://energy.economictimes.indiatimes.com/news/renewable/samudrayaan-mission-india-intensifies-the-race-for-clean-energy-through-deep-seabed-mining/103796325
25. https://theprint.in/theprint-essential/india-wants-to-dig-deep-into-metal-rich-indian-ocean-seabed-all-about-deep-sea-mining/2018169/
26. https://faradion.co.uk/reliance-new-energy-solar-to-acquire-faradion-limited/
27. https://faradion.co.uk/reliance-new-energy-solar-to-acquire-faradion-limited/
28. https://lithiumwerks.com/reliance-new-energy-limited-acquires-assets-of-lithium-werks/
29. https://economictimes.indiatimes.com/industry/renewables/tatas-uk-electric-car-battery-plant-to-be-in-bridgwater/articleshow/108056570.cms?from=mdr
30. https://www.tatachemicals.com/Asia/Products/Specialty-chemistry/Material-Sciences/energy-storage-solutions
31. https://www.hindalco.com/media/press-releases/hindalco-set-up-battery-foil-manufacturing-facility-Odisha-tap-ev-market
32. https://www.hindalco.com/media/press-releases/hindalco-phinergy-and-iop--partner-revolutionary-aluminium-air-batteries-evs-and-energy-storage

33. https://www.moneycontrol.com/news/business/exclusive-hindalco-eyes-lithium-nickel-mines-in-india-to-enter-critical-minerals-mining-md-satish-pai-12261101.html

34. https://www.birlacarbon.com/birla-carbon-acquires-nanocyl-to-drive-growth-in-battery-materials-for-lithium-ion-batteries/

35. https://www.birlacarbon.com/birla-carbon-and-chasm-advanced-materials-enter-joint-development-agreement-to-develop-nanotube-enhanced-carbons/

36. https://www.business-standard.com/companies/news/hyundai-kia-join-hands-with-exide-for-li-ion-cells-for-evs-in-india-124040800987_1.html

37. https://economictimes.indiatimes.com/tech/funding/deeptech-battery-startup-log9-raises-40-million/articleshow/97242499.cms?from=mdr

38. https://economictimes.indiatimes.com/industry/renewables/amara-raja-lays-foundation-stone-for-rs-9-5k-cr-lithium-cell-facility-in-telangana/articleshow/100032839.cms?from=mdr

39. https://www.tcgcrest.org/institutes/rise/

40. https://www.hindustantimes.com/car-bike/ola-electric-weighs-bid-for-lithium-mining-rights-says-report-101707305413815.html#:~:text=Ola%20Electric%2C%20the%20e%2Dscooter,electric%20vehicle%20(EV)%20batteries.

41. https://economictimes.indiatimes.com/markets/stocks/news/himadri-specialty-chemical-acquires-12-8-stake-in-sicona/articleshow/100644138.cms?from=mdr

42. https://www.indianchemicalnews.com/battery/pcbl-to-form-jv-with-australian-kinaltek-pty-in-nano-silicon-technology-for-ev-battery-application-19743

43. https://energy.economictimes.indiatimes.com/news/renewable/epsilon-carbon-to-set-up-rs-10000-crore-integrated-carbon-complex-in-odisha/106990585

44. https://www.thehindubusinessline.com/companies/epsilons-650-m-graphite-plant-in-us-to-be-part-funded-by-offtaker/article68187008.ece

45. https://www.kpit.com/news/kpit-unveils-breakthrough-sodium-ion-battery-technology-to-alleviate-lithium-dependency/

46. https://hegltd.com/wp-content/uploads/2023/11/Stxcovering201123signed.pdf

47. https://www-business--standard-com.cdn.ampproject.org/v/s/www.business-standard.com/amp/companies/news/jsw-signs-mou-with-odisha-to-set-up-rs-40-000-crore-ev-project-in-state-124021000577_1.html?amp_gsa=1&amp_js_v=a9&usqp=mq331AQIUAKwASCAAgM%3D#amp_tf=From%20%251%24s&aoh=17129377807925&referrer=https%3A%2F%2Fwww.google.com&ampshare=https%3A%2F%2Fwww.business-standard.com%2Fcompanies%2Fnews%2Fjsw-signs-mou-with-odisha-to-set-up-rs-40-000-crore-ev-project-in-state-124021000577_1.html

48. https://www.moneycontrol.com/news/business/jsw-group-looks-to-participate-in-lithium-mines-auction-sajjan-jindal-12496141.html#:~:text=Conglomerate%20JSW%20Group%20is%20looking,and%20lithium%20is%20very%20important.

49. https://economictimes.indiatimes.com/industry/renewables/panasonic-to-form-jv-with-indian-oil-to-manufacture-cylindrical-lithium-ion-batteries-in-india/articleshow/108918524.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst

50. https://www.vedantaresources.com/MediaDocuments/Press%20Release_%20Vedanta%20Acquires%20Nicomet%20-%20Updated.pdf

51. https://indianexpress.com/article/business/companies/india-to-leverage-us-led-minerals-security-partnership-to-help-psus-secure-critical-mineral-assets-abroad-9155151/

52. https://www.thehindubusinessline.com/resources/nmdc-subsidiary-legacy-iron-ore-to-mine-gold-in-australia/article67503271.ece

53. https://www.thehindubusinessline.com/companies/nmdc-to-ramp-up-gold-mining-in-australia-pre-feasibility-studies-soon-for-lithium-reserves/article67849322.ece

54. https://www.thehindubusinessline.com/resources/nmdc-subsidiary-legacy-iron-ore-to-mine-gold-in-australia/article67503271.ece

55. https://www.ndtvprofit.com/business/hindustan-copper-to-ramp-up-copper-ore-production-capacity-to-122-mtpa-by-fy29

56. https://www.reuters.com/world/india/india-launches-first-part-critical-minerals-auction-worth-54-bln-2023-11-29/

57. https://www.reuters.com/markets/commodities/indias-ntpc-mining-arm-explore-battery-minerals-overseas-sources-2023-09-18/

58. https://energy.economictimes.indiatimes.com/news/coal/nlc-india-exploring-possibility-of-mining-critical-minerals-will-participate-in-auction-cmd/104598125

59. https://www.cecri.res.in/ResearchAreas/ElectrochemicalPowerSources/ElectrochemicalPowerSources.aspx

60. https://www.immt.res.in/

61. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1794781

62. https://dst.gov.in/newly-synthesised-cathode-materials-sodium-ion-batteries-promises-cost-effective-and-sustainable

63. https://www.iitm.ac.in/happenings/press-releases-and-coverages/iit-madras-researchers-develop-next-generation-battery

64. https://government.economictimes.indiatimes.com/news/technology/dst-scientists-get-breakthrough-in-developing-solid-state-batteries-that-charge-faster-and-cost-cheaper/92465152

65. https://dst.gov.in/sites/default/files/ETN%20-%20DST.pdf

CHAPTER-8:

STEEL

8.1. Material and its Background

In modern civilization, the application of steel can be seen everywhere and in every part of human life. Some of its unique qualities are (a) high strength and toughness with simple and lean compositions, (b) different grades and properties for different applications, (c) most inexpensive among all the structural materials, (d) 100% recyclability, etc. Steel has always been the most versatile material for the fabrication of numerous types of articles; the wide range of structural applications include almost everything, such as, building construction to ship manufacturing. While steel is being replaced to some extent in many applications, by other materials, such as aluminium and magnesium alloys, ceramics, composites, polymers, etc., it is still difficult to conceptualize a replacement of structural steels in construction of a bridge, or a building, or a container ship.

Therefore, steel has its own and well known importance, which is expected to continue for many more years. The infrastructure development of any country in the world is closely associated with the development and application of various structural steel grades. Therefore, steel is undoubtedly the most suitable and most widely used material for various structural applications. The present article is an attempt to briefly understand the prospect and areas of the technological research and development of modern steel grades, to meet the requirements of modern India.

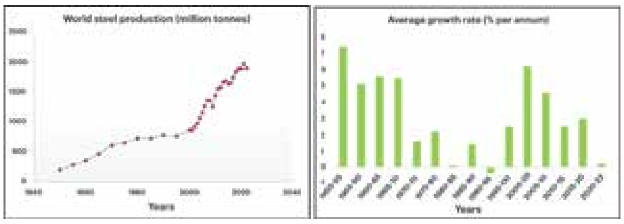
8.2. Strategic Importance of the Material for India

The infrastructure development of a country cannot be imagined without application of structural steels. This is more pertinent for the developing countries like India. It is, in fact, more appropriate to say that India is now on a journey towards achieving the identity of an advanced developing country, which is evident from the fast growing infrastructures in various fields, starting from the construction of expressways for long distance road connectivity to the elevated track construction for bullet train, or cross country pipelines for the transportation of petroleum products, etc. Everything requires huge quantity of steel. The steel consumption per capita is often considered a yardstick of overall development of any country. From this point of view, while India was still way below the world average of 233 kg by FY23, the per capita consumption in India was 77.2 kg, which was a 50% improvement over past 8 years [1]. This is a significant figure, which depicts the growth rate in the infrastructure, despite the negative effect of COVID-19.

Therefore, the strategical importance of steel for India is well understood, and it does not require any special preface. The question is that whether we are prepared enough to respond to the technical challenges of present and future.

8.3. Global Value Chain

A look at the trend of crude steel production in the world for the period 1950-2022 reveals almost a 10-fold increase in about last 72 years. Figure 1a[2] shows the world production figures over a period from 1950 to 2022, and Figure 1b[2] shows the average growth rate per annum during the same period. In 2022, China topped the list with 1018.0 million tonnes (Mt), followed by India, with a production figure of 125.3 Mt[2]. While comparing the production figures for the years 2021 and 2022, as shown in Figure 2, it is interesting to note that the crude steel production figures for the most prominent steel producing countries have seen a marginal decrease, while for India, it has seen an increase. Figure 3 shows how the crude steel production and usage have changed in past 10 years in the world.



1(a) 1(b)

Figure 1: Crude steel production in the world [2]; (a) steel production, (b) annual growth rate

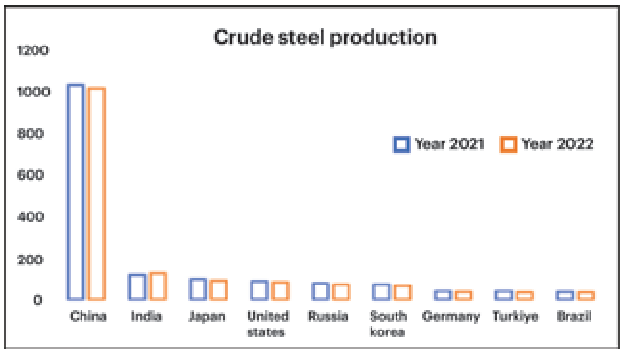


Figure 2: Crude steel production during 2021 and 2022 in the top steel producing countries[2]

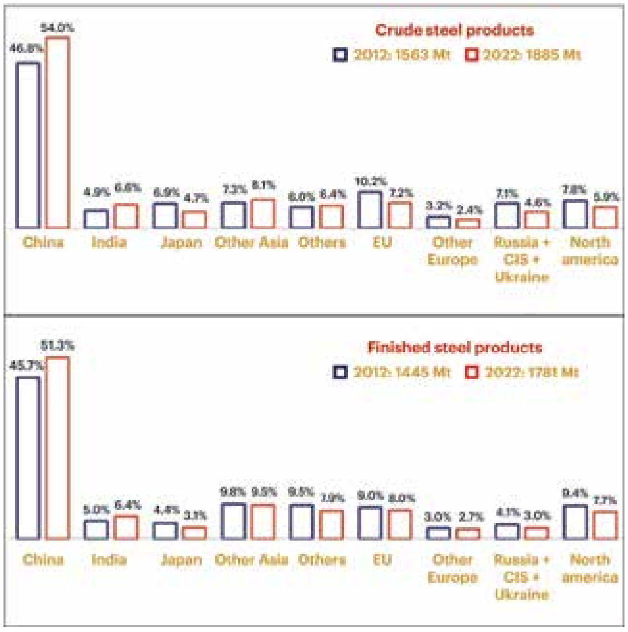


Figure 3 – Steel production and use in 2012 vis-à-vis 2022: geographical distribution[2]

The increasing global pollution and warming are resulting in a drive in every possible field to reduce the carbon footprint and touch the mark of net zero. The technologies for green steel manufacturing, which is based on the principle of using electricity along with renewable and non-fossil fuels (such as hydrogen) are now being developed in many countries. The main reasons are:

- Green steel manufacturing will help mitigating the emission norms, by reducing the use of fossil fuel and increasing the use of renewable energy.
- Green steel production will make the steel industry sustainable.
- Several countries have set specific targets to reduce the carbon dioxide emission and achieve the net zero mark.
- With increasing awareness of the global climate condition, the consumers also demand environment friendly products. This tendency makes green steel more competitive.

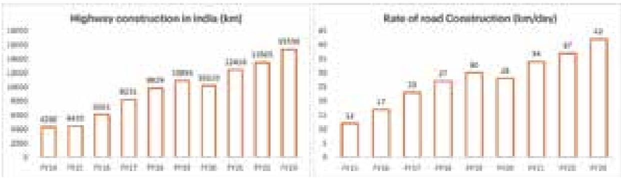
With an aim of net zero steel manufacturing by mid-century (2050), the current near zero steel production is even less than 1 Mt[3]. However, with the investment in this field by leading steel manufacturers all over the world, it is expected to rise in the coming years.

8.4. Indian scenario

The huge amount of usage of steel, that spans over different segments of structural applications, boosts the infrastructure development. A few prominent sectors, such as, construction, transport, clean energy, mobility, etc. are discussed briefly in the following paragraphs.

8.4.1. Infrastructure - Construction and Transport

Transport and Utility are the two most important segments among infrastructure development. Steel is required for bridges, tunnels, rail tracks and in constructing buildings such as fuelling stations, railway stations, ports and airports. About 60% of steel used in these applications is as rebar and the rest is in the form of sections, plates and rail track. Over 50% of the steel used for utility (fuel, water, power) application is in underground pipelines to distribute water and to distribute gas. The rest is mainly rebar for power stations and pumping houses. The construction sector alone accounts for more than 50% of world steel demand[4]. Figure 4a[5] shows the growth of highway construction in India. The gradual enhancement of road construction rate is depicted in Figure 4b[5], which shows an improvement of 3.5 times in between FY15 and FY23.



4a 4b

Figure 4 - Highway construction in India[5];
(a) year-wise highway construction in km,
(b) rate of highway construction in India in km/day

Building construction is an important part of the entire construction sector. Steel is readily available, affordable and safe. Its strength, versatility, durability and 100% recyclability allow for improved environmental performance across the entire life cycle of buildings. Various fabrication steps during the construction of a building, and the subsequent operation of a building, which involves direct consumption of fuel and electricity, lead to substantial CO2 emission throughout its life cycle. The buildings, in general, account for about 28% of global CO2 emission[6]. It is believed that steel has an important role to play in making buildings with net zero operational carbon by 2050 [4], and there is ample opportunity of research for developing new energy-efficient building designs.

Railways is another sector that plays a vital role in the development of the entire country, and also from the point of view of usage of steel. Rail steel is a specific grade of steel, which is used for extension, replacement or doubling of railway tracks throughout the country. Apart from rail steel, other structural applications for steel include manufacturing of locomotives, coaches and wagons, construction of station buildings, railway bridges, tunnels, electric poles, etc. As of 2023, the total track length of Indian Railways was more than 129000 km over a route length of 68907 km[7].

A UN report, published in 2019, indicates that the world population is going to be inflated by another 2 billion by 2050[4]. The associated urbanization, which is expected to be around 50% by 2050, would require steel for buildings and infrastructure. This real estate market is expected to grow to a figure of around one trillion USD by 2030, and the overall infrastructure segment is expected to contribute about 15% to Indian economy by 2030. Airport Authority of India (AAI) now also aims at constructing a number of airports in tier II and tier III cities. In addition, the huge railway network of India, the fourth largest in the world, is expanding every year to reach the ever-increasing population and urbanization. The developmental activities would need an investment worth Rs. 50 lakh crores by 2030[5]. The fulfilment of all these plans will not be possible without using a huge quantity of steel, and therefore, the National Steel Policy (2017) focuses specifically on enhanced budgeting on infrastructure and construction through various government initiatives.

8.4.2. Clean energy

With the ever increasing demand for energy in all industrial segments, the increasing environmental pollution has now taken the shape of a serious threat to earth and mankind. Therefore, in true sense, we need ‘clean energy’. In the present scenario, natural gas has been identified as a major source of clean energy. Apart from that, usage of unconventional energy sources, such as solar power, wind energy, etc. are also expected to rise significantly in the coming years. With the increased usage of natural gas, there is a need of huge storage facilities and pipelines across the country for transportation, and all these require a huge quantity of steel. The steel required for oil and gas pipelines must fulfil some specific quality aspects, such as high strength (different levels based on application), combined with superior low temperature fracture toughness. The quality requirement is more stringent for the transportation of crude oil and sour gas. The present pipeline projects (IOCL, ONGC and GAIL) would require high quantity of API X65 and X70 grades of steel in near future, both for non-sour and sour applications.

Irrespective of the source of energy, steel always has a crucial role to play in creating the infrastructure for the production and distribution of energy, ensuring ample usage of steel. Some of the areas of renewable energy are:

- **Solar energy:** Steel is used as a base for solar thermal-panels and in pumps, tanks and heat exchangers.
- **Wave and tidal energy:** A steel pile is the main component of a tidal turbine in tidal energy systems. Steel is also used to fabricate wave energy devices. This application demands appropriate resistance to corrosive marine environment.
- **Hydroelectricity:** Steel is needed to reinforce the concrete dams.
- **Wind energy:** Steel is the main material used in onshore and off-shore wind turbines. Almost every component of a wind turbine is made of steel, including foundation, tower, gears and casings. Steel provides the strength for taller and more efficient wind turbines.
- **Hydrogen:** This is an important source of clean energy for future world, in a journey towards carbon-free economy. Renewable energy is required to produce green hydrogen. Japan started the largest green hydrogen plant, with a 20 MW solar energy system, which feeds a 10 MW electrolyser plant[8]. In India also, the roadmap development of 2016 included the scope of extensive R&D on developing advanced electrolysers, and high pressure storage and transportation equipment, which means gas tanks, pipelines and cryogenic liquid hydrogen trucks. All these will require usage of advanced structural steels. Ministry of New and Renewable Energy, in partnership with NTPC, have proposed to launch a pilot project on fuel cell buses.

Out of all these applications, the wind power generation system is going to play a very important role in future development of the country. The wind turbine towers are basically tubular steel structure, carrying a rotor and a nacelle at the top, which can weigh as much as 200-300 tonnes[9]. Structural steels are the only solution for this segment. Longer rotor blades and taller towers are required to maximize power generation, which means the usage of high strength structural steel in huge quantity. Figure 5 shows an increasing trend of electricity generation from renewable sources in India[5]. The importance of wind power within the class of renewable energy is depicted in Figure 6[5]. According to the 2023 Climatescope report, India is ranked 1st among the list of most attractive markets for renewable energy.

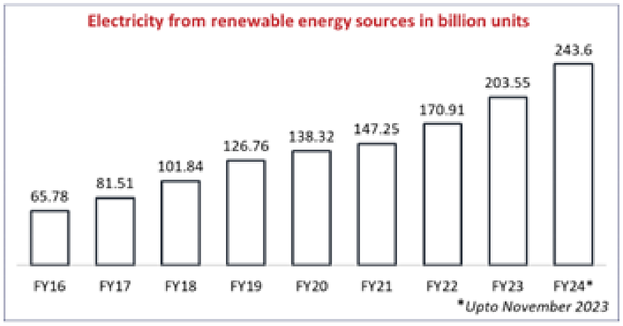


Figure 5 – Electricity generation from renewable energy sources in billion units (*as of November 2023)[5]

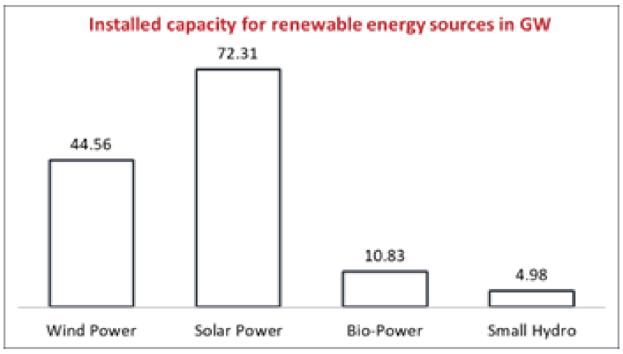


Figure 6 – Installed capacity for different renewable energy sources in GW, (as of November 2023)[5]

The International Energy Agency (IEA) forecasts a 30% rise in global demand for energy by 2040, most of which will come from developing countries. In India, there is a focus on enhancing the use of natural gas to about 15% of the energy mix by 2030[10]. The estimated demand of natural gas is going to be about 5.0 Tcf by 2040[5]. For hydrogen, as a source of clean energy, the demand is expected to rise by 3-10 times by 2050[11]. All these are great opportunities for steel sector in India, as the 'Make in India' drive is also going to encourage internal production of high quality structural steels for new pipelines, instead of importing the material. As far as the renewable energy source in India is concerned, the Government has an aim of installed electricity generation capacity to 40% by 2030[5], and the investment in this area may be of the order of US$ 500 billion by 2028.

8.4.3. Mobility

The automobile sector has seen some significant transitions over past few decades. Earlier, automobile body used to be built with thick steel sheet. Heavy cars like Ambassador ruled over Indian roads for several decades. The concept of low emission and fuel efficiency came later, when it was realised that controlling the emission level was essential for the earth and mankind.

Driven by government policies, the automobile manufacturing industry has responded to the situation with a series of solutions, such as, stricter emission norms, small size lightweight cars with higher fuel efficiency, advanced technology for the fuel-efficient engines and transmission systems, usage of advanced high strength steels to ensure passenger safety, etc. Despite all these efforts, pollution level has kept on increasing due to burgeoning number of vehicles on the road. So, there is a need of looking further ahead and finding out suitable solutions to fulfil the need of mobility, instead of just continuing with existing concept of automobiles with some incremental improvements year on year. This has resulted in the development of electric vehicle, which is considered as the technology of future.

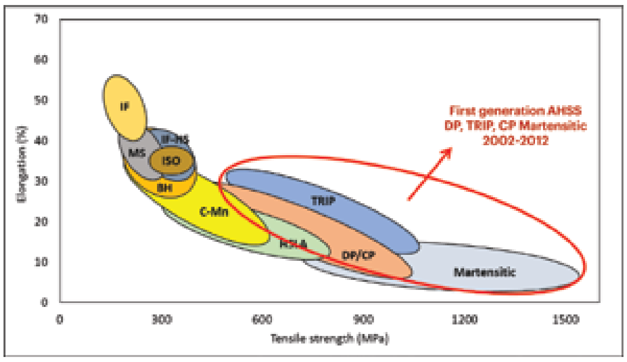


Figure 7 – Tensile strength and elongation of various automotive steel grades[12]

The development of the family of advanced high strength steels (AHSS) (Figure 7)[12] came as a revolution, which led to a massive technological boost in automobile industry. Over the years, the application of high strength steel gradually increased in automobile manufacturing[13]. Optimisation is the key word in the application of material for manufacturing of automobile components, which involves the design of component, vis-à-vis design of material, depending on the specific role of the component. The second generation AHSS mainly consisted of single phase austenitic steels, combining strength as high as 1000 MPa along with elongation as high as 70-80%. However, usage of these steel grades has been limited due to the factors like high cost, heavy alloying, difficulty of steel making, etc. The research interest then gradually shifted to developing third generation AHSS. The goal is to achieve multi-phase microstructures with leaner composition but enhanced strength and ductility (Figure 8)[14]. Researchers are now mainly engaged in developing innovative processing routes for the stringent control of microstructure[15-19].

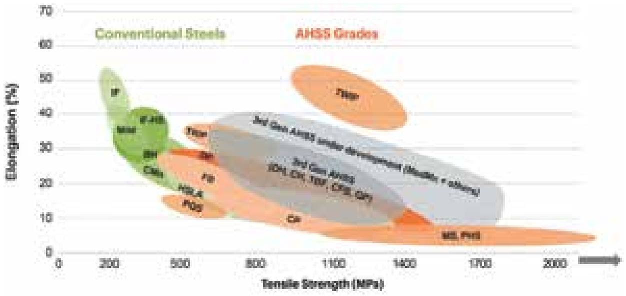
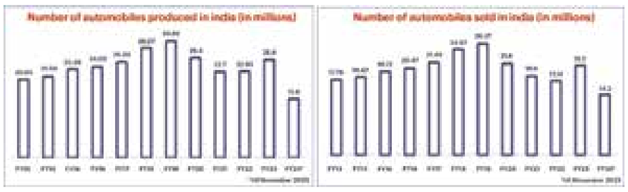


Figure 8 – Schematic representation of the position of 3rd generation AHSS[14]

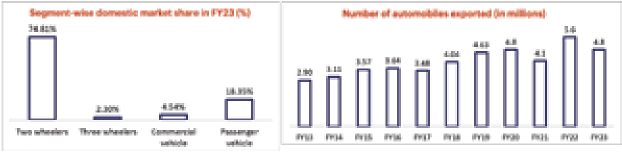
On an average, 900 kg of steel is used per vehicle, out of which, about 40% is used in the body structure, panels, doors and trunk closures for high-strength and energy absorption in case of a crash. About 23% of steel is used in the drive train, while about 12% is used in the suspension, using rolled high-strength steel strip. The remaining steel is used in wheels, fuel tank, and other auxiliary systems. In today's vehicles, advanced high strength steels constitute as much as 60% of the body weight, making lighter, optimised vehicle designs, ensuring safety and improved fuel efficiency[20]. The new grades of AHSS enable car-makers to reduce vehicle weight by 25-39% compared to conventional steel, leading to a net weight reduction of about 170 to 270 kg, for a standard 5-seater family car. This means a lifetime saving of 3 to 4.5 t of greenhouse gases over the vehicle's total life cycle, which is more than the total amount of CO2 emitted during the production of all the steel in the vehicle. Indian automobile segment has now shifted to BS VI version of emission norm, as Government of India is also implementing stricter norms for pollution control. Regarding safety, the awareness is gradually picking up among the Indian consumers, which is already prompting the car manufacturers to offer better safety features, indicating more incline towards the usage of advanced high strength steels.

The gradual rise in production and sale figures over the years, in the field of automobile manufacturing, are presented in Figure 9[5]. The graphs reveal a steady growth till FY19, with a CRGA little less than 7%, the economic setback being clearly reflected in the figures of FY20, FY21 and FY22, which coincides with the period of COVID-19. The production and sales figures of FY23 indicates that the industry is back on the track and gradually recovering from the setback. The segment-wise domestic market share of different types of vehicles and export figures are presented in Fig. 10.



9a 9b

Figure 9 – Trends of automobiles produced and sold in India; (a) automobiles produced, (b) automobiles sold[5] (*Till November 2023)



10a 10b

Figure 10 – Status of production and export as of FY23; (a) segment wise domestic market, (b) number of automobiles exported[5]

While there is an increasing trend of using high strength and ultra high strength steels in automobile body manufacturing[21], the light weighting drive is even replacing steel with some light metals like aluminium or magnesium, or with some non-metallic components as well. Cost is an important driving factor, and steel has an edge over other materials in this aspect. Components made of aluminium or magnesium alloys are definitely being used in modern cars, but those are mainly in the very high end cars. However, the market is driven by volume, and middle-class economy dominates the volume. Therefore, it is difficult to replace steel as a structural material, as far as overall automobile industry is concerned. Steel is being replaced even in small and cheaper cars, where it is adequately cost effective, for example, bumpers of four wheelers, or front fender, engine head cover, chain case cover, etc. of two wheelers are now being made of plastics and polymers.

In order to reduce the use of fossil fuel, as well as emission, the entire world is now inclined towards electric driven mobility. The number of EV models is rising quite rapidly, with some significant improvement in battery range as well (nearly 500 km in single charge). We can already see many EV models available in the Indian market, which indicates that electric vehicles are now ready to capture the market in almost all segments.

Figure 11 – Li-ion battery cost over the years[22]

The main driver for this electrification race is again affordability. Lithium-ion battery prices have dropped about 75% since 2013, hitting $139/kWh in 2023 (Figure 11)[22]. Apart from that, packaging efficiency and the cell energy density also are improving. For example, the 2011 Nissan Leaf EV components were made of aluminium, while the 2019 Nissan leaf EV closures are made of steel. The advantages of steel, in general for EVs, are as follows[23]:

- Narrower and compact transverse electric powertrains, leading to shorter front end, with increased occupant space.
- Lack of an exhaust system and fuel tank / filler leads simplifies the design of many components such as cross members.
- Higher safety requirement for the protection of high voltage electric powertrain and large, under-floor battery pack (300 litres, 500 kg).
- The EV body structure load path requirements are ideal for AHSS application.
- The floor cross members, being straight, can use very high-strength martensitic roll-formed sections.
- Safety is a serious concern, as EVs are different in nature, because of the high voltage electric system. Some of the applications of steel in this regard are listed below:

Application	Material
Cross members	3rd generation AHSS, with strength more than 1000 MPa and over 20% elongation
Frontal crash load management	3rd generation AHSS
Minimise passenger/battery compartment intrusions	
Structural members like rocker, rails, cross members, pillars	AHSS or UHSS
Frontal crash load management	AHSS and 3rd generation AHSS (for better protection from road-debris impact on the bottom of the vehicle).

The most important feature is that almost all the automobile manufacturers in India are now in a competition of making 'safe' cars, which prompts more usage of advanced high strength steels. In addition, these manufacturers are also exploring the avenues for sourcing the advanced steel grades from local manufacturers, which is a great opportunity for the Indian steel market. It is envisaged that the use of cold rolled advanced steel grades of minimum strength ranging from 780 MPa to 1180 MPa will increase, and all these would require appropriate research support for the timely indigenous developments of these steel grades.

8.4.4 Indian defence sector

Application of structural steels is an integral part of defence industry. Steels in various forms, such as cold finished bars, hot rolled bars and round bars, etc. are used in the manufacturing of missile components, shell casings, morters, track pins, etc.; high strength structural steel plates are used in the fabrication of ship and submarines, military trucks, ballistic resistant armoured vehicles, etc. India is one of the major importers of defence equipment, which requires a huge budget. The capital expenditure projection of defence budget by 2025-26 is INR 296,514 Cr[24]. The most important point at this stage is that India is now inclined towards complete indigenisation of strategic industries, such as railways, defence, etc. This is indeed going to be a significant boost to Indian steel industry. The effect of the drive for indigenous development initiative is already seen as India has started manufacturing high quality strategic equipment like light combat aircraft, Tejas, and light combat helicopter, the HAL-LCH. The main usage of structural steel would be in battle tanks, ships and submarines, armoured trucks and vehicles, etc. The first indigenous aircraft career of India, INS Vikrant, weighing more than 40,000 tons, is already in service. Nuclear powered ballistic missile submarines, each weighing about 6000-7000 tons, are also being manufactured in India. Initiatives for indigenous development and manufacturing of battle tanks and armoured vehicles are also in progress (example: Arjun Mk-1A rugged battle tank, weighing 68 tons). All these are good signs for Indian steel industry, as there would be ample opportunity for the development and production of advanced defence grade structural steels through advanced research.

8.5. Major Gap Areas

8. 5.1 Overall volume of steel manufacturing

It has already been discussed that the per capita consumption of steel in India is still way below the world average[1, 25]. However, being a highly populated developing country, India is surely going to use huge quantity of structural steel in all possible segments in the coming years. So, the volume of steel production is one area, where improvement is needed. The National Steel Policy 2017 foresees a demand of about 300 Mt of steel by 2030-31[25], which appears to be an encouraging factor under present circumstances.

8.5.2 Steel for mobility

An important area is the usage of high end steel grades, where substantial boost is required. The applications of advanced high strength steel (AHSS) grades in India, except Dual Phase steel, is still very limited. However, the leading steel makers of other advanced countries like USA, UK, Japan, Korea, Germany, France, or Austria have at least their manufacturing capabilities ready for such steel grades. On the other hand, due to inadequate demand of such advanced steel grades, India is still in a stage of development and trials. Cost is always an important factor, and so, the specific requirements for the automobile segment are fulfilled by importing the material. Though it is expected that the usage of AHSS grades would increase in automobile sector to support the steady supply of these grades from domestic steel makers, it is difficult to predict the time frame of required maturity.

8.5.3 Infrastructure

It is also difficult to predict how many years it would take to use AHSS grades in areas other than mobility. When India is on the track of huge development in the coming years, with possibilities of construction of high rise buildings, roads and railways at tough geographical locations, there will be need for catching up with developments in the field of high strength steels. Although construction of large dams is always a threat to nature, the prospect of constructing dams of different sizes with different purposes cannot be completely ruled out in a developing and power-hungry country like India, and all these constructions would lead to usage of structural steels. The supporting manufacturing capabilities should also be developed either by installation of new facilities or by augmentation of existing mills.

8.5.4 Energy

The fabrication of pipelines for the transportation of natural gas, as well as crude and refined petroleum products, require huge quantity of API grade steel plates. These are highly advanced steel grades, with extremely low level of impurities and inclusions and high fracture toughness at sub-zero temperatures. The pipe fabrication industries of India are gaining maturity, and they are now looking for the supply of high quality API X65 and X70 grade steels from Indian steel manufacturers. There is also some demand of X80 grade as well. Steel manufacturing companies like Tata Steel and JSW are already responding to the needs of the customers with X65 and X70 grades. However, sour grade linepipe steels are still under development. A significant demand will also be expected in the coming years in the field of the steels for hydrogen storage and transportation. The Indian steel industries should be in a position to supply all these advanced steel grades, and this is high time to carry out all the development activities.

India already holds a leading position in the field of renewable green power generation. However, the present output is still much lower than what is required for the most populated country in the world. The coming days will see the installation of more renewable power generation units (solar power or wind power), and this sector will definitely consume a large quantity of steel. Not only quantity, the fabrication of wind power mills is a potential field of application for advanced high strength steels as well.

8.5.5 Green Steel

While most of the countries have taken net zero targets by mid-century, India is also no exception. However, the path is not very easy for India. The financial sector is showing tendency of shifting the funds from the industries that require fossil fuel to green industries. A similar indication is also coming from the buyers, like construction, mobility, other metal products, etc. This is more important for the export market. That means, Indian steel manufacturing industry is at a vital point of transition. The technology development, initially for lower emission, and finally for zero emission, is absolutely necessary at this stage. Being the second largest producer of crude steel, the complete conversion into green steel manufacturing technology is an extremely challenging task. In addition to advanced net zero carbon footprint steel manufacturing, it will also require drastic upscaling of renewable power generation capacity[26].

8.6. Role of stakeholders

The development of steel industry in any country is not just a kind of business for profit. It is actually closely related to the development of an entire nation, and therefore, it is impossible without collaborations between government, industry, academia and research institutes.

The government has the main role to play in this entire field, as the policies adopted by the government are the main driving forces that can lead to the overall development. For example, the infrastructures like roads, bridges, flyovers, dams, etc. are the results of long term policies of the government, which boost up the construction industries, and the growth of construction industry boosts steel industry.

The “Make in India” drive is such a strong policy that it is now steering almost every sector of industries in our country, starting from electronics to steel manufacturing. This policy is directly or indirectly boosting all areas where steel is required as raw material. Examples are pipe line fabrication using high quality steel from domestic market, or driving the manufacturing and fabrication of indigenously developed semi high speed trains, war ships, aircraft carriers, submarines, war tanks, etc., thereby raising the demand of high quality steels every year. Strict implementation of emission and safety norms are prompting the automobile manufacturers to use advanced high strength steels for passenger vehicles.

The role of steel industry is to respond to all these needs. On one hand, this should take care of increasing demand of general steel grades, such as commercial quality hot rolled strips or cold rolled sheets, or wire rods for construction. On the other hand, the industry has a very significant role to develop all the advanced steel grades indigenously. This is very important from the point of view of saving foreign currency, which directly impacts the economic stability of the country.

Indigenous development of advanced steel grades, which may also include something completely new to the entire world, requires dedicated effort and investment. The investment may be in terms of time, and/or resources. The R&D cells of the steel manufacturing companies play a very significant role in this regard. The primary role of the R&D is to understand and foresee the need of the new development and act accordingly. It is very important that the R&D cell of the steel manufacturer work hand to hand with academia and research institutes. The simple reason is that one single R&D unit cannot be equipped with all kinds of equipment, or expertise in every subject. Collaboration between industry, academia and research institute leads to overall enrichment of knowledge, which results in technological development for future.

8.7. Recommendation with Specific Actions and Conclusion

The world is changing fast, driven by some critical factors like population growth, rise in pollution level and global temperature, ever-decreasing fossil fuel reserve, ever-increasing number of automobiles on road, etc. The effects are already visible, as the governments of all the countries worldwide, India being no exception, are coming up with new and stricter policies, with an aim of protecting the mankind from possible disaster. Therefore, while considering the application of steels by the year 2030, it is most important to visualise the situation after ten or twenty years from now, which is a difficult task at this stage, as it involves new possibilities and uncertainty factors. Despite this uncertainty, it may be safely assumed that steel will continue to be the cheapest and strongest material, and therefore, a superior choice for structural applications and infrastructure development for many more decades.

The timely stands taken by the Indian Government in different areas, such as 'green energy', 'green building' and 'green mobility', and above all, 'make in India', are strong driving forces towards the development of new generation high strength steels. Accordingly, adequate research support would be required in developing such steel grades.

At the same time, it should also be considered that development of completely new microstructures or unique properties in steels is gradually reaching a phase of saturation. Developing a completely new steel grade, which can also be successfully manufactured with existing facilities and commercialised as well, is quite difficult. Therefore, catering for the market in next 5-10 years from now will essentially require improvement and incremental research activities on some of the existing steel grades. The development activities may be classified as below:

1. Indigenous development and commercialization – replacement of imports
   a) AHSS grades
   b) Steels for pipeline, up to API X80
   c) Ultra high strength steels for manufacturing lifting and excavation equipment
   d) Steels for building construction with improved seismic resistance
   e) Steel for structural applications with improved fire resistance
2. Expanding the area of applications:
   a) Wider applications of AHSS, in areas other than automobile sector
   b) Enhanced usage of high strength micro-alloyed steels for infrastructure and construction
   c) High strength steels for taller wind mills
3. Development of steels that can combine critical properties together, such as high strength, high stretch forming, high hole expansion
4. Development of a large family of 3rd generation AHSS, to combine very high strength (over 1500 or 2000 MPa) with high ductility and appropriate forming properties
5. Developing steels for hot forming that will need no coating
6. Understanding the property requirements for different steel components of EVs, particularly chassis and battery chamber components, and research for developing appropriate materials to achieve them
7. Initiatives for the manufacturing of green steel
   a) Advanced steel production technology, to drastically cut down the carbon foot print and the cost of production
   b) Alternative and renewable fuel technology to completely replace the use of carbon or fossil fuel in iron making
8. Innovation in steel manufacturing – green steel
   a) Alternative and auxiliary processing technology for developing ultra high strength novel steels with high ductility
   b) Development of light weight steels with high stiffness, requiring innovative processing route
   c) Development of stronger and light weight composites with steel base

9. Design and development of advanced steel based structures for effective thermal management of future generation green buildings and cabins of electric vehicles For the long term goals,

   research institutes and academia will have to play a very important role. They are the main resources of innovative solutions, and it is the responsibility of the Steel manufacturing R&Ds to provide with accurate inputs regarding the future needs. The concept of effective collaboration between industry and research institute / academia is based on the following:

   a) The industry must have a very clear idea about what to achieve, so that the academia or research institute can formulate the research proposal based on this concept.

   b) The industry must know the exact time frame for the development. This is very important, because the research partner must be allowed to take the minimum required time to carry out the research and deliver the desired output.

   c) It is very important for the industry to foresee the problem, so that the research partner can start the work well in advance, instead of initiating a project at the eleventh hour.

   d) The output delivered by research partner is often in the form of scientific output. The R&D cell of industry should have sufficient expertise to convert that scientific knowledge into an implementable technology.

   e) The research partner (academia or research institute) should be careful about the research project, so that the output delivered by them is actually suitable for industrial implementation, and not just a set of raw data for some technical publications. They should also have substantial knowledge about the manufacturing route and associated challenges, so that their scientific output is in line with the existing processing technologies.

To conclude, steel is the most versatile and most easily affordable structural material as of now, which finds a wide range of applications in present days, out of which, a few prominent ones have been discussed briefly in the present article. India, being a highly populated developing country, is doing fairly well in steel manufacturing sector, as the country has already occupied the second position in the world of crude steel production. The per capita steel consumption figure in India is also improving, although still below the world average. All these indicate that there is ample opportunity for growth and development in India. Considering some of the most important areas of development, such as, construction of highways and other infrastructures, railways, clean energy, mobility, defence, etc., it may be anticipated that the period of next 5-10 years is going to be crucial for India, as the nation is already going through a significant transition. On one hand, there is a pressure of infrastructure development at a faster pace, while on the other hand, the expense has to be reasonably under control. Environmental issues are additional challenges. In order to be both economically sustainable and technologically superior, the "Make in India" drive is actually boosting the Indian industry, and also throwing some healthy challenge. The issue of environment and conservation of nature are going to enhance this challenge by several times. The Indian steel industry will have to fulfil the expectations of the nation, not only by supplying the huge quantity of steel, but also by coming up with innovative solutions for future generation advanced structural steels through green technology.

8.8 Case Studies

Case Study 1: Value analysis and value engineering (VAVE)

1. Executive Summary of the project

   Value Analysis and Value Engineering (VAVE) is a study of vehicle structures and assemblies in a controlled and systematic manner to identify weight and cost reduction opportunities. Over the years, automobile designers have been under constant pressure to reduce the vehicle weight and improve safety due to statutory requirements. Weight reduction can be achieved through innovative design and alternative materials, leading to energy efficiency, better performance, and emission controls. Apart from delivering premium products and services, Tata Steel also creating a value to customers through the VAVE platform to provide weight and cost reduction opportunities. Since the inception of VAVE in 2011, Tata Steel has conducted around 70 VAVE workshops with over 25 customers on approximately 80 vehicle models.

2. Key challenges faced

   - Customer acceptance: Creating confidence with the customer as the material and design solution provider.
   - Data Sharing: Original Equipment Manufacturers (OEMs) are unwilling to share confidential design information about vehicle to material supplier (Tata Steel).
   - Preparation for VAVE with physical car BIW, parts and assemblies at workshop location.
   - Disruption due to COVID, However Tata Steel mitigated with Virtual VAVE called e-Drive.

3. **Partners involved:** Tata Motors, Bajaj, Mahindra & Mahindra, Volkswagen, Ashok Leyland, TVS, Daimler, Hero Motors, Toyota Kirloskar Motor and Renault–Nissan.

4. **Benefits:** Unlocked value to customers though cost and weight reduction which has resulted in to total potential cost saving ~ 600 Cr and average 5% weight reduction/vehicle reduces GHG emission correspondingly.

5. **Figures/illustration:** The VAVE process is schematically illustrated in Figure 12.

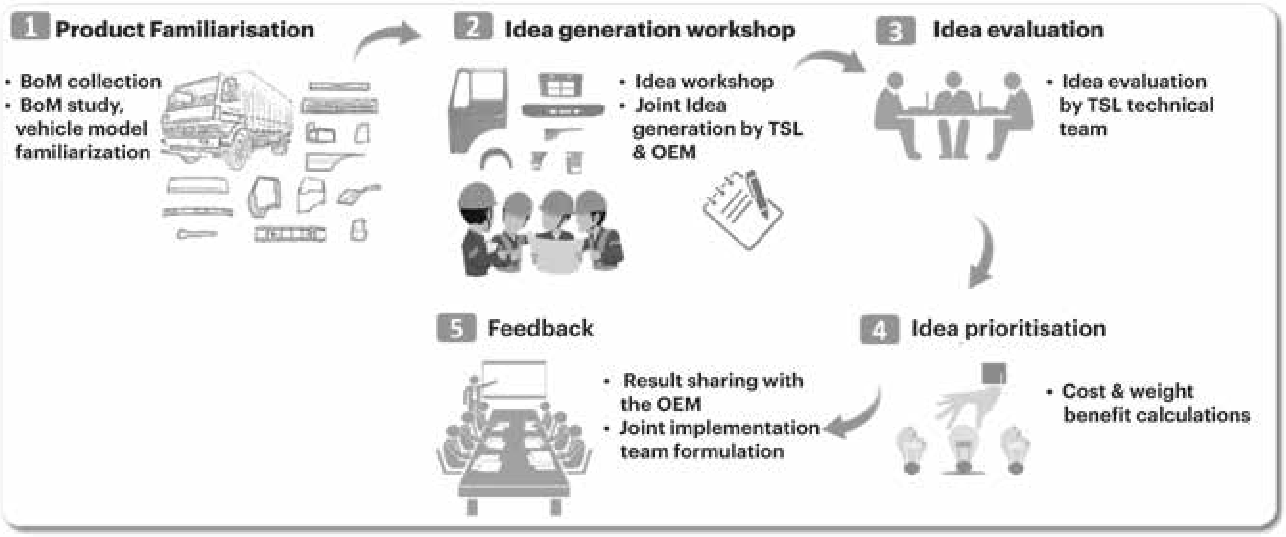


Figure 12 – A schematic illustration of VAVE process

Case Study 2: Development of HS800 Steel Grade

1. Executive Summary of the project

   Applications of Advanced High Strength Steels (AHSS) are gradually increasing in automotive industries due to its weight saving potential, improved crashworthiness and other superior properties. HS 800 (with ultimate tensile strength > 800 MPa) is a superior Advanced High Strength Steel (AHSS) to carter primarily the automobile industry for various components (potential use for long member, chassis, tipper body etc). Fully polygonal ferrites with nano interphase precipitate dispersed within the ferrite matrix are essential for both obtaining higher strength as well as adequate formability. The present development was initiated by R&D to achieve > 800MPa strength advanced high strength steel using conventional hot rolling mill. Both chemistry and critical processing conditions can significantly influence the microstructure and thereby the final mechanical properties. Therefore, composition, hot rolling parameters like reheat temperature, finish rolling temperature, coiling temperature were optimized to achieve the final properties. Lower carbon level concept was adopted to avoid welding related issues. Subsequently, the grade has been successfully developed and commercialized. The steel is now regularly produced and supplied to various automakers and other customers.

2. Key challenges faced

   The superior properties are attributed to single phase ferrite microstructure with nano scale precipitates (~5nm in size). Therefore, both stringent control of chemistry and processing parameters were the foremost important and challenging part. Traditionally, Indian automakers did not use such a high strength material in their manufacturing line. Therefore, convincing automakers to use this grade in their benefit was another challenge.

3. Partners involved

   Tata Motors were the main partner for the application of this grade in long members of commercial vehicles.

4. Benefits, including Techno-commercial benefits

   HS 800 is now a regular product of Tata Steel's product basket. To date, several thousand tons of materials have been successfully sold in the Indian market, and this number is still rising.

   Initially the steel grade was developed for application in long members of automotive. But, today, it may be used for other applications, including tipper body. The technical concept has been further utilized to develop higher strength steel grades or other unique products.

5. Figures/illustration

   The development process of HS 800 is schematically presented in Figure 13.

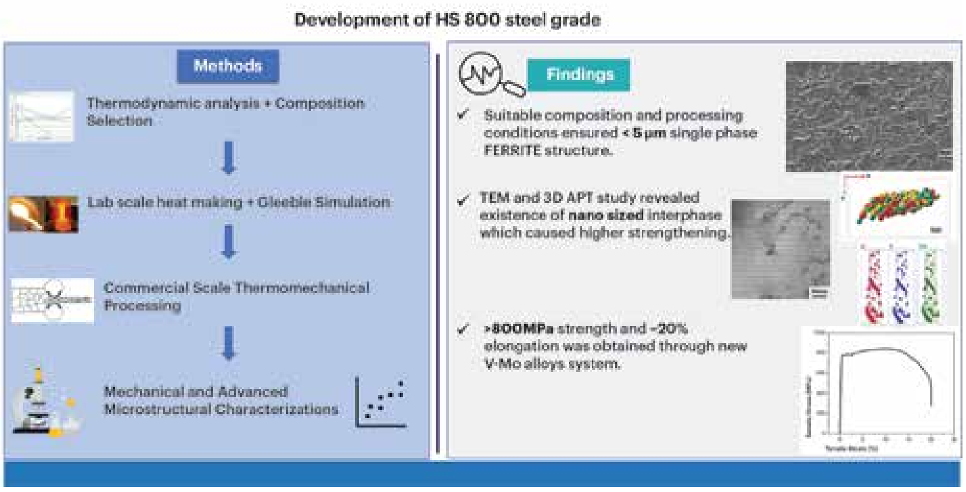


Figure 13 – A schematic illustration of the process of HS 800 steel grade development

8.9. Advanced Materials Market Company Analysis

There are many steel manufacturers in India, who can supply quality products to the customers in various segments. However, as of now, there are only few manufacturers, who have the capability of manufacturing advanced steel grades. Few major names are listed below.

Advanced Materials Market Analysis

S.NO	Company	Product / Technology / Advanced Materials Product and Solutions
1.	Tata Steel Limited	Advanced high strength steel grades, VAVE
2.	SAIL	High strength steel grades
3.	Tata Steel Limited	Advanced high strength steel grades
4.	ArcelorMittal Nippon Steel India Limited (ESSER Steel Limited)	Advanced high strength steel grades

Chapter contributors

- Dr Debashish Bhattacharjee, Vice President, Technology & R&D, Tata Steel Ltd.
- Dr Basudev Bhattacharya, Principal Scientist, Product Development Research Group, R&D, Tata Steel Ltd.
- Dr Subrata Mukherjee, Head, Advanced Materials & Characterization Research Group, R&D, Tata Steel Ltd.
- Dr Pinaki Biswas, Head, Product Application Research Group, R&D, Tata Steel Ltd.
- Mr Manoj Krishna Majumder, Principal Researcher, Product Application Research Group, R&D, Tata Steel Ltd.
- Mr Pundan Kumar Singh, Principal Researcher, Product Application Research Group, R&D, Tata Steel Ltd.
- Mr Shashank Choudhary, Principal Researcher, Product Application Research Group, R&D, Tata Steel Ltd.
- Dr Manikandan G , Principal Scientist, Product Application Research Group, R&D, Tata Steel Ltd.

References

1. "Steel consumption in the country", Ministry of Steel, Govt. of India, Release id: 1896882, https://www.pib.gov.in/PressReleasePage.aspx?PRID=1896882.
2. World steel in figures, World Steel Association, "https://www.worldsteel.org/", 2023.
3. Breakthrough Agenda Report 2023: Steel, https://www.iea.org/reports/breakthrough-agenda-report-2023/steel .
4. Constructsteel, "https://constructsteel.org/".
5. India Brand Equity Foundation, "https://www.ibef.org".
6. World Green Building Council, "https://www.worldgbc.org/embodied-carbon".
7. Rail Transport in India, https://en.wikipedia.org/wiki/Rail_transport_in_India.
8. Driving India towards the clean energy technology frontier, W. Hall, The Energy and Resource Institute (TERI), New Delhi, India, http://www.teriin.org/
9. Steel Solutions in the Green Economy: Wind turbines, "https://www.worldsteel.org/", 2019.
10. India 2020 Energy Policy Review, International Energy Agency: https://niti.gov.in/sites/default/files/2020-01/IEA-India%202020-In-depth-EnergyPolicy_0.pdf
11. Fuel cell and hydrogen development in India, Fuel cell and hydrogen energy association, Washington, USA, www.fchea.org/in-transition/2020/6/9/fuel-cell-and-hydrogen-development-in-india
12. High Strength Steel Application Guidelines, International Iron and Steel Institute, 2005, "www.worldautosteel.org"
13. A. Abraham, Ducker Worldwide, "Future Growth of AHSS" May 2011 [Presentation at Great Designs in Steel Seminar – 2011]
14. Global formability diagram, (2021). "WorldAutoSteel", https://ahssinsights.org/blog/a-new-global-formabilitydiagram/
15. R. Rana, Editorial – "Special issue on medium manganese steels", Mater. Sci. & Tech., Vol. 35, No. 17, 2019, pp. 2039-2044.
16. R. Schneider, K. Steineder, D. Krizan and C. Sommitsch, Mater. Sci. & Tech., Vol. 35, No. 17, 2019, pp. 2045-2053.
17. A. Arlazarov, M. Goune, O. Bouaziz, F. Kegel and A. Hazotte, Mater. Sci. & Tech., Vol. 35, No. 17, 2019, pp. 2076-2083.
18. Y. Li, F. Huyan and W. Ding, Mater Sci & Tech., Vol. 35, No. 2, 2019, pp. 220-230.
19. D. Raabe, Medium Mn Steels, "http://www.dierk-raabe.com/medium-mn-steels/"
20. "https://www.worldsteel.org/steel-by-topic/steel-markets/automotive.html"
21. C. Lesch, N. Kwiaton and F. B. Klose, Steel Res. Intl., Vol. 87, pp. 2076-2083, doi: "https://doi.org/10.1002/srin.201700210"

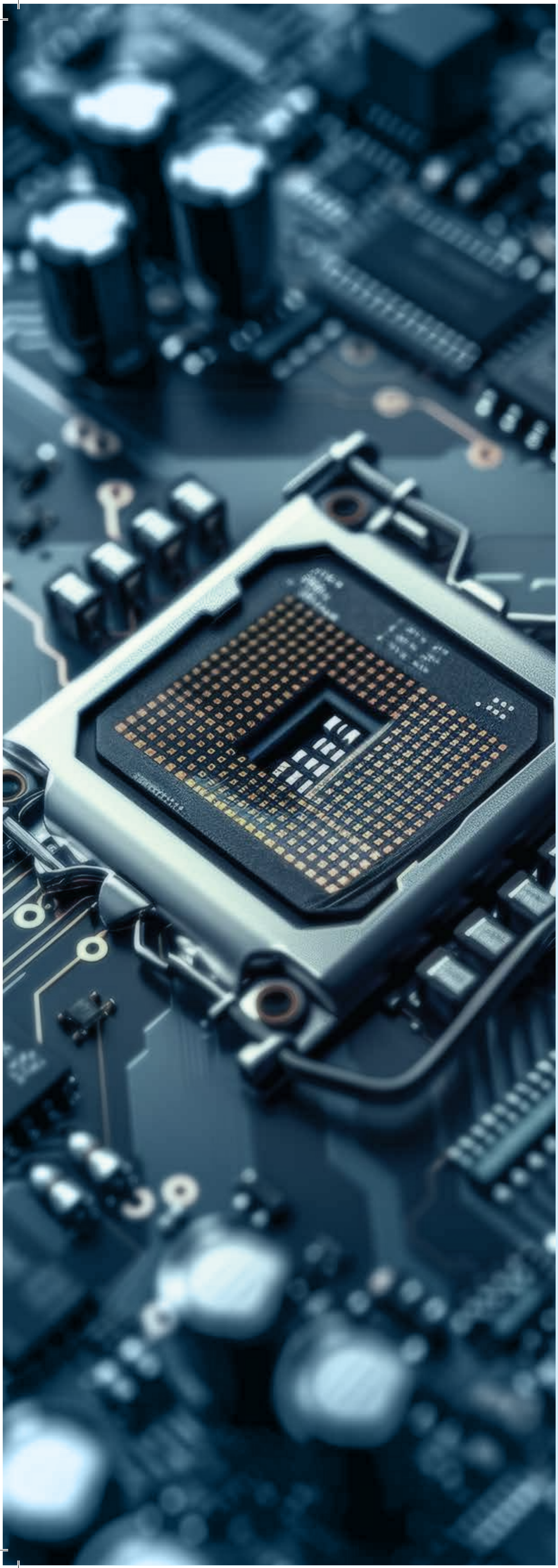
22. Bloomberg NEF, "https://about.bnef.com/blog/lithium-ion-battery-pack-prices-hit-record-low-of-139-kwh/"

23. Don E. Malen, Mass Benchmarking Analysis of Electric Vehicles, A2Mac1, WorldAutoSteel

24. INDIAN DEFENCE INDUSTRY – An Agenda for Making in India, Laxman Kumar Behera, The Institute for Defence Studies and Analysis, New Delhi, Pentagon Press, 2016.

25. "Quality and consumption of steel", Ministry of Steel, posted on 2019-07-10 by PIB in Delhi.

26. Achieving Green Steel – Roadmap to a Net Zero Steel Sector in India, The Energy and Resource Institute, 2022, https://www.energy-transitions.org/publications/net-zero-steel-sector-india/.



CHAPTER-9:

SEMICONDUCTORS

9.1 Executive Summary

Semiconductors are indispensable materials with tunable electronic properties and are critical to the function of everyday consumer electronics, communications, computing devices, energy, internet of things and artificial intelligence. As technology becomes more connected, autonomous, virtual, and intelligent, semiconductors play an increasingly significant role in individuals' lives and many products have become inevitable for mankind. In short, semiconductors serve as a translator from the physical world to the digital world.

Globally integrated supply chain such as design, manufacturing, assembly, testing, packaging, and distribution is the backbone of this industry. Carrying out each activity requires great specialization and offers a chance to add significant values. The supply chain thus becomes a value chain, with each activity contributing to the overall competitive edge of the final product. The actors in the value chain form part of a semiconductor ecosystem also populated by materials suppliers, design service providers, developers of "IP cores" or "IP blocks," and makers of equipment to manufacture semiconductors.

India has a visible fabless semiconductor design ecosystem with talented human resource. However, focus is lacking in high-end research and development, shortage of essential materials supply chain, state of the art fab facilities and sophisticated equipment support. In order to get an edge on the semiconductor manufacturing ecosystem, India should gainfully use its growing specialty chemical sector for the manufacturing of critical raw materials like acids, solvents, photoresists, developers, etchants, gases etc. Large quantities of ultra-high pure water (~8 million gallons per day), uninterrupted power supply (~169 MWh), pollution-free environment, sophisticated process equipment, and effluent disposal strategies need to be sourced. Indigenous availability of high pure silicon dioxide as input material for the growth of semiconductor grade silicon wafer is another important challenge.

9.1.1 Silicon as electronic semiconductor material

Semiconductors are widely used in familiar electronic appliances such as personal computers, televisions, smartphones, digital cameras, IC cards, displays, military, intelligent machines, healthcare, network devices, energy sector, etc. The material most frequently used in semiconductors is Silicon, which is found in soil and rock, and it is also contained in natural water, trees and plants. In nature, however, Silicon is found in the form of compounds with Oxygen, Aluminum and Magnesium. Hence, the Silicon element must be extracted from the compound and purified for usage in the semiconductor industry. It is the most fascinating semiconductor material due to its favorable energy gap, tunable carrier concentration, high charge carrier mobility, ability to produce highest purity large-size defect-free single crystal by virtue of its better heat and mass transport properties, along with high stacking fault energy and critical resolved shear stress, in addition to the ease with which its electronic properties can be altered by doping, temperature, pressure, electric field and light. Needless to mention about its second largest natural abundance in the earth's crust after oxygen. No wonder silicon is termed as the work horse of the semiconductor industry. 80% of the semiconductor market is captured by commercial grade silicon. Silicon used in integrated circuits (IC) requires a single crystal structure of ultra-high-purity "99.999999999%" (the so-called "eleven nines") and is refined using various processes after extraction.

9.1.2 Raw material: MG grade silicon production

High pure polysilicon is manufactured by the purification of metallurgical grade silicon (MG silicon). MG silicon is produced from high-purity silicon dioxide using an electric arc furnace process and is typically about 98.5% pure. The feed materials silica and carbon (such as high-purity coals, charcoals, wood chips, cokes, etc.) are reacted in a furnace according to the following high temperature reduction:

$$SiO2\ (s) + 2C\ (s) = Si\ (l) + 2CO\ (g)$$

Metallurgical-grade silicon is widely used in the metallurgical, chemical, and electrical industries. Metallurgical grade silicon is produced in an amount of more than 3 million ton per year (tpy) and used as charge for aluminum (silumines) and magnesium alloys. In the chemical industry silicon (organic silicon) processes for use in the production of plastics, paints and varnishes, lubricants etc. are currently developed. Further refined silicon is converted into trichlorosilane (TCS) to produce polysilicon for Solar and semiconductor chip manufacturing.

For semiconductor and solar applications, ultrapure silicon is separated into electronic-grade silicon (EG silicon) and solar-grade silicon (SG silicon). Metallurgical grade silicon contains a large number of impurities. Poly-Si production preferably requires purer metallurgical grade silicon.

Table 1 represent the different grades of MG silicon for solar and electronic grade poly-Si and industrial processes

Grade	Chemical Composition				
	Si (min%)	Fe (max%)	A1 (max%)	Ca (max%)	P (max%)
Level 1101	99.79	0.1	0.1	0.1	30
Level 1501	99.69	0.15	0.15	0.1	30
Level 1503	99.67	0.15	0.15	0.3	30
Level 1515	99.60	0.15	-	0.15	30
Level 1202	99.58	0.2	0.2	0.02	30
Level 1502	99.48	0.25	0.25	0.02	30
Level 1103	99.40	0.3	0.1	0.03	30
Level 1303	99.30	0.3	0.3	0.03	40
Level 411	99.2	0.4	0.08	0.1	50
Level 421	99.2	0.4	0.15	0.1	-
Level 421	99.0	0.4	0.4	0.1	-
Level 553	98.5	0.5	0.5	0.3	-

9.1.3 Polysilicon production processes

There are two different manufacturing technology processes namely Siemen's process and Fluidized Bed Reaction (FBR) for production of polysilicon. The Siemen's process mainly used for semiconductor and solar applications, and holds 95% of the market, whereas conventional FBR process only used for solar applications with 5% market share. The FBR process is relatively cheaper compared to Siemen's process, however the quality of Siemen's process is always superior. There is trade of between the cost and the quality of the polysilicon as per the application/requirement.

Siemen's process starts with hydrogeneration of MG-Si with HCl to produce crude TCS, which undergoes quenching process through chlorosilane. Further purification of TCS using Hydrogen used in CVD process to deposit polysilicon after reduction process. The high pure 10 -11N poly Silicon is produced using this process. The flow chart of industrial polysilicon process is presented in Figure 1. The Siemens TCS process is currently dominating in the industry.

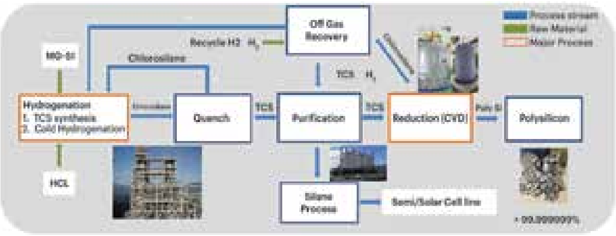


Figure 1: Industrial polysilicon process

Table 2 Different grades of polysilicon along with important parameters used in electronic and solar industries

Parameters	Electronics Grade	Solar Grade
Mani Substance Fraction	>99.99999999999 (>11N)	99.9999999-99.9999999999 (8-11N)
Uses	Microelectronics and high-power Si single crystal devices	Si single crystal photoelectric converters
Donor	(P, As, Sb) (n-type, ρ>1000 ohm.cm); ≤0.05ppba	(P, As, Sb) (n-type, ρ>500 ohm.cm); ≤0.1ppba
Acceptors	(B,Al) (p-type, ρ>9000 ohm.cm); ≤0.03 ppba	(B,Al) (p-type, ρ>5000 ohm.cm); ≤0.05ppba
Carbon (C)	≤0.1 ppma	≤0.2 ppma
Metals:-in the bulk (Fe, Cu, Ni, Cr, Zn, Na)	≤0.5 ppbw	≤0.5 ppbw
On the surface (Fe, Cu, Ni, Cr, Zn, Na)	≤1 ppbw	≤1 ppbw
Minority Carier lifetime (more than)	400 mks	250 mks

9.2 International Best Practices

9.2.1 Current poly-Si market condition and Main poly-Si producers:

Aimed at optimizing their production costs the poly-Si producers have clearly delimited the quality of their product material for various purposes. As a result, the follow¬ing terms have emerged:

- Poly-Si for multi-silicon production by casting or solar grade poly-Si for multicrystalline cells (multi grade) with a purity of 99.99999% (7N) – 99.999999% (8N);
- Poly-Si for solar grade single crystal silicon production by the Czochralski method or solar grade poly-Si for monocrystalline cells (mono grade) with a purity of 9N to 11N;
- Electronic grade poly-Si for semiconductors with a purity of 11N or higher.

Electronic grade poly-Si is produced and consumed in an amount of about 35–40 tpy. The solar grade polysilicon production has exceeded 500 tpy (Figure 3). However, the quality of electronic grade polysilicon and purest solar grade poly-Si which is also intended for Cz single crystal growth differs considerably (Table 2). The number of poly-Si production facilities has grown multiply over the two last decades. Intense growth periods have often caused significant facility excess in turn leading to price drop (Figure 4). The poly-Si market currently sees a slight reduction of excess facilities and a price growth after a long price decline period (7–8 $/kg). It is however anticipated that the offer will still be above the demand for several years ahead.

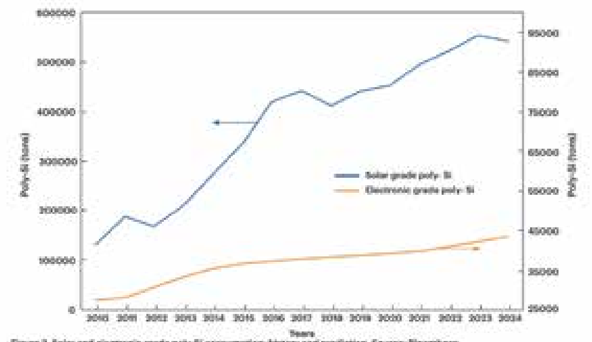


Figure 3. Solar and electronic grade poly-Si consumption. History and prediction. Source: Bloomberg

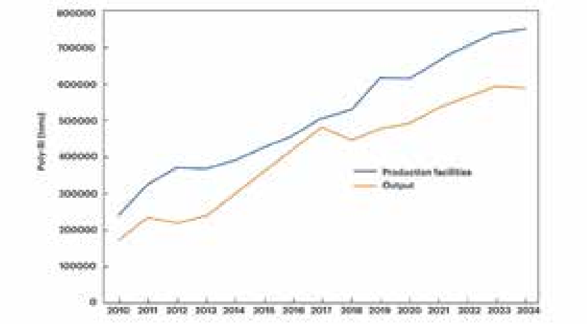


Figure 4. Growth of the number of poly-Si production facilities and actual output (solar + electronic grade) in 2004-2024. Source: Bloomberg.

Over the recent 3–4 years the world's distribution of po¬ly-Si producing companies has changed dramatically. The traditional PS production leaders such as Wacker (Ger¬many), Hemlock (US), REC (Norway-US), Tokuyama (Japan), SunEdison (former MEMC Electronic Materi¬als, US) have lost the top positions both in product out¬put and in production efficiency. The multi-year efficien¬cy leaders Wacker and Hemlock lost their top positions back in 2018 (Hemlock has furthermore fallen a prey of Chinese counter-sanctions and had to greatly reduce its product output). One should however consider that these companies as well as the Japanese Tokuyama and Mitsubishi are the main producers of the more resource-consuming and costly electronic grade poly-Si (Figure 6).

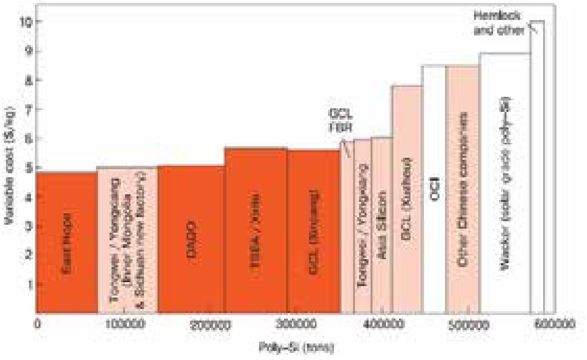


Figure 6 Efficiency and product output of major ploy-Si producers in 2021. Source: Bloomberg

Table 4. Production build-up plans of some poly-Si producers

Company	Location	Planned output (t/y)	Terms	Comments
GCL-Poly	Xinjiang	20,000	Start in 2021	Conventional Siemens process
	Leshan	100,000	Start in 2022	
	Xuzhou	100,000	1st stage in 2021	Granulated silicon
	Baotou	100,000	1st stage of 60,000 tons planned	
Xinte	Baotou	200,000	1st stage of 100,000 tons planned	Conventional Siemens process
Tongwei	Leshan	25,000	Start in 2021 Q3	Conventional Siemens process
	Baotou	45,000	Start in 2021	
	Baoshan	40,000	Start in 2021 Q4	
Tongwei TBW	Baotou	40,000	Start in 2022	Conventional Siemens process
Tongwei Jinko	Leshan	45,000	Start in 2022	Conventional Siemens process
Daqo New Energy	Xinjiang	35,000	Start in 2021	Conventional Siemens process
Asia Silicon Industry	Xining	50,000	20,000 tons in early 2022	Conventional Siemens process
OCI	Malaysia	5000	Start in 2022	Conventional Siemens process
[illegible]	[illegible]	100,000	N/A	Conventional Siemens process
TBEA, JinkoSolar, JA Technology	Baotou	100,000	June 2023 at latest	Conventional Siemens process
Tongwei shares	Leshan	200,000	Start in December 2022	Conventional Siemens process
Xinjiang [illegible]	[illegible]	100,000	N/A	Conventional Siemens process

9.2.2 Silicon Single Crystal Growth

Silicon Crystal Growing Furnace is a specialized equipment used to prepare single crystal silicon. Following are the industrial scale crystal pulling techniques from polysilicon;

1. Czochralski (CZ) crystal puller.

2. Float zone (FZ) crystal puller.

Over 90% of today's single crystal silicon is produced by CZ pullers and the remaining by FZ. CZ puller needs container to hold the melt and contributes to impurity pickup, while in FZ molten zone is contactless & is held by surface tension in addition to RF inward pressure against gravity, turbulence and centrifugal forces. Typically, oxygen impurities in FZ pulled silicon crystal is 100-fold less as compared to the CZ pulled crystal, under same environmental and source material specifications. Due to better economics, ease of operation and moderate impurity acceptance, CZ pulled silicon crystals are preferred for low power electronic devices and in general semiconductor industry; whereas FZ pulled silicon crystals having resistivity greater than 10 kΩcm are used in high power devices.

In India, currently some industries are making ingots, wafers, modules, and solar panels using imported polysilicon. We are completely dependent on importing these components/cells from global market, especially China. A significant percentage of such imported cells are mono c-Si which are grown by CZ process. The costs of monocrystalline silicon solar cells and modules are in part reduced by improving yield and reducing the production time of the Czochralski (CZ) process. The temperature and pull rate will be carefully monitored and controlled throughout the growth process to maintain crystal quality and to avoid unwanted instabilities or defects. Additionally, the crystal can be either p-type or n-type, with different electronic properties, by adding dopant impurity atoms to the silicon, such as boron or phosphorous, respectively.

Mono-Si can be grown by different methods such as Czochralski(CZ), float-zone (FZ), Casting and Bridgman technique. Among them, CZ is widely used in the industry to produce mono-Si ingots. Using CZ method to produce mono-Si is advantageous because high growth rate can be achieved and relatively stress-free and defect-free single crystal silicon can be grown. Of the total cost of a mono-Si module, 53% is accounted for non-silicon module manufacturing cost, 17% is accounted for cell manufacturing costs, 19% is accounted for wafer manufacturing costs and 12% is accounted for poly-Si raw material. Wafer manufacturing technology, contributing to 17% of the cost of a mono-Si module involves various processes such as single crystal growth, edge trimming of the grown crystal, pseudo squaring of the cylindrical crystal, chamfering and polishing of edges and finally wafering.

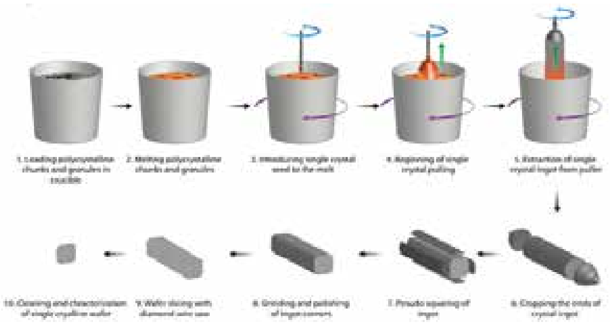


Figure Illustration of making mono-Si ingots and wafers using CZ process

9.3 Indian Scenario: Market Review

The Government of India had initiated the National Solar Mission in 2010 to promote solar power and had one of its objectives ‘domestic production of critical raw materials, components and products, as a result to achieve grid tariff parity by 2022. It is an established fact that polysilicon is the basic semiconductor material used in the manufacturing of the most popular type of solar photovoltaic (PV) cells as well as the semiconductor integrated circuit (IC) chips. With increased importance of renewable energy, the production of polysilicon globally has increased from hundreds to thousands of tonnes. It is found that with current technology, the polysilicon demand by the PV industry is equivalent to the consumption of 2.9–3.3 kt/GW. Therefore, requirement of polysilicon is huge for 100 GW target set by Indian Government under National Solar Mission. Recounting the PV history in India, in the late seventies the Central Electronics Ltd (CEL), Sahibabad was the pioneer in PV cell production based on single-crystal silicon with completely Indigenous technology. Another example is, in the mid-seventies Mettur Chemicals started polysilicon production leading to Si wafers at a commercial scale till the mid-eighties. Afterwards, considerable R&D was carried out at NCL, Pune and NPL, New Delhi, but these did not lead to technology transfer. Thus, all Si device production at SCL, BEL, BHEL and IITs depended on imported wafers.

With this historical background, the country as large as India with ambitions of becoming a global superpower need to leap into Semiconductor technology required for solar energy harvesting. PV energy conversion is also a potent weapon against global warming, since direct conversion of light into electricity is clean and pollution free. This is in line with the Government if India’s net zero program- a step towards achieving India’s long-term goal of reaching net-zero by 2070. India’s manufacturing capacity for solar photovoltaic (PV) modules will likely reach 110 gigawatts (GW) by 2026. India will also have a notable presence in all upstream components of PV manufacturing, such as cells, ingots/wafers and polysilicon.

According to the International Energy Agency (IEA), China has 97% of the global solar wafer manufacturing capacity holding 80–85% of the manufacturing capacity of polysilicon, the raw material for wafer manufacturing. Very few countries like U.S., Germany etc. have the polysilicon production capacity (15–20%) besides China which can translate to 60-80GW. Therefore, as an alternative to China, India must produce its own polysilicon for domestic wafer manufacturing. Indian manufacturers like Reliance, Tata and Adani, will likely be at the forefront of domestic polysilicon manufacturing.

Under the second tranche of PLI scheme, the Indian government has reserved Rs. 120 billion (US$1.45 billion) for companies setting up integrated manufacturing of polysilicon, wafers, cells and modules. Various companies like Shirdi Sai Electricals, Reliance, Adani, Waaree, ReNew, Vikram Solar, and Tata Power Solar etc are setting an integrated polysilicon-to-module manufacturing units in India under PLI scheme. Also, First Solar, U.S. based solar manufacturer is setting up a 3,400 MW integrated polysilicon-to-module factory in India.

However, a significant portion of the manufacturing capacity by these developers will be for self-consumption in their own solar projects. Over the next few years, the PLI scheme will directly lead to the setting up of 27.4 GW of integrated polysilicon-to-module manufacturing capacity in India. Below Table 2, compares the current status of polysilicon production capabilities of India and China.

Table 2: Polysilicon production capabilities of India and China

Parameter	India	China
Cost to develop (per GW)	US$130 million	US$ 60 million
Polysilicon nominal capacity (2023)	NIL	340 GW
Proposed polysilicon capacity (by 2026)	38 GW	637 GW

9.4 Major Gap Areas in Silicon

Adani Solar is the only player in India having integrated solar module manufacturing facility starting from wafer manufacturing to cell module. Presently, Adani solar have in house Ingot growth, wafer, cell and module manufacturing facility for 4 GWp at Mundra Gujarat and likely to reach 10 GWp via 2026. The source of polysilicon for solar cell fabrication is in the control of either China or some bigger players such as US or Germany. There are no in house production facilities not only for polysilicon but also for materials like Quartz crucible, EVA, back-sheet, glass, etc.

India's indigenous capabilities in various manufacturing process steps such as single crystal growth, edge trimming of the grown crystal, pseudo squaring of the cylindrical crystal, chamfering and polishing of edges and finally wafering, etc., are not robust and need major investment and trained manpower. Given India's ambitious economic growth targets and the consequent need for secure, sustainable and affordable electricity generation capabilities, it is imperative to develop mono-Si wafer manufacturing technologies in the country.

Along with Silicon, high-k dielectrics and compound semiconductors such as GaAs and GaN are also required for the electronics and optoelectronics industry. Currently, India does not produce the high purity SiC and GaN substrates. Although pilot plants have been set-up at a DRDO lab, many challenges need to be overcome to realize the commercial production of these wafers.

9.5 Recommendations

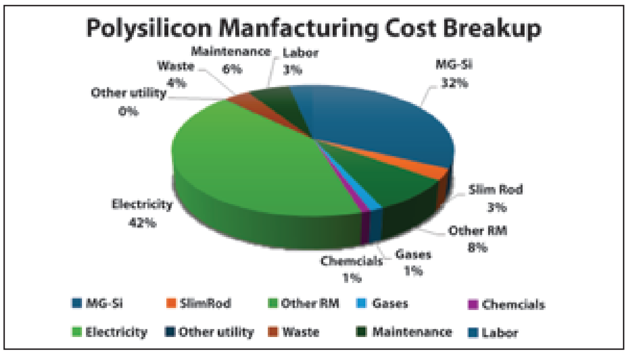
- In solar PV value chain >90% market is captured by China and controlling entire value chain
- Some capacity exist in India for solar cell and module manufacturing, however no progress in down stream products like ingot and polysilicon
- Significant progress is observed in solar PV cell and module products in terms of its quality and cost parity, however long way to go to match with manufacturing cost at par with imported sources (cost is also driven by volume)
- Government policies to enact incentive schemes are necessary to revamp this sector
- Even if existing PLI-1 and PLI-II schemes are attractive, dependency on import will continue in the area of MG Silicon and other key raw materials of reactor spares and quartz crucible for ingot growth etc.
- The R&D, and industries for the development of high-k dielectrics and compound semiconductor (GaAs, GaN, etc.) materials and high purity wafers should also be encouraged.
- Industry-academic partnership to be strengthened not only in the cell technology, but also up stream vertical of poly and metal Silicon

- Many in the business and industry are satisfied with the present situation and say it is not worthwhile making large investments in a matured technology. Some incentives are necessary initially, as is the case in Germany and elsewhere to encourage public–private partnerships.

9.6 Conclusion

The poly-Si market is entering into a new developmental phase. With some market proficiency being retained, the "green turn" of the energy industry announced by all the governments, the development of local markets and the price recovery to an investment attractive level have promoted the development of new poly-Si fab projects. However, the new projects should comply with the best practices elaborated during the low price period.

PV industries current polysilicon consumption on an average cell thickness (170um), efficiency (20%) and utilization rate (70%), would results in 2.82 kt per GW.



Chapter Contributors

On behalf of the CII National Mission for Technology, Innovation and Research, we would like to acknowledge and express gratitude to the following for their contributions in the Chapter on Semiconductors:

- Dr R Ratheesh, Director, C-MET Hyderabad
- Dr Manish Kumar Hooda, Head Technology Development Division at Semi-Conductor Laboratory
- Prof Satinder Kumar Sharma, Indian Institute of Technology (IIT)- Mandi MANDI (Himachal Pradesh)
- Dr Mayank Srivastava , Associate Professor ESE, IISC Bangalore
- Dr Suresh Kumar G, Assistant Professor, MSME, IIT Hyderabad
- Dr Sandeep Mahajan, Scientist, C-MET Hyderabad
- Dr Akshdeep Sharma, Scientist, C-MET Hyderabad
- Dr Nageswara Rao SVS, Professor, CASEST, University of Hyderabad

References

1. Naumov AV, Orehov DL (2021) The modern phase of the polysilicon market. Modern Electronic Materials 7(4): 115–126. https://doi.org/10.3897/j.moem.7.4.81721

2. Global PV market outlook, Growth, Hangovers and a game of Chicken, Bloomberg NEF Report, November 22,2023

CHAPTER-10:

ALUMINIUM

10.1 Material and its Background

Aluminium, a crucial engineering metal, excels in diverse applications like construction, transportation, packaging, and utensils due to its lightweight and superior strength-to-weight ratio compared to steel. Its recyclability, with approximately 75% of all aluminium ever produced still in use, stands as a remarkable achievement, pivotal in advancing towards a more circular economy

Production processes: Aluminum is extracted primarily from bauxite through the Bayer process to obtain alumina, which is then converted into aluminium through the Hall-Héroult process, the production process involves significant energy consumption, about 18-19 MWh/t, contributing to one-third of production costs. The molten aluminium is subsequently utilized in alloying, casting, forming, and heat treatment processes to create a wide array of alloys and products.

Products & Applications: Aluminum is a highly favoured engineering material for its versatility across sectors like transport, energy, packaging, architecture, and electrical transmission. It efficiently substitutes materials such as copper and steel, serving vital roles in electrical conductivity, building materials, packaging (notably cans), insulation, and lightweight solutions in transport and marine applications.

10.2 Strategic Importance of Material for India

Aluminium has become pivotal in India's engineering sector, driven by initiatives like "Atma Nirbhar Bharat," "Make in India," and "Digital India." With expanding automotive and infrastructure industries leading growth, India ranks as the world's second largest aluminium producer, benefitting from ample bauxite and coal reserves that have doubled its primary production capacity over the past decade, bolstering its export market.

Global Value Chain:

Global aluminium demand is projected to rise by nearly 40% by 2030, requiring an additional 33.3 million metric tons (Mt) of production, driven mainly by transportation, construction, packaging, and electrical sectors. Bauxite, primarily sourced from equatorial regions, is vital for commercial extraction due to its high aluminium content, with key producers including Australia, China, and Guinea supplying global markets.

10.3 Role of the stakeholders such as, Government, Academia, Industry and Research Institutes

India's competitive edge in alumina production costs is reinforced by its rich mineral resources, supported by economic policies from NITI Aayog and the Production Linked Incentive (PLI) Scheme. This is driving growth in infrastructure, automotive, aviation, defence, and power sectors, fueled by urbanization and socio-economic progress. Hindalco, Nalco, and Vedanta lead in primary production, with expansions and new smelting complexes boosting domestic self-reliance, while global markets benefit from diversification strategies like China plus one.

Research & Development : Primary aluminium production in India requires approximately 18-19 MWh per ton, with electricity costs contributing significantly to production expenses. This results in a high carbon footprint of around 19-20 tons of CO2 per ton of aluminium. To mitigate these impacts, the industry is focusing on reducing energy consumption and emissions through R&D, including innovations like inert anodes and wetted drained cathodes. Alternative smelting methods such as chloride and carbothermic processes are also being developed to improve energy efficiency and address environmental challenges like bauxite residue and solid waste management.

Talent Development: The aluminium industry, akin to other metal sectors, confronts difficulties in attracting and retaining skilled workers, exacerbated by slower industrial adaptation and misalignment between student projects and industry demands. Unlike the steel industry supported by the Steel Ministry's grants and academic partnerships, the aluminium sector lacks similar initiatives, underscoring the need for a consortium approach involving established institutes and research organizations to enhance workforce capabilities.

10.4 Sectoral Perspectives

Key process and applications areas discussed in details in this section covering opportunities, challenges, gap areas & recommendations.

A. Alloy Development & Casting:

Aluminium alloys excel in corrosion and fatigue resistance, ensuring prolonged service life and sustainable recyclability. Despite aerospace's adoption of composites, high-strength aluminium alloys remain essential. Advanced aviation alloys represent a promising technological frontier. Challenges persist in casting practices, including gas and shrinkage porosity in high-pressure die casting and hot-cracks in continuous casting, necessitating ongoing global efforts for precise component analysis and process optimization. Thermodynamic databases for multi-component alloys often rely on theoretical estimates, potentially leading to inaccuracies in partitioning and phase equilibrium. Aluminum alloys face challenges in adapting to additive manufacturing due to hot cracking susceptibility, while ongoing research targets improving corrosion resistance and exploring metal matrix composites and Al foams for enhanced mechanical properties.

B. Metal Joining:

Joining processes are crucial for optimizing performance, safety, and aesthetics in aluminum applications, especially alloys. With increasing global and Indian aluminum consumption, sectors like fabrication and automotive adopt specialized joining technologies. Arc welding methods such as MIG, TIG, and plasma welding dominate due to their effectiveness, while Industry 4.0's robotic welding cells enhance efficiency and reduce waste. However, aluminum welding remains complex due to thermal conductivity and oxide layer challenges, hindering adoption of advanced techniques like friction stir welding and laser welding.

Accelerating aluminum consumption, with per capita usage rising from 3.1 kg, highlights the critical role of joining processes. Opportunities in automotive and construction for aluminum substitution from steel and composites necessitate advanced adhesives and laser welding for light-weighting. Industry 4.0's shift demands skilled labor in robotic programming and aluminum welding, while challenges persist in multi-material joining's documentation and competency gaps in advanced techniques like friction stir welding and laser welding for aluminum alloys. IIW's certification programs need expansion into specialized Al-focused methods, complemented by sector-specific competency initiatives for non-ferrous alloys to enhance practical skill development and welding safety.

C. Aerospace:

ISRO's demand in India for Hot Rolled Plates includes those wider than 1600 mm (30% of total), thicker than 40 mm (6% of total), and Sheets (54% of total). The closure of ISRO's funded heat treatment infrastructure at BALCO, Korba, heightens India's reliance on imports for critical defense applications, affecting applications at HAL Bengaluru, Indian naval shipyards, BEML, BAPL, BDL, DRDL, RCI, and Raksha Udyog Ratnas.

Due to the absence of domestic infrastructure for heat treatable aluminium alloy flat rolled products, India imports most of these semi-products, except small quantities of annealed sheets. Opportunities exist in aerospace, including fighters, transport, cargo, civilian aircraft, helicopters, and jet trainers, as well as for naval vessels, armoured vehicles, military bridging systems, Advanced Medium Combat Aircraft (AMCA), Unmanned Aerial Vehicles (UAVs), and export commitments for BrahMos missiles to the Philippines. The defense sector requires flats up to 40 mm thick, with fighter aircraft often needing over 150 mm thickness. Naval applications prioritize wider sheets and plates over 2100 mm to minimize welds, with thicknesses under 40 mm. Meeting demands from shipyards, ISRO, HAL, and export needs calls for rolling mills up to 3000 mm wide and 180 mm thick, with heat treatment and stretching facilities. High-capacity 35,000-ton presses are also needed for fighter aircraft components and specialized melting and casting units for aluminum-lithium alloys for ISRO's satellite launches.

D. Defence Applications:

Aluminium alloys, which have historically been imported and are essential for various defence applications like ammunition, missiles, radars, aircraft, military vehicles, and ships, are now being produced domestically by DRDO under a decisive government policy to ensure self-reliance and enhance national security by reducing dependence on foreign imports. Partners in indigenous Al alloy development for defence include YIL, HINDALCO ALMEX, BALCO, and L&T Defence, with type approvals from CEMILAC, DNA, and CQ under DRDO's supervision.

Major challenges include lacking infrastructure for wide plates, large forgings, cold stretching, and heat treatment, uncertain demands for strategic alloys, and the need for a harmonious manufacturing ecosystem with industry-academia-R&D collaborations.

E. Railway Wagons:

India is developing extensive infrastructure for Vande Bharat trains and showing increased interest in using aluminium for freight wagons, though usage remains low compared to developed countries where aluminium use is significantly higher—30-70% in coal/fuel freight and 40-60% in carrier cars. High-speed trains use 100% aluminium bodies for speeds above 200 km/hr, curved path operation, and better aerodynamics. Additionally, 50-80% of wagons in suburban/metro trains in developed countries use aluminium to save on electricity costs due to lightweighting.

Aluminium wagons incur a 5-7% higher initial cost than steel wagons but offer lower operational costs due to reduced weight and a 75% higher reclaimable value. Opportunities include maximizing track utilization with faster, lighter wagons, enhancing safety, reducing maintenance, and mitigating steel-related import expenses. Recommendations include policy backing for lightweight train technology, mandatory aluminium tenders, expedited freight wagon design approvals, operator performance criteria, and financial and technological support for aluminium in rail infrastructure and manufacturing.

F. Solar Panels

At present, Solar Frames for all Solar Installations are imported considering significantly lower Import prices. The required policy support includes developing stringent industry standards for solar frames, favouring domestic suppliers in government projects, promoting rooftop solar, establishing smart inverter standards for grid interaction, and mandating minimum energy storage capacities with subsidies and tax benefits. Financing and business model support involve PLI benefits, concessional interest rates for MSMEs, tax holidays, creation of supply chain clusters, and incentives for strategic sector exports. Technology and manufacturing support include waiving import duties on machinery, accelerating depreciation, establishing R&D centers for automated line development, investing in skill enhancement through training centers, and collaborating for advanced alloy development suitable for solar frames with universities and startups.

G. Building & Construction

Globally, the construction sector consumes 25% of aluminium, while in India it accounts for 9%, indicating significant potential for growth driven by urbanization and government infrastructure initiatives like the National Infrastructure Pipeline and housing programs. Utilizing aluminium doors, windows, and facades can lower energy consumption in buildings, while aluminium formwork systems can halve project turnaround times and reduce costs. Lack of comprehensive standards for aluminium products leads to market flooding with low-quality, sub-standard items. Subsidized imports of ACPs from China exacerbate this issue.

Skilled manpower availability is crucial for proper fabrication and installation of certified products, as improper installation can significantly impact product performance. To address these gaps, it is recommended to establish Building Material Codes through NFRC India for fenestration and ACPs, enforce standardized performance criteria, mandate flame retardant properties and fire-rated ACP panels, implement energy ratings by BEE, enhance skill availability through specialized courses, and mandate formwork use and longer warranty periods in government building projects.

H. Foil Products and Packaging

In the past 8 years, India has installed 14 new foil mills with widths up to 2150 mm and rolling capabilities down to 5 μm, with 5 more mills currently being installed, bolstering production capacity to meet market demands. Major challenges include the need to achieve cost competitiveness with China and addressing regulatory complexities in recycling multilayer laminates. Opportunities arise from a growing foil market at 7% CAGR, driven by sectors like pharmaceuticals, liquor, food & beverage, FMCG, and boosted by bans on single-use plastics and plastics in online food delivery. However, gaps remain in reducing CO2 emissions per ton of production, increasing aluminium recycling, and fostering innovation in value-added foil products. To address these gaps, it is recommended to develop processes for delaminating multi-layer laminates and invest in innovative facilities for value-added foils such as carbon-coated, etched, perforated, and passivated foils to enhance performance and durability in various applications.

I. Metal Recycling

Between 2015 and 2023, India's secondary aluminium recycling industry expanded at a CAGR of 9-11%, driven by imported scrap due to inadequate domestic collection infrastructure. In fiscal 2020, 85-90% of aluminium scrap demand was fulfilled through imports, primarily in northern India, supported by automotive hubs such as the NCR, while southern and western regions also showed substantial demand. The recycling process involves scrap collection, sorting, trading, pre-processing, and melting into solid metal, with sorting techniques like magnetic separation utilized. Indian recyclers typically diversify their scrap sources across multiple countries to ensure reliability and adhere to ISRI guidelines for categorization.

The challenges in India's aluminium scrap recycling industry encompass inadequate technology adoption, heavy dependence on imports for raw materials, high costs, lack of automation, industry fragmentation, and downstream impurity risks. The sector's focus on landfilling rather than maximizing recycling efficiency highlights gaps in effective scrap collection systems. Opportunities include strong demand growth in auto and construction sectors, lower capital requirements compared to primary aluminium plants, and substantial environmental benefits. Achieving higher recycling rates akin to global standards requires comprehensive government support and customized financial and operational strategies. Recommendations to bridge the gap in India's aluminium recycling sector include implementing regulations on scrap imports to ensure quality control and prevent sub-standard dumping, establishing standards for aluminium recycling, and developing incentives for cost-effective scrap sorting technologies. Government support through tax holidays and cooperative schemes for informal scrap workers can formalize the sector, while encouraging investment in post-consumer scrap collection and subsidizing container deposit schemes can boost recycling rates.

Chapter Contributors

Detailed chapter with specific case studies will be published separately. On behalf of the CII National Mission for Technology, Innovation and Research, we would like to acknowledge and express gratitude to the following for their contributions in the short note on Aluminium and Its Alloys:

- **Dr Vilas Tathavadkar,** Chief Technology Officer (Aluminium Upstream & Copper) Hindalco Industries Ltd, Mumbai and Functional Head Metals & Mining, Aditya Birla Scie & Tech Centre (ABSTC), Mumbai, Lead - Aluminium chapter
- **Dr R K Rayudu,** Scientist G, Group Director (Materials) Aeronautical Development Agency, Vimanapura Post, Bangalore 560017
- **Dr Murty Susarla,** General Manager, Materials Development and Production Group · Liquid Propulsion Systems Centre (LPSC), ISRO
- **Dr Chandan Mondal,** Scientist F, DMRL, Hyderabad
- **Mr Shekhar Dravid,** Head-Business Transformation, Pooja castings Pvt Ltd, Chakan, Pune
- **Mr A Krishna Kumar,** Chief Technology & Engineering Officer (Aluminium Downstream), Hindalco Industries Ltd, Mumbai
- **Prof Shyam Prasad K,** Department of Mechanical Engineering, IIT Bombay

Notes

Confederation of Indian Industry

The Confederation of Indian Industry (CII) works to create and sustain an environment conducive to the development of India, partnering Industry, Government and civil society, through advisory and consultative processes.

CII is a non-government, not-for-profit, industry-led and industry-managed organization, with around 9,000 members from the private as well as public sectors, including SMEs and MNCs, and an indirect membership of over 300,000 enterprises from 286 national and regional sectoral industry bodies.

For more than 125 years, CII has been engaged in shaping India's development journey and works proactively on transforming Indian Industry's engagement in national development. CII charts change by working closely with Government on policy issues, interfacing with thought leaders, and enhancing efficiency, competitiveness and business opportunities for industry through a range of specialized services and strategic global linkages. It also provides a platform for consensus-building and networking on key issues.

Extending its agenda beyond business, CII assists industry to identify and execute corporate citizenship programmes. Partnerships with civil society organizations carry forward corporate initiatives for integrated and inclusive development across diverse domains including affirmative action, livelihoods, diversity management, skill development, empowerment of women, and sustainable development, to name a few.

As India strategizes for the next 25 years to India@100, Indian industry must scale the competitiveness ladder to drive growth. It must also internalize the tenets of sustainability and climate action and accelerate its globalisation journey for leadership in a changing world. The role played by Indian industry will be central to the country's progress and success as a nation. CII, with the Theme for 2023-24 as 'Towards a Competitive and Sustainable India@100: Growth, Livelihood, Globalisation, Building Trust' has prioritized 6 action themes that will catalyze the journey of the country towards the vision of India@100.

With 65 offices, including 10 Centres of Excellence, in India, and 8 overseas offices in Australia, Egypt, Germany, Indonesia, Singapore, UAE, UK, and USA, as well as institutional partnerships with 350 counterpart organizations in 133 countries, CII serves as a reference point for Indian industry and the international business community.

Confederation of Indian Industry
The Mantosh Sondhi Centre, 23, Institutional Area, Lodi Road, New Delhi - 110 003 (India)
T: 91 11 45771000 • E: info@cii.in • W: www.cii.in

Follow us on

cii.in/facebook | cii.in/twitter | cii.in/linkedin | cii.in/youtube

Reach us via CII Membership Helpline Number: 1800-103-1244