Azadi Ka Amrit Mahotsav

विज्ञान और प्रौद्योगिकी विभाग
DEPARTMENT OF SCIENCE AND TECHNOLOGY
सत्यमेव जयते

WHITE PAPER ON

EVolution

Catalysing Technology-Led Ecosystem for e-Mobility

CONTEXTS, CHALLENGES AND R&D IMPERATIVES

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डॉ० जितेन्द्र सिंह
राज्य मंत्री (स्वतंत्र प्रभार)
विज्ञान एवं प्रौद्योगिकी मंत्रालय;
राज्य मंत्री, प्रधान मंत्री कार्यालय;
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राज्य मंत्री अंतरिक्ष विभाग
भारत सरकार

सत्यमेव जयते

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Minister of State in the Department of Atomic Energy and
Minister of State in the Department of Space
Government of India

MESSAGE

Under India's Climate Action Plan, the country has an overarching goal to achieve Net-Zero emission target by 2070 and reduce total projected carbon emissions by one billion tonnes by 2030. In order to harness and guide this change, electrification of road transport is a necessity for decarbonizing the mobility sector. Electric vehicles(EVs) are promising alternatives for the road transport sector to replace conventional fossil fuel-based vehicles.

India, the 5th largest economy is driven by thriving mobility sector that is poised for growth with investments, government support, enabling policy and incentive schemes such as FAME, ACC PLI and Auto component PLI, innovations and technological advancements.

The world is looking at India to be next destination as global manufacturing hub for electric vehicle components, systems and charging solutions. To realise the vision of the government in promoting Atma Nirbhar Bharat, India needs to establish a strong manufacturing base for battery, motor and power electronics meeting the global standards. In order to meet industry requirements, there is a greater need to create a conducive environment for domestic industry ensuring supply chain and raw material security.

Research and Development (R&D) and technology innovation being pivotal for self-reliance and long-term sustainability, our scientific research community needs to work in tandem with government and industry to establish strong R&D ecosystem for EVs in the country.

I congratulate Department of Science &Technology (DST) for bringing out the **White Papers on Evolution: Catalysing Technology led ecosystem for Bharat e-Mobility**. This important document in reflective of humungous exercise carried out by DST through series of extensive consultations and indepth analysis by engaging large cross section of stakeholders from industry, startups, academia, R&D laboratories, government and others viz. DISCOMs, charging infrastructure providers.

I hope this document will be instrumental, not only in setting forth an outcome oriented industry-focused R&D program in the country but also in paving way for India's mobility sector to swifty shift gears towards e-mobility with speed, scale, safety and success.

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आज़ादी का अमृत महोत्सव

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Secretary
Government of India
Ministry of Science and Technology
Department of Science and Technology

16th February, 2024

MESSAGE

Electric vehicles are rapidly replacing conventional fossil fuel-powered automobiles in the Indian automotive sector. Significant and remarkable new developments are taking place in the areas of traction batteries, motors, power electronics and charging infrastructure. In India, many start-ups are sprouting in the battery manufacturing and charging infrastructure spaces.

In the recent interim budget 2024, the government has unveiled a strategy to strongly support and encourage more investments in the EV manufacturing and charging infrastructure domains. Although numerous laboratories and academic institutions have proven lab-scale technologies, the industries have not been able to scale these to produce goods that satisfy the market demands. There is an emergent and clear need to close this gap and boost the industry's capability and capacity through R&D, for long-term sustainability.

Considering this, the Department of Science and Technology (DST) initiated the formulation of the 'White Paper' with the goal to identify the technological gaps, outline viable fixes, and devise an industry-focused R&D roadmap to develop indigenous components/processes/technologies for the benefit of the industries. This exercise was carried out in collaboration with Centre for Science and Environment (CSE), World Resource Institute (WRI) India, Environmental Resource Foundation (ERF) Global and Technology Information Forecasting and Assessment Council (TIFAC).

The tropical EV battery, Motors and Power electronics, and EV charging infrastructure were the highlights of this 'White Paper', which was produced after a rigorous year-long consultation process involving more than 200 stakeholders. Its findings and recommendations will now be transformed into concrete, workable national R&D initiatives. With the establishment of the Anusandhan National Research Foundation (ANRF), DST can now also enlarge its focus on decarbonisation and sustainable energy, which would aid India in navigating its energy transition journey and achieving its Net Zero target by 2070.

I extend my congratulations to the whole DST team and acknowledge the tremendous efforts and sincere contributions of domain experts from academia, industry, and ecosystem partners in bringing out these much-needed changes in the e-mobility sector. I am optimistic that this document will serve as a valuable resource and an important reference for the R&D community, that will lead to further advancements in industry-oriented R&D efforts in the electric mobility in India.

(Abhay Karandikar)

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सत्यमेव जयते
डा. अनिता गुप्ता
Dr. Anita Gupta

सलाहकार एवं प्रमुख वैज्ञानिक 'जी'
जलवायु परिवर्तन एंव स्वच्छ ऊर्जा
विज्ञान और प्रौद्योगिकी विभाग
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MESSAGE

In the pursuit of decarbonizing India, Indian Mobilty sector is undergoing transformation and evolution with Electric Vehicles in focus as sustainable future- ready mobility solution. India is also aspiring to become a global manufacturing hub for electric vehicles. To achieve this ambitious goal and spur conducive environment for new innovations, Department of Science and Technology (DST) steered a pioneering exercise to bring out white paper on e-mobility to comprehensively analyse the existing capabilities, identify gaps and challenges and suggest actionable approaches to accelerate advancements in indigenous technologies , create robust R&D and manufacturing ecosystem.

The main white paper titled **EVolution: Catalysing Technology led Ecosystem for Bharat e-Mobility focusses on three major areas of interventions. From the nation's perspective, nurturing an enabling tropical** EV Battery ecosystem is a well identified need. To be self-reliant in battery manufacturing, the paper has stressed on setting up of pilot production facilities in the country for cell manufacturing. White Paper on Motors and Power Electronics focuses market driven indigenous product development by creating Centre of Excellence (CoEs) .The paper has also delved into the challenge of supply chain of critical materials such as lithium salts for cell manufacturing and rare earth oxides for traction motors. It emphasizes on developing standardized processing technologies for extraction, product development and circularity from end-of-life of these products. A few low-cost indigenous innovative technology solutions have been proposed to facilitate ease of doing business in the EV Charging Infrastructure domain.

Alongside product development, performance testing of innovative products is extremely crucial. Creating a strong network of testing facilities to provide services with reduced lead time , affordability and accessibility for faster market translation is a way forward.

DST greatly acknowledges the collective efforts of over 100+ industries , startups, OEMs, and domain experts engaged during year long consultative process. I am optimistic that these documents will help country to not only nurture the technological advancements but also foster an effective R&D ecosystem for electric mobility. Complimenting the evolving ecosystem, schemes such as FAME, ACC PLI and Auto Component PLI , Indian e-mobility industry and market is set to boom and secure a leadership position.

Finally, I extend my deeper appreciation to the Advisory Committee, led by Prof. B.G Fernandes, IIT Bombay and the noteworthy contributions by domain experts namely Prof. Raghunathan, Prof. S Mukhopadhay, Dr. ZV Lakaparampil, Mr. Sajid Mubashir, Prof. Vijay Mohanan Pillai, Mr. Suuhas Tendulkar, Ms. Veena Koodli, Mr. Kiran Deshmukh, who have extensively contributed in shaping up the white papers with quality content, in-depth analysis and actionable framework.

I greatly acknowledge the role of lead agencies such as CSE, WRI India, TIFAC and ERF Global in providing their valuable support and contributions in the documents preparation. Last but not the least, I acknowledge the efforts and overall contribution of my colleague, Mr. Suresh Babu, Scientist E, who engaged industry, experts and relevant stakeholders for critical thinking to amass deeper knowledge and collective wisdom resulting in the form of White Papers.

(Dr. Anita Gupta)

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ACKNOWLEDGEMENT

The White Paper on catalyzing technology-led ecosystem for eMobility, is a concise version of three white papers prepared by DST in the areas of EV battery, Motors & Power Electronics and EV Charging Infrastructure. The White Paper assesses the technology gap areas, identifies potential solutions & suggestes an R&D roadmap to develop indigenous products/systems for battery, motor & power electronics and EV Charging Infrastructure.

This white paper has benefited from extensive consultation with OEMs, component industry, startups, DISCOMs etc. Think Tanks such as Centre for Science & Environment, TIFAC, WRI India and Environmental Resource Foundation (ERF) have been actively involved in preparation of this document. The initial draft put together by this group went through detailed discussions in various brainstorming sessions during last one year. The final draft has been circulated twice to major auto industries and other stakeholders involved in entire EV ecosystem. The inputs/ suggestions received from stakeholders have been incorporated in the white paper.

I would like to express my sincere gratitude to **Prof. Abhay Karandikar**, Secretary, Department of Science and Technology for his kind support and overall guidance. Special thanks to **Dr. Akhilesh Gupta**, Senior Advisor, DST for his guidance during preparation of the white paper.

I would like to thank Dr. Anita Gupta, Head, Climate, Energy and Sustainable Technology (CEST) Division, DST for her concerted efforts and guidance in shaping the recommendations as well as program plans aligned with national priorities.

The white paper could not have seen the daylight without the sincere efforts and guidance of Prof. BG Fernandes, IIT Bombay, Chairman, Advisory Committee, in bringing the final shape to this white paper.

I would like to place on record initial efforts led by Mr. Sajid Mubashir, Former Scientist G, DST. Ms. Anumita Roy Chowdary and Ms. Moushumi Mohanty from Centre for Science and Environment; Dr. Raghunathan, IIT Madras; Mr. Arghya Sardar from TIFAC; Dr. Parveen Kumar from WRI India; Mr. Suuhas Tenddulkar, Environmental Resource Foundation (ERF) Global; Ms. Veena Koodli, Robert Bosch, have contributed immensely in bringing out this document.

Excellent support was received from NITI Aayog, Office of PSA, Department of Heavy industry (DHI), Central Electricity Authority (CEA), Bureau of Indian Standards (BIS). Special thanks to TERI (Mr. Sharif Qamar, Mr. Anurag Verma) for extending support to organize the release of the White Paper.

Last but not the least, I acknowledge contributions of more than 200 industries, startups and researchers, who have voluntarily spent enormous time during online weekly meetings and shared their knowledge to enrich the discussions.

We hope this report will play a crucial role in providing the right direction and impetus to the R&D activities and will bring together all stakeholders into synergistic collaborations to achieve the desired goals.

(Suresh Babu)

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01 INTRODUCTION

As one of the world's largest and fastest growing economies, India stands at a critical crossroad in its journey towards sustainable development while striking a balance between economic growth and environmental responsibility. Electric Vehicles (EVs) present a sustainable substitute to fossil fuels within the road transportation sector. Prime Minister Narendra Modi's five principles as commitment to mitigate climate change, often referred to as "Panchamrit," resonate deeply with the need of transitioning to cleaner modes of transportation. These principles—sustainability, adaptability, efficiency, inclusivity, and synergy—align well with the goals of the EV revolution. Amidst challenges, India aims for 30% EV market share by 2030, but only 6.3% of vehicles are electric in 2023, necessitating concerted efforts from stakeholders.

Road transport sector accounts for about 85% of passenger traffic and 60% of freight traffic movement in the country. A large variety of vehicles of various sizes and speeds - cars, motorcycles, scooters, auto-rickshaws, buses, trucks (dominant), rickshaws, and cycles share the road. Indian road transportation is completely dependent on petroleum-based fuel, which exposes India to the instability of global oil markets, as well as to severe air pollution and greenhouse gas emissions, posing serious threats to the health and well-being of its population and the environment. A sustainable, affordable and acceptable road transportation system is essential for driving national development, fulfilling global environmental commitments and empowering individual citizens. EVs offer a promising solution to India's energy and environmental challenges. These vehicles run on electricity instead of gasoline or diesel, which can be generated from renewable sources such as solar, wind, or hydro-power. They also have lower operating and maintenance costs, higher energy efficiency, and lower emissions than conventional vehicles.

1.1 INDIA'S ELECTRIC MOBILITY PROGRAM: EVOLUTION AND CONTEXT

In 2013 a scenario paper was published by the Ministry of Heavy Industries (MHI) suggesting the introduction of hybrid and electric vehicles (xEVs) to promote national fuel security. In the year 2015 the MHI launched the FAME India (Faster Adoption and Manufacturing of Electric Vehicles), as a pilot program which also kept a provision for 20% expenditure for technology development activities. The Department of Science and Technology was a major partner in the pilot Mission Programme, and a joint Technology Platform for electric mobility was planned with 20% provision in Mission Funds. After two years, the NITI Aayog took over the leadership of the programme in 2017 and carried out extensive brainstorming with all the stakeholders. An inter-ministerial programme was constituted with the participation of six ministries – heavy industry, road transport, power, renewable energy, urban development and science and technology.

The focus during 2019 to 2023 was on promoting domestic manufacturing through Phased Manufacturing Programs (PMP). A large number of EV startups such as Ather Energy, Ola Electric, Mahindra Electric, Tata EV, TVS Motors, Log9 Materials, etc., emerged, and most of the existing vehicle manufacturers started programs for developing EVs. The following Production Linked Incentive (PLI) Schemes were launched.

- Automobile and Auto Components PLI Scheme to attract investments and boost domestic manufacturing of Advanced Automotive Technology (AAT) products, with a strong emphasis on EVs.
- Advanced Cell Chemistry PLI Scheme for Battery Cell Manufacturing aimed to encourage domestic manufacturing, is focused on technologies like Lithium-ion Battery.

1.2 CHALLENGES AND THE R&D IMPERATIVES

However, with the above initiatives the success has been limited. To mitigate climate change the percentage of xEVs sold in India must increase much above the current level, which is about 6%. There are serious hindrances to achieving this and it is now urgent that interventions are made so that, by the year 2030, a robust domestic manufacturing industry will get established to provide components for electric and hybrid electric vehicles including hydrogen powered vehicles for India and for export.

The main areas of concern are the following:

- EV economics: xEVs have significantly higher acquisition cost compared to ICE vehicles, the battery costs being the main reason for this. Associated concerns arise due to life, warranty and second hand price of batteries, all of which contribute to adverse life cycle costs.
- Battery technology: Battery cost limits capacity; limited capacity causes range anxiety; fast battery degradation also

increases depreciation cost; cheap batteries cause fire safety concerns. The lack of data, standards and models for the battery poses challenges to the automakers for successful implementation in vehicles.

- Technology scale up and manufacturing capability need to be established.
- Charging infrastructure: Public charging stations are sparsely installed, hindering widespread adoption. Charging also takes a long time.
- Lack of key raw materials supply, second life usage and recyclability of batteries tend to make the EV adoption less sustainable.
- Limitations of innovation, design and manufacturing competency and resources hinder the adoption of advanced technologies at affordable costs.

The current programs to promote domestic manufacturing need to be metamorphosed to provide the breakthrough to overcome the hindrances. The Indian consumers will consider the alternative of purchasing xEV in numbers only if their expectations are met at a reasonable cost, and that depends on the adoption of affordable and efficient EV technologies specifically suitable for the climate and usage pattern in India. Many of the technologies and manufacturing equipment needed for several key components are outside the current capabilities of the indigenous industry, requiring persistent and pervasive imports in the EV sector.

In view of the above, the EV R&D program should focus on the following.

- Design and advanced manufacturing of EV components such as battery cells and packs, motors and chargers as per Indian conditions. In addition, it is also necessary to develop machines and processes for manufacturing, enhance quality, reliability and safety.
- Establish state-of-the-art facilities for rapid scale-up of promising technologies and provide tools for seamless adoption into EVs
- It is also needed to focus on technologies for raw material manufacturing, recycling and waste management as well as on second life usage and maintenance to ensure a sustainable and circular economy. The development of technologies that use alternate raw materials needs to be explored thoroughly.
- Development of charging infrastructure is critical for EVs and all related issues from chargers to grid supply, as well technologies to enable battery swapping.

In the following sections the above priority issues and recommended interventions to address those are presented. It is also important to mention here that there are some other areas for which strong R&D are needed:

- Develop vehicle - level technologies (like vehicle level control electronics and software such as ADAS, Connected EVs leveraging 5G wireless networks, Software Defined Vehicles, Battery and Energy Management, Digital Twins etc.). These can add significant ownership values for EVs by saving energy, extending component life, enhancing reliability, safety and drivability.

- Hybrid electric vehicles improve the energy economy of vehicles by operating the propulsion energy sources at improved operating points. If combined with fossil fuel-based propulsion, such as petrol or CNG engines, they are not completely free from emissions. However, they offer significantly improved fuel economy, reducing emissions. They also offer significant advantages in terms of cost, charging and range, the three most adverse factors for EV adoption. Recently, these are becoming popular in the Indian market.

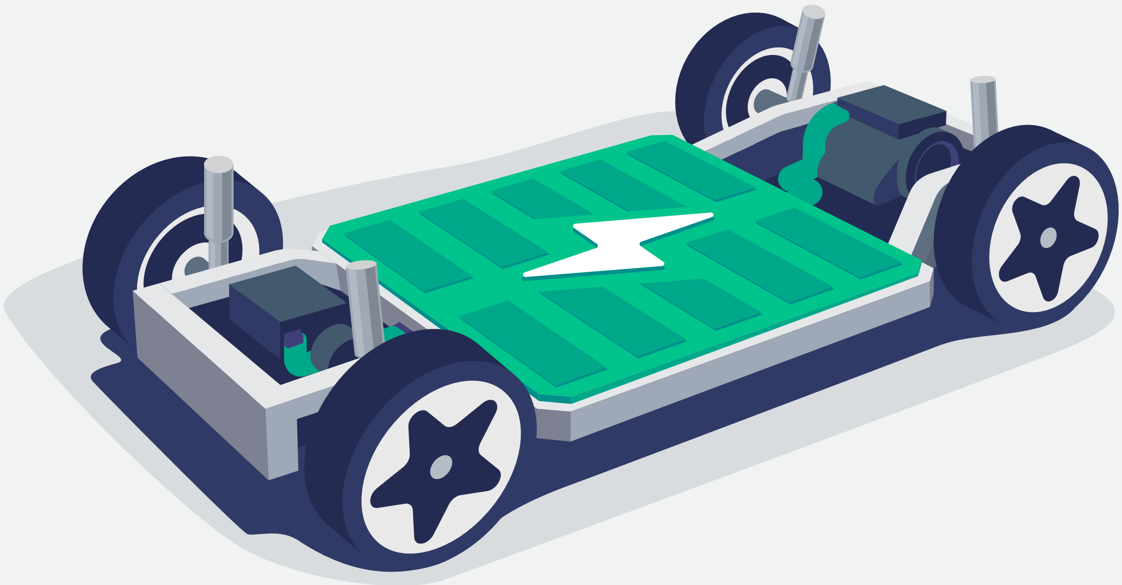
- Utilization of green energy sources (such as green hydrogen or ammonia) for transportation is an important consideration for climate change. These may be combined into pure battery EVs or HEVs. Recently, efforts have been launched by the Government to strengthen R&D and technology capabilities in hydrogen generation, storage, transportation, etc. These technologies need to be applied for high power applications such as for trucks, buses and marine transport.

- Develop self-reliance in manufacturing of EV related electronic components such as for power switches, sensors, embedded systems.

However, these are not in the scope of this report.

1.3 OUTLINE OF THE DOCUMENT

The Ministry of Science and Technology has carried out extensive consultations at various levels to create White Papers focusing on the three major subsystems of the EV to delineate the hindrances and propose specific recommendations for translational R&D. These are described briefly in the subsequent chapters. The three chapters are titled (1) Tropical EV Batteries (2) Power Electronics, Motors and Drives, and (3) Charging Infrastructure.



02
TROPICAL EV BATTERY

To drive eMobility in India, the Department of Science and Technology (DST) has taken the lead to identify major hindrances to electric vehicle (EV) adoption. As the first step, DST has prepared a series of three White Papers to identify the key technical barriers and to identify a roadmap and framework for technology development. These White Papers focus on (a) Tropical EV Battery (b) Power Electronics, Machines and Drives and (c) Charging Infrastructure. This chapter presents the first one, Tropical EV Battery.

2.1 TROPICAL EV BATTERY: STATUS AND CHALLENGES

Batteries are one of the most critical parts of an electric vehicle, and a battery (pack) is an assembly of a number of battery cells in cylindrical, prismatic or pouch format. Battery requirements for an EV include high energy density (relates to the vehicle range in km) and power density with a trade-off between the two. They must also have fast charge capability targeting 15 minutes to charge the battery from 20% to 80% capacity; and safety, especially with regard to fire incidents. In addition, durability is also a feature required, and is measured by the total distance and duration before the battery capacity drops to about 80-90% of its initial capacity, termed the end of useful life. All the above are to be achieved at the lowest vehicle and warranty cost.

There are additional considerations for EV adoption in India:

- The tropical conditions can adversely affect the life and safety of the battery

- The market is dominated by two- and three-wheeler applications with the drive profiles being different from those of larger vehicles. Battery technology selection, subsequent battery characterization and operation need to be tuned to Indian conditions.

- Our EVs rely entirely on imported battery cells since there is no cell manufacturing capability in India currently. Much of these are of inadequate quality and lead to high life-cycle costs and compromised safety.

- For new cell technologies developed at the research level, it requires significant time and cost to scale up to full-scale production. Even for mature technologies, systematic scale up testing is required before production. There is no established framework for efficiently scaling up a cell technology to commercial cell manufacturing.

- Lithium Ion Battery (LIB) is the typical choice for EVs. The critical cell components, such as the cathode active material (CAM), are not manufactured in India. India has very limited known reserves of raw materials, such as lithium and cobalt. Supply uncertainty and cost volatility are significant risks to the Indian EV industry.

- Battery Management System (BMS) and Battery Thermal Management System (BTMS) ensure reliability and safety for vehicles deployed. Both need to improve, addressing Indian conditions. Battery onboard diagnostic tools need to be developed for early warning against cell failure (sudden capacity loss) and safety incidents.

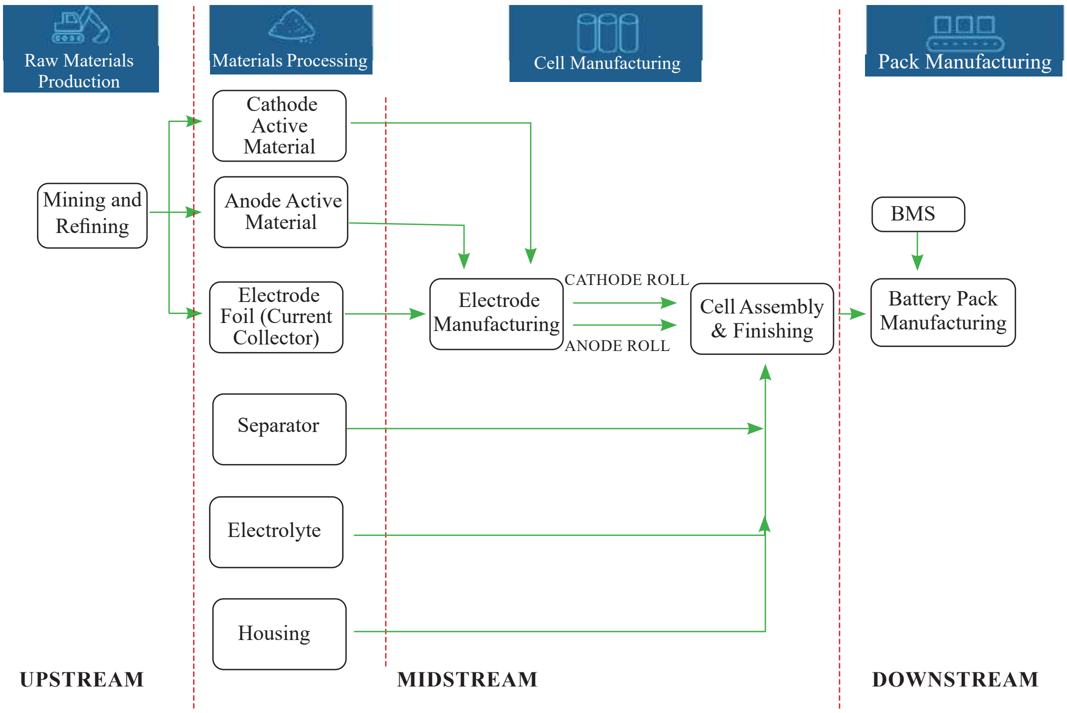
- When the EV market grows, managing the spent batteries will become a major concern. At the end of its useful life in an EV, the battery still will have significant remaining capacity and options for deploying them for other applications need to be evaluated. It is critical that India develops a strong recycling capability to recover costly and scarce metals as well as address battery disposal.

2.2 EV BATTERY TECHNOLOGY OPTIONS AND ASSESSMENT

The EV battery production value chain is shown in the Figure 2.1 and it spans a wide range of industries and processes, spread across the globe.

The cathode and anode active materials and the current collectors contain metals that are mined and processed upstream. The next level shown as midstream is the battery cell components including the active materials, current collector foils, separator, electrolyte, etc., coming from various suppliers, shipped to the cell manufacturing plant where the cells are produced. The cells are then shipped to downstream battery pack manufacturing plants to build battery modules and packs, which are sent to vehicle manufacturers who assemble the battery into vehicles.

FIGURE 2.1: BATTERY PRODUCTION VALUE CHAIN



2.2.1. CELL TECHNOLOGIES AND MATERIALS

In the near term, LIB technology will continue to be the most common choice in EVs because of its maturity and widespread use globally [1]. The prominent cathode materials in LIBs are Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP). Other options include Lithium Manganese Iron Phosphate (LMFP), Nickel Cobalt Aluminium (NCA), etc. LIB cells used in India are imported, with LFP or NMC chemistry. LFP has better thermal stability, which is ideal for the tropical climate of India. However, the lower energy density of the LFP, compared to NMC, would limit the vehicle range. LFP chemistry also has a supply side advantage. Apart from lithium, all component materials such as iron oxide, phosphate and graphite can be developed and sourced domestically. It has a price advantage as raw materials for NMC such as Nickel and Cobalt are expensive and experience significant price volatility. The anode material is predominantly graphite, although graphite-silicon blends are gaining acceptance. Table 2.1 provides a summary of existing battery technologies.

TABLE 2.1: EXISTING BATTERY CELL TECHNOLOGIES WITH EVs IN INDIA

Cell component	Chemistry	Strengths	Weaknesses
Cathode	NMC	High energy density (up to 300 Wh/kg)	High cost and unsustainable supply chains
	LFP	Environmentally safer and more sustainable	Low energy density (~160 Wh/kg)
Anode	Graphite	Low cost, abundant raw materials, high stability	Low energy density
	Si-blended graphite	Higher energy density than graphite	Lower cycle life, cell volume expansion
Electrolyte	Liquid ($LiPF_6$)	Widespread usage	Low thermal stability

The key raw materials in the LIB cells are the cathode active material (CAM) and anode active material (AAM). The lithium comes either from spodumene ore, or from salt flats (hard rock mining or brine pools) which is processed into lithium carbonate or hydroxide while nickel, manganese, cobalt and iron are processed into sulphates. They are combined (depending on the cell chemistry) to produce the CAM. The AAM production is separate, based on carbon. Other cell components include the electrolyte, copper and aluminium foils, electrode additives, etc. These raw materials are sourced from different suppliers and shipped to the cell manufacturing plant. Many of these component materials, such as CAM, are not manufactured in India.

From the long term perspective, other battery cell chemistries are being developed [2]. Sodium Ion Batteries (SIB) and Solid-State Batteries (SSB) are emerging as promising options, and Lithium-Sulphur and Lithium Metal chemistries are still in contention. SIB, where sodium replaces lithium, offers a potential cost benefit but suffers from lower energy density. SSB has superior thermal stability but lower cycle life and manufacturability hinder the development of commercial EVs. Metal-air batteries may be explored, especially for large vehicle applications. They are non-rechargeable but recyclable. Zinc-air and aluminium-air technologies do not rely on imported materials, which addresses the raw material scarcity and cost associated with LIB.

2.2.2. BATTERY CELL MANUFACTURING

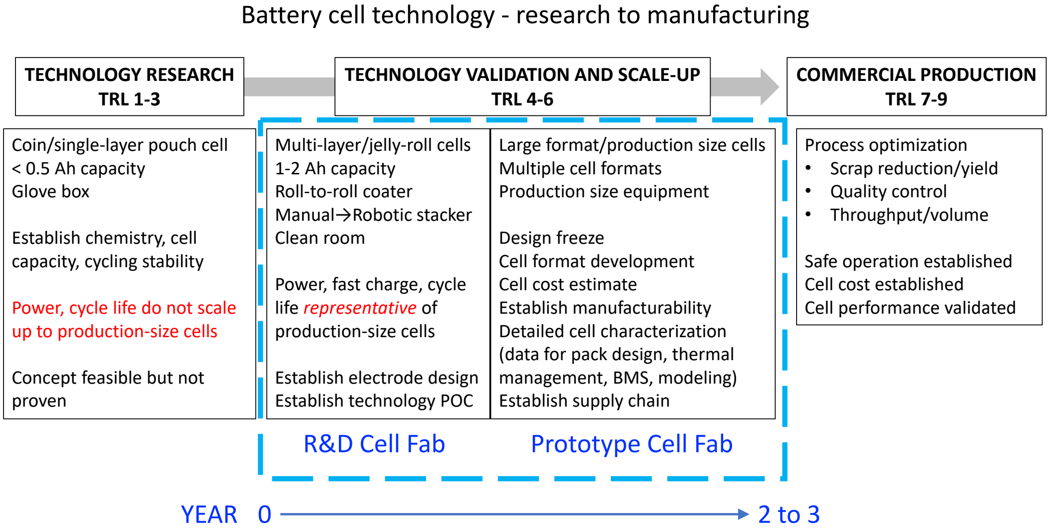
Currently in India, battery cells for EVs are imported. These imported cells are not necessarily tailored to suit Indian conditions, their cost is high, and the supply may be limited. Furthermore, since India is not attracting top cell manufacturers, the cell quality is compromised, leading to safety (fire) incidents and cell failure. The local cell manufacturing industry is very nascent. There is strong interest from the government in developing and expanding local manufacturing capacity. The INR 18,000 crore PLI subsidies for local battery manufacturing facilities have been successful in bringing players like Ola Electric (20 GWh), Reliance New Energy Solar (20 GWh), and Rajesh Exports (5 GWh). The projected capacity demand in India is 220 GWh by 2030 and 500 GWh by 2035.

The cell manufacturing involves slurry preparation for the cathode and the anode where the active material, binder, and the conductive aid are mixed into a slurry. In the coating and drying section, the slurry is coated as a thin layer onto a metal foil and dried, and subsequently calendared to achieve target thickness and porosity. The next is the cell assembly section, where the coated electrodes are cut into individual electrode sheets and stacked together along with the separator to form a "cell stack" for a pouch cell. Alternatively, the electrodes are wound into a "jelly roll" along with the separator for a cylindrical cell. The cell stack or jelly roll is encased in a pouch or a cylinder and then filled with an electrolyte, typically a mixture of lithium salt and organic solvents, and sealed. The cells then undergo a formation step where the cells are "conditioned" for stability and performance. The cells are shipped to battery plants for module/pack manufacturing and subsequent assembly into vehicles. A cell manufacturing plant requires clean rooms, process automation, and quality control systems. It requires specialized equipments that are not built in India and are in short supply from foreign vendors due to high global demand.

2.2.3. SCALE UP FROM RESEARCH TO MANUFACTURING

For the technology to evolve from a research stage to commercial production requires a Technology Readiness Level (TRL) roadmap. The definition of TRLs for cell manufacturing is shown in Annexure A. TRL 1-3 is concept development in a laboratory research scale; TRL 4-6 is scale up to prototype, demonstrating proof of concept, design validation, and manufacturability; and TRL 7-9 is full-scale commercial production. Figure 2.2 shows the steps necessary to take a concept from the research level to full-scale manufacturing. The scale-up step typically involves (a) R&D Cell Fab - fabrication and testing of small capacity multi-layer cells whose performance is representative of (but not the same as) production size cells and then (b) Prototype Cell Fab – where the cells are large format, production size cells whose testing can demonstrate techno-commercial viability of a candidate cell technology for full-scale cell manufacturing and subsequent implementation in EVs. This step takes time (2-3 years) and incurs significant cost. Such a scale up capability is a critical requirement in achieving the eMobility goals in India.

FIGURE 2.2: SCALE UP OF BATTERY CELL TECHNOLOGY TO COMMERCIAL PRODUCTION



2.2.4. IMPLEMENTATION OF BATTERIES IN EVS

2.2.4.1. Battery characterization, modelling, and diagnostics

Before assembly into the vehicles, the cells need to be tested and their performance characterized. Using the test data directly, or through building cell models using the data, optimum pack design can be achieved, and battery operating limits in a vehicle established. Models are also used to establish fast charging protocols which minimize charging time without adversely affecting the performance and life of the battery. Despite these efforts, it is still possible that a safety incident (fire) or battery failure (sudden loss of capacity) can occur. Cell diagnostics techniques using onboard vehicle data can provide early warning for such events. The testing and characterization should be performed under Indian road and climatic conditions. The above data and tools can significantly improve the capability of the Battery Management System (BMS).

2.2.4.2. Battery Management System

The BMS controls battery charge and discharge functions, manages optimum operating conditions, governs safety limits, runs the battery charge and health algorithms, monitors battery parameters, and communicates with other associated devices. An effective BMS can protect the battery from damage, ensure safety, predict battery life, and maintain the battery operation in order to keep the efficiency high. One of the issues with Indian two and three-wheeler OEMs is the use of off-the-shelf, non-customized BMS without any safety simulations that can lead to safety issues. A majority of system failures point to either the absence of a BMS, inaccurate BMS algorithms, or malfunctioning/ limited functionality in BMS control. While there are advantages of LFP chemistry as discussed above, the cell has a flat voltage profile, making it difficult to estimate cell state of charge from voltage measurements alone. There is a need to deploy fairly sophisticated tools and customization according to the cell chemistry and material proportions in the BMS.

2.2.4.3. Battery Thermal Management System (BTMS)

The BTMS is responsible for controlling the operating conditions of the battery in a high ambient temperature environment. It is also responsible for dissipating the heat generated within the battery. BTMS should prevent the battery from exceeding the temperature limits during normal operation and prevent thermal runaway. A combination of cell characterization measurements and modelling is needed to establish a robust BTMS. Multiphysics simulation techniques for the optimal thermal design and development of new materials for thermal management, optional placement of sensors, etc., need to be investigated.

2.2.4.4. Safety and durability

Safety and durability are major concerns for Indian conditions. As spate of fire incidents have plagued two wheelers largely, and some light duty cars. Thermal runaway typically initiates at a single cell (Cell 0) and proceeds through three stages: (1) internal short caused by dendrite formation, (2) separator melting, electrolyte decomposition and anode oxidation, and (3) cathode and electrolyte oxidation and steep temperature rise. The energy released from Cell 0 then propagates through the battery pack, setting the entire battery on fire.

Durability of the battery is measured by the retention of the battery capacity after prolonged vehicle usage and time. Higher temperatures and improper battery operation, often the case under Indian conditions, are some of the major causes of poor cycle life. The internal mechanisms responsible for cycle life decay are excessive growth of solid electrolyte interphase (SEI), loss of active material, electrode delamination and lithium plating. Along with battery capacity, power degradation also may be connected to durability of battery.

Poor quality cells, inadequate thermal management, and deficient BMS are major causes of safety and durability issues.

2.2.5. BATTERY CIRCULAR ECONOMY AND ADDRESSING RESOURCE SCARCITY

India has very limited known reserves of lithium, and there is not enough cobalt and nickel to hedge against uncertainties in the battery supply chain. It does not have the refining capacity to produce battery-grade materials to manufacture-them. Building a new mine and refining the ore into battery-grade materials typically takes five to ten years.

2.2.5.1. Minimizing or substituting materials

A shift to cell chemistries that require lower cobalt or nickel content may be considered/developed. Low-cobalt NMC technology studies exist and require closer attention. LFP is free from cobalt and nickel and is a promising cell chemistry option for India. The next generation technologies with SIBs and SSBs may eliminate the need for lithium.

2.2.5.2. Second life of EV batteries

Battery manufacturers usually consider the end of life (EOL) for an EV battery to be when the battery capacity drops to 80 or 90% of the rated capacity. However, these EOL batteries can still deliver usable energy, although they will produce shorter runtimes. The reusable batteries can be deployed in low-power vehicles such as e-rickshaws and e-carts, or in grid storage applications. This can also improve the second-hand prices of EVs.

2.2.5.3. Material recovery through recycling

Spent LIBs contain a significant amount of valuable metals. After refurbishment and second life-use, the battery can move into EOL management to extract valuable metals contained in it. More than 90% of EV battery materials can be recovered and used as feedstock in new batteries. Recycling of LIBs is complicated, and very few companies around the world have the required expertise. A focus on LIB recycling technology development provides India with a great opportunity to not only support domestic EV industry, but also evolve as a world leader.

2.3 RECOMMENDATIONS AND WAY FORWARD

There is a clear need to create a strong R&D ecosystem that enables indigenous manufacturing of battery cells and successful technology implementation and operation in vehicles tailored for Indian conditions. The following are the areas that need to be addressed:

2.3.1. BATTERY TECHNOLOGY SELECTION AND DEVELOPMENT

The focus can be divided into two categories based on the TRL:

1. Short-to-medium term (high TRL) where the goal is to enable quick vehicle electrification, especially in the low-cost and low-load two- and three-wheeler segments, with subsequent extension to four wheelers. The battery chemistry may involve NMC at varying nickel and cobalt contents, LFP, and its variant LMFP candidates on the cathode. Similarly, on the anode side, it may involve LTO, graphite, silicon-based anodes, and supercapacitors. The lab-scale studies can be completed in a short time frame since these technologies are well understood. The scale-up studies, as described above, are still required to provide data for manufacturing. Thus, indigenous battery cells of high quality and low cost can be achieved, and can be available to OEMs so that our EVs are on par with those in global markets.

2. Long-term (low TRL) technologies that are promising but not yet matured to large-scale production: The candidates are sodium-ion batteries (SIB) and solid-state batteries (SSB). Metal-air batteries, especially zinc-air and aluminium-air batteries, also need to be evaluated from an Indian context. Other promising

technologies may emerge, given the extensive studies and innovations in India and globally in cell technology development. Such development may be further refined to specifically cater to Indian conditions. Promising results from the lab scale may qualify the candidate technology for the scale-up phase.

Additional development work may also focus on indigenous manufacturing of cell raw materials such as cathode and anode active materials, current collectors, electrolyte, etc. Opportunities exist, for example, with CAM, for tailoring the material for superior thermal performance and stability. It will also be useful to explore the metallurgical processing of lithium to produce CAM precursors in the event we gain access to lithium from mines.

2.3.2. BATTERY CELL TECHNOLOGY SCALE UP TO MANUFACTURING

The promising technologies will need to be taken through scale-up studies (TRL 4-6) to determine their commercial viability, in two phases as shown in Figure 2.2.

- The first phase will require R&D cell fabrication centres where small multi-layer cells are fabricated. The process steps will be similar to those in a cell manufacturing plant with slurry mixing units, roll-to-roll coaters, and automated cell assembly, but at a smaller scale. Each centre will also include cell testing and characterization capabilities. Successful results would establish technology proof of concept and electrode design, ready for the next scale-up phase.

- The second scale-up phase will involve establishing Prototype Cell Fabrication Centre, which would mimic a commercial manufacturing process but at a lower throughput; it should have the capability to build production-size cells with multiple formats (cylindrical, prismatic, pouch) and include quality control measures. An extensive testing lab with multiple cyclers/thermal chambers, as well as analytical and safety labs, may be co-located. The purpose of such a centre is to demonstrate the techno-commercial viability of a candidate cell technology for full-scale cell manufacturing and subsequent implementation in EVs. The data and knowledge derived will enable cell manufacturers to rapidly translate cell technology into full-scale production. This is envisioned as a centre that is accessible to various R&D activities across India, with streamlined operation and administration.

2.3.3. CELL MANUFACTURING SUPPORT

Most of the manufacturing equipment is imported, and hence, there is a need to shift to domestic development. There should be a target-oriented dialogue between battery manufacturers, production researchers and the engineering industry for low-cost indigenization of critical equipment. Expertise can be drawn from the pharma and textile industry. Indigenous cell manufacturing should target frugal innovation to simplify processes, increase throughput and lower costs. Other focus areas may include the development of dry coating technology, advanced welding techniques, special integrated machines for punching and stacking, and the building of low-cost clean and dry rooms.

2.3.4. IMPLEMENTATION OF BATTERY TECHNOLOGY IN EVS

2.3.4.1. Cell modelling and diagnostics

For all candidate cells, the R&D and Prototype Fabrication Centres described above generate a wealth of test data that can be used to establish physics-based cell models and cell failure diagnosis. Physics-based and machine learning based battery models can render optimum battery performance and accurate prediction of battery life. Pack models incorporating thermal behaviour are needed for mitigating thermal runaway. Models can rapidly screen multiple pack design and battery operation scenarios, saving the OEMs significant time and cost. Cell diagnostics techniques can be developed for early warning against thermal runaway and battery capacity failure, which can enhance the safety and save OEMs high battery replacement costs. The diagnostics and models may also be deployed onboard by incorporating them into the battery BMS. There is a case for onboard cell diagnostics that can be done for swappable batteries. The diagnostics can be run before a new pack is inserted into the vehicle, providing information on the health of the battery and the likelihood of degradation.

2.3.4.2. Battery Management System

The BMS relies on the battery voltage data and Coulomb count and keeps track of battery's state of charge (SOC) and state of health (SOH). Cells with LFP exhibit a flat voltage profile, making it challenging to estimate SOC from voltage data. Along with a flat Open Circuit Voltage curve, LFP and Sodium batteries also show remarkable hysteresis properties that need to be accounted for. Advanced techniques incorporating Electrochemical Impedance Spectroscopy, Differential Capacity Analysis, Kalman filters, physics-based models and machine learning tools need to be developed and deployed under the BMS.

2.3.4.3. Battery Thermal Management System

Battery cooling strategies vary with application (two to four-wheelers), cell chemistry, and cell type. They include air cooling, indirect liquid cooling, direct liquid immersion cooling, tab cooling and phase change materials. The areas to be considered may include (a) engineering the battery pack for better heat dissipation during charging and discharging at various rates and (b) use temperature data from cell characterization for building models to aid with robust pack design and thermal management.

Techniques for monitoring battery ageing, including the effect of C-rate, depth of discharge and temperature need to be developed for onboard implementation. Similarly, techniques for early detection of faults and safety incidents also need to be incorporated.

2.3.4.4. Safety and durability

As mentioned above, test data and pack thermal models can be used to select technology options, such as pack potting materials or cooling systems, to mitigate thermal runaway. A safety lab will be part of the Prototype Cell Fabrication and Test Centre, with specialized equipment for studying thermal runaway. It will include an Accelerated Rate Calorimeter (ARC) which can characterize the battery cell as it undergoes thermal runaway, and a Differential Scanning Calorimeter (DSC) to characterize cell component materials. The ARC will be fitted with various sensors to measure voltage, temperature, pressure, smoke, gas, etc., during thermal runaway, to identify and provide early warnings. These studies can help select cell chemistries and electrolytes that reduce thermal runaway risks. The wealth of data available will also be used to identify cell degradation mechanisms and, hence, build physics-based cell degradation models. These models can be used to predict cell life and set warranty costs. Safety and durability prediction tools are critically needed by the OEMs to meet important customer needs.

2.3.5. BATTERY REUSE AND RECYCLING

When the EV volumes increase, managing the spent batteries will become a major concern. It is critical that India develops a strong recycling capability to recover costly and scarce metals as well as address battery disposal. Recycling is a challenging process, and recycling-friendly battery design would need innovation. One of the biggest challenges to be addressed with the circular economy of EV batteries is the collection of the batteries. Battery reuse options need to be explored. End-of-life EV battery still has 80-90% of its original capacity, and options for deploying them for other applications need to be evaluated. It is essential to determine the residual value of the battery using accurate State of Health (SOH) prediction tools.

2.4. R&D STRATEGY AND PROGRAM ECOSYSTEM

2.4.1. STRATEGIES FOR INNOVATION

A mechanism has to be created to accelerate the connection between academic research and industry in order to fast-track development, adoption and deployment of new technologies in the market. The proposal is to set up a multi-stakeholder ecosystem of Innovation Clusters to incubate, demonstrate and leapfrog technology interventions. This can be achieved with comprehensive target-oriented dialogue between battery manufacturers, production researchers and the machine engineering industry for low-cost indigenization of critical equipment.

In India, the current emphasis is on two and three-wheelers, light-duty vehicles and heavy-duty buses, for each of which the R&D focus has to be specifically established. At a later stage, heavy-duty trucks may be given special attention and evaluation for implementation.

India has to develop strategies to gain access to both intellectual property, manufacturing capability, and process know-how. So far, the public-private partnership model has been limited to fiscal policies and investment sharing (as in the PLI scheme). This requires much stronger investments in technology development guided by recognised methods for investing in industrial R&D.

A consortium model of engagement to further the research initiatives towards the manufacturing phase may be envisaged. The model requires a program administration suited for industrial research activity with a very focused approach to tendering support to this fledgling industry. The roadmap of activities will include technology development, validation, field trials, and small volume production of key materials and subsystems, with an emphasis on developing the ability to manufacture suitable EV Components in India. Stakeholder consultations conducted for the White paper revealed a need for a two-pronged roadmap for India that should run concurrently.

2.4.2. SHORT-TERM THRUST AREAS (5 YEARS)

Prioritize technology that have passed TRL 3 with credible likelihood of implementation within the next five years and provide scale-up results that enable rapid progression towards commercial production. Examples include cell chemistries with LFP, LFMP, and NMC on the cathode side and graphite and silicon-graphite blends on the anode. The list of projects which may be taken up for the short term includes:

- Design, develop and validate relatively mature battery cell technology/ products for meeting tropical climate conditions.
- Manufacturing of electrode materials, including current collector foils for battery cells and super-capacitors
- New electrolyte systems to enhance the life and safety of the battery systems
- Battery diagnostics and modelling for early warning against thermal runaway and rapid (unexpected) capacity loss; prediction of battery performance and cycle life
- Battery Management System support using physics-based models and machine learning tools, and made available as open source
- Set up energy storage systems for cell/module & pack at the Prototyping Centre: Nickel Manganese Cobalt (NMC), Lithium Iron Phosphate (LFP) and Lithium Manganese Iron Phosphate (LMFP); graphite and graphite-silicon blends; Lithium Titanate Oxide (LTO), Hybrid Super-capacitors
- Develop low-cost manufacturing equipment (Special Purpose Machines):
    - ◊ Solvent free technology for coating of Li-Active material on substrate foils
    - ◊ Special integrated machines for punching and stacking of electrodes using Z-type folding

2.4.3. LONG-TERM THRUST AREAS (5-10 YEARS)

Focus on technologies that are still at TRL 3 or below with a clear advantage for the Indian EV industry. Examples include SIB and SSB, along with Metal-Ion cell technology. List of projects to be considered:

- Design, develop and validate relatively new battery cell technology/products, including cell chemistries such as Sodium Ion and Solid State, for meeting tropical climate conditions.
- Develop metal-air batteries, evaluating their application segments
- Manufacturing of cell raw materials, especially cathode active materials
- Develop Lithium-Ion batteries with reduced cobalt content
- High voltage cathodes
- High capacity anodes
- Non-flammable electrolytes include aqueous, ceramic solid electrolytes, polymer electrolytes, ionic liquids, and heavily fluorinated systems.
- Develop battery recycling technology
- Metallurgical processing of lithium ores

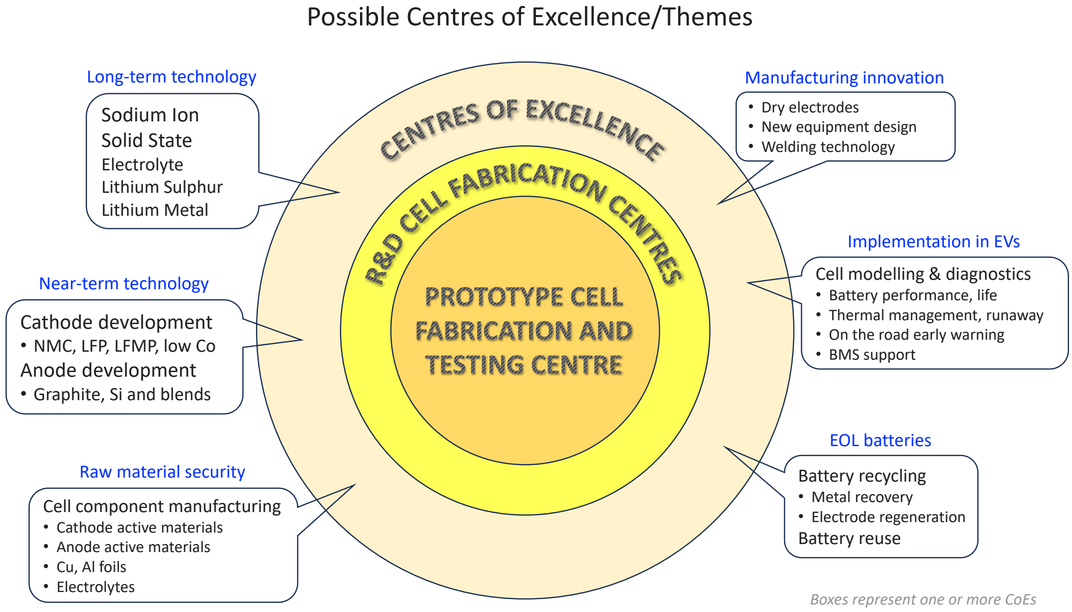
2.4.4. Creation of Centres of Excellence (CoEs)

Considering the nature of projects that may emerge, which are interdisciplinary in nature, there is a need to develop consortium approach wherein expertise from different fields may be pooled in to address the identified scientific problem. Therefore, it is proposed that the CoEs may be created in the identified thematic areas (described above) wherein each theme may become a consortium with a lead, and other participating agencies with defined objectives/goals and deliverables. The participating agencies will have demonstrated expertise in the area and may consist of academic institutions, research labs, startups, and commercial manufacturers.

R&D Cell Fabrication Centres will support the various CoEs, and the Prototype Fabrication and Testing Centre will provide the support for the entire program. It may also serve as the central facility for Battery Standards and Certification. The facility scope may be further extended to provide testing services for startups across the country, even if they are not part of the program.

Figure 2.3 depicts the possible CoEs under this program and the supporting fabrication and testing centres. This framework allows participating agencies, particularly startups, access to the fabrication and testing centres, eliminating the need for them to build their own facilities.

FIGURE 2.3: FRAMEWORK OF DEVELOPMENT CENTRES OF EXCELLENCE AND CELL FABRICATION & TESTING



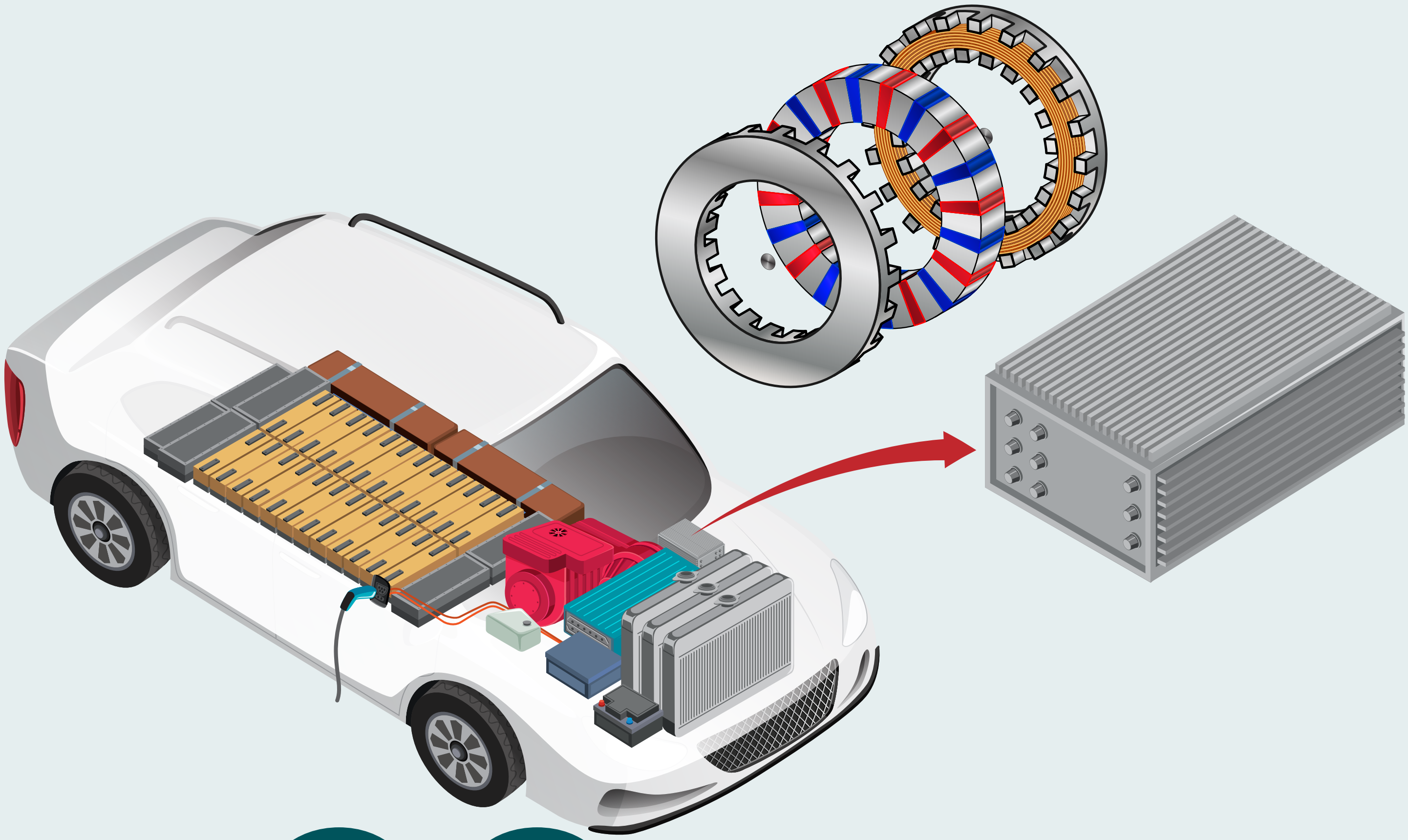
The program may cover technology development, validation, field trials, and small volume production of key materials and subsystems, with an emphasis on developing the ability to manufacture suitable EV Components in India. Measurable results expected from the program include:

a. Skill development: A large pool of expert technical personnel will be developed in the country in the new and advanced technologies

b. Development of components and systems: A wide variety of new EV components/ subsystems/ systems and platform technologies are expected to be developed under the CoEs. They will be utilized by the participating companies in the program, or licensed to third parties.

c. Incubation of component companies: Several industries capable of producing material and machinery to support the electric vehicle component industry is expected to evolve.

In summary, this chapter describes the entire ecosystem for battery technology needed for electric mobility in India. It identifies major challenges and provides a roadmap and a framework to address the challenges and enable indigenous commercial cell production and subsequent implementation into EVs.



03

POWER ELECTRONICS, MACHINES AND DRIVES (PEMD)

Power Electronics, Machines and Drives (PEMD) is a major constituent technology of the EV propulsion system. They have a key role to play in overcoming many of the hindrances [3],[4] mentioned in Chapter 1.

There are various commercially existing, as well as emerging motor technologies for use in EV traction. To meet the demand for compact, highly efficient motors with high torque and power density, permanent magnet brushless DC (BLDC) and Permanent Magnet Synchronous Motors (PMSM) are widely used at present in vehicles and remain the preferred choice, at least in the recent past. Development of low-cost non-rare earth motor technologies is important for long-term sustainability, and options such as Switched Reluctance Motor (SRM), Synchronous Reluctance Motor (SynRM) and Permanent Magnet assisted Synchronous Reluctance Motor (PMaSynRM) have emerged as serious contenders to PMSM. Alternative magnets that either do not use critical raw materials, or use a reduced amount of them, is another approach towards addressing the issue associated with imports of Rare Earth (RE) magnets for the motors [5].

EV motors are very sophisticated in terms of manufacturing due to their high power density, low air gap, high speed and harsher vibration. There is a serious gap between the demand for such motors and local sources of supply. Special emphasis should, therefore, be placed be on the development of competency in the various parts of the electric motor supply chain, including the equipment, magnet manufacturing, and packaging and integration. Capability for precision manufacturing functions such as machining, joining, assembly, etc., plays a vital role in developing high speed and efficient electric motors. Additive manufacturing and 3D printing can potentially help in the development of lightweight electric motors and their integration with the drive units. [6],[7]

In India, there is a lack of commercial-scale technology for producing RE metals from Rare Earth Ores (REOs). Currently, Indian players who manufacture small-size magnets for finished goods source it from abroad and do value addition using powder metallurgy processes to manufacture the RE magnets. Although IREL (India) Limited is already operating a Samarium-Cobalt (SmCo) magnet plant in Vizag and an RE metal plant in Bhopal, the development of a supply chain with established downstream activities is yet to take place.

EV power electronics is evolving to a stage wherein further scope of innovation in conventional silicon-based power semiconductor devices is saturated, and use of Wide Bang Gap (WBG) semiconductors is expected to gain more importance [8]. The development of various topologies for inverters and DC-DC converters with higher power density, high-temperature operation and high switching frequency has been a major focus of power electronics for electric vehicles in recent times. India needs to develop competency in the fabrication of power semiconductor devices. India is importing key components like the power modules and controls. The ability to design and manufacture them will be a significant boost to the industry's competitiveness. Currently, India has no manufacturing or packaging of semiconductors, although some of the major global players have established their R&D/Design Centers in India. A close linkage with relevant Government initiatives such as the India Semiconductor Mission is needed in these areas.

Development of competency in the integration of the components into an effective EV drive is also important. Integrated and efficient cooling systems for batteries, power electronic switches and motors are critical for Indian conditions. Integrated e-axles comprising the electronics, motor, sensors, cooling, transmission, etc., lead to efficient designs in terms of cost, weight and energy. However, realizing these require advanced competencies in design and development. It is for these reasons that such components are often obtained at very high costs from international tier-1 suppliers.

Catalyzing technology development and adoption in the field of PEMD is envisaged to be achieved through an industry-led R&D ecosystem comprising a few Innovation Clusters or Centres of Excellence. Three functional Centres of Excellence (CoE) are proposed: 1) CoE for Electric Vehicle Motors 2) CoE for Power Electronic Converters, and 3) CoE for the Integration of Electric Vehicle Systems. A consortium shall be initiated with the participation of agencies like ARAI, National Laboratories, manufacturing industries, etc. They shall work along with the CoE for Electric Vehicle Motors and CoE for Power Electronic Converters, to develop packaging technology to meet road vehicle applications.

3.1 ROLE OF POWER ELECTRONICS, MACHINES AND DRIVES IN OVERCOMING HINDRANCES

A few of the major hindrances to the widespread use of electric vehicles in the country are general inadequacies of innovation, design, development, testing competencies and resources [9],[10]. Power Electronics, Machines and Drives (PEMD) technologies have a key role to play in overcoming most of these hindrances. There are several ways in which the Power Electronics, Machines and Drives can address the major hindrances of electric mobility [11]. These are listed in Table 3.1.

TABLE 3.1: ROLE OF PEMD

Hindrances to Electric Mobility	Role of Power Electronics, Machines and Drives
High initial cost of vehicles	• There is a reliance on imports for motors, power electronics systems, components, devices, high-quality electrical steel, magnets, and related technologies. There's a need to indigenize these technologies • Reduction in sensor usage (e.g., in motor control) • Adaption of technology that utilizes a reduced quantity of power conversion units. • Better designs lead to higher efficiency, reduced size/ ratings, reduction in the number of components, and better material utilization. • Reduced RE material usage or RE material-free design
Limited range	• Enable appropriate regenerative braking. • Enhance the overall efficiency of the drivetrain. • Refined control methodology tailored to suit particular drive cycles with better efficiency. • Enable faster charging. [12] • Reduce weight using compact components with higher power density.
Safety	• Intelligent control of the charging of battery pack. • Better thermal management system[13],[14]. • Condition monitoring and detection of any failure in the traction motor, e.g., stator, rotor, and bearing faults. • Use of Intelligent Gate Driver to protect IGBT / MOSFETs. • Introduce fault prognosis systems for motors, power converters, batteries, charging systems, etc
Limited power/ speed/ acceleration	• Enhance the power density of the motor and other components that handle the flow of power. • Fast motion control with a combination of power electronics and Digital Signal Processing to achieve better performance.

Hindrances to Electric Mobility	Role of Power Electronics, Machines and Drives
High charging time	• Develop High Voltage System to accelerate charging time • Faster charging • Standardisation/ interoperability of charging systems • Promote HV, DC fast charging. • Reliable, fast, and efficient charging technology for domestic charging.
Environment for development and testing	• Different motor configurations and the power circuit topology can be developed to meet the functional requirements of vehicle types. • A simulation environment with a Software in Loop (SiL) feature supports the sizing of components to meet the load cycle demanded by the vehicle. The built-in embedded controller usually needs a good amount of tuning to meet the functional requirements demanded by road vehicles • Digital controller firmware with Hardware in Loop (HiL) feature is needed to fine-tune the firmware.

3.2 TRACTION MOTORS

There are various commercially available and emerging motor technologies for use in electric vehicle traction. The most reliable and well-used industrially, the induction motors have also been used for EV drives [15],[16]. However, to meet the demand for compact, high-speed motors with high torque and power density, BLDC and PMSMs are widely used. Further, the development of low-cost, non-rare earth motor technologies are important for long-term sustainability, and to avoid supply-chain bottlenecks. Options such as SRMs, SynRMs, and PMaSynRMs have emerged as serious contenders to PMSM. Axial flux motors have a large diameter-to-length (D/L) ratio, which makes them ideal for applications requiring such space profiles. They prove to be an excellent option for direct-drive in-wheel motors, particularly in the context of two-wheelers. Outer-rotor/hub motors are considered for direct-drive applications. Each of the motor topologies discussed above are associated with some challenges that need to be addressed. Table 3.2 outlines some of the challenges and potential solutions.

TABLE 3.2: ISSUES IN MOTOR TOPOLOGIES THAT REQUIRE R&D FOCUS

Challenges	Potential Solution
Induction Motor	
Low efficiency – rotor, mechanical, and stray losses	• Enhance conductivity - use of copper cage rotor [17] • Structural design to enhance efficiency • Better thermal design
Low power density	• Integrated motor-inverter. • Use of high saturation-flux-density, low specific core loss material with thin (<= 0.2 mm) lamination with good structural stability (such materials include Cobalt Iron laminations like Hiperco 50, Vacodur 49, etc.) • Hairpin winding based distributed winding to achieve high slot fill factor [18] • Oil-cooled stator with oil channels inside the stator core
Faults occurring at the bearings and insulation materials	• Study the physical and chemical properties responsible for the failure • Use higher grade enamel, varnish/potting material in the stator. • Use high-grade, high-temperature grease in the bearing. • Use higher-class sealing in the bearing. • Use shaft grounding ring to reduce electrical erosion in the bearing. • Provide proper creepage and clearance distances in design to handle high voltages.

Challenges	Potential Solution
Permanent Magnet Synchronous Motor (PMSM)	
Demagnetization at higher temperatures, causing reduction in torque and efficiency [19]	• Demagnetization fault detection method • Demagnetization prevention algorithm. • Rotor thermal management and cooling [20]. • Temperature-based de-rating strategy. • Rotor cooling with hollow shaft design. • Use of higher temperature grade magnets.
Geographical concentration of RE magnet supply chain Price pressure of rare earth elements Missing midstream (commercial-scale) and downstream capabilities of RE magnet supply chain in India	• Development of alternate magnets. [21] • Development of alternative motor topologies and improve their performance to match that of PMSM. • Use of magnets with high remnant flux density, high temperature withstanding capability but low coercitivity (such as AlNiCo, Fe16N2, etc.) without demagnetization.
High cost	• Develop manufacturing competency locally • Develop equipment required to manufacture • Reduction in material usage. • Additive manufacturing for windings and other motor components for better material usage.
Switched Reluctance Motor	
High torque ripple, high noise and vibrations. Control is challenging due to non-linear characteristics caused by magnetic saturation.	• Structural design, use of advanced material • Novel topologies regarding number of stator/ rotor poles, pole shape, etc. • Advanced control methods: current and angle modulation, torque sharing function (TSF) control, optimized power topologies.

Challenges	Potential Solution
Low torque density	• Use of high saturation flux density material. • Additively manufactured winding and core. • Optimization of the shape of stator/ rotor poles. • Use of liquid cooling through hollow windings. • Development of carbon nanotube technology to replace copper in the winding. • Use of flooded stator cooling technology for better thermal management and high current density.
Audible noise	• Novel stator/ rotor topology. • Independent control of pole currents. • Randomizing turn-on/ off angle.
Synchronous Reluctance Motor (PM assisted)	
Lower specific (peak) power	• Increasing rotor operating speed and flux weakening region, maintaining the mechanical integrity of the rotor. • Optimized rotor design. • Integration of high flux density, non-rare-earth PM. (such as AlNiCo, Fe16N2, etc.)
Axial Flux Motors	
Magnetic pull in single air-gap machines Axial laminations are of different shapes and dimensions	• Symmetric double air-gap machines • Concentric spiral laminations

Apart from the motor technology specific challenges, issues related to the manufacturing ecosystem of traction motors need to be addressed, including supply chain competency in input materials such as electrical steel, high precision manufacturing and associated equipment.

3.3 REE MAGNET SUPPLY CHAIN

3.3.1 MAGNETIC MATERIALS

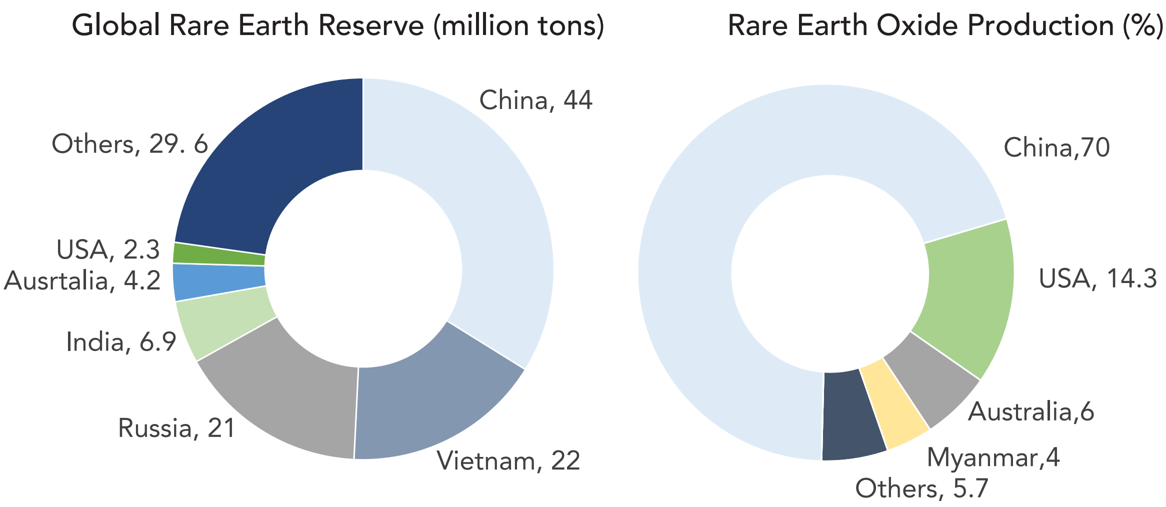
Using permanent magnets made of Rare Earth Elements (REE) leads to motors with high torque to weight ratios and high efficiency. Among general permanent magnets such as ferrite, alnico, samarium-cobalt (Sm-Co), and neodymium-iron-boron (Nd-Fe-B), ferrite- and Nd-Fe-B-based magnets account for over 90% of the global production. Although the RE used in NdFeB (e.g. Neodymium (Nd), praseodymium (Pr), Dysprosium (Dy), and terbium (Tb)) constitute only 25% of the total RE production volume, they account for 80% to 90% of the total RE market value. In 2020, the total global demand for NdFeB magnet was dominated by application in Industrial motors (~36%), Consumer electronics (~35%), offshore wind turbines (~17%), Electric vehicles (~7%) and others, which is expected to dominated by application in offshore wind turbines (~36%), Electric Vehicles (~30%), Industrial motors (~14%), consumer electronics (~11%) and others by 2030 [22],[23],[24],[25].

Strategies to address the supply-chain uncertainty of rare-earth permanent magnets should be the following.

- Utilize more abundant materials such as Cerium to replace rarer elements such as Dysprosium (Dy) or Terbium (Tb). Grain Refining or Grain Boundary Engineering may play an important role in the development of such technologies.

- Reduce RE content: Another approach is using alternative materials and reducing the grain size of the magnets to a nanoscale level to achieve a similar maximum energy product.

FIGURE 3.1: GLOBAL RARE EARTH RESERVE AND REO PRODUCTION IN 2022 [SOURCE: (A) USGS-RARE EARTH 2023 (B) N HENSEL, 2023]



- Development of RE free magnets with high remnant flux density, high permissible operating temperature, and high coercivity.

3.3.2 RESOURCE ASSESSMENT

Global rare earth reserve and REO production in 2022 is shown in figure 3.1. In India, Monazite is the primary source of rare earth minerals, and the Atomic Minerals Directorate for Exploration and Research (AMD) has estimated the presence of 13.07 million tonnes (as of September 2022) of in-situ Monazite (containing ~55-60% total REO) in the coastal beach in parts of Kerala, Tamil Nadu, Odisha, Andhra Pradesh, Maharashtra and Gujarat and in the inland places in parts of Jharkhand, West Bengal and Tamil Nadu. Although IREL (India) Ltd has an installed capacity to process about 10,000 MT of rare earth-bearing minerals, the production of Monazite is around 4000 MT per annum, and it is capped due to reasons such as CRZ regulations, Mangroves, Forest and inhabitation, etc. [25]. In addition, this rare earth found in monazite sand occurs together with radioactive elements such as thorium, which are radioactive materials and are classified as strategic subjects [26]. Moreover, the lack of downstream manufacturing activity related to permanent magnets and their applications has also been one of the reasons behind the under-utilization of existing Indian resources [27],[28].

3.3.3 TECHNOLOGIES

India has capabilities in the upstream segment and some midstream capabilities with industries like IREL (India) Ltd, the Toyotsu subsidiary of the Japanese company Toyota engaged in the separation and purification of rare earth elements. IREL (India) Ltd extracts rare earth in the form of RE Chloride as RE concentrate, which is further processed to produce and refined as individual high pure RE oxides. In India, there is a lack of commercial-scale technology for producing RE metals from REOs. The next step is RE magnets manufacturing from purified extracted rare earth metal [29]. Currently, Indian players who manufacture small-size magnets for finished goods either buy RE magnet blocks from abroad and machine them into the required size and form or may import the metal powder and use powder metallurgy processes to manufacture the RE magnets [30]. Although IREL (India) Limited is already operating a SmCo magnet plant in Vizag and an RE metal plant in Bhopal, the development of a supply chain with established downstream activities is yet to take place.

3.3.4 SUPPLY CHAIN

Out of 200 minerals that contain REEs, monazite, bastnasite, and xenotime are the main sources of REEs, and these minerals account for ~95% of all the world`s rare earth resources [31],[32]. The high demand for Nd, Pr, Dy & Tb for permanent magnets, required for EVs and Renewable Energy (RE) sector along with their demand in various civilian and defence applications, accounts for ~91% of the total value of the global REE metal market. The price of rare earth oxides varies greatly, from less than 2 USD to nearly 2000 USD per kg. The variation in prices is mainly influenced by the unequal distribution of individual rare earths in ores, the imbalance in supply and demand, and geopolitical risk [33],[34],[35].

3.4 POWER ELECTRONICS

Power and voltage levels, efficiency, reliability, size/weight and cost are considered the major figures of merit for EV Power electronics. Improvements in these figures for inverters and DC-DC converters require operations at higher power density, higher temperature and higher switching frequency, and constitute the major focus areas of power electronics for electric vehicles in recent times. The ability to design and manufacture key components like power modules and controls, which are currently being imported, will be a significant boost to the industry's competitiveness. Therefore, efficient and cost-effective design as well as packaging, are important competencies to be developed. EV power electronics is evolving to a stage where the use of Wide Bang Gap (WBG) semiconductors is expected to grow, especially in high-power applications such as commercial and public transport vehicles. Therefore, ensuring affordable supply of WBG semiconductors is an essential step for the modern power electronics ecosystem. India needs to develop competency in the fabrication of power semiconductor devices. Some of the challenges, specifically in EV power electronics, are mentioned below.

3.4.1 CHALLENGES AND SOLUTIONS FOR TRACTION INVERTERS

The challenges and possible solutions pertaining to traction inverters are listed in Table 3.3.

TABLE 3.3: TRACTION INVERTER - CHALLENGES AND POSSIBLE SOLUTIONS

Challenges	Possible solutions
Inverter design and integration	
Improving inverter efficiency, performance and power density	1. Adaptive control techniques to maximize efficiency with minimal distortion in inverter output resulting in filter size reduction. 2. Functionally integrated drives for higher power densities with reduced weight and better system efficiencies. Integrate inverter with motor to minimise the cable drop and increase the performance 3. Enhanced thermal management for inverters to reduce stress during peak acceleration / regeneration events. Options such as immersion cooling or advanced liquid cooling plates to be employed. 4. Design with smart gate driver to minimise the part count and improve the reliability of power switches even at high speed and power operation. 5. New concepts such as converter in package, die embedded in PCBs or dies with integrated sensing gate drives and copper sintering of power switches.

Challenges	Possible solutions
Enabling economies of scale	1. Modular converter architectures that can be deployed in different vehicle platforms for increased economies of scale. 2. Standardized wide-band-gap power modules across different power range. 3. Reconfigurable converters – Inverter, DC-DC, on-board charger (OBC) combinations. 4. Additive Layer Manufacturing for converters / power modules to maximise performance (i.e., better heat sinks, optimized packaging).
Improving LV systems for e-mobility	1. Continued improvement of Si device designs: IGBT, MOSFETs and Power Integrated Circuits (ICs). 2. Low cost GaN based converter designs.
Inverter control	
Advanced software and control techniques	1. Software and control for converters with advanced topologies. 2. In-service condition monitoring, health management and load-adaptive control algorithms will enhance converter performance.
Control hardware	Controller software shall be developed on a hardware independent platform, such as software on VHDL platform to program firmware on FPGA
Semiconductor	
Limitations of existing Si technology	The low cost and embedded performance gains can still be achieved through smaller chip sizes, thinner wafers and innovative Si IGBT/MOSFET designs (e.g. faster switching; reverse-blocking; and reverse-conducting IGBTs.)

Challenges	Possible solutions
Ramp-up wide-band-gap device developments	1. The crystal-growing techniques, producing larger SiC and GaN wafers with fewer defects will reduce costs, enabling innovative device designs and broader adoption. 2. Improved reliability models for WBG devices 3. Complete more reliability tests and identify the safe operating region and various failure modes in WBG semiconductors. 4. Identifying commonality in Si and wide-band-gap device manufacturing and adjusting processes to create reduced cost manufacturing capability for wide-band-gap devices.
Components	
Gate drivers	1. Smart gate drivers to enable more control of the switching behaviour, improved reliability with protection and monitoring, and minimization of the switching losses, surge voltage, and EMI emissions. 2. Integration of the driver IC with the power module is a preferred solution to limit the stray inductance.
Passive, Sensors, and PCBs	1. Passives, Sensors and PCBs with new materials and manufacturing routes need to be developed to deliver high operating temperatures and lower losses at higher voltages. 2. Proper selection of dielectric and magnetic materials helps to shrink capacitors and inductors respectively to work at higher frequencies.
Packaging	1. Converter in-package concept (single- and multi-chip modules) by integrating gate drivers, control software, sensing and passives that can operate at higher currents and temperature, greatly enhance the power densities through miniaturization of power electronics. 2. Optimized Si, SiC power module packaging materials and assembly processes for higher temperature capability (e.g. sintered packaging).

Challenges	Possible solutions
Life Cycle	
Possibilities in life cycle reduction	1. Improve extraction and refining processes for reduced environmental impact and higher use of renewable energy. Optimize life cycle assessment (LCA) impact. 2. Improvements in life extension and end of life (EOL) technologies for the re-use of materials. 3. Holistic, through-life, predictive design tools for enhanced sustainability. 4. Develop recycling processes to recover high-value materials from power electronics devices in a cost-effective, clean, safe and energy efficient manner.
Other Challenges	
Improving modelling and simulation techniques using advanced data	1. Multi-domain virtual prototyping environment for converters (electrical, thermal, mechanical, reliability). 2. Develop a better understanding of duty cycles for urban mobility.
Enriching testing and validation capabilities	1. Testing procedures for semiconductor device reliability and performance targeted at automotive power applications (especially for SiC and GaN). 2. Improved accelerated test methods and non-destructive evaluation/validation for PE components and packaging.

3.4.2 CHALLENGES AND SOLUTIONS FOR DC-DC CONVERTER

Challenges for the DC-DC converter are shortage of semiconductors, maintaining high performance with compact size and minimum cost, and achieving higher switching frequency. Details are listed in Table 3.4.

TABLE 3.4: DC-DC CONVERTERS: CHALLENGES AND SOLUTIONS

Challenges	**Potential Solutions**
Requirement of two separate power converters for high voltage battery pack and low voltage auxiliary power module, resulting in high volume and weight	Integrating the On-Board Charger and Auxiliary Power Module. The other way is the multi-port converter (TPC), which has fewer components than the existing two individual power converters.

Challenges	Potential Solutions
At higher switching frequency, a small parasitic inductance will result in high voltage spikes. High di/dt can impress negative source voltage transient, which in turn increases the risk of shoot through. High dv/dt may result in high capacitive current transients. The transformer/inductor inter-winding capacitance, gate driver insolation capacitance, coupling capacitance between heat sink and PCB can increase common mode noise. The higher common mode current may lead to false turn-on of the device.	The gate driver and power board layout loop shall be optimized to minimize the inductance as much as possible. This may be obtained through Finite element and Multi-physics simulation analysis. Adoption of novel design methodology for transformer with reduced inter and intra-winding capacitance, less coupling capacitance between the heat sink and PCB, high transient immune gate driver power supply, and gate driver IC shall be adopted.
Magnetic components contribute significantly to the volume and losses of the DC-DC converters.	Novel design techniques, new magnetic core materials and planar transformers with less losses and high flux density shall be built to increase the magnetic component efficiency and with further reduction in volume and cost. Novel integrated magnetic technology that utilizes inter winding parasitic capacitance for DC-DC converter to reduce the converter volume. The PCB inductor shall be built by making the spiral winding on multilayer PCB which covers magnetic material.
Unwanted high frequency parasitic resistance, capacitance, and inductance	Optimization of the winding arrangement and structure

3.4.3 CHALLENGES AND SOLUTIONS FOR POWER SEMICONDUCTOR DEVICES

The R&D associated with the manufacturing and application of WBG semiconductors in electric mobility are listed in Table 3.5.

TABLE 3.5: RD ISSUES FOR WBG SEMICONDUCTORS

Issues	R&D Need
Design	New process for GaN bulk crystal growth with higher speed and quality
Manufacturing	Investment in new manufacturing equipment
Stress and high defect densities in GaN devices due to epitaxial growth on the non-native surface	Alternative epitaxial approaches
Module and packaging	Improving high voltage insulation, thermal management, partial discharge, and EMI to enable high-performance modules high-performance discrete packages that can operate at higher temperatures and voltages. New layouts, gate drive and construction techniques to handle EMI/ EMC issues
Surge voltage	To adopt soft-switching techniques. Soft-switching technique requires additional soft-switching circuits including resonant inductors, resonant capacitors, and active switches
Reliability	Understanding the materials defects that can occur during the manufacturing process. Gaining a better understanding of degradation/failure mechanisms under harsh conditions
Simulation tools	Ability to simulate complex operating modes and fault conditions

3.5 STRATEGIES AND RECOMMENDATIONS

3.5.1 THE FRAMEWORK FOR INTERVENTION

Catalyzing technology development and adoption in the field of PEMD is envisaged to be achieved through an industry-led R&D ecosystem comprising a few innovation clusters or Centers of Excellence.

It is important to ensure that adequate R&D takes place at all levels of TRL maturation. This is well known to be a deficient area of advanced technology research in India. Proper framework of technology evaluation and maturation in participation of the industry is critical for generating IP and indigenous products worthy of a global market.

It also needs to be emphasized that effective R&D dissemination and providing R&D support must be an important activity of the R&D centres. MSMEs and startups must benefit from the R&D and also get their own innovation support in terms of design, prototyping, and testing & validation.

Global technology benchmarking exercises must form an integral part of technology development. There would have to be clear well-thought, and globally established metrics for assessment of the R&D centres themselves, and they have to be continuously assessed by expert global peers in terms of these metrics. Accountability and productivity of R&D are critical to be ensured, especially in view of the much higher level of investments that are called for.

3.5.1.1 National Programme on Power Electronics, Machines, and Drives for EV

The structure and the activities of the proposed National Programme are summarized as follows:

FIGURE 3.2: BROAD STRUCTURE OF THE PROPOSED NATIONAL PROGRAMME ON PEMD

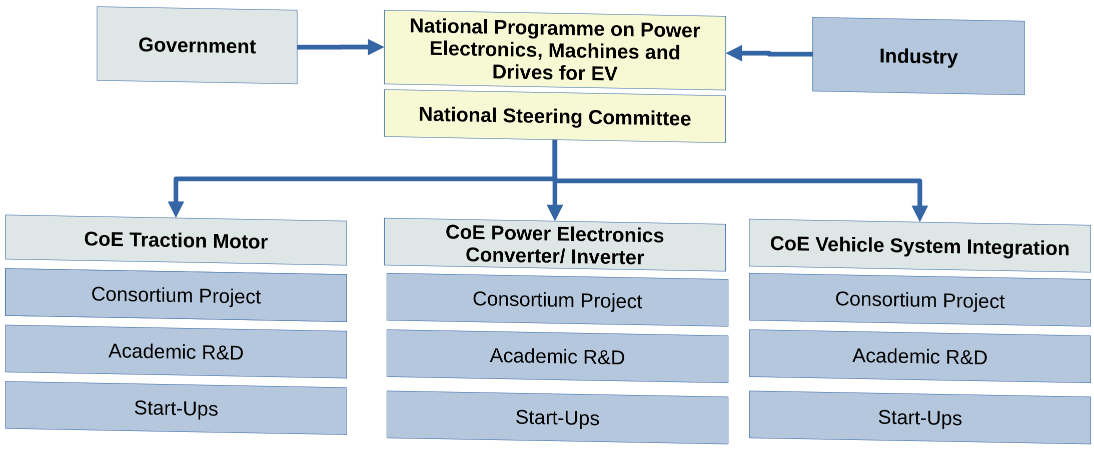
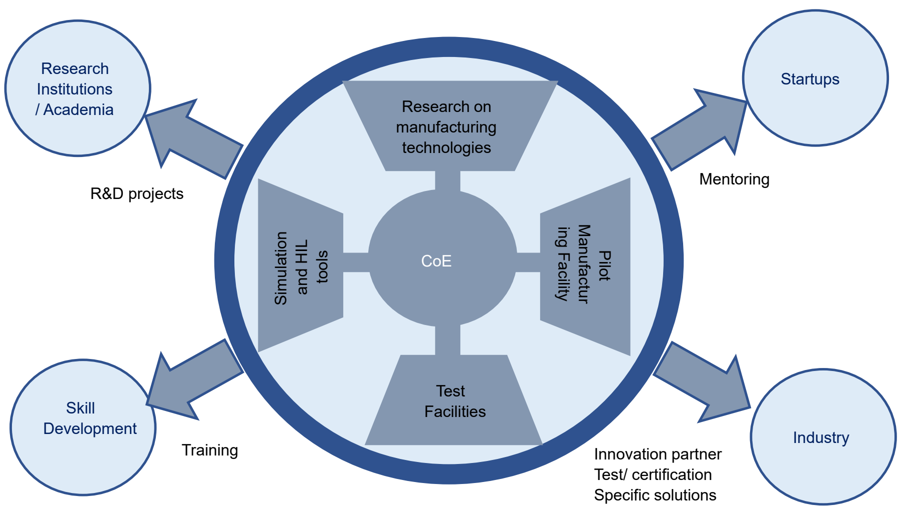


FIGURE 3.3: FACILITIES AND ACTIVITIES OF THE CENTRES OF EXCELLENCE



- Technology dissemination programmes
- Promotion of Startups and MSMEs
- Collaborative R&D Programmes
- Enabling Ecosystem

3.5.2 BROAD PRIORITY AREAS

Based on the extensive stakeholder consultations during the preparation of this report, hindrances to electric mobility in the context of power electronics, machines, and drives and the possible technological approaches towards addressing these issues have been discussed in detail. Based on these, the broad priority areas for the CoEs/ Innovation Clusters on Power Electronics, Machines, and Drives will be as listed in the following section.

3.5.2.1 CoE on Traction Motors

Short-Term Priorities:

- Establishment of a motor manufacturing pilot facility/ motor technology test-bed where various types of motors and their components can be manufactured and tested. Facilities both for prototyping and limited series production need to be built.

- Development of indigenous technologies for motor subcomponents and materials such as winding, lamination, electrical steel etc. [36],[37],[38]

- Enhance efficiency, quality and reliability of EV motor: Establish technologies for the development of rotor (e.g. copper rotors for IM), stator (development of winding machines for better winding factor), high quality stampings, high speed rotor, Integration with inverter and thermal management.

- Establish manufacturing, assembly, maintenance and retrofitting practices.

- Condition monitoring, incipient stage fault detection and diagnostics of EV Motors.

- Switched Reluctance Motor: Improve torque density, better design, control and materials for reducing vibration.

- PM assisted Synchronous Reluctance Motors: Improvement in specific power and specific torque. Design for mechanical integrity at high speed.

- Additive manufacturing technology for complex customised frames.

- Hairpin winding, with copper moulding, bending and welding facility: Improvement in the power density of the machine from the stator side can be accomplished with the help of solid conductors. It improves slot fill factor, electric loading, and heat transfer between the slot and stator core, making it an attractive choice for traction motors. The facility for hairpin winding should be established to reduce the dependency on RE PMs to improve power density [39].

Long-Term Priorities:

- New materials such as insulators, thermal fluids, coatings, etc., which can contribute towards higher efficiency, lower cost, and higher power and torque density.
- Manufacture of motors with improved power density, torque density and efficiency.
- Development of alternative PM with characteristics suitable for EV motors.
- Development of emerging motor topologies such as Transverse Flux Machines
- Carbon Nano Tube (CNT) Conductors: The power density of the machine is limited because of the current carrying capability of the copper. It can be increased significantly with the help of CNT.

3.5.2.2 CoE on Power Electronics Converters/ Inverters

Short-Term Priorities:

- SiC/ GaN based inverters. Ability to withstand high temperature and operate with low loss.
- Develop inverter topologies suitable for multiphase motors.
- Motor controllers based on VHDL based software that can be ported to any standard FPGA.
- Functionally integrated drives for higher power density and reduced weight. Development of a modular converter architecture that can be deployed in different vehicle platforms.
- Improved inverter control: in-service condition monitoring, health management and load-adaptive control algorithms. Alternative sensing/ sensor less methods.
- Standardized wide band-gap power modules across different power ranges.
- Reconfigurable converters – Inverter, DC-DC converter, onboard charger combinations.

Long-Term Priorities:

- 3-D printed drives with power electronics embedded on the stator or rotor of the motor.
- Advanced manufacturing techniques for converters/ power modules to maximize the performance (i.e., better heat sinks, optimized packaging, etc.)
- Advanced thermal management systems and materials.
- Integration of the inverter subcomponents - Component packaging, gate driver design, system integration, and manufacturing techniques.
- High frequency inverters for Dynamic Wireless Power Transfer (DWPT) Systems.
- Development of material- and device-level technologies for wide band gap and ultra-wide bandgap semiconductors.

3.5.2.3 CoE for the Integration of Electric Vehicle Systems.

Priorities:

Setting up an appropriate platform/ mechanism for the collection of data related to electric vehicle use, charging etc. Data collection and analysis of region-wise real-life drive cycles for various categories of EVs

- Research on optimization of the parameters for energy management systems of xEVs.
- Establishment of a simulation environment with a Software in Loop (SiL) feature to support the sizing of components meeting the road cycle demanded by the vehicle.
- Simulation tools to analyse thermal management requirements, materials level characteristics, etc.
- Facilities for realistic Hardware-in-Loop (HiL) simulation to test the performance of powertrain subsystems such as drives in a realistic traffic context.

04 CHARGING INFRASTRUCTURE

4.1 INTRODUCTION

The charging infrastructure for Electric Vehicles (EVs) in India needs to adequately meet the requirement of low-power charging for Light Electric Vehicles (LEVs), which comprise more than 90% of the total vehicle population in India. At the same time, the charging infrastructure must also comply with the requirements for supporting high-power fast charging to cater to medium and heavy vehicles such as e-buses and e-trucks. In addition to these distinct challenges, another expectation is to satisfy the globally acceptable technical and service standards of product development and delivery.

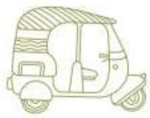
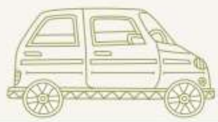
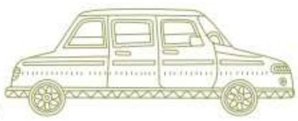
As India's EV market is targeted to reach a 30% market share by 2030, the consequent impact of EV charging on the local and regional transmission networks calls for a deeper investigation into the system reinforcements to ensure stability, reliability, and quality of power supply.

4.2 LOW-POWER CHARGING INFRASTRUCTURE

The battery capacity for the 2W and 3W LEVs typically may not exceed 15 kWh in the short- to medium-term due to space and pricing constraints. Most of the current LEV ecosystem has deployed batteries with voltages in the 48 V to 72 V range. Considering the C/2 charging rate for an off-board charging system employing a 48 V battery, the maximum power requirement is expected to be limited to 6 kW. Similarly, the maximum power requirement for higher voltage LEV batteries in the 96 V to 120 V range would generally not be more than 12 kW. Even a futuristic 120 V system with 125 A charging current may not require a power rating more than 15 kW (250 Wh/min). The LEV charging infrastructure can also serve the first generation e-cars with battery capacity up to 21 kWh and battery voltage up to 72 V. Indian standards for LEV charging define AC charging (level 2) of 11-22 kW (IS-17017-1) and DC Charging power up to 12 kW (IS-17017-25).

For 2nd generation e-cars, having higher battery capacity and higher battery voltage in comparison to LEVs, the grid needs to be equipped with additional infrastructure to support fast charging. Figure 4.1 shows the various vehicle categories and corresponding specifications for charging.

FIGURE 4.1: BATTERY SIZE FOR DIFFERENT EV SEGMENTS (SOURCE: NITI AAYOG)

VEHICLE SEGMENT	BATTERY CAPACITY	BATTERY VOLTAGE
E-2W 	1.2-3.3 kWh	48-72V
E-3W (passenger/ goods) 	3.6-8 kWh	48-60V
E-cars (1st generation) 	21 kWh	72V
E-cars (2nd generation) 	30-80 kWh	350-500V

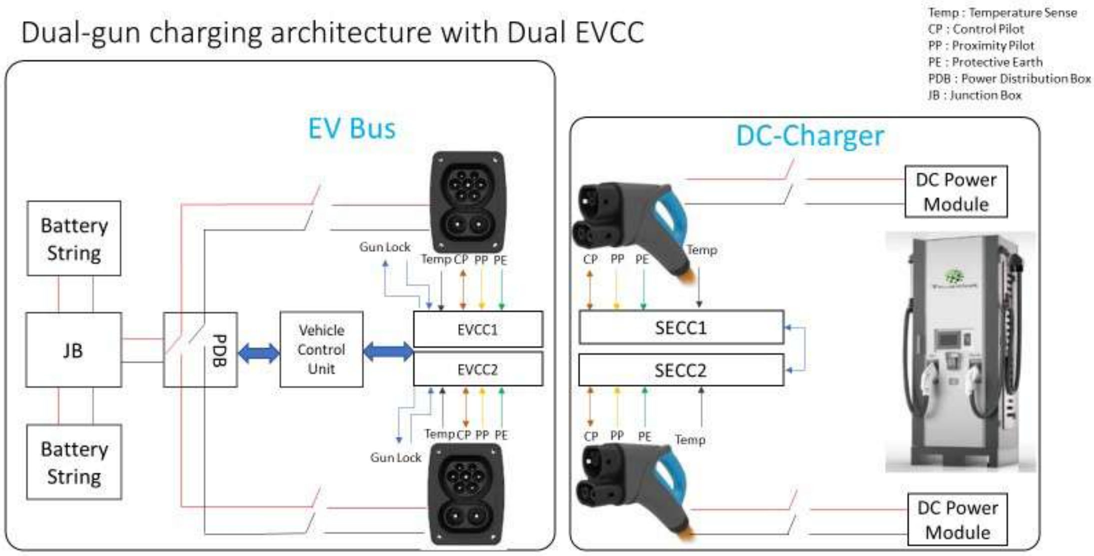
4.3 HIGH-POWER CHARGING INFRASTRUCTURE

Beyond cars, high-power charging for heavy trucks, buses, and fleets demands a significant infrastructure upgrade, including (a) the power delivery infrastructure, such as 11/33 kV power connection with its own separate 11 kV substation and transformer, and (b) civil infrastructure such as level foundation, cable trenches, charger shed, control room etc.

In addition to the above, another critical consideration for high-power charging for electric trucks and electric buses will be the choice of the charging system (power delivery technology). Multiple configurations of high-power charging systems need to be assessed for strategic fit and suitability. Some of these technologies are given below.

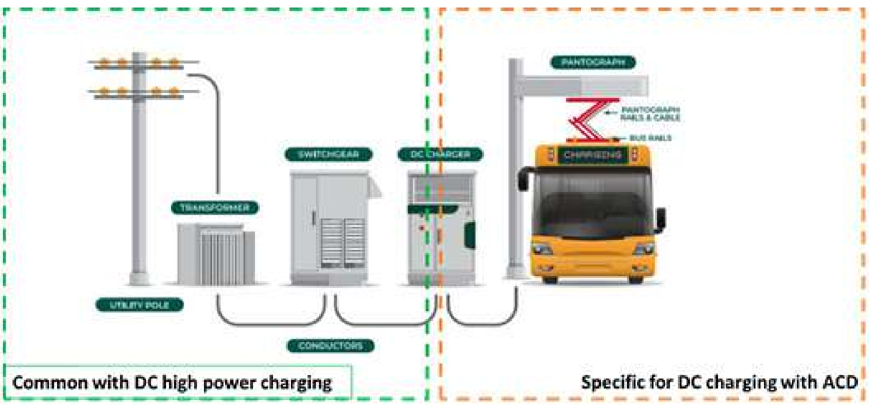
a. Dual Gun Charging, which can support power delivery up to 500 kW, reduces the need for expensive upgrades [40]. Dual gun charging is relatively faster as a single charger delivers the required power from two outlets, doubling the total power delivery through two cables, thus reducing the charging time by half. The dual gun with Dual EV Communication Controller (EVCC) charging architecture is shown in Figure 4.2.

FIGURE 4.2: ARCHITECTURE OF DUAL GUN CHARGING WITH DUAL EVCC (BUREAU OF INDIAN STANDARDS – BIS)



b. Pantograph down Charging (Overhead fixed infrastructure mounted with inverted Pantograph for stationary applications) is a safe and reliable automated power delivery mechanism. The key benefits of this technology include fast charging with a wide range of power levels up to 600 kW, enabling high uptime due to robust design, remote diagnostics, and management tools [41]. The architecture of pantograph charging is shown in Figure 4.3.

FIGURE 4.3: ARCHITECTURE OF PANTOGRAPH CHARGING (IMAGE SOURCE: KING-COUNTY METRO, SEATTLE)



c. Catenary Charging (Overhead fixed lines with an EV-mounted pantograph for mobile charging) for trucks consists of two wires strung along designated routes. Battery electric trucks equipped with a pantograph can draw current from physical contact with overhead catenary wires. This can also help reduce the battery size and allow for extended ranges and faster transit times. The power transfer capacity can be up to 500 kW, and voltages can go up to 1500V DC [40]. Catenary systems can be powered from a central location, including on-site and off-site renewable energy harvesters. An overhead catenary system can also provide power to the wayside stations that would otherwise require interfacing with the local grid. Figure 4.4 shows the image of a truck being charged from catenary-charging system.

FIGURE 4.4: CATENARY-CHARGING SYSTEM (IMAGE SOURCE: CLEAN ENERGY WIRE)

d. Inductive Charging (Stationary and Dynamic), where power transfer occurs through magnetic resonance coupling, caters to diverse needs with two distinct power transfer capabilities: (1) Low-Power Charging (up to 50 kW): Ideal for overnight or depot charging of cars, buses and trucks. These are dedicated overnight power stations, quietly replenishing batteries while fleets rest. (2) Dynamic Charging (50 kW and above): Enabling on-route charging while vehicles are in motion or at designated stops, primarily intended for buses and specific truck routes (like electrified stretches of highway or designated charging zones, where vehicles top up their batteries on the go) [42]. The key benefit of inductive charging is that it can support all EVs and help reduce battery size considerably.

e. Megawatt Charging System (MCS) is a new charging system. A MCS is used for fast charging of heavy-duty electric vehicles such as trucks and buses. MCS DC charging solution can provide up to 3.75 MW of peak power with a single MCS connector with a charge voltage up to 1250 V and 3000 A of current [43]. However, the feasibility assessment for MCS from the perspective of grid readiness and EV compatibility has to be carried out.

Note on Split Charging Systems for Enhanced Power Management: *The Split Charging system is not a power delivery technology but a power management solution*. Charging Systems (DC chargers) have gained global popularity, featuring separate cabinets for power module and dispenser post for charging gun. This design enables intelligent power distribution, allowing simultaneous charging of multiple EVs with adjustable capacity at the charging guns. Unlike integrated chargers, split chargers offer multiple dispenser posts, configurable with up to 12 single guns or 6 double guns, with power settings ranging from 40 kW to 120 kW, and potentially higher with advanced cooling technologies.

4.4 INTEROPERABILITY

Interoperability is the ability of multiple systems and processes to work together cohesively without conflict to deliver the desired output. Interoperability in electric vehicle charging infrastructure allows all components, i.e., electric vehicles, charging stations, charging hardware, charging network, and the grid, to work together seamlessly and efficiently.

a. Vehicle to Charger Interoperability: This interoperability concerns the hardware and communication interoperability between the EV and the EV Supply Equipment (EVSE). This involves electro-mechanical hardware compatibility (pin-to-socket) and communication interoperability between the EV and the charge point management system of the charger.

b. Charger to Network Interoperability: This interoperability is related to the communication between the charging points and the Charging Management System's (CMS) network. The CMS system is typically networked software that helps manage the charging business. It allows charge point operators to track charger utilisation, facilitate remote start/stop operation, authenticate users, and collect payments for chargers within its network. Open Charge Point Protocol (OCPP) is a widely adopted communication protocol for charger-to-network interoperability.

c. Network-to-Network Interoperability: This interoperability is about the ability of one Charging Point Operator (CPO) or Mobility Service Provider (MSP), which is a network operator, to communicate and work with another CPO/ MSP. Without this interoperability across networks, the EV user will have to subscribe to each network separately for access, typically by downloading an app and paying a subscription fee. Open Charge Point Interface (OCPI) is the most well-known open communication protocol, which supports network-to-network interoperability.

d. Battery Swapping Interoperability: Battery interoperability mainly concerns ease in battery swapping technology. It involves issues related to battery-to-charger connectivity, battery-to-CMS and battery-to-battery interoperability.

4.4.1 IDENTIFIED BARRIERS AND SUPPORT REQUIREMENTS

Various barriers that are identified in low-power, high-power and interoperability of EV charging infrastructure are listed in the following table with the proposed support needed.

Identified Barriers	Proposed Supports
Low-Power Charging Infrastructure	
Public charging infrastructure is locked in with specific vehicle connector guns. For example, a public DC charger meant for one type of connector (say, GB/T) may not be accessible to EV users having CCS plug or Type 6/ Type 7 (Light Electric Combined Charging System - LECCS). This limits the ability of the charge point operators to provide widespread access to fast charging for LEVs.	Universal Infrastructure Socket (UIS): The UIS can provide charging power in the range of 2 kW to 22 kW (variable DC power range of 48 V to 500 V) to all LEVs from a single charge point. The main idea is to untether the cable from the charger and use a detachable cable with a type-2 plug on the charger side. The EV side of the cables can have any compatible connector that meets Indian standards. Product development involves repurposing the type 2 connector for transferring power and the development of a communication-capable cable with the intelligence to speak the language of the relevant charging protocols. To enable communication, the cable must be enhanced with in-cable electronics to 'translate' the EV-side communication protocol with the charger.

Identified Barriers	Proposed Supports
Mass manufacturing of low-power DC chargers and associated Power Electronic Controllers (PEC)	Indigenization of low-power DC chargers through product development and support: The structure of the power electronic converter should be such that it draws a balanced and sinusoidal current from the three-phase LT connection. The question of load balancing can be addressed by employing suitable control strategies for the power electronic converters. Product development is also needed for designing low-cost indigenous AC-DC-DC converter technology. Development of high-frequency magnetic designs compatible with power electronic converters employing wide-bandgap devices (e.g. SiC, GaN) must be pursued.
Public charging with multiple chargers may have an adverse impact on the grid, particularly in areas where the distribution network is weak.	An innovation that could help augment the supply side is the inclusion of in-situ renewable and energy storage systems and their optimal operation.
The power quality of the single-phase residential connection in semi-urban and rural areas is generally weak. Consequently, charging EVs with moderate power levels from the residential single-phase plug-point in the semi-urban and rural areas will adversely affect the other residential loads and create unbalance.	A systematic investigation/assessment of these case scenarios is of importance to formulate strategic developments required in the EV infrastructure.
High-power Charging infrastructure	
Dual Gun Charging: a. Power management and synchronization of power delivery through the two guns.	a. Assessing the feasibility of cable-based systems with respect to other high-power charging systems b. Development, testing, validation, and standardization of dual gun charging in a controlled or real environment

Identified Barriers	Proposed Supports
Pantograph-based charging a. Challenges of low-voltage and high-current pantograph designs b. Protection of rails (Indian conditions) c. Safety considerations related to short circuit	a. Need to develop advanced pantograph to support low-voltage and high-current power transfer. b. Feasibility study of Panto-down system with respect to cable-based system c. Limited Product development support to CPOs and OEMs for the development of infrastructure components
Catenary charging system a. The catenary system used in the railway has a high level of maturity. However, the use of the same fixed system on roads can bring new challenges. b. Installation of pantograph and power electronics for EV c. Low-voltage, high-current catenary is not feasible. d. Safety considerations	a. Controlled field trials to assess the power transfer capabilities on the grid and the EV side b. On-board power electronics and protection switch gear are to be developed for high-voltage and low-current catenary systems. c. Support to OEMs for technology maturation and product development
Inductive charging system a. Robust communication during charging without any disturbance due to movements/ misalignments b. Limited evidence on the impact of electromagnetic interference (EMI) on people and animals.	a. Lab testing in a controlled environment to assess the impact and potential safety concerns related to electromagnetic interference (EMI). b. Controlled field trials to assess the power transfer capabilities of the system.
Megawatt charging system - Power levels in tens of MWs range must be made accessible in remote charger locations	a. Feasibility assessment for MCS from the perspective of the grid and EV readiness. b. HV System Design and electrical safety

Identified Barriers	Proposed Supports
Study on initial capital cost, maintenance cost, and other financial requirements	An economic study of various high-power charging schemes discussed is required to promote the relevant technology.
Standards related to high-power charging station	There are no standards related to the high-power charging station infrastructure. Need to develop relevant standards which guide the manufacturers to come on a common platform.
Power Electronic system support	Development of the following • High power, low-voltage converters and Silicon Carbide (SiC) based high power converters, suitable for direct connection to medium-voltage grid. • Medium-frequency and high-frequency magnetics
Increase the charge power capacity of cables connecting the charger to EV charge inlet	Need to develop high current carrying cables for facilitating high power charging to EVs
Grid stability and support for high-power delivery	When large power is drawn from the grid in one place, it may affect its stability, voltage profile and power quality. A possible solution to reduce the adverse effects on the grid is the inclusion of solar photovoltaics (PV) and high-efficiency energy storage systems in a DC microgrid system configuration for high-power charging stations.

Identified Barriers	Proposed Supports
Interoperability of EV infrastructure	
Non-standard connectors used: many LEVs have custom hardware design, wherein, communication protocols are either absent or rudimentary, and have limited charging capacity. In addition many of these connectors have current rating only up to 75 A, compared to standardized LEV connectors developed in India like Type 6 and Type 7 connectors. The main reason for not using standardized connectors is the high cost of such connectors.	Product development support for lowering the cost of manufacturing standard connectors
The cost economics for installing a standardized communication protocol for LEVs is markedly different from that of 4W EVs. A standard software cost per charge session, which includes data storage and transfer for enabling interoperability, could have disproportionate impact on LEV charging (as compared to electric car charging) as the transaction amount for LEVs is small. This cost difference is attributed to the way communication protocols are defined, including data packet size and the frequency of relaying data to accommodate various features. Adjusting these aspects can optimize the cost structure to better suit the needs of an LEV charging ecosystem.	a. Collaborating with established protocol-defining organizations to streamline the communication stack. b. Rethinking and creating LITE versions of existing communication stacks to align with the cost structures prevalent in the Indian LEV market. c. Placing a strong emphasis on enhancing the user experience to reduce barriers in EV adoption and standardizing interaction patterns through a novel Plug & Charge model. d. Implementing certification programs to guarantee that deployed products conform to the established standards.

Identified Barriers	Proposed Supports
India has multiple charging network operators who are offering public and semi-public charging services with each operator having multiple charge points stations under its network. Most of the network providers have their proprietary customer facing apps that need to be downloaded and subscribed to by the EV users for using their charging network. Cooperation between the network operators will require them to provide specific data related to charging station location, specification, operational status (operational-in-use, operational-not-in-use and un-operational), tariff information, along with subscriber information and authentication. Most of the network operators consider subscriber base and charger utilization data as proprietary and sensitive, and have reservations on sharing this data.	An Indigenously developed standard and interoperable network called the **Unified Energy Interface (UEI)** is recommended. UEI leverages a made in India open sourced protocol called the Beckn Protocol. UEI is envisaged to be decentralized network like the UPI (Unified Payment Interface)] that can help facilitate charging across customers and charge points operators. It is very similar to how UPI facilitates the movement of cash between customers' bank accounts and banks. It enables location-aware, EV chargers to be discovered and engaged by any app of the EV user that is registered as a buyer app on the UEI network.

Identified Barriers	Proposed Supports
A battery swap involves four different identities: Vehicle Identification Number (VIN), Battery Identification Number (BIN), Battery Charging Station Number (BCSN), and BaaS Outlet Number (BON). When the battery packs, swap stations and vehicles are from different companies then the interoperability among the BaaS operators has to be ensured through a system of communications between the different CMS that are maintained by each of the operators.	The technology of establishing state of charge, health of a variety of batteries need to be established to determine the cost of a fair exchange involved in a battery swap. A system of tracking battery pack usage may be developed for purposes of warranty settlements, lifecycle optimisation and safety. Supporting testing and validation programmes that can help in framing policy and regulations. Prototyping and testing • Overall system level demonstration using Battery Pack and Battery Storage System (BSS). • Swap connector & communication system • Backend interoperability

4.5 BROAD PRIORITY AREAS

Various hindrances related to electric mobility have been analyzed in the context of EV charging infrastructure. Thereafter, possible technological approaches are explored to address these issues. The broad priority areas for the CoEs/Innovation cluster on EV charging infrastructure are summarized below.

Short-Term Priorities:

- Development of universal infrastructure socket (UIS) and charging cable with in-cable electronics for low-power charging stations facilitating 2W and 3W EVs (standardization of UIS and charging cable).

- Product development support for an adaptor design that will provide compatibility for connecting dominant non-standard sockets with type-6 or type-7 sockets (with or without communications capability).

- Development of a low-cost and light-weight charger to network communication protocol for LEV charging.

- Development of system architecture and associated embedded signal processing and computing technologies for battery swapping system, primarily for 2W and 3W EVs. Development of swap connector, IoT-based and other communication systems, along with backend interoperability.

- Study of weak grid cases and solutions for the issues pertaining to increasing penetration of fast charging infrastructures to cater to the demand of EV load.

- Extending the destination charger to support Renewable Energy (RE) and Battery Energy Storage System (BESS) based microgrid charging stations with smart power management and Vehicle-to-Grid (V2G) power management capability.

- Indigenous development of low-cost AC/DC converter technology for charging facilities. (Single-phase and/or three-phase variants).

- High-power charging stations using 50 Hz step-down transformer consisting of

    ◊ High-power bidirectional converters.

    ◊ Charge ports supporting different vehicle segments (eg: 800 V, 400 V, etc.)

- Case study and Proof of Concept exercises to make a comparison of cable-based vs. pantograph-based charging systems, cost analysis considering 10 years of time duration, operational efficiency, and to understand the amount of battery that can be reduced when adopting these types of charging systems.

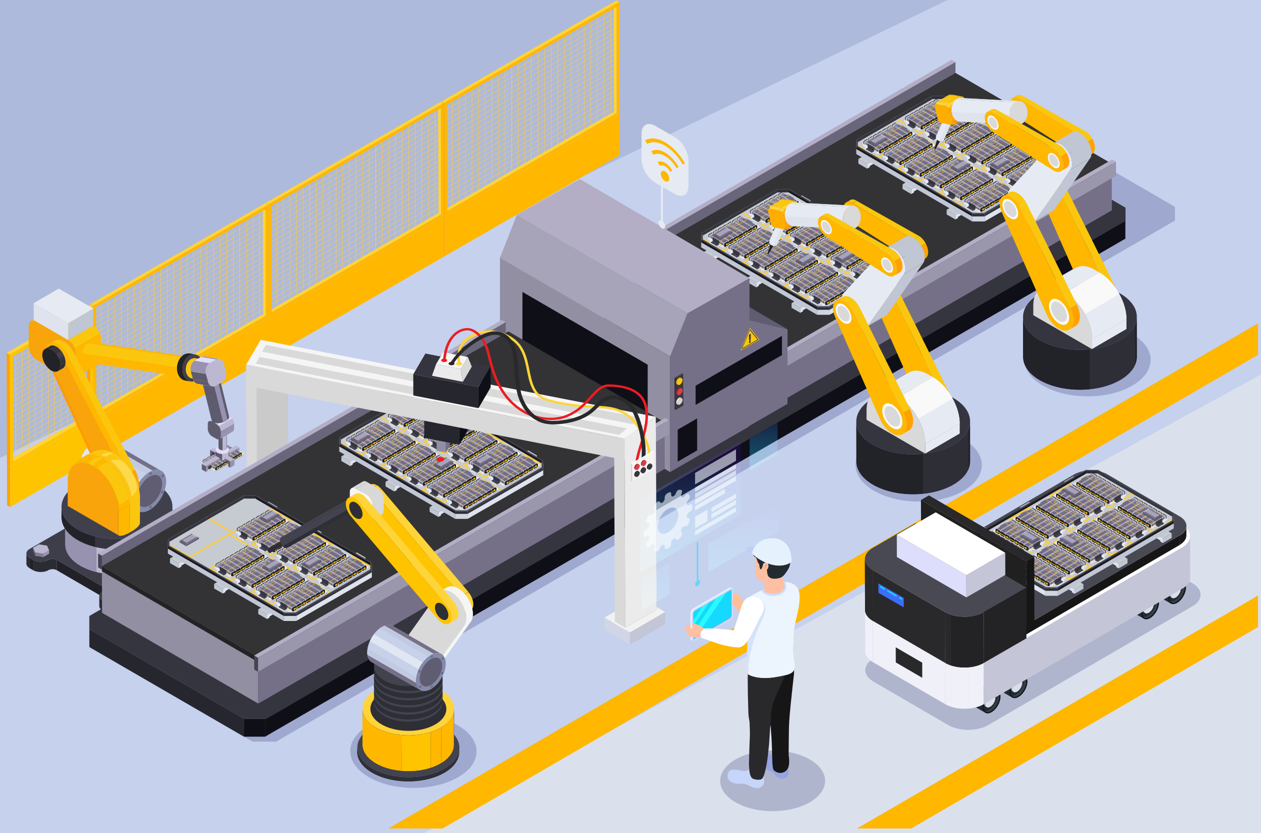
Long-Term Priorities:

- High power charging stations using Solid State Transformer (SST) consisting of

    ◊ SiC-based high-power bidirectional converters suitable for direct connection to medium-voltage grid

  - ◊ Isolated DC-DC converters (eg: DAB)
  - ◊ Charge ports supporting different vehicle segments (eg: 800 V, 400 V, etc.)

- Proof of concept and validation of the high-power charging schemes like dual gun, pantograph, and catenary.
- Economic study of high-power charging stations with integration of RE and BESS.
- Testing and validation of inductive charging in a controlled environment, to assess the impact and potential safety concerns from EMI and controlled field trials to verify the power transfer capabilities and system efficiency.
- Supporting technology development for pantograph charging (pantograph down and overhead continuous pantograph design) and field trials.
- Feasibility study for MCS considering the future mobility requirements and scope of growth in India.
- Development of high-power, high-frequency magnetic design compatible with power electronic converters employing wide-bandgap devices (such as SiC, GaN), suitable for low-power and high-power charging infrastructures.
- Study the effect of high-power charging stations on the voltage profile, power quality and stability of the grid.
- System development of high-power charging station with grid-connected converters based on wide gap band devices to cater to various DC charging requirements.
- Validation and field trial of Solid State Technology (SST)-based power converter systems/architectures, which are connected to the medium voltage AC grid (e.g. 11kV) directly and facilitate use in constrained space for high-power charging stations.
- Development of new materials/methods for low voltage (800 V to 1200 V), high current (>500 A) cable technology.
- Development of a Battery Passport system to track EV batteries throughout their life cycles to eventually support business models such as Battery as a Service (BaaS).



05 CONCLUSIONS AND WAY FORWARD

As our nation strives to accelerate EV penetration, both opportunities and challenges emerge. To exploit opportunities and meet the challenges, an ecosystem approach where all stakeholders participate synergistically is the key to create growth of the EV market.

India is actively promoting the electrification of road transport vehicles through various incentive schemes/programs. Spurred by these initiatives, the industry has gained momentum for developing EV indigenously. In order to enable sustainable development, there is a need to strengthen the technological capability of the industry through R&D support.

Successful EV adoption will be measured by the market shift from conventional vehicles to electric vehicles. Customer requirements for an EV are vehicle affordability (cost), safe and reliable operation, vehicle range, and charging convenience. For the Indian industry to meet these requirements, the Department of Science and Technology (DST) has identified three major areas of EV technology that need to be strengthened: (1) Battery Technology (2) Motors and Power Electronics, and (3) Charging Infrastructure. Challenges arising from Indian conditions such as climate, market segments (two- and three-wheeler dominance), road conditions, etc., have also been identified.

In India, though significant research is happening at academic institutions and R&D labs, there are considerable gaps between technologies developed at the laboratory scale and those which are needed for deployment at the industrial level. The DST plays a crucial role in bridging this gap by identifying niche areas for technology development and supporting the maturation of Technology Readiness Levels (TRL). This document has assessed the status of the EV sector, identified its current challenges, and proposed potential technological interventions to address them.

It is crucial to devise an R&D strategy to address the hindrances faced by the industry and the users towards wider adoption of electric mobility in the automotive sector. New models of partnership need to be explored, where Government and Industry can come together to co-create the much needed facilities for manufacturing at the pilot level, testing and validation, and life cycle analysis of EV systems and components. Three areas which need immediate attention on priority have already been described above. Some of the enabling technological interventions that the country needs to prioritize are emphasized below.

5.1 ESTABLISHING SCALE-UP CAPABILITY TO ENABLE BATTERY CELL MANUFACTURING

The automakers are responsible for providing affordable vehicles with safe and reliable operation to the customer. They need high-quality battery cells/packs at low cost.

Currently, India relies on imported battery cells, assembling them into modules and packs to satisfy domestic needs. Much of these are of inadequate quality and lead to high life-cycle costs. There is an urgent need for domestic cell manufacturing for the auto industry. Significant research is being carried out at academic institutions and R&D labs, focused mainly on basic research (Technology Readiness Level, TRL 1-3). A cell manufacturer needs scale-up data and large-format cell samples (TRL 4-6) to take any promising cell technology to production (TRL 7). India's manufacturing industry is nascent, and establishing the scale-up infrastructure and framework would remove a major hurdle for manufacturing. It will also empower India's flourishing startup industry, where many creative ideas get an opportunity to move up to TRL 6 instead of being shelved at TRL 3.

To bridge this gap, India requires a central prototype cell fabrication and testing facility that can build production-size cells, as well as several smaller satellite R&D facilities for the fabrication of smaller multi-layer cells. The prototype facility will involve high operational costs and require a significant quantity of materials for fabrication. The R&D fabrication facilities will do the first screening of technology developed in research labs, and successful results will qualify the technology to the prototype scale.

Such a capability will help the new generation of cell manufacturers since it will allow product validation without incurring the financial risks associated with commercial cell manufacturing. These facilities are also expected to provide a platform for hands-on training, upskilling, and knowledge exchange, cultivating a skilled workforce ready to support future large-scale production.

5.2 EQUIPMENT DEVELOPMENT FOR MANUFACTURING OF EV COMPONENTS

One of the major challenges that the Indian industry faces today is import of equipment for EV component manufacturing. While these equipment are expensive in nature, the long lead time involved in getting this machinery is another stumbling block for domestic EV component industries. Since most of the equipment and processes are technology agnostic, this machinery needs to be developed in India. Existing expertise in the country in the manufacturing industry can be leveraged to develop R&D competency in the country. Emphasis should be given to battery cell manufacturing, motor manufacturing, the equipment needed for RE magnet manufacturing and fabricating high-power power electronic components/ products.

5.3 ESTABLISHING DISTRIBUTED TESTING FRAMEWORK

For a robust EV sector in India, establishing nationwide testing facilities is important. Currently, the Automotive Research Association of India (ARAI) and the International Centre for Automotive Technology (ICAT) serve as designated testing and certification agencies. Their evaluations, encompassing performance, safety, durability, and environmental aspects, ensure EVs meet standards. This instills consumer confidence in the safety and reliability of these revolutionary vehicles.

However, fostering a vibrant EV ecosystem necessitates more. Supporting innovative startups not only in EV battery manufacturing but also in motors, power electronics, and chargers demands a wider network of testing facilities. This expansion will lead to higher quality, adherence to safety standards, and consumer trust.

5.4 TECHNOLOGY INTERVENTION IN VALUE CHAIN OF EV COMPONENTS

At the heart of the EV revolution lies the pursuit of sustainability. EVs offer the potential to significantly reduce carbon emissions, improve air quality, and conserve natural resources. By transitioning to electric mobility, India can establish a harmonious equilibrium between ecological sustainability and economic advancement.

A truly circular EV battery ecosystem rests on three pillars: responsible sourcing, innovative reuse strategies and efficient recycling. Each requires technological advancements, scalable processes, and business models that prioritize sustainability and economic viability.

The EV revolution hinges on the efficient and sustainable lifecycle of its batteries. It involves extracting critical minerals like lithium, nickel, cobalt, and graphite. Responsible sourcing practices are crucial to ensure ethical and environmentally conscious extraction. Diversifying supply chains beyond a few dominant countries further bolsters sustainability. These minerals are refined and processed into battery components, ultimately assembled into the EVs.

There is a need to evolve and standardized Lithium processing technology both for the first mile, i.e., primary extraction, and the last-mile, i.e., recycling and circularity from end-of-life cells. Recent discovery of mines at Jammu & Kashmir and other regions can be explored. Geological exploration of raw materials related to e-mobility can be taken up.

As the EV boom matures, managing end-of-life batteries becomes critical. While recycling reclaims valuable materials, the economics can be challenging due to cheaper virgin alternatives. Extending battery life through repurposing in grid storage offers promise, but requires innovative business models and efficient processes. When second-life applications reach their end, responsible recycling comes into play.

5.5 WAY FORWARD: SUGGESTED OVERALL FRAMEWORK FOR ACCELERATING AND AMPLIFYING EV EVOLUTION IN INDIA

The outcome and recommendations of this document will be translated into actionable national R&D programmes for implementation. With Anusandhan National Research Foundation (ANRF) in place, DST, in partnership with industry, is poised to have a greater focus on clean energy. By addressing the various elements of e-mobility ecosystem as enumerated below, India will be in a better position to embark on an EV revolution.

- **Research and Development:** Investments in R&D are essential for breakthroughs in EV components technologies, to minimize import dependency and lower the cost of components, to improve efficiency, and to optimize vehicle performance. Collaborations between academia, industry, startups, and research institutions can foster innovation, resulting in affordable, cost-effective and efficient EV solutions for a price-sensitive market like India. The three chapters have emphasized the need for designing specific research programmes through a Centre of Excellence (CoE) concept. These programs should include (a) Industry-led technology development in the area of battery, motor and power electronics, and EV Charging infrastructure and (b) A manufacturing technology R&D program which will encompass both lower and higher TRL technologies.

- **Supply Chain Challenges:** The EV ecosystem requires a complex supply chain involving battery, motor, and charging infrastructure. Building a seamless supply chain that supports the EV industry's growth is a considerable challenge and needs due attention.

- **Academia-Industry Collaboration:** Active participation of academia and industry in the form of collaborative research and product development is essential. A cohesive partnership between automotive leaders, auto component makers (including battery, motor and power converter) and technology providers is imperative. Joint ventures can accelerate the production of high-quality, locally manufactured EV components, reducing dependency on imports and lowering costs.

- **Charging Ecosystem Innovation:** The expansion of EV adoption hinges on a robust charging infrastructure. Promoting innovation to develop advanced charging solutions and innovative software platforms to manage charging networks efficiently is vital. This includes wireless charging technology, smart grid integration, and exploring renewable energy sources to power charging stations. Integration with home solar systems can further enhance energy efficiency.

- **Integration with Renewable Energy:** When large power is drawn from the grid at a location, it may affect its stability, voltage profile and power quality. To truly maximize the environmental benefits of EVs, integrating them with renewable energy sources is therefore crucial. This integration poses technical and infrastructural challenges that need to be overcome.

- **International Collaboration:** Learning from global best practices can expedite EV adoption. International collaborations can facilitate knowledge exchange, technology transfer, and the adoption of successful policies.

Interventions that other line Ministries can offer include the following:

- **Government Policies, Regulations and Incentives:** Clear and consistent government policies are instrumental in building investor and consumer confidence. Setting targets for EV adoption, establishing emission standards, and providing grants for research and development can drive the industry forward. These initiatives will aim to encourage the industry to increase domestic value addition through indigenous technology/product development progressively (viz. advanced battery systems, motors and electronic components, charging devices, etc.).

- **Software Integrators:** As EVs become more digitally integrated, electronics, communication, software and data companies play a crucial role, developing algorithms for optimized energy management in EVs, infocom technologies that facilitate connected vehicles and data analytics for EVs needs to be interpreted. These platforms enable remote monitoring, over-the-air updates, asset management and predictive maintenance, and enhancing the user ownership experience.

- **Capacity Building and Skill Development:** Creating a skilled workforce proficient in EV manufacturing, maintenance, and repair is essential. Technical training programs can equip individuals with the expertise needed to support the growing EV ecosystem.

- **Public Transportation Electrification:** Focusing on electrifying public transportation including last-mile mobility, leveraging as buses, two and three-wheelers, can have a cascading effect. It not only reduces emissions but also familiarizes the public with EV technology, thereby encouraging adoption at the consumer level.

- **User Perspective and Raising Consumer Awareness:** For a conducive ecosystem to enable accelerated market development, the benefits of EVs and educating the consumer about the technological advancements and environmental advantages need to be undertaken by the EV industry and key market players.

In conclusion, the journey towards widespread EV adoption in India requires a unified effort from all corners of the e-Mobility ecosystem. Apart from the Government, Industry and R&D have a critical role to play. By collaborating, innovating, strategizing and investing together, the Government, Academia and Industry can transform the electrification of the road transportation sector and can effectively contribute to realizing the aspirations of decarbonizing India.

ANNEXURES

Annexure A

Tropical EV Battery – Technology Readiness Levels

TRL	TRL Activity	TRL Description
TRL 1	Theoretical Concept Development, idea formulation	Define EV applications and scope, cell chemistry and design
TRL 2	Determine fundamental component (electrode) properties	Build and test half cells. Establish material electrochemical properties and electrode design/formulation.
TRL 3	Establish concept feasibility Full cells, small cells: Coin cells, single-layer pouch cells, < 1 Ah	Establish cell electrochemical performance. Performance parameters - Cell Voltage (including open circuit voltage - OCV), cell capacity, cycling stability, first-cycle efficiency. Improve electrode formulation and cell design. Estimate of cell energy density and preliminary cell cost when scaled to a production-size cell
TRL 4	Establish proof of concept Small format, multi-layer pouch cells < 5Ah	Roll-to-roll (or similar high quality) cell fabrication Establish full-cell performance. Performance Parameters – Cycle life (80% capacity retention in 500 cycles), cell power, fast charge; OCV changes with cycling. Develop physics-based electrochemical cell models Build battery state estimators (BSEs)
TRL 5	Establish proof of technology Large-format cell A sample Pilot or prototype scale	Freeze cell design, Bill of Materials (BOM); identify BOM suppliers Performance parameters: Cell cycle life (Typically 1500 cycles at 90% SoH), fast charge and power performance and safety testing Establish charging protocols Identify suppliers for cell components and raw materials Identify and scope manufacturing site Set BMS requirements

TRL	TRL Activity	TRL Description
TRL 6	Establish cell manufacturability – Production size sample Pilot or prototype scale	Full-scale cell performance and safety testing. Verify that cell performance meets vehicle requirements Supplier qualification Cell cost established Safe operation established Start BMS design
TRL 7	Demonstrate full scale cell production capability Production size cells, limited quantity manufacturing scale/ plant	Process capability (quality, throughput defined) Determine process capability and quality Extensive cell testing Preliminary BMS requirements
TRL 8	Full-scale production	Demonstrate continuous operation Optimize production process (quality, yield) Validate process capability, yield, safety, throughput Validate cell performance, safety Complete BMS specifications
TRL 9	Commercialisation Full-Scale operational plant	Demonstrate plant utilization, continuous operation, QC Supplier and inventory management Customer delivery Assess field data from vehicles and confirm technology robustness

Annexure B

Indian Standards for Electrotechnology in Mobility

S.N	IS No.	Title
1.	IS/ISO 15118-1 : 2013	Road vehicles - Vehicle to grid communication interface Part 1 general information and use - Case definition
2.	IS/ISO 15118-2 : 2014	Road vehicles - Vehicle - To - Grid communication interface Part 2 network and application protocol requirements
3.	IS/ISO 15118-3 : 2015	Road vehicles - Vehicle to grid communication interface Part 3 physical and data link layer requirements
4.	IS/ISO 15118-4 : 2019	Road vehicles - Vehicle to grid communication interface Part 4 network and application protocol conformance test
5.	IS/ISO 15118-5 : 2018	Road vehicles - Vehicle to grid communication interface Part 5 physical layer and data link layer conformance test
6.	IS/ISO 15118-8 : 2020	Road Vehicles --- Vehicle to Grid Communication Interface Part 8 Physical Layer and Data Link Layer Requirements for Wireless Communication First Revision
7.	IS 17017 (Part 1) : 2018	Electric Vehicle Conductive Charging System Part 1 General Requirements
8.	IS 17017 (Part 2/ Sec 1) : 2020	Electric Vehicle Conductive Charging System Part 2 Plugs Socket-Outlets Vehicle Connectors and Vehicle Inlets Section 1 General requirements
9.	IS 17017 (Part 2/ Sec 2) : 2020	Electric Vehicle Conductive Charging System Part 2 Plugs Socket Outlets Vehicle Connectors and Vehicle Inlets Section 2 Dimensional compatibility and interchangeability requirements for a c pin and contact-tube accessories
10.	IS 17017 (Part 2/ Sec 3) : 2020	Electric Vehicle Conductive Charging System Part 2 Plugs Socket Outlets Vehicle Connectors and Vehicle Inlets Section 3 Dimensional compatibility and interchangeability requirements for d c and a c d c pin and contact-tube vehicle couplers

S.N	IS No.	Title
11.	IS 17017 (Part 2/ Sec 6) : 2021	Electric Vehicle Conductive Charging System Part 2 Plugs Socket Outlets Vehicle Connectors and Vehicle Inlets Section 6 Dimensional compatibility requirements for DC pin and contact t
12	IS 17017 (Part 2/ Sec 7) : 2023	Electric Vehicle Conductive Charging System Part 2 Plugs Socket Outlets Vehicle Connectors and Vehicle Inlets Section 7 Dimensional compatibility and interchangeability requirements for ac
13.	IS 17017 (Part 21/ Sec 1) : 2019 IEC 61851-21-1:2017	Electric Vehicle Conductive Charging System Part 21 Electromagnetic Compatibility EMC Requirements Section 1 On-board chargers
14.	IS 17017 (Part 21/ Sec 2) : 2019 IEC 61851-21-2:2018	Electric Vehicle Conductive Charging System Part 21 Electromagnetic Compatibility EMC Requirements Section 2 Off-board chargers
15.	IS 17017 (Part 22/ Sec 1) : 2021	Electric Vehicle Conductive Charging Systems Part 22 AC Charging Configurations Section 1 - AC Charge Point for Light Electric Vehicle
16.	IS 17017 (Part 23) : 2021	Electric Vehicle Conductive Charging Systems Part 23 dc Electric Vehicle Supply Equipment
17.	IS 17017 (Part 24) : 2021	Electric Vehicle Conductive Charging System Part 24 Digital Communication between a DC Electric Vehicle Supply Equipment and an Electric Vehicle for control of DC Charging
18.	IS 17017 (Part 25) : 2021	ELECTRIC VEHICLE CONDUCTIVE CHARGING SYSTEM Part 25 DC EV supply equipment where protection relies on electrical separation
19.	IS 17896 (Part 1) : 2022 IEC TS 62840-1:2016	Electric vehicle battery swap system - Part 1 General and Guidance
20.	IS 17896 (Part 2) : 2022	Electric vehicle battery swap system - Part 2 Safety requirements

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