Office of the Principal Scientific Adviser
to the Government of India

eMobility R&D Roadmap for India

July 2024

अजय के. सूद
भारत सरकार के प्रमुख वैज्ञानिक सलाहकार
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FOREWORD

As the fifth largest economy in the world, with rapidly growing incomes, urbanization, and industrialization, India's energy demand is expected to exponentially rise. India is poised for its ambitious vision of achieving energy independence by 2047. The Indian government's vision to reduce petroleum and coal imports includes a strategic mix of investment in renewable energy, battery storage, Electric Vehicles, and green hydrogen.

The Government of India has set an aggressive target of EV sales penetration with target of EV30@2030 with 30% of newly registered private cars, 40% of buses, 70% of commercial cars, and 80% of 2-wheelers and 3-wheelers will be electric by 2030. India needs robust R&D capabilities to build a complete EV ecosystem. In this context, I am delighted to present the "eMobility R&D Roadmap" which details the technical areas and research projects that require immediate action in the Indian context over the next five years to become *Atmanirbhar* and to emerge as a global leader in innovative mobility solutions.

This comprehensive document integrates several key elements specifically identified as key enablers to ensure systematic and effective execution of proposed R&D projects. It includes a master plan to outline the overall strategy, TRL assessment to evaluate technology maturity, horizon scanning and gap analysis, risk identification for identified projects etc. Each roadmap specifies objective research goals, project methodologies, indicative timelines & budget requirements, and recommendations on agencies with extant capabilities to undertake specific R&D projects. This novel approach of research project documentation would facilitate meticulous planning and financial accountability throughout the project lifecycle.

I firmly believe that by accelerating the industry-focussed research workstreams outlined in this roadmap, India will meet its national commitments and achieve global leadership in eMobility through research and innovation led value propositions in indigenous product manufacturing.

I extend my appreciation to all members of the Consultative Group on eMobility (CGeM) and industry experts who generously dedicated their valuable time and significantly contributed in shaping the eMobility R&D Roadmap.

Ajay K Sood

(Ajay K. Sood)

Dated: 18th June, 2024

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Message

The Office of the Principal Scientific Adviser (PSA) to the Government of India actively supports and promotes Science and Technology R&D, in priority areas of national importance, through its missions and programs.

The Electric Vehicle Mission, conceptualized by the Prime Minister's Science, Technology Innovation and Advisory Council, aims to reduce fossil fuel consumption, mitigate emissions, and facilitate the production of Electric Vehicles (EVs) in India. The Office of PSA has constituted a 'Consultative Group on eMobility (CGeM)', which is a panel of experts from Government, Academia and industries to devise technical roadmaps, studies, documents for accelerating migration of prevalent fossil fuel-based transportation sector towards electric mobility in India.

The CGeM and a pool of contributors, after detailed discussions and multiple rounds of consultations, have now prepared "eMobility R&D Roadmap of India". The methodology adopted for identification of critical streams, research and evidence-based approach, and pattern of documentations makes this Roadmap extraordinary and unique in nature. Recognizing the value and utility of this initiative, we are pleased to share the roadmap with all relevant stakeholders in the eMobility sector.

I extend my appreciation to members of CGeM Working Committee, experts from the Automotive Research Association of India and individual contributors who have prepared the roadmap. I acknowledge sincere efforts and contribution of Dr. Preeti Banzal, Adviser/Scientist 'G ', PSA office, Prof. Karthick Athmanathan, PSA Fellow, Sh. Abhijit Mulay, Deputy Director ARAI, Pune, and Dr. Sneha Malhotra Chief Technology Officer, PSA office for this accomplishment.

I am sure this document will act as important reference and will help in initiating multiple R&D projects by different ministries/departments and institutes under various programs and Government led initiatives.

PMaini

(Parvinder Maini)

Executive Summary

Since 2015, eMobility in general and EVs in particular have started occupying significant mind space in India amongst Policy Makers, Industry and the Mobility EcoSystem. Significant initiatives have been taken from Government as well as Industry on different fronts, including policy initiatives, investments and awareness building.

On the Research and Development (R&D) front, India has seen the following commendable initiatives for eMobility:

1. Rapid absorption of existing technologies from abroad, adaptation to the Indian context and market-driven ramp up of production.
2. Independent rediscovery of certain technologies that were already available abroad- but with minor modifications to suit the Indian context.
3. Faster and simpler clean slate R&D in technologies by the Start Ups, who have been able to make significant impact on the eMobility technology landscape in India.

WHAT AREAS ARE BEING ADDRESSED IN THIS ROADMAP?

Three areas that have seen limited investment and action till date in the eMobility R&D space are given below- and these are areas where there have been no major breakthroughs internationally yet:

a. The fundamental science behind the manufacturing of certain highly promising materials such as Graphene. These require significant investments while holding higher risks of failure as well. But the benefits of success are immeasurable.
b. Materials development, research and productization of new storage chemistries as well as EV Power Train componentry. These too hold higher risks of failure but offer very high benefits in case of success.
c. Production Engineering of Level 3 and Level 4 items in the Bill Of Materials in eMobility- for items such as Wide Band Gap devices, Fuel Cell membranes, Cell Separators, etc. Here, while the failure risks are minimal, the investments and technical management required are very high. Unlike the above two, this activity has seen remarkable success internationally in Taiwan, China, USA and, to some extent, Europe.

It is a well known matter that, for the eMobility value and supply chain, there is still considerable dependence for India on imports- this being the result of the actions that the various stake holders like Government, Industry and Academia did not take in the early days around 2010 ~ 2015. This report helps address, in limited focus areas, actions that will need to be taken now in order for India to not find itself in a similar position in 2030 or later. It does not address the current situation regarding reliance on imports- there are other Government and Industry initiatives that are addressing this current issue. Rather, this report identifies the RoadMap and projects that the country will have to take in order to be at the cutting edge of both Value and Supply Chains five to seven years down the line- say in 2030. If we do not take these actions now, we are likely to be in the same situation a few years down the line, where other countries have taken risks and invested in upcoming new ideas and we are left depending on them.

WHICH WOULD BE AN EFFICIENT APPROACH TO LAUNCH THIS ACTION?

There are massive benefits to be reaped in taking up the above activities since India would then be at the forefront and cutting edge in terms of fundamental metrics in eMobility- Energy Density, Power Density, Costs, etc.

A RoadMap was prepared first for different critical streams in the eMobility space- and, as a follow up deliverable, specific projects are identified to keep India competitive and competent at a global level in this RoadMap.

Given the longer timelines required for most of the above items and the higher levels of risks of failure, new Administrative Mechanisms, Schemes and Review Methods are required- in line with what is practiced successfully in Europe, USA, Japan and China.

There is also a need for all the higher-risk phases to be funded publicly with suitable provisions for IPR- and the Industry support is initially limited to non-fiscal and non-management obligations. Once there is success demonstrated in lab scale, industry engagement in terms of investments as well as project management/ lead are to be ramped up from PoC to Pilot to Industrialisation- the last phase being the largest investment and entirely funded by Industry.

The visual below (Figure 1) provides an idea of how funding is typically done between public and business entities.

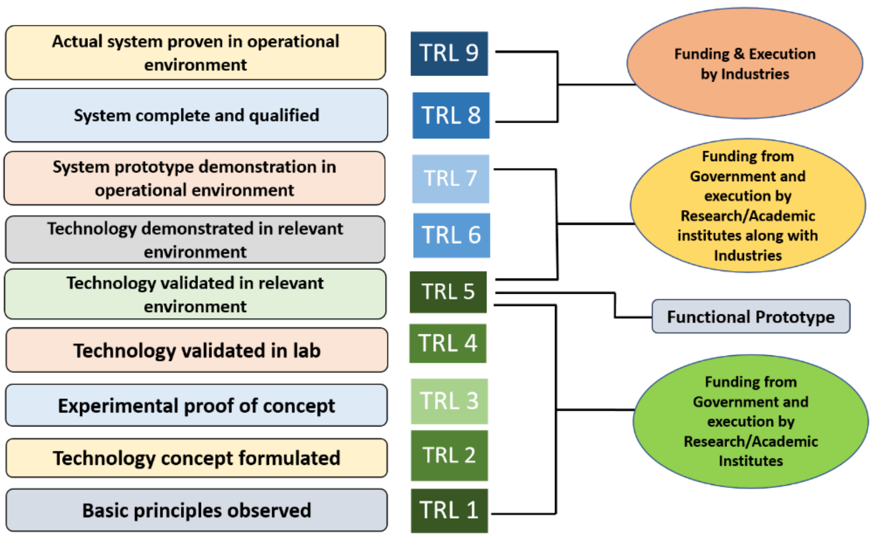

Figure 1: Budget distribution mechanism according to TRL level

In this document, four different and critical streams (Figure 2) are shown in eMobility with a fifth stream on Hydrogen being limited to mention and deferring to India's Hydrogen Mission. The four streams are:

1. Energy Storage Cells- addressing new areas in the Chemistry and Physics behind Cells and their Manufacture.
2. EV Aggregates- capturing actions in the entire value chain of all items that are specific to eMobility other than Cells.
3. Materials & Recycling- focusing on Material Science and different tools that can further augment Materials Research.

4. Charging & Refuelling- enumerating the opportunities that will help with improved speeds and safety in charging/ refuelling.

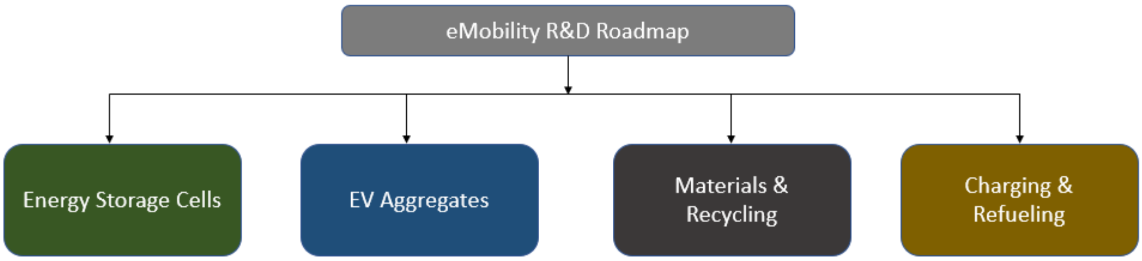

Figure 2: Four critical streams of eMobility R&D Roadmap

It may be noted that, while a majority of the items identified are projects where success is not yet achieved even globally, some are actually items where there is significant success achieved globally already and India has not yet started preparations here. These projects are included in order to ensure that there is sufficient foundation for the country to take up future innovations in that space as and when opportunities arise.

WHAT ARE THE CONSIDERATIONS TO CARRY OUT THE ACTIONS?

The Projects are elaborated to sufficient level of detail so that successful RFPs can be prepared with these leading pointers:

1. Gap Analysis & Background
2. Global Benchmark
3. Current TRL Levels for RFP
4. Targets to ensure product competitiveness in market/ society
5. Methodology
6. Deliverables
7. Impact
8. An indicative but not comprehensive list of agencies that can do the project
9. Rough-cut timeline for the project- assuming the procurement of equipment
10. Indicative and approximate budget for the project- including equipment as well as, where applicable, provision for two parallel projects
11. Risks on different fronts- in terms of potential failure/ success
12. Some thoughts on a suitable Administrative Mechanism

It will help to note that the projects in this document are likely to see rapid change in status globally- new discoveries and inventions are making ideas and technologies obsolescent every six months. So it becomes important to target bold and longer term initiatives to avoid being beaten to any new technology in the medium term.

As can be seen from the visuals below (in Figure 3 and Figure 4), the funding requirements for each of these streams are disproportionate to the possible impact. However, the overall funding being so small, and given that there is a need for India to start occupying the driver seat on these topics, it will be imperative that all projects are given sufficient but conditional and success-based milestone funding.

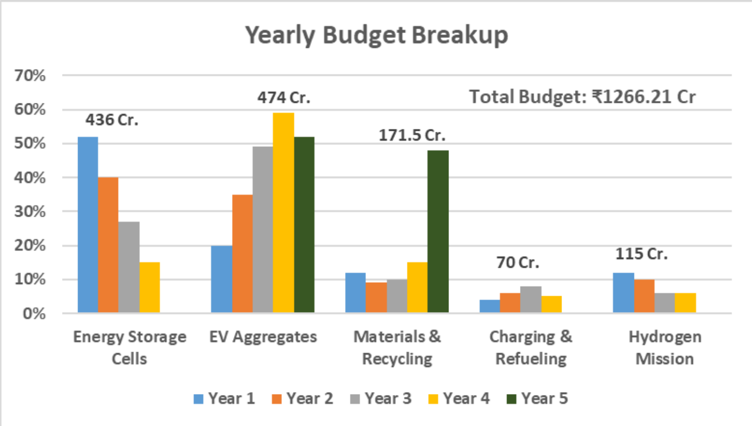

Figure 4: Yearly Budget Breakup

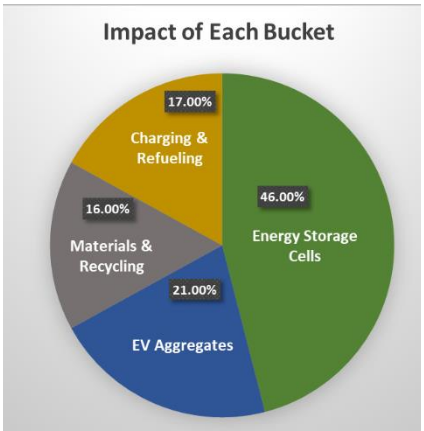

Figure 3: Impact of Each Bucket

Given the high risks of failure as well as high risks of obsolescence, the entire set of projects in general and the Clean Slate R&D items in particular, should be taken up in closely managed special schemes- with strong involvement of Industry Experts as well as Academic Experts. The result of this roadmap is illustrated in Figure 5.

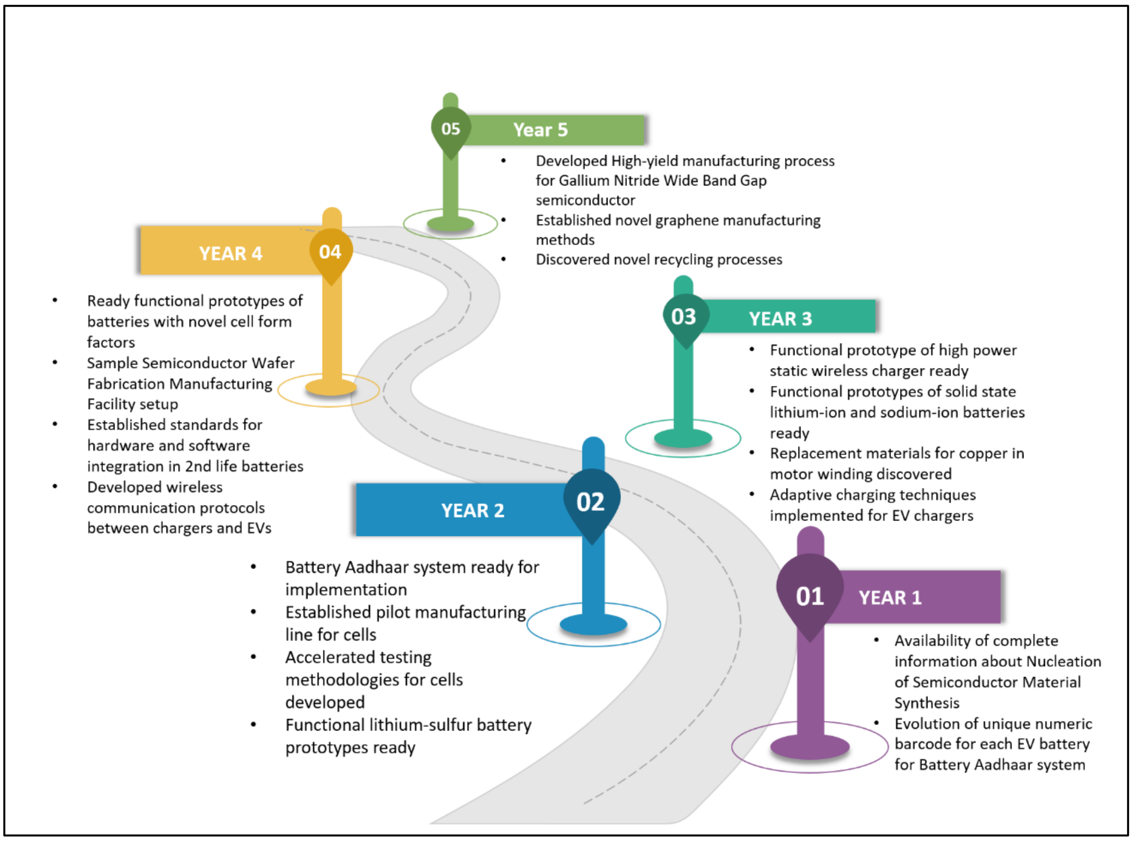

Figure 5: What can be achieved from this Roadmap?

At an Executive level, it can be appreciated that these projects and the RoadMap will need bold initiatives and trust-based collaborations, with constant reviews resulting in decisions on an ongoing basis. There is also a need to constantly identify new ideas and opportunities and enable them with suitable financial and administrative actions under special Programs or Missions or Schemes. A broad level summary of the budgets for the projects are given in Annexure C with clear distribution of budget required for R&D and pilot manufacturing. This distribution aims to ensure that promising research can be effectively transitioned into practical applications.

Contents

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
ACCPLI	Advanced Chemistry Cell Production-Linked Incentive
ARAI	The Automotive Research Association of India
ARCI	International Advanced Research Centre for Powder Metallurgy and New Materials
BARC	Bhabha Atomic Research Centre
BHEL	Bharat Heavy Electrical Limited
BLDC	Brushless Direct Current Motor
BOM	Bill of Materials
BOP	Balance of Plant
CAD	Computer-Aided Design
CAMYEN SE	Catamarca Minera Y Energética Sociedad Del Estado
CAN	Controller Area Network
CCA	Copper-clad aluminium
CCS	Combined Charging System
CDIL	Continental Device India Pvt. Ltd.
CECRI	Central Electrochemical Research Institute
CFD	Computational Fluid Dynamics
CGCRI	Central Glass and Ceramic Research Institute
CGeM	Consultative Group on eMobility
CHAdeMO	Charge de Move
C-MET	Centre for Materials for Electronics Technology
DC	Direct Current
DMRL	Defense Metallurgical Research Laboratory
DST	Department of Science and Technology
EMI	Electromagnetic Interference
EV	Electric Vehicle
FAME-2	Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles-2
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FEA	Finite Element Analysis
GaN	Gallium Nitride
GoI	Government of India
GSI	Geological Survey of India
GWHr	Giga Watt Hours
HVDC	High-voltage direct current
IC	Internal Circuit
IGBT	Insulated-Gate Bipolar Transistor
IISc	Indian Institute of Science
IIST	Indian Institute of Space Science and Technology

IIT	Indian Institute of Technology
IOCL	Indian Oil Corporation Limited
IREL	Indian Rare Earths Limited
ISTI	India Science, Technology and Innovation
KABIL	Khanij Bidesh India Limited
LiB	Lithium-Ion Battery
LIB	Lithium-ion Battery
LiPS	Lithium Poly-Sulfide
Li-S	Lithium-Sulfur
LOHC	Liquid Organic Hydrogen Carriers
MEA	Membrane Electrode Assembly
MHI	Ministry of Heavy Industries
MNRE	Ministry of New and Renewable Energy
MOSFET	Metal Oxide-Semiconductor Field-Effect Transistor
MWHr	Mega Watt Hours
NCL	National Chemical Laboratory
NEERI	National Environmental Engineering Research Institute
NFTDC	Nonferrous Materials Technology Development Center
NIIST	National Institute for Interdisciplinary Science and Technology
NIT	National Institute of Technology
NMET	National Mineral Exploration Trust
ORNL	Oak Ridge National Laboratory
PAMC	Project Advisory and Monitoring Committees
PMSM	Permanent Magnet Synchronous Motors
RF	Radio Frequency
RFID	Radio-Frequency Identification
SiC	Silicon Carbide
SOC	State of Charge
SRM	Switched reluctance motors
TRL	Technology Readiness Level
VSSC	Vikram Sarabhai Space Centre
WBG	Wide Bandgap
WRSM	Wound-rotor synchronous motor

Background

In recent years, the Government of India has launched several programs to promote indigenous R&D and manufacturing capabilities in the country including the 'Make in India' initiative, launched in 2014. The Make in India initiative has been undertaken to promote manufacturing, creating jobs through manufacturing and enhancing investment in the country and making it a global hub for innovation driven growth. Besides, the government of India has undertaken initiatives like 'Atal Innovation mission', which is aimed at promoting innovation and entrepreneurship. Recently the government of India has approved multiple missions and programmes like Green Hydrogen Mission, India Semiconductor Mission, National Quantum Mission etc. with strong focus on enhancing R&D capacities and indigenous manufacturing capabilities to absorb out come of such efforts within India.

As per the current norms for R&D funding by the Government Institutions in India are based on project selection by a nominated Project Advisory and Monitoring Committees (PAMC). Largly such projects are designed and developed by basic understanding of funding organisations and influenced by the competencies and breakthroughs available with principal investigators and research institutes. As a result research outcome of such project, rarely, rise up in Technology Readiness Level and get converted to commercially deployable products. The Department of Science & Technology (DST) has recently released a white paper which offers insight into existing challenges and identifies different topics for future research in the eMobility domain [94]. The Office of Principal Scientific Adviser, through its Electric Mobility Mission has constituted a Consultative Group on E-Mobility (CGeM) consisting of experts from Academia, Industry, Policy makers (Ref. Annexure B) for comprehensively assessing sector requirement and creating a roadmap to provide clear pathways to significant R&D outcomes. This roadmap indicates futuristic R&D projects with implementation strategies while keeping a forward looking approach to satisfy India-specific requirements.

Methodology For Selection of Research Projects

The initiative on drafting an E-Mobility R&D roadmap started under guidance from the advisory committee of CGeM. The working committee, with the help of enthusiastic members of a dedicated Project Management Assistance Unit in ARAI Pune started consultations through virtual and hybrid plenary sessions. Such consultations led to a list of indentified specific areas of research required for achieving self-sufficiency and creating vibrant eMobility sector in India. This list of items was circulated and continually evaluated on various indicators such as dependency on global players, import substitution, enhancing existing capabilities available with academic institutes and government labs, building innovative scaling up capabilities within Indian OEMs and alignment with national priorities, upcoming Missions, PLI schemes etc. The draft list of identified research areas was then further evaluated through filters of novelty, relevance of research through risk of technology adoption and final deployment by industry, defining potential supportive role of the industry and identifying policy gaps and need assessment of supportive policy measure.

Systematically evaluated and finalized list of research areas have been grouped based on domain, existing TRL level and proposed TRL range to cover proposed research project timeline etc. An indicative list of execution agencies is created based on references available from the ISTI / DST website and also following the suggestions from CGeM members. This list is quite wide-ranging and may keep progressing and be updated with time based on the available database. Each research project is carefully assessed for the risk involved and the same is defined in terms of risk for Industrialization, Obsolescence, available Market and Technology. Utmost care has been taken to do horizon scanning and ensuring the proposed areas of research do not lead to duplicity of existing successful efforts. The research projects are summarized in Table 1. Methodology and deliverables are specified based on the TRL range and other technical considerations.

Summary of Research Projects

Table 1: Summary of Research Projects

SN	Broad Area/ Bucket	Project Name	Range of Technology Readiness Level- Start TRL to End TRL	Project Duration (Months)	Risk (Percentage)				Project Priority	Details
					Industrialization	Obsolescence	Market	Technology		
1.1	Energy Storage Cells	Semi-Solid Electrolytes for Lithium-ion Batteries	2 to 8	30	Medium	Medium	Medium	Low	Moderate	Details
1.2		Research on Advanced Liquid Electrolytes for Lithium-ion Batteries	2 to 5	24	Medium	Medium	Medium	Low	Moderate	Details
1.3		Solid-State Electrolytes for High Energy Lithium-ion Batteries	2 to 8	36	Medium	Medium	Medium	High	High	Details
1.4		New Paradigm Separators for Lithium-ion Batteries	2 to 5	48	Medium	Medium	Medium	Medium	High	Details
1.5		Highly Accelerated Testing of Cells	2 to 6	24	Low	NIL	Medium	Medium	High	Details
1.6		AI-Enabled Discovery of Cell Materials	2 to 5	36	Medium	Low	Medium	Medium	High	Details
1.7		Novel Fire Suppressant Materials for High Energy Lithium-ion Batteries	2 to 4	36	Low	NIL	Medium	Medium	High	Details
1.8		Innovation of Lithium-Sulfur Battery Technology	2 to 5	24	High	Medium	Medium	Medium	High	Details

1.9		Surface Engineering and Material Synthesis of Anode Materials via Dry Coating for Enhanced Energy Storage in Sodium-Ion Batteries	2 to 7	35	Medium	Medium	Medium	Medium	Moderate	Details
1.10		Optimizing Cathode and Anode Electrolyte Interfaces for Enhanced Performance in Sodium-Ion Batteries	2 to 5	18	Medium	Medium	Medium	Medium	High	Details
1.11		Design and Development of Manufacturing Line and Equipment for Next Generation Battery Chemistries	1 to 5	24	NIL	Medium	High	High	High	Details
1.12		Innovation of Solid-State Electrolytes for High Energy Sodium-ion Batteries	2 to 5	36	High	Medium	Medium	High	High	Details
1.13		Research on Aluminium-ion Battery Technology	2 to 5	48	High	Medium	Medium	High	High	Details
1.14		Innovation of Novel Battery Cell Form Factors for Electric Vehicles	1 to 5	48	High	Medium	Medium	High	High	Details
2.1	EV Aggregates	Replacement of Copper with Alternative Material or its alloy for Winding of Electric Motor	2 to 5	36	High	Medium	Low	Medium	High	Details
2.2		Research on Non-Rare Earth material of Permanent Magnet	2 to 5	36	High	Medium	High	Medium	High	Details
2.3		Research on Manufacture Toolchain and Equipment for Manufacturing of Power Semiconductor (MOSFET, IGBT, SiC etc) in India	2 to 6	36	Medium	Medium	High	Medium	Moderate	Details
2.4		Nucleation and Growth Mechanisms in Semiconductor Material Synthesis and Manufacturability	NA	6	Medium	Medium	Medium	Medium	High	Details
2.5		Design and Development of a High-Voltage DC Inverter (more than 800V) with Advanced Power Electronics and Control Technologies	3 to 8	24	Medium	Medium	Medium	Medium	Moderate	Details
2.6		High-Yield Manufacturing Process for GaN WBG Semiconductor	2 to 5	60	Medium	High	Low	Medium	High	Details

2.7		Novel Thermal Management System for Battery Pack	2 to 5	24	Medium	Medium	Medium	High	Moderate	Details
2.8		India-Centric Identification of Phase Change Material for Thermal Management System	2 to 5	36	Medium	Medium	Low	Medium	High	Details
2.9		Enhancing Efficiency in High-Speed Electric Vehicle Propulsion Systems through Motor Control Optimization	2 to 5	24	Medium	Medium	Low	Medium	Moderate	Details
3.1	Materials & Recycling	Research on Competitive Manufacturing Methods of Graphene	2 to 5	60	High	NIL	Medium	High	High	Details
3.2	Materials & Recycling	Research on Novel Material Composition for Battery Pack and Cell Casing	3 to 5	24	High	Medium	High	Medium	Moderate	Details
3.3	Materials & Recycling	Research on Novel Recycling Processes other than Hydro/Pyro Metallurgy Processes	1 to 5	60	High	NIL	Medium	High	High	Details
3.4	Materials & Recycling	Development of Battery Aadhaar System	2 to 5	18	Medium	NIL	Medium	Medium	High	Details
3.5	Materials & Recycling	Standardizing Hardware and Software Integration for Second Life Applications of EV Battery	2 to 5	18	High	Medium	Medium	High	Moderate	Details
3.6	Materials & Recycling	Magnet Reuse and Recycling and its impact on developing magnets for new applications.	2 to 5	24	High	Medium	Medium	High	High	Details
4.1	Charging & Refuelling	Research on High Power Density Static Wireless Charging System	2 to 5	36	High	NIL	Medium	Medium	High	Details
4.2	Charging & Refuelling	Research on Far-Field Wireless Power Transfer System	1 to 5	36	High	Low	High	High	High	Details
4.3	Charging & Refuelling	Research on Dynamic Charging System for EV	2 to 5	36	High	Low	High	High	Moderate	Details

4.4		Research on Adaptive Charging Techniques	2 to 5	36	Medium	NIL	Medium	Medium	High	Details
4.5		Research on Wireless Communication Protocols for EV	2 to 5	36	Medium	NIL	Medium	Medium	High	Details
A.1	Hydrogen	Research on Design Optimization of Bipolar Plates of Fuel Cell Stack	2 to 7	36	Medium	Medium	Medium	Medium	High	Details
A.2		Research on Novel Membrane Materials and Structures for Enhanced Fuel Cell Efficiency	3 to 5	48	Medium	Medium	Medium	Medium	High	Details
A.3		Liquid Organic Hydrogen Carriers (LOHC) Storage Technology for Fuel Cell Electric Vehicles	3 to 5	24	Medium	Medium	Medium	High	High	Details
A.4		Development of New Sealing Methods for Components Deployed in BoP	2 to 6	36	Medium	Medium	Medium	High	Moderate	Details
A.5		Design and Development of Components Deployed in Balance of Plant	2 to 7	24	High	Medium	Medium	High	High	Details
A.6		Research on Communication Protocols for H2 Filling Station	2 to 5	24	Medium	Low	Medium	Medium	High	Details

Legends of section: "Summary of Research Projects"
High Project priority: Green
Moderate Project priority: Orange

How to use this Document?

1. The document, based on proposed research project groups, is divided in 4 broad chapters namely Energy Storage Cells, EV Aggregates, Materials and Recycling and Charging and Refueling. Considering that there is a dedicated Green Hydrogen Mission, hydrogen associated research areas are not detailed out. However, Annexure A provides a brief overview of the R&D requirements for the Hydrogen.
2. Research projects on various sub-topics have been identified under the respective broad areas or buckets mentioned above. The list of these research projects is summarized in Table 1.
3. This table presents a structured overview of various projects, each categorized under specific broad areas or buckets. For each project, information is provided, including the project name

and the range of Technology Readiness Levels (TRL), which signifies the stage of technological development and maturity.

4. The project duration column specifies the estimated time required to complete each project. The tentative budget outlines the financial resources expected to be allocated. The risk column provides a multifaceted assessment of potential risks related to industrialization, obsolescence, market conditions, and technological challenges.
5. Project priority indicates the strategic importance or urgency of the projects. Additionally, the "Details" column will direct readers to the specific one or two pages in the document where further details about each project can be found.

The timeline for the project was decided by dividing the project into tasks and phases and by taking a cue from the government portals like DST, ISTI, MNRE etc. Various aspects like risk management, resource planning and the complexity of the project were also considered. The inputs from various executive agencies, industrial experts, CGeM members, and experts from research institutions were also noted while deciding the timeline.

It is pertinent to mention here that the proposed research projects in this roadmap have not yet been completed globally, hence risks are high and timelines are long as it will involve exploratory and trial-based work. Risks of failure have been emphasized for sustainable development. The risks for the project were determined based on the following four parameters viz Industrialization, Obsolescence, Market and Technology Risk. The level of the risk was decided based on the perception of the current status of technology, manufacturing equipment or supply chain availability. A project risk identified does not tell us if the timeline will be achieved or if it will be completed within the indicated budget. Interpretation of risks is mentioned below:

a. **Industrialization Risk**: This risk reflects the likelihood of the technology not reaching mass production and application in the field for different reasons. This risk can be diverse and complex, making it essential for manufacturing companies to identify, assess and mitigate them effectively.

NIL risk -No risks are foreseen in industrialization of this technology after the R&D phase.

Low risk: There are high chances of competitive manufacturability with no major challenges for equipment procurement, cost management/control or process engineering.

Moderate risk: While the technical and operational aspects of Industrialisation are not expected to be hurdles, there are likely to be competitive and economic issues. Project requires continuous monitoring.

High risk: The possibility of productionisation is dependent on new types of equipment and processes with very limited clarity on competitive and economic issues. Project requires continuous monitoring.

b. **Obsolescence Risk:** This is the risk of the project becoming redundant due to the development of better /alternate technologies, or other innovations that can render the project irrelevant.

NIL risk: The technology and project outcome is sure to find technical, operational and commercial relevance in eMobility.

Low risk: There are low chances of technology to become obsolete- no other parallel competing technologies are identified and this project outcome will always be a desired output.

Moderate risk: Development of other technology which is superior to this project outcome or alternate technologies in the value chain which eliminates the need for this project. Project to be reviewed regularly by experts who are aware of global benchmarks and developments.

High risk: There is an outside chance of alternate technologies either at the project level or at the next value chain level rendering this project irrelevant and unnecessary. Project to be reviewed regularly by experts who are aware of global benchmarks and developments.

c. **Market Risk:** The development of new technology can come down to several external factors including customer sentiment and economic conditions. Often, timing is critical when introducing an innovative technology into the market.
NIL risk: There is every possibility for this project to be successful in the market, in terms of operational, industrial and economic success.
Low risk: The project is very likely to offer sufficient value to users in the market with no specific concerns on the competitive nature of the solution.
Moderate risk: The outcome of the project, even if technically acceptable, is likely to face economic and competitive pressures.
High risk: The cost and value offered by the project outcome has an outside chance of not being competitive for the market- project requires continuous monitoring for relevance.

d. **Technology Risk:** This risk reflects the inability of the project to deliver on its targets and outcomes as proposed due to currently unidentified blind spots (unknown unknowns).
NIL risk: There is every possibility for this project to finish successfully in terms of the metrics and targets.
Low risk: There is a high chance of the project meeting its targets with possible deviations on time and budget.
Moderate risk: There is a possibility of some of the metrics and targets not being met in full-resulting in a sub-optimal and possibly uncompetitive project outcome.
High risk: All the project targets have potential for failure or partial success only.

Certain key aspects related to the proposed administrative mechanism are highlighted for each project. Projects with TRL range from 2 to 5, it is expected that research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from industry. From TRL-6 onwards to TRL-8, the industry shall take the lead in commercial activities and production. For critical research projects with very high risk in achieving targets, the estimated budget is divided equally between two or more parties for research & development and a separate budget is assigned for pilot manufacturing. The budget distribution mechanism according to TRL level is illustrated in Figure 1. The priority for each project is also defined for planning and phasing of funds. Priority is also assessed based on the dependency on other project's outcomes. Periodic, fair, transparent, and smart assessments are essential to determine whether to continue or terminate a project. This roadmap will need to be revised in future to incorporate future technological advancements.

Priority for research projects was assigned based on their potential impact on achieving national energy independence, the feasibility of implementation within the set timelines, and their ability to leverage existing infrastructure and resources. High priority is given to projects that address critical gaps, have immediate applicability, and align with strategic goals such as reducing petroleum/lithium imports and enhancing grid stability. Moderate priority is assigned to projects that are essential but have longer-term impacts or require more extensive development and investment.

The process of determining budget estimates for the projects is meticulously crafted, drawing insights from multiple sources. Primarily, suggestions from CGeM members formed a foundational basis. Furthermore, extensive discussions were conducted with relevant industry players, ensuring a comprehensive understanding of the financial landscape. Additionally, valuable references were gleaned from the ISTI/DST online portal, providing information about previous ongoing projects funded by the Government of India. The estimated budget is also inclusive of new equipment required for the projects.

The budget figures mentioned in this document are indicative and final costs may vary depending on the propsals received from research organisations. The topics of some research projects are very urgent and possess high priority, hence it is worth involving multiple parties in the same research project to ensure a high success rate. Hence, the estimated budgetary funds are considered by multiple parties. The estimation of budgetary funds is also influenced by technological risks identified for each project. The estimated budget breakup with a timeline is given in Table 2.

Table 2: Estimated yearly budget breakup with timeline

Buckets & Topics		Expected Timeline and Estimated Cost Breakup (in INR Crores (Cr))					Total Estimated Cost (INR Crores (Cr))
		Year 1	Year 2	Year 3	Year 4	Year 5	
Energy Storage Cells	Semi-Solid Electrolytes for Lithium-ion Batteries		8.3	8.3	8.4		25
	Research on Advanced Liquid Electrolytes for Lithium-ion Batteries		1.5	1.5			3
	Solid-State Electrolytes for High Energy Lithium-ion Batteries	16.6	16.7	16.7			50
	New Paradigm Separators for Lithium-ion Batteries	7.5	7.5	7.5	7.5		30
	Highly Accelerated Testing of Cells	10	10				20
	AI Enabled Cell Chemistry Discovery System	3.3	3.3	3.4			10
	Innovation of Lithium-Sulfur Battery Technology	30	30				60
	Surface Engineering and Material Synthesis of Anode Materials via Dry Coating for Enhanced Energy Storage in Sodium Ion Batteries		6.67	6.66	6.67		20
	Optimizing Cathode and Anode Electrolyte Interfaces for Enhanced Performance in Sodium-Ion Batteries	4	4				8
	Design and Development of Manufacturing Line and Equipment for Next Generation Battery Chemistries	50	50				100
	Innovation of Solid-State Electrolytes for High Energy Sodium-ion Batteries	10	10	10			30
	Research on Aluminium-ion Battery Technology	13.33	13.33	13.34			40
	Novel Fire Suppressant Materials for High Energy Lithium-ion Batteries	3.4	3.3	3.3			10
	Innovation of Novel Battery Cell Form Factors for Electric Vehicles	7.5	7.5	7.5	7.5		30

EV Aggregates	Replacement of Copper with Alternative Material or its alloy for Winding of Electric Motor	5	5	5			15
	Research on Non-Rare Earth Material of Permanent Magnet	2	2	2			6
	Research on Toolchain and Equipment for Manufacturing of Power Semiconductor (MOSFET, IGBT, SiC etc.) in India		83.34	83.33	83.33		250
	Nucleation and Growth Mechanisms in Semiconductor Material Synthesis and Manufacturability	0.5					0.5
	Design and Development of a High-Voltage DC Inverter (more than 800V) with Advanced Power Electronics and Control Technologies			2.5	2.5		5
	High-Yield Manufacturing Process for GaN WBG Semiconductor	30	30	30	30	30	150
	Novel Thermal Management System for Battery Pack		7.5	7.5			15
	India-Centric identification of Phase Change Material for Thermal Management System	10	10	10			30
	Enhancing Efficiency in High-Speed Electric Vehicle Propulsion Systems through Motor Control Optimization		1.25	1.25			2.5
Materials & Recycling	Research on Competitive Manufacturing Methods of Graphene	20	20	20	20	20	100
	Research on Novel Material Composition for Battery pack Casing		5	5			10
	Research Novel Recycling Processes other than Hydro/Pyro Metallurgy Processes	8	8	8	8	8	40
	Development of Battery Aadhaar System	0.4	0.4				0.8
	Standardizing Hardware and Software Integration for Second Life Applications of EV Battery			0.425	0.425		0.85
	Magnet Reuse and Recycling and its Impact on Developing Magnets for New Applications	10	10				20
Charging & Refuelling	Research on High Power Density Static Wireless Charging System	6.67	6.67	6.66			20
	Research on Far-Field Wireless Power Transfer System	3.33	3.34	3.33			10
	Research on Dynamic Charging System for EV		6.67	6.67	6.66		20
	Research on Adaptive Charging Techniques	3.33	3.33	3.34			10
	Research on wireless communication protocols for EV		3.34	3.33	3.33		10
Total Budget per Year (in INR Cr)		**254.860**	**377.940**	**276.535**	**184.315**	**58.000**	-
Total Budget (in INR Cr)		**1151.650**					

Legends of section: “Expected Timeline and Estimated Cost Breakup (in INR Crores (Cr))”

High Project priority: Green

Moderate Project priority: Orange

*For simple understanding, each project has been assigned an evenly distributed annual funding cost.

Chapter 1: Energy Storage Cells

1.1 Introduction

Energy storage cells, commonly known as batteries, are a foundation of modern technology, offering versatile and efficient electrical energy storage and delivery. Various battery chemistries cater to diverse applications; lithium-ion batteries power smartphones and electric vehicles, lead-acid batteries serve automotive starting systems and backup power, and nickel-based batteries contribute to portable electronics and hybrids. Currently, the research is focused on the discovery of novel cell chemistries which may prove to be potential candidates to replace lithium-ion batteries.

Energy storage cells are crucial for addressing modern challenges, enabling efficient use of intermittent renewable energy sources, and advancing electric vehicle adoption. Ongoing research aims to enhance energy density, cycle life, and safety, with emerging technologies. These cells have revolutionized energy utilization, making devices portable, facilitating renewable energy integration, and promoting sustainable transportation, with an increasingly pivotal role in our evolving energy landscape and a more efficient, sustainable future.

1.2 Current Scenario in India

For the last two years, because of localization FAME-2 subsidy, OEMs have been importing the cells from other countries and manufacturing and integrating the battery packs in India. Various research institutions/organizations in India are working on scaling up and commercialization of existing and novel cell chemistries.

Currently, India's growing electric vehicle sector heavily depends on lithium imports, sourced from other countries. Intending to achieve a 30% electric vehicle adoption rate by 2030, the Indian government recognizes the importance of lithium in this endeavor. As a result, the exploration of lithium deposits has garnered significant attention. To reduce the import of lithium, the Geological Survey of India (GSI) initiated numerous lithium-focused projects in various regions. Also, many research institutes and organizations in India are currently exploring novel cell chemistries such as Sodium-ion, Lithium-air, Aluminium-air, Lithium-sulfur, Sodium-air, and Zinc-air etc. which may act as potential replacements for lithium-ion batteries.

In order to meet the rising demand for lithium and remove the dependence on imports, there is a need to discover more lithium reserves in India. Recognizing the significance of discovered lithium reserves, the Indian Parliament recently passed a bill amending the Act. The 2023 Amendment of the Mines and Minerals (Regulation and Development) Act, 1957, marks the first instance where private parties are permitted to conduct exploration for certain identified minerals. Previously, this Act did not authorize private entities to engage in initial exploration efforts for essential minerals like lithium, cobalt, graphite, gold etc. These activities were exclusively conducted by government entities using public resources.

1.3 Research Pathways

1.3.1 Existing Lithium-ion batteries

Lithium-ion batteries, while widely used in various applications, face several key challenges. Safety concerns related to thermal runaway and the potential for fires or explosions persist, demanding ongoing research into safer electrolytes and cell designs. Also, limited energy density and capacity, constrain their use in long-range electric vehicles, necessitating advancements in electrode materials and energy storage technologies. Whereas, resource availability, safety, performance and environmental impacts associated with lithium mining and disposal raise sustainability concerns, driving efforts to develop more sustainable battery materials and recycling methods.

1.3.1.1 Discovery of Lithium Reserves in India

India's lithium reserves, relatively limited compared to other nations, have shown promise with recent discoveries. The Geological Survey of India initiated projects in various states, confirming a 5.9-million-ton reserve in Jammu & Kashmir and a larger one in Rajasthan's Degana region [1]. These reserves might satisfy 80 per cent of India's lithium demand, but further exploration and sustainable mining methods are needed. The National Mineral Exploration Trust (NMET) also identified significant lithium deposits in Jharkhand's Koderma and Giridh districts and is exploring mining potential in East Singhbum and Hazaribagh. The Ministry of Mines, Government of India, has reached a significant milestone by signing an agreement between Khanij Bidesh India Limited (KABIL) and Cantamarca Minera Y Energética Sociedad Del Estado (CAMYEN SE), a state-owned enterprise of Canatmarca province, Argentina, on January 15, 2024. This agreement grants KABIL the exploration and exclusivbity rights for five blocks to assess, prospect, and explore for lithium minerals [2].

These discoveries are significant in light of the global demand for lithium-ion batteries, driven by the growing adoption of electric vehicles and renewable energy storage solutions. The process of finding more reserves in India need to be accelerated considering the government initiatives such as Advanced Chemistry Cell Production-Linked Incentive (ACCPLI) scheme under which the government is giving production-linked incentives to cell manufacturers. Hence, there is an urgent need for the raw materials to be ready for the manufacturers, to start manufacturing cells in India.

Also, successful development will necessitate partnerships, infrastructure development, investments in mining technologies, and collaboration with domestic and international stakeholders to harness this valuable resource while considering environmental and social impacts.

1.3.1.2 Extraction of raw material from discovered lithium reserves

The extraction of raw lithium material from reserves involves several stages: exploration and assessment, drilling and sampling, mining, crushing, and beneficiation. Environmental considerations are crucial to minimize impacts, followed by its integration into supply chains for various industries. However, the extraction process varies depending on the type of deposit. Technological advancements and sustainability concerns are influencing the development of more efficient and environmentally friendly extraction methods. India can implement globally available, established extraction technologies for the extraction of lithium from the discovered deposits.

1.3.1.3 Raw Material Process Base

Extraction processes such as pegmatite mining, concentration, roasting, acid treatment, solar evaporation, and direct extraction are generally applicable to various types of lithium-bearing ores and deposits, including those found in India. However, the suitability and feasibility of each process depend on the specific characteristics of the lithium ores in India.

Successful implementation of these processes also depends on factors like economic feasibility, environmental impact, technological advancements, and the presence of associated minerals or impurities affecting extraction. Ongoing developments in extraction technologies, like direct lithium extraction, offer the potential for more efficient and sustainable alternatives in the future, however, India can utilize existing established technologies for the extraction of lithium from the discovered reserves.

1.3.1.4 Material supply chain establishment

The establishment of a robust and efficient supply chain will be crucial for effectively optimizing the production and delivery process of lithium to the battery manufacturers. Existing supply chain strategies implemented in other domains can be utilized in effective supply chain management of lithium battery/cell production.

1.3.1.5 Electrode Materials

Developing effective electrode materials for lithium-ion batteries also poses several challenges. One of the primary issues is the limited capacity of traditional graphite anodes, which can hinder battery performance and energy density [3]. Silicon anodes, while promising higher capacity, face challenges related to severe volume expansion during cycling, leading to structural degradation [4]. The formation of lithium dendrites on anode surfaces is another significant challenge, as it can cause safety concerns and reduce battery lifespan [3]. Additionally, ensuring a stable and efficient cathode material with high energy density while minimizing cost and environmental impact remains a complex task [5]. Researchers from various Indian research institutions/organizations are actively addressing these challenges through various material innovations and engineering solutions to enhance the overall performance, safety, and longevity of lithium-ion batteries.

1.3.1.6 Electrolytes

Electrolytes are one of the vital components in lithium-ion batteries, facilitating the movement of lithium ions during charge and discharge cycles. While electrolytes offer advantages like high energy density, good ionic conductivity, wide operating temperature range, and compatibility with various electrode materials, they also pose significant challenges. One key concern is their flammability, as many organic solvents used in electrolytes can ignite, creating safety risks. Researchers are exploring non-flammable alternatives like solid-state electrolytes to address this issue [6]. Moreover, electrolyte degradation over time can reduce battery performance and lifespan, requiring efforts to improve stability and prevent the formation of problematic thick solid electrolyte interfaces (SEIs) [7]. Overcoming these challenges by researching and innovating novel electrolyte materials is critical for advancing lithium-ion battery technology in India.

Internationally, many universities/institutes are working on novel materials, solid-state batteries etc. Notably, a Germany-based start-up has developed a solid-state battery for large-scale production [8] [9]. In Spain, the Basque Government has approved a considerable capital investment in the start-up BASQUEVOLT with the aim of producing 10 GWh of solid-state batteries by 2027 [10]. A US-based company has recently unveiled its patented direct deposition separator technology, which could replace conventional film separators and deliver incremental improvements in safety and performance [11].

Proposed Research Project- 1.1

Semi-Solid Electrolytes for Lithium-ion Batteries

1. **Gap Analysis & Background**
   This project aims to improve lithium-ion battery performance and safety by developing novel semi-solid electrolytes. By addressing key challenges related to flammability, stability and limited energy density in conventional liquid electrolytes, this project seeks to pave the way for safer and more efficient lithium-ion batteries.

2. **Global Benchmarking**
   Conventional liquid electrolytes are flammable in nature, this affects the safety of the lithium-ion batteries. Hence, semi-solid electrolytes are being explored as a safer alternative. Companies such as Ionic Materials and 24M Technologies have commercialized semi-solid polymer-based electrolyte technology for lithium-ion batteries. [12] [13]

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-8

4. Research Goal

To research and develop novel semi-solid electrolyte materials that improve the energy density and safety of lithium-ion batteries.

5. Targets for Project

a. Develop semi-solid electrolyte materials that significantly reduce the risk of thermal runaway and fire hazards in lithium-ion batteries
b. Achieve energy density of 300 Wh/Kg or more
c. Achieve an increase in cycle life for available technologies
d. Ensure that semi-solid electrolytes can operate within a temperature range of -20°C to 80°C
e. Develop scalable and cost-efficient manufacturing processes to facilitate the commercial adoption
f. Cost of energy cells using semi-solid electrolytes must not exceed the existing cell prices

6. Methodology

The following tasks are involved in achieving the targets:

a. Benchmark and identify potential semi-solid electrolyte materials
b. Develop and optimize synthesis methods for selected materials considering factors like scalability and cost-effectiveness
c. Fabricate electrolyte samples for testing
d. Characterize the samples
e. Assemble small-scale lithium-ion battery prototypes for testing the suitability of developed semi-solid electrolytes
f. Conduct thorough testing to assess the performance of prototypes
g. Analyze the collected data to identify areas for improvements and optimize the electrolyte composition, fabrication methods or battery design if needed

7. Deliverables

The following are the proposed deliverables of this activity:

a. Semi-solid electrolyte materials with an improved energy density of or more than 300 Wh/Kg
b. Functional battery prototypes supporting a temperature range of -20°C to 80°C
c. Usable Experimental dataset and advanced analytics
d. Scalability plans for commercial adoption
e. Detailed design and specifications for cells - Pouch, Prismatic and cylindrical cell form factors
f. Target compliance report

8. Impact

a. Semi-solid electrolytes are less prone to leakage and thermal runaway, making lithium-ion batteries safer
b. These electrolytes can enable higher energy density and better cycle-life, leading to longer-lasting batteries

9. Indicative list of Execution Agencies

a. CSIR-Central Electro Chemical Research Institute (CSIR-CECRI), Tamil Nadu
b. SRM University, Tamil Nadu
c. Indian Institute of Technology (IIT), Hyderabad
d. Indian Institute of Technology (IIT), Jodhpur, Rajasthan
e. Indian Institute of Technology (IIT), Madras
f. Indian Institute of Space Science and Technology (IIST), Thiruvananthapuram

10. Timeline: 24-30 months

11. Estimated Budget: ₹20 - 25 Cr

Research & Development: ₹20 Cr (Divided equally between two parties)
Pilot Manufacturing: ₹5 Cr

12. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market		✓		
Technology		✓		

13. **Priority:** Moderate

14. **Administrative Mechanism**
For projects lying in the range of TRL-2 to 5, research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from the industry and for TRL-6 to TRL- 8, the industry should take the lead for commercial production. This project has been assigned moderate priority so that it receives attention without overshadowing the development of solid-state electrolytes which exhibit the potential to greatly enhance the safety and energy density in the near future. However, the development of semi-solid electrolytes will be a crucial step taken to increase the energy density, in case, if the solid-state technology fails to commercialize. The estimated budget of ₹20 Cr is divided equally between two parties for research & development and ₹5 Cr is assigned for pilot manufacturing.

Proposed Research Project- 1.2

Research on Advanced Liquid Electrolytes for Lithium-ion Batteries

1. **Gap Analysis & Background**
The prevalent use of liquid electrolytes presents significant challenges, including safety concerns, limited energy density, and slow charging times. This project delves into the development of advanced liquid electrolytes, aiming to bridge these gaps and unlock safer, higher-performing battery technology.

2. **Global Benchmarking**
Researchers are currently investigating electrolyte formulations capable of withstanding high voltages in order to increase energy density. Furthermore, research is also focused on optimizing ionic liquids to enhance battery performance and safety. Various additives and solvents are also being explored to improve electrolyte properties. [14]

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-5

4. **Research Goal**
Develop innovative formulations of liquid electrolytes to enhance the performance and safety of lithium-ion batteries.

5. **Targets for Project**
   a. Achieve an energy density of 350 Wh/Kg or more
   b. Enhance safety by developing non-flammable or inherently safer liquid electrolyte formulations
   c. Ensure scalability and compatibility with existing battery manufacturing processes
   d. The cost of the materials used to produce the product must be at least at the commodity level
   e. The supply chain for the material must be sourced entirely from India

6. **Methodology**
   a. Thoroughly research and select candidate materials for liquid electrolyte
   b. Experiment with various electrolyte compositions
   c. Fabricate electrolyte samples for testing
   d. Characterize the samples

e. Integrate the advanced formulations of electrolytes in prototype lithium-ion cells and assess the performance in real-world conditions
f. Conduct thorough testing to assess the performance of prototypes
g. Analyze the collected data to identify areas for improvements and optimize the electrolyte composition, fabrication methods or battery design if needed

7. Deliverables

The following are the proposed deliverables of this activity:

a. Advanced electrolyte formulations with optimized compositions exhibiting increased energy density
b. Experimental data and analysis
c. Scalability plans for commercial adoption
d. Detailed design and specifications for cells - Pouch, Prismatic and cylindrical cell form factors
e. Target compliance report

8. Impact

a. Improved energy density and faster charging times will contribute to enhanced energy efficiency
b. Safer electrolyte formulations will mitigate the risk of thermal runaway and battery fires

9. Indicative list of Execution Agencies

a. CSIR-Central Electro Chemical Research Institute (CSIR-CECRI), Tamil Nadu
b. SRM University, Kattankulathur, Tamil Nadu
c. National Institute of Technology (NIT), Rourkela
d. Indian Institute of Technology (IIT), Hyderabad
e. Central Glass and Ceramic Research Institute (CGCRI), Kolkata, West Bengal
f. Indian Institute of Technology (IIT), Bombay
g. Indian Institute of Technology (IIT), Delhi
h. Indian Institute of Technology (IIT), Madras

10. Timelines: 18-24 Months

11. Estimated Budget: ₹3 Cr

Research & Development: ₹2 Cr

Pilot Manufacturing: ₹1 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market			✓	
Technology		✓		

13. Priority: Moderate

14. Administrative Mechanism

This project is deliverable to TRL-5, hence research institutions and laboratories will participate in developing technologies. This project, while assigned a moderate priority, acknowledges the robust research in liquid electrolytes. The research on safer and non-flammable liquid electrolytes is challenging due to their inherent instability, hence this research project is proposed so that research can be carried out simultaneously while focusing on other aspects of battery technology such as solid-state electrolytes, electrode-electrolyte interfaces etc. An estimated budget of ₹2 Cr is assigned for research & development and ₹1 Cr is dedicated to pilot manufacturing.

1.3.1.7 Novel materials

Various advanced materials are being explored to enhance lithium-ion battery performance. Silicon anodes offer higher capacity, potentially increasing energy density, but face challenges with volume expansion during cycling. Whereas, graphene and carbon nanotubes have proved to enhance conductivity and structural integrity [15]. Metal-organic frameworks (MOFs) have proven to provide high lithium-ion storage, while nanostructured materials offer increased surface area. Nonetheless, the practical implementation of these novel materials must address scalability, cost-effectiveness, and long-term reliability challenges.

Proposed Research Project- 1.3

Solid-State Electrolytes for High Energy Lithium-ion Batteries

1. **Gap Analysis & Background**
   Conventional liquid electrolytes pose critical challenges such as dendrite formation, limited energy density and limited operating temperature range. Solid-state electrolytes are a potential alternative to overcome these limitations. This project focuses on the development of solid-state electrolytes for lithium-ion batteries as they are safer, and offer higher energy densities and resistance to dendrite formation as well as degradation.

2. **Global Benchmarking**
   Solid-state electrolytes are a potential alternative to overcome limitations such as dendrite formation, limited energy density and limited operating temperature range. Companies like QuantumScape have developed scalable solid-state lithium-ion batteries which are safer than conventional liquid electrolytes [16]. Samsung SDI is working on pilot manufacturing of solid-state batteries and is expected to start mass production in the year 2027 [17].

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-8

4. **Research Goal**
   Develop novel solid-state electrolyte materials that improve the energy density and safety of lithium-ion batteries.

5. **Targets for Project**
   a. Achieve an energy density of 500 Wh/Kg or more, using solid-state electrolytes
   b. Achieve an improvement in cycle life as compared to liquid electrolyte technology
   c. Ensure that solid-state electrolytes can operate within a wide temperature range
   d. Achieve faster charging rates as compared to currently existing technologies
   e. Making sure that the solid-state electrolyte technology is compatible with various lithium-ion battery chemistries and designs
   f. Develop scalable and cost-efficient manufacturing processes to facilitate the commercial adoption
   g. The cost of the materials used to produce the product must be at least at the commodity level
   h. The supply chain for the material must be sourced entirely from India

6. **Methodology**
   The following tasks are involved in achieving the targets:
   a. Benchmark and identify potential solid-state electrolyte materials
   b. Develop and optimize synthesis methods for selected materials
   c. Fabricate electrolyte samples for testing
   d. Characterize the samples by employing various analytical techniques
   e. Assemble small-scale lithium-ion battery prototypes using the developed solid-state electrolytes
   f. Conduct thorough testing to assess the performance of prototypes in terms of charge-discharge cycling, capacity measurements, rate capability and thermal stability
   g. Analyze the collected data to identify areas for improvements and optimize the electrolyte composition, fabrication methods or battery design if needed

7. **Deliverables**
   The following are the proposed deliverables of this activity:
   a. Solid-state electrolyte materials with an energy density of 500 Wh/Kg or more
   b. Functional battery prototypes supporting a wide temperature range
   c. Manufacturing equipment for solid-state batteries
   d. Experimental data and analysis

e. Scalability plans
f. Detailed design and specifications for cells - Pouch, Prismatic and cylindrical cell form factors
g. Target compliance report

8. Impact

a. Solid-state electrolytes can lead to performance increase in terms of energy density, cycle life and rate capability of lithium-ion batteries
b. These electrolytes can reduce degradation of battery components, resulting in longer battery life

9. Indicative list of Execution Agencies

a. CSIR-Central Electro Chemical Research Institute (CSIR-CECRI), Tamil Nadu
b. Indian Institute of Technology, Madras
c. SRM University, Tamil Nadu
d. Indian Institute of Science (IISc), Banglore
e. Indian Institute of Technology (IIT), Hyderabad
f. Indian Institute of Technology (IIT), Jodhpur, Rajasthan
g. Indian Institute of Space Science and Technology (IIST), Thiruvananthapuram
h. KPIT Technologies
i. Qpi Volta Technologies

10. Timelines: 24- 36 months

11. Estimated Budget: ₹50 Cr
Research & Development: ₹40 Cr (Divided equally between two parties)
Pilot Manufacturing: ₹10 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market			✓	
Technology				✓

13. Priority: High

14. Administrative Mechanism

For projects lying in the range of TRL-2 to 5, research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from the industry and for TRL-6 to TRL-8, the industry should take the lead for commercial production. Prioritizing this project at a high level recognizes the transformative impact it could have on the performance, safety, and overall capabilities of lithium-ion batteries. An estimated budget of ₹40 Cr is assigned to conduct research & development parallelly between two parties and an estimated budget of ₹10 Cr is assigned for pilot manufacturing.

Proposed Research Project- 1.4

New Paradigm Separators for Lithium-ion Batteries

1. **Gap Analysis & Background**
This project aims to enhance lithium-ion battery technology by developing and optimizing novel separators, vital for battery safety and performance. This project focuses on improving material performance, enhancing energy density, and thermal stability; addressing current limitations in battery technology.

2. **Global Benchmarking**
One of the many functions of the separators is to prevent the dendrites from reaching one electrode to the other electrode, in order to prevent short-circuit. Many researchers across the globe are meticulously researching novel materials that can increase ionic conductivity and safety. For example, PolyPlus Battery has invented a conductive glass separator designed for rechargeable lithium-ion batteries. The researchers identified that thin monolithic glass sheets possess ample flexibility and conductivity. Conductive glass separators can stabilize the battery by preventing dendrites from breaking through the separator [18]. Toray Industries (Japan) has created a non-porous separator for lithium-ion batteries, that could dramatically increase capacity by enhancing the safety of lithium metal anode batteries [19]. General Motors and battery manufacturer Microvast are working together to develop specialized EV battery separator technology. This advanced technology is designed to enhance the thermal stability of EV batteries and work with nearly all types of lithium-ion cells, including graphite, silicon, and lithium-metal anodes and nickel-rich, cobalt-free, lithium iron phosphate-type and high-voltage cathodes [20].

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-5

4. **Research Goal**
To enhance lithium-ion battery performance by innovating novel separators and optimizing their material composition and design.

5. **Targets for Project**
   a. Achieve an increase in ionic conductivity and charging speed as compared to current technologies
   b. Develop separators that demonstrate improvement in thermal stability
   c. Ensure that prototype batteries with novel separators meet safety regulation requirements such as thermal propagation, fire resistance, mechanical integrity etc.
   d. Ensure that novel separators can be integrated seamlessly into existing battery manufacturing processes

6. **Methodology**
   a. Benchmark and identify potential novel separator materials
   b. Develop optimized separator designs
   c. Conduct comprehensive performance testing
   d. Produce prototypes of lithium-ion batteries using the novel separators and assess their performance in real-world conditions
   e. Analyse the data obtained from laboratory testing and real-world performance to measure progress toward the project targets
   f. Implement rigorous quality control measures to ensure consistency and reliability of the separators during production
   g. Continuously gather feedback to refine separator designs and manufacturing processes for ongoing improvement

7. **Deliverables**
   a. Functional prototypes of batteries with novel separators with improved ionic conductivity and charging speed
   b. Material and design specifications
   c. Cost analysis report
   d. Manufacturing integration guidelines
   e. Performance data
   f. Scalability plans
   g. Equipment for manufacturing

h. Target compliance report

8. Impact

a. Novel separators will increase the energy density of lithium-ion batteries
b. Improved safety will result in reduced risk of thermal runaway and battery fire

9. Indicative list of Execution Agencies

a. Indian Institute of Science (IISc), Bangalore
b. National Chemical Laboratory (NCL), Pune

10. Timeline: 48 months

11. Estimated Budget: ₹30 Cr
Research & Development: ₹20 Cr
Pilot Manufactruing: ₹10 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market			✓	
Technology			✓	

13. Priority: High

14. Administrative Mechanism

This project is deliverable to TRL-5, hence research institutions and laboratories will participate in developing technologies, and industries will play a supporting role. Research on separators is important to address the present issue of low ionic conductivity and material performance. An estimated budget of ₹20 Cr is allotted to conduct research & development and ₹10 Cr is dedicated to pilot manufacturing.

Proposed Research Project – 1.5

Highly Accelerated Testing of Cells

1. Gap Analysis & Background

The current challenge in EV battery development lies in the time-consuming nature of traditional testing methods, hindering the rapid advancement of battery technology. The gap in existing approaches highlights the need for an innovative and highly accelerated testing methodology. This project aims to bridge this gap by devising a faster, yet more accurate, testing process to evaluate the long-term durability, safety, and performance of EV battery cells.

2. Global Benchmarking

Various types of tests are currently used globally such as Hybrid Pulse Power Characterisation (HPPC) testing, temperature cycling tests etc. High Precision Coulometry (HPC) is one of the lifecycle tests; its analysis is based on high-accuracy Coulombic Efficiency (CE) measurements of the battery which uses high-precision cyclers. Its measurements provide a reliable estimation of battery lifetime within 3-4 weeks. [21]

3. TRL Level: Starting with TRL-2, deliverable to TRL-6

4. Research Goal

To develop and implement a highly accelerated testing methodology for EV battery cells that significantly reduces the testing time while maintaining accurate and reliable assessment of long-term durability, safety and performance.

5. **Targets for Project**
    a. The system should be able to predict the battery performance after 10,000 cycles; within the time required for 200-300 charge cycles
    b. Achieve a minimum of 80-90 percent reduction in testing time compared to traditional methodologies without compromising accuracy
    c. The testing system should be compatible with all cell chemistries
    d. Develop a testing framework that maintains a high level of reliability in predicting the long-term durability, safety, and performance of the cells
    e. Implement a robust validation framework to ensure the accuracy and consistency of the testing results

6. **Methodology**
    a. Conduct an extensive review of existing research on battery testing methodologies and accelerated testing techniques
    b. Develop a set of accelerated testing protocols based on factors such as cell chemistry, temperature variations, charging/discharging cycles, usage patterns etc.
    c. Build or acquire the necessary testing apparatus to execute the accelerated testing protocols
    d. Implement a robust data collection system to gather relevant metrics during testing. Ensure real-time monitoring and recording to capture dynamic changes
    e. Employ statistical and machine learning techniques to analyse the collected data
    f. Validate the developed methodology by comparing testing results with real-world performance data
    g. Iteratively optimize the testing protocols and methodology based on initial results and feedback
    h. Fine-tune parameters to improve efficiency and address any unforeseen challenges encountered during the testing process

7. **Deliverables**
    a. Accelerated Testing methodology documentation
    b. Testing protocols handbook
    c. Predictive models
    d. Required equipment & tools for testing methodology
    e. Data Analysis toolkit
    f. Validation Reports
    g. Target compliance report

8. **Impact**
    a. Implementation of the methodology can significantly reduce the Time-to-Market
    b. The methodology's focus on accelerated testing without compromising accuracy ensures a more thorough and quick evaluation of battery cell durability and safety

9. **Recommended Execution Agencies**
    a. CSIR-Central Electro Chemical Research Institute (CSIR-CECRI), Tamil Nadu
    b. The Automotive Research Association of India (ARAI), Pune

10. **Timeline:** 24 months

11. **Estimated Budget**: ₹20 Cr
    Research & Development: ₹5 Cr
    Equipment, tools etc: ₹15 Cr

12. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization		✓		
Obsolescence	✓			
Market			✓	
Technology			✓	

13. **Priority:** High

14. **Administrative Mechanism**
From TRL-2 to 5, research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from the industry. Research on Highly Accelerated Testing of Cells recognizes the need to reduce the time required to bring new EV batteries to market, enabling manufacturers to respond more rapidly to consumer demands and technological advancements. The Estimated budget of ₹20 Cr is divided into two parts; ₹5 Cr is assigned for research and development and ₹15 Cr is assigned for equipment, tools etc.

Proposed Research Project – 1.6

AI-Enabled Discovery of Cell Materials

1. **Gap Analysis & Background**
Battery chemistry research traditionally relies on trial-error experimentation, which can be slow and expensive. With the rapid increase of research data, there is a need for advanced tools to analyse and interpret large datasets effectively. The current pace of discovering new cell chemistries is not keeping up with the fast-rising demand of more efficient, and eco-friendly batteries. Developing and manufacturing new battery chemistries can be expensive. There is a need for a cost-efficient process. There is a gap in integrating Artificial Intelligence (AI) into the battery chemistry discovery process to expedite and optimize material selection and design.

2. **Global Benchmarking**
General Motors and Battery Materials Innovator Mitra Chem, together will be developing advanced iron-based cathode active materials (CAMs) by using the potential of AI. Mitra Chem's battery R&D facility can simulate, synthesize and test thousands of cathode-designs monthly. These processes drive significantly shortened learning cycles, enabling shorter time to market for new battery cell formulas [22]. IBM has combined conventional and AI-assisted scientific methods to develop brand-new battery chemistry without using costly heavy metals like cobalt and nickel [23].

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-5

4. **Research Goal**
This research aims to leverage AI algorithms, machine learning techniques, and computational modelling to streamline the identification of optimal cell chemistries, thereby enhancing the efficiency, performance, and sustainability of batteries.

5. **Targets for Project**
   a. Develop advanced AI algorithms capable of rapidly analysing vast time-consuming datasets and implement machine learning models to predict the performance of various cell chemistries in a short period
   b. The AI algorithms should be able to rapidly analyse suitable combinations
   c. Integrate diverse datasets, including experimental results, literature data, and simulation outputs, into a unified database for AI-driven analysis
   d. Design and implement a system for automated experimentation, allowing the AI system to suggest and prioritize experiments for cell chemistry discovery
   e. Achieve a high level of accuracy in predicting cell chemistry performance metrics such as energy density, cycling stability, and charge-discharge efficiency
   f. The AI system should provide optimization recommendations for enhancing specific aspects of cell chemistry, such as material composition and electrode design

6. **Methodology**
   a. Conduct a comprehensive review of existing literature on AI applications in material science, chemistry, and energy storage to understand current methodologies and challenges
   b. Gather diverse datasets related to cell chemistry, including experimental results, literature data, and simulation outputs. Develop a unified database and establish protocols for consistent data integration

c. Design AI algorithms and machine learning models tailored to predict cell chemistry performance and prepare a curated dataset for training the AI models, ensuring it is representative of diverse cell chemistries and experimental conditions
d. Train machine learning models using the prepared dataset and implement rigorous validation techniques to assess model accuracy and generalization
e. Develop interfaces and protocols for integrating the AI system with experimental setups to suggest, prioritize, and analyse experiments
f. Implement automated experimentation protocols based on AI recommendations, allowing for efficient exploration of novel cell chemistries
g. Design and develop a user-friendly interface for researchers to interact with the AI system, providing insights, recommendations, and visualizations.
h. Implement algorithms to provide optimization strategies for improving specific aspects of cell chemistry, such as energy density or cycling stability
i. Establish mechanisms for continuous improvement based on user feedback, advancements in AI technology, and emerging trends in cell chemistry research

7. Deliverables

a. Documentation of the data integration framework, including protocols and methods for collecting, curating, and integrating diverse datasets related to cell chemistry
b. AI algorithms and models
c. Training datasets
d. Trained AI models
e. User Interface prototype
f. Automated experimentation system
g. Optimization strategies module
h. Performance evaluation report
i. Target Compliance report

8. Impact

a. The implementation of the AI-enabled system is anticipated to significantly accelerate the cell chemistry discovery process. By automating tasks, optimizing experiments, and rapidly analyzing data, researchers can explore a broader range of possibilities in a shorter timeframe
b. The AI system's ability to suggest optimized experiments and analyze vast datasets can lead to improved resource efficiency. Researchers can allocate resources more effectively, reducing costs associated with experimentation and accelerating the pace of discoveries
c. Outcome of this tool will help in deciding further research roadmap
d. The optimization strategies provided by the AI system can contribute to the development of innovative approaches for improving specific aspects of cell chemistry, such as energy density, cycling stability, and charge-discharge efficiency

9. Recommended Execution Agencies

a. Indian Institute of Technology, Madras (IITM)
b. Indian Institute of Technology, Kharagpur (IITK)
c. Indian Institute of Technology, Delhi (IITD)
d. Indian Institute of Science (IISc), Bangalore
e. Chennai Mathematical Institute (CMI)

10. Timeline: 36 months

11. Estimated Budget: ₹10 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence		✓		
Market			✓	
Technology			✓	

13. **Priority:** High

14. **Administrative Mechanism**
This project is deliverable to TRL-5, hence research institutions and laboratories will participate in developing technologies. This project is an important initiative because AI-enabled systems will significantly accelerate the cell chemistry discovery process which will immensely help the researchers to rapidly explore a broader range of possibilities in a shorter timeframe. An estimated budget of ₹10 Cr is assigned for this project.

Proposed Research Project – 1.7

Novel Fire Suppressant Materials for High Energy Lithium-ion Batteries

1. **Gap Analysis & Background**
One of the major safety concerns for lithium-ion batteries is the risk of thermal runaway, which can lead to fires and explosions. One of the main causes of this thermal runaway is the formation of internal short circuits caused by the growth of lithium dendrites and the resultant internal short circuits. Currently available fire suppressants face a few challenges such as limited effectiveness, toxicity, negative environmental impact etc. Hence, there is a need to develop novel fire suppressant materials that are highly effective in suppressing fires while being non-toxic and environmentally friendly.

2. **Global Benchmarking**
Ceramic blankets are commonly used for protection above cells and below the lid to delay fire propagation outside the pack. Mica sheets, providing excellent dielectric performance between cells, are often used above modules. Aerogels are gaining global acceptance, with notable adoption from companies like GM, Toyota, and Audi. Encapsulating foams, adopted by Tesla, offer lightweight thermal insulation and structure for cylindrical cell battery packs. For pouch cells, compression pads accommodate cell swelling, with some material suppliers integrating fire protection for a multifunctional solution. [24]

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-4

4. **Research Goal**
To develop and implement novel, environmentally friendly, non-toxic fire suppressant materials for high-energy lithium-ion batteries to enhance safety without compromising performance.

5. **Targets for Project**
    a. Ensure the fire suppressant materials are environmentally friendly and non-toxic
    b. Develop a scalable synthesis method for the identified fire suppressant materials to facilitate the commercial adoption
    c. Ensure that prototype batteries meet safety regulation requirements such as thermal propagation, fire resistance etc.
    d. The developed material should be suitable for deployment in portable canisters for use in 2&3 wheeler applications
    e. The cost of the materials used to produce the product must be at least at the commodity level
    f. The supply chain for the material must be sourced entirely from India

6. **Methodology**
    a. Benchmark and identify potential fire suppressant materials
    b. Develop and optimize synthesis methods for selected materials considering factors like scalability and cost-effectiveness
    c. Perform thermal stability tests to evaluate the effectiveness of the fire suppressant materials
    d. Evaluate thermal stability, conductivity, and compatibility with lithium-ion battery components
    e. Conduct tests and evaluate the environmental impact and toxicity of the developed fire suppressant materials
    f. Optimize the composition and loading of the fire suppressant materials based on the performance and safety evaluation results

g. Develop guidelines for the industrial adoption of the fire suppressant materials in high-energy lithium-ion batteries

7. **Deliverables**
   a. Functional prototypes of batteries with novel fire suppressant materials with improved thermal stability
   b. Material and design specifications
   c. Cost analysis report
   d. Manufacturing integration guidelines
   e. Performance data
   f. Scalability plans
   g. Target compliance report

8. **Impact**
   a. Mitigation of thermal runaway and suppression of fires in high-energy lithium-ion batteries will significantly enhance safety in automotive applications
   b. The development of environmentally friendly, non-toxic fire suppressant materials will reduce the environmental impact associated with lithium-ion batteries

9. **Recommended Execution Agencies**
   a. Centre for Fire, Explosive & Environment Safety- Defence Research & Development Organisation (CFEES, DRDO), Delhi
   b. Fire Engineering Laboratory-CSIR
   c. National Chemical Laboratory (NCL), Pune
   d. Indian Institute of Technology, Madras (IITM)
   e. Indian Institute of Technology, Delhi (IITD)
   f. Indian Institute of Science (IISc), Bangalore

10. **Timeline:** 36 months

11. **Estimated Budget**: ₹10 Cr
    Research & Development: ₹8 Cr
    Pilot Manufacturing: ₹2 Cr

12. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization		✓		
Obsolescence	✓			
Market			✓	
Technology			✓	

13. **Priority:** High

14. **Administrative Mechanism**
    This project is deliverable to TRL-2, hence research institutions and laboratories will participate in developing technologies. This project is a significant initiative as the development of new fire suppressant materials will notably improve the safety of high-energy lithium-ion batteries, making them safer for use in electric vehicle applications. An estimated budget of ₹8 Cr is assigned research & development and ₹2 Cr is dedicated to pilot manufacturing.

1.3.1.8 Cost-Effective Indigenous Resources

To develop cost-competitive resources for lithium-ion batteries in India, a comprehensive approach is essential, encompassing research, innovation, infrastructure, and collaboration. This can be achieved through geological surveys to identify domestic sources of key battery materials, followed by substantial investments in R&D in materials science specifically for battery technology. Additionally, it is essential to concentrate on innovating and optimizing materials, especially those that are abundant in India. To support these efforts, the development of infrastructure, including research centers and specialized labs, is vital. Finally, fostering public-private partnerships between research institutions, academia, and industry will expedite technology development and propel India towards its goal of self-sufficiency in lithium-ion battery materials.

1.3.2 Lithium-Sulfur Batteries

Lithium-Sulfur batteries have emerged as a promising candidate for next-generation energy storage due to their high theoretical energy density and low cost, making them ideal for applications like electric vehicles. These batteries operate on the principle of reversible sulfur redox reactions, where sulfur serves as cathode material. However, Li-S batteries face several significant challenges, including issues related to sulfur's low electrical conductivity, the formation of insulating lithium sulfide deposits, and the need for stable electrolytes, all of which must be addressed to unlock their full potential for practical use.

1.3.2.1 Current Status & Challenges

Lithium-sulfur battery-based chemistry has been identified as a promising technology to achieve the highest energy density compared to current lithium-ion batteries in terms of weight and the utilization of the most abundant sulfur as an active cathode material. It has equally garnered extra attention from academia and industry.

Several challenges persist in the development of Li-S batteries; the inherent low electrical conductivity of sulfur and the dissolution of intermediate polysulfides during cycling can lead to poor charge/discharge kinetics and capacity fading. Enhancing the utilization of sulfur in Li-S batteries is a key challenge. Many sulfur cathodes suffer from low active material utilization, leading to suboptimal energy density. Research is needed to design cathode materials that can fully exploit the theoretical capacity of sulfur and porosity of cathode electrode. Controlling sulfur's behavior in the cathode and mitigating the "shuttle effect" are ongoing challenges. In current lab research the excess use of lithium metal is implemented to maintain the lithium inventory during cycling. The practical cell should use less than 100 percent of lithium metal in thin film form or as a composite with carbon-based materials. Also, the development of stable and efficient electrolytes that can withstand the highly reactive nature of lithium and sulfur is crucial. Finding suitable materials that balance ionic conductivity and chemical stability remains a challenge. Additionally, ensuring the long-term durability and safety of Li-S batteries for use in electric vehicles is essential. In Europe, Stellantis has invested in Lyten's breakthrough lithium-sulfur EV battery technology which has proven to exhibit significant gains in terms of energy density of the batteries [25].

The unavailability of multi-layered pouch cell data and characterization makes it more difficult to understand the technology readiness level. The gap between lab cell characterization and prototype cell development, misinterpretations, and false projections are frequently reported, mostly resulting from excess use of lithium and electrolytes. These challenges require continued research and innovation to make Li-S batteries a practical solution for EV applications.

<u>Proposed Research Project- 1.8</u>

<u>Innovation of Lithium-Sulfur Battery Technology</u>

1. **Gap Analysis & Background**
   Lithium-sulfur batteries currently face several challenges, such as poor cycle life, limited power density, and issues related to sulfur utilization and electrode stability. By leveraging advancements in material science, electrolyte design and electrode architecture, this project seeks to significantly enhance the performance, longevity, and safety of Lithium-sulfur batteries, ultimately making them commercially viable for the automotive industry.

2. **Global Benchmarking**

   Researchers are exploring innovative sulfur cathode designs to enhance sulfur utilization and prevent polysulphide dissolution [26]. Company OXIS Energy has successfully tested its Lithium-sulfur battery cell prototypes. OXIS has also successfully developed a standard Li-S battery module that saves production time and cost. [27]

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-5

4. **Research Goal**

   To develop a stable and high energy density lithium-sulfur battery through novel materials and engineering solutions to address commercial viability and performance limitations.

5. **Targets for Project**
   a. Investigate and develop novel cathode materials and structures to improve the overall energy density (> 350 Wh/kg, 800 Wh/L) and cycle life (>1000 cycles) of Li-S batteries
   b. Enhance the performance and stability of Li-S batteries by developing advanced electrolytes. Research could focus on solid-state electrolytes, ionic liquids, and polymer electrolytes etc. aiming to improve safety and energy density
   c. Explore various sulfur hosts, such as carbon-based materials (e.g., porous carbon, graphene), metal oxides, and polymers, to improve sulfur utilization, prevent polysulfide shuttling, and increase cycle life
   d. Investigate the use of additives and catalysts to mitigate the polysulfide shuttle effect and improve the kinetics of the sulfur cathode, ultimately enhancing the overall performance of Li-S batteries
   e. Develop scalable and cost-efficient manufacturing processes to facilitate the commercial adoption
   f. The cost of the materials used to produce the product must be at least at the commodity level
   g. The supply chain for the material must be sourced entirely from India

6. **Methodology**
   a. Conduct literature review, identify and develop sulfur-based cathode materials and lithium-based anode materials
   b. Develop optimized electrode fabrication techniques, focusing on uniform and high-loading electrode structures
   c. Investigate novel electrolytes to improve stability and conductivity, aiming to suppress polysulfide dissolution and enhance ion transport
   d. Manufacture battery prototypes based on developed materials and designs
   e. Conduct thorough testing to assess the performance of prototypes in terms of energy density, charge-discharge cycling, capacity measurements, rate capability and thermal stability
   f. Continuously refine the battery components and assembly processes based on testing outcomes

7. **Deliverables**

   The following are the proposed deliverables of this activity:
   a. Battery prototypes
   b. Materials and component specifications
   c. Electrode and electrolyte designs
   d. Experimental data and analysis
   e. Equipment needed for manufacturing
   f. Process documentation
   g. Scalability plans
   h. Manufacturing feasibility report
   i. Detailed design and specifications for cells - Pouch, Prismatic and cylindrical cell form factors
   j. Target compliance report

8. **Impact**
   a. Improved energy density and faster charging times will contribute to enhanced energy efficiency
   b. Enhanced cycling stability and longevity could lead to safer and longer-lasting batteries

c. Successful innovation in lithium-sulfur batteries could enable accelerated adoption of this technology in electric vehicles

9. **Indicative list of Execution Agencies**
   a. CSIR-Central Electro Chemical Research Institute (CSIR-CECRI), Tamil Nadu
   b. SRM University, Kattankulathur, Tamil Nadu
   c. National Institute of Technology (NIT), Rourkela
   d. Indian Institute of Technology (IIT), Hyderabad
   e. Central Glass and Ceramic Research Institute (CGCRI), Kolkata, West Bengal
   f. Indian Institute of Technology (IIT), Bombay
   g. Indian Institute of Technology (IIT), Delhi
   h. Indian Institute of Technology (IIT), Madras
   i. Indian Institute of Science (IISc), Bangalore

10. **Timelines:** 18-24 Months

11. **Estimated Budget:** ₹60 Cr
    Research & Development: ₹40 Cr (Divided equally between three parties)
    Pilot Manufacturing: ₹20 Cr

12. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence			✓	
Market			✓	
Technology			✓	

13. **Priority:** High

14. **Administrative Mechanism**
    This project is deliverable to TRL-5, hence research institutions and laboratories will participate in developing technologies. This project is a high priority initiative because innovation in this technology could lead to breakthroughs that address existing limitations, such as cycle life and stability, cost-effectiveness, and propel the development of high-performance, energy-dense batteries. An estimated budget of ₹60 Cr is assigned out of which ₹40 Cr is assigned for research & development which will be equally divided between three parties and ₹20 Cr is assigned for pilot manufacturing.

1.3.2.2 Electrode Materials

One of the primary challenges in electrode materials for lithium sulfur batteries is addressing the low electrical conductivity of sulfur. Sulfur is inherently insulating, which hinders the efficient flow of electrons during charge and discharge cycles, leading to poor performance and limited cycle life. Developing electrode materials that can promote better sulfur utilization while maintaining good conductivity is a major hindrance in making Li-S batteries commercially viable. Researchers are exploring various strategies, including nanostructured materials, conductive additives, and composite structures, to overcome this conductivity issue and enhance the overall performance of Li-S batteries [28].

1.3.2.3 Electrolytes

The major challenge in Li-S battery electrolytes is achieving stability in the presence of reactive sulfur species while balancing ionic conductivity and chemical stability. Sulfur's formation of intermediate lithium polysulfides (LiPS) can trigger the "shuttle effect", causing capacity loss and reduced cycle life. Finding electrolytes that suppress this effect by immobilizing LiPS is crucial. However, striking the right balance between high ionic conductivity and chemical stability remains challenging. Traditional carbonate-based electrolytes react with LiPS, leading to undesired side reactions, while alternative formulations like solid-state and polymer-based electrolytes introduce their own complexities such as electrode-electrolyte interface resistance and dendrite formation respectively [29]. Addressing these challenges is essential for realizing the potential of Li-S batteries and improving their energy density, cycle life, and safety for broader applications.

1.3.2.4 Manufacturing process

Manufacturing lithium-sulfur batteries presents significant challenges, primarily due to the sensitivity of sulfur and the need for precise control of electrode coating. Sulfur's tendency to expand and contract during cycling can lead to electrode degradation and loss of electrical contact. Additionally, the electrolyte's sensitivity to moisture and impurities requires meticulous handling in a controlled environment. Achieving consistent performing and high-loading sulfur cathodes while ensuring uniform electrode structures is complex. Moreover, Li-S battery manufacturing involves multiple assembly steps, each demanding rigorous quality control to avoid contamination and safety risks. Addressing these manufacturing challenges is crucial to achieving reliable, cost-effective, and scalable production of Li-S batteries for commercial applications.

1.3.2.5 Other potential area

Some potential areas of research in lithium-sulfur batteries may include:

1. Electrolyte Design: Creating advanced electrolyte formulations, including solid-state and polymer electrolytes, to enhance both ionic conductivity and chemical stability.
2. Shuttle Effect Mitigation: Finding effective ways to suppress the shuttle effect, such as using functional coatings, porous separators, or selective membranes, to extend cycle life.
3. Scaling Up Production: Developing scalable manufacturing processes and cost-effective electrode and cell assembly techniques to enable mass production for commercial viability.
4. Hybrid Systems: Exploring hybrid battery systems that combine Li-S with other energy storage technologies, like lithium-ion or supercapacitors, to achieve the benefits in terms of both energy density and power output.
5. Modeling and Simulation: Advancing modeling and simulation techniques to better understand Li-S battery behavior, predict performance, and guide material and system design.

1.3.3 Sodium-ion Batteries

Sodium-ion batteries present a promising advancement in energy storage technology. Their cost-effectiveness stems from the abundant availability of sodium resources, offering an economically viable alternative to traditional lithium-ion batteries. Enhanced safety features mitigate thermal runaway risks, ensuring a more secure energy storage solution. However, sodium-ion batteries also face several challenges. Their energy density and cycle life are currently lower than lithium-ion batteries, necessitating research into advanced electrode materials and cell designs. They require the development of suitable high-performance electrolytes that can operate effectively at low temperatures. Also, the availability of sodium resources and sustainable sourcing practices need to be addressed to avoid potential supply chain constraints. Additionally, the development of efficient sodium-ion battery manufacturing processes and scaling up production remains a challenge. Overcoming all these challenges is crucial for the successful adoption of sodium-ion batteries as a viable energy storage solution.

1.3.3.1 Current Status & Challenges

Repurposing the existing infrastructure of lithium-ion batteries for sodium-ion batteries is feasible without the need for a different setup. Researchers have demonstrated promising results using carbon-based materials, showing good specific capacity and extended electrode lifespan. Exploring layered materials like selenide holds the potential for enhancing various parameters, with a particular emphasis on solid electrolytes, given the limited research in the area of sodium-ion batteries in India. Prioritizing advanced electrode materials and standardized investigations into surface kinetics is essential to achieve higher practical specific energies. While sodium-ion battery R&D in India is mainly driven by government institutions, private labs are yet to establish a significant presence in this field. Moreover, there's a scope for improvement in India's progress in solid-state and thin-film methodologies for battery development, warranting focused attention to enhance overall R&D capabilities in sodium-ion battery technology.

KPIT Technologies, an independent software integration partner in the automotive and mobility sector, has unveiled its Sodium-ion battery technology. With promising applications for electric two-wheelers, and commercial vehicles and extends to the marine and defense sectors, more companies are now stepping up to commercialize this battery technology [30]. A Swedish Company named ‘Northvolt’ is making Sodium batteries using Prussian blue analogues cathodes (in collaboration with Altris AB company). They are claiming an energy density of 160 Wh/kg for their Sodium-ion cells, aligning with the range cited by KPIT Pune [31].

1.3.3.2 Electrode materials

Developing effective electrode materials for sodium-ion batteries presents several challenges. One major hurdle is achieving a balance between high energy density and long cycle life. Many promising materials suffer from significant volume changes during charge and discharge, leading to electrode degradation and a decrease in overall performance. Moreover, ensuring the availability of cost-effective and sustainable raw materials for large-scale production is essential. Addressing issues related to limited rate capability and low conductivity in some materials is crucial to enable rapid charge and discharge rates for practical applications, while ensuring the safety of electrode materials, especially under extreme conditions, is a paramount concern.

Proposed Research Project- 1.9

Surface Engineering and Material Synthesis of Anode Materials via Dry Coating for Enhanced Energy Storage in Sodium-Ion Batteries

1. **Gap Analysis & Background**
   Conventional wet coating processes use solvents which are flammable and have variable viscosity which makes it difficult to achieve uniform dispersion of solvents on electrodes. Furthermore, these solvents may induce surface defects after drying which may lead to reduced battery performance. In this context, the project aims to overcome these challenges by utilizing dry coating methods, which involve applying functional coatings onto the surface of anode materials without the need for solvents or wet processes. This approach offers the advantage of precise control over the coating composition, thickness, and distribution, leading to improved electrochemical performance and durability.

2. **Global Benchmarking**
   The researchers are working on the synthesis of carbonaceous materials into the pores of the carbon electrodes for increasing the structural and thermal stability of the anode, thus achieving more desirable, cycling performance and capacity [32]. The use of MXene-TiO_2 as a layer on anodes has increased the surface area significantly which exhibited the highest initial discharge capacity [33].

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-7

4. **Research Goal**
   To utilize innovative dry coating techniques to enhance the energy storage capacity, cycle life, and overall efficiency of sodium-ion battery anode materials.

5. Targets for Project

a. Achieve an energy density of 200 Wh/Kg or more
b. Achieve a longer cycle life of up to 5,000 cycles by deploying coated battery electrodes compared to uncoated electrodes, to ensure prolonged durability
c. The cost of the materials used to produce the product must be at least at the commodity level
d. The supply chain for the material must be sourced entirely from India

6. Methodology

The following tasks are involved in achieving the targets:

a. Study suitable anode materials for sodium-ion batteries
b. Evaluate a range of coating materials
c. Design and optimize dry coating methods and determine optimal coating thickness through systematic experiments
d. Compare coated electrodes against uncoated electrodes in terms of energy density, cycle life, rate capability, and efficiency
e. Perform prolonged cycling tests on coated electrodes to assess long-term stability and degradation patterns
f. Analyze experimental data to draw correlations between coating parameters and electrode performance improvements
g. Ensure the feasibility of integrating dry coating techniques into industrial manufacturing processes

7. Deliverables

The following are the proposed deliverables of this activity:

a. Coated electrode samples along with characterization reports
b. Electrochemical Performance Data
c. Performance Comparison Analysis
d. Long-Term Stability Analysis and production feasibility assessment
e. Target compliance report

8. Impact

a. This project could lead to the development of anode materials with improved performance, increased energy density and cycle life of sodium-ion batteries
b. The use of dry coating techniques will help to reduce manufacturing costs

9. Indicative list of Execution Agencies

a. Indian Institute of Technology (IIT), Jodhpur, Rajasthan
b. Indian Institute of Technology (IIT), Delhi
c. Indian Institute of Technology (IIT), Bombay
d. Indian Institute of Technology (IIT), Madras
e. SRM University, Kattankulathur, Tamil Nadu
f. CSIR-Central Electro Chemical Research Institute (CSIR-CECRI), Tamil Nadu
g. Indian Institute of Technology (IIT), Kanpur
h. Exide Batteries
i. Amar Raja Batteries

10. Timelines: 18-35 Months

11. Estimated Budget: ₹20 Cr

Research & Development: ₹15 Cr
Pilot Manufacturing: ₹5 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market			✓	
Technology			✓	

13. Priority: Moderate

14. Administrative Mechanism

Research institutions/labs and academia will be responsible for developing technologies, with support, engagement, and commitment from industry. Electrode coating methods focus on improving the safety and longevity of electrodes, but at this stage, the primary objective of research on sodium-ion batteries is to obtain energy density equal to or more than currently available lithium-ion batteries. Other parameters such as electrode materials, electrolyte compositions, etc. have more impact on energy density than the coating methods, hence this project has been moderately prioritized so that research on coating methods will continue simultaneously. [34] Estimated budget of ₹15 Cr is assigned for research & development, and ₹5 Cr is allotted to pilot manufacturing.

1.3.3.3 Electrolytes

Electrolytes are pivotal in sodium-ion batteries, playing a major role in ion transport during charge and discharge. Similar to their lithium-ion counterparts, sodium-ion battery electrolytes can be flammable, therefore more research is required in non-flammable alternatives like solid-state electrolytes or ionic liquids. Ensuring the stability of these electrolytes is crucial, as degradation over time can result in diminished battery performance. The formation and management of solid electrolyte interfaces (SEIs) on electrode surfaces are also critical challenges to address [29]. Moreover, temperature sensitivity and the cost of raw materials pose additional hurdles, pushing researchers to develop electrolytes that can operate effectively over a wide temperature range while remaining cost-efficient. Tackling these challenges will be crucial in advancing sodium-ion battery technology, making it a viable alternative for various energy storage applications.

Proposed Research Project- 1.10

Optimizing Cathode and Anode Electrolyte Interfaces for Enhanced Performance in Sodium-Ion Batteries

1. Gap Analysis & Background

Cathode and anode electrolyte interfaces play a significant role in the efficiency of sodium-ion batteries. This project delves into these interfaces to enhance performance, addressing challenges like capacity fading and electrode degradation. By investigating interfacial behavior and proposing innovative solutions, the project aims to unlock higher energy density, longer cycle life, and improved safety for sodium-ion batteries.

2. Global Benchmarking

Current research is focused on improving the interface stability to mitigate the degradation mechanisms such as electrolyte decomposition and formation of SEI layer which can affect the battery lifespan. Researchers have implemented computational modelling for understanding the complex process occurring at the electrode-electrolyte interface. [35]

3. TRL Level: Starting with TRL-2, deliverable to TRL-5

4. Research Goal

To investigate and optimize the cathode and anode electrolyte interfaces in sodium-ion batteries to enhance battery performance in terms of energy density, cycle life and rate capability.

5. Targets for Project

a. Achieve an energy density of 250 Wh/kg by enhancing interfacial interactions
b. Achieve a cycle life of 5000 cycles by addressing capacity fading and electrode degradation issues
c. Improve the rate capability, enabling efficient charging and discharging at high currents
d. Achieve interface enhancements with cost-effective materials and manufacturing processes
e. The cost of the materials used to produce the product must be at least at the commodity level
f. The supply chain for the material must be sourced entirely from India

6. Methodology

The following tasks are involved in achieving the targets:

a. Study suitable cathode and anode materials for sodium-ion batteries
b. Develop electrolyte formulations tailored for enhanced interfacial compatibility with selected electrode materials and evaluate electrode-electrolyte compatibility
c. Assemble prototype sodium-ion cells using optimized cathode, anode, and electrolyte components
d. Conduct thorough safety tests to ensure that the optimized interfaces do not compromise the battery's safety, addressing concerns like dendrite growth and thermal runaway
e. Analyze experimental and simulation results to draw conclusions regarding the effectiveness of the interface optimization strategies
f. Assess scalability and cost-effectiveness of optimized interface engineering methods for potential industrial implementation

7. Deliverables

The following are the proposed deliverables of this activity:

a. Prototype cells with enhanced interfaces
b. Cycle life improvement and safety report
c. Equipment for manufacturing
d. Simulation models
e. Scalability plans
f. Target compliance report

8. Impact

a. Improved interfaces can lead to increased overall battery performance, including higher energy density, better rate capability and longer cycle life
b. The lifespan of batteries can be significantly extended by reducing side reactions and increasing the stability of interfaces

9. Indicative list of Execution Agencies

a. CSIR-Central Electrochemical Research Institute (CECRI), CSIR Madras Complex, Chennai
b. Jawaharlal Nehru Centre for Advanced Scientific Research, Bengaluru
c. Indian Institute of Technology (IIT), Bombay
d. Indian Institute of Technology (IIT), Madras
e. Indian Institute of Technology (IIT), Kharagpur
f. CSIR-Central Electro Chemical Research Institute (CSIR-CECRI), Tamil Nadu

10. Timelines: 12- 18 months

11. Estimated Budget: ₹8 Cr

Research & Development: ₹6 Cr (Equally divided between two parties)
Pilot Manufacturing: ₹2 Cr

12. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market			✓	
Technology			✓	

13. **Priority:** High

14. **Administrative Mechanism**
This project is deliverable to TRL-5, hence research institutions and laboratories will participate in developing technologies. The interfaces between electrodes and electrolytes are responsible for the longevity and effective performance of electrodes. Due to the urgency to achieve a solution to the technical intricacies involved in electrode-electrolyte interfaces for sodium-ion batteries, this project is given a high priority. The solution to the technical intricacies will yield good results in terms of energy density and battery life; two main parameters which will improve the performance of sodium-ion batteries so that they will perform at par with lithium-ion battery technology. An estimated budget of ₹6 Cr is assigned for research & development which will be divided equally between two parties and ₹2 Cr is assigned for pilot manufacturing.

1.3.3.4 Manufacturing process

Manufacturing sodium-ion batteries entails addressing several critical challenges. Ensuring a stable and cost-effective supply of battery materials, especially cathode materials, remains a priority. Precise material processing, safety considerations to mitigate thermal and electrical risks, managing electrode stability with volume changes during cycles, and maintaining consistent cell assembly procedures are central manufacturing concerns. Additionally, developing high-performance and stable electrolytes, implementing rigorous quality control measures, minimizing environmental impacts, and addressing scalability from research to large-scale production are formidable tasks. Manufacturers must also navigate regulatory compliance in an evolving landscape to deliver safe, reliable, and sustainable sodium-ion battery solutions for diverse applications.

Proposed Research Project- 1.11

Design and Development of Manufacturing Line and Equipment for Next Generation Battery Chemistries

1. **Gap Analysis & Background**
This project aims to revolutionize the battery industry by creating advanced production systems and equipment specifically tailored to the manufacturing of cutting-edge battery technologies. This project seeks to bridge the gap between laboratory-scale advancements and their large-scale, cost-effective production. It involves the design and development of specialized manufacturing lines and equipment that can handle the unique characteristics and production requirements of next-generation battery technologies.

2. **TRL Level:** Deliverable to TRL-5 with the capability to demonstrate TRL-9 level in cell manufacturing.

3. **Research Goal**
To design and develop production processes and equipment for next-generation battery chemistries to ensure cost-efficiency, scalability and superior product quality.

4. **Targets for Project**
    a. Design and optimize production processes for various cell form factors and their chemistries
    b. Design and development of equipment needed for specialized manufacturing line
    c. Target throughput rate of 350-500 MWHr per year

5. **Methodology**
   a. Benchmark manufacturing processes and identify the equipment requirements and layout for different advanced cell chemistries and form factors
   b. Design specialized manufacturing equipment such as coating machines, drying ovens, electrode assembly systems etc., tailored to the production needs of the advanced cell chemistries
   c. Develop scalable manufacturing processes such as coating, calendaring, solvent mixing, electrode winding etc. that consider the specific characteristics of the new battery technologies
   d. Implement rigorous quality control measures and testing protocols to ensure consistent and reliable battery cell production that meets or exceeds industry standards
   e. Continuously iterate and refine the equipment and manufacturing processes based on feedback and performance data

6. **Deliverables**
   a. Customizable manufacturing equipment (Designs, BOM, Specifications) for various cell chemistries
   b. Optimized and customizable production processes
   c. Process capability
   d. Supply chain in India
   e. Target compliance report

7. **Impact**
   a. The development of specialized manufacturing equipment and processes can significantly enhance efficiency and boost battery production in India
   b. This project can lead to the design of more streamlined and automated manufacturing lines minimizing potential errors in production
   c. This project can enable better quality control and consistency in battery production in India
   d. Through optimized manufacturing techniques and equipment, the production costs can be lowered
   e. Developing domestic manufacturing capabilities for these batteries can enhance India's supply chain resilience by reducing reliance on foreign sources

8. **Indicative list of Execution Agencies**
   a. International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI)
   b. CSIR-National Chemical Laboratory (NCL), Pune
   c. NFTDC, Hyderabad
   d. Ola Cell Technologies Pvt. Ltd.
   e. ACC Energy Storage Pvt Ltd.
   f. Reliance New Energy Battery Storage Ltd.
   g. Bharat Heavy Electricals Ltd.
   h. Bharat Earth Movers Ltd.

9. **Timelines:** 18-24 months

10. **Estimated Budget:** ₹100 Cr
    Research & Development: ₹20 Cr
    Equipment, tools etc: ₹80 Cr

11. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization	✓			
Obsolescence			✓	
Market				✓
Technology				✓

12. **Priority:** High

13. Administrative Mechanism
This project is deliverable to TRL-5, hence research institutions and equipment manufacturers will participate in developing technologies which will be capable of showing TRL-9 level in cell manufacturing. This project is given a high priority to tend to the urgency of meeting/ fulfilling the manufacturing needs of next-generation battery technologies in India. An estimated budget of ₹20 Cr is assigned for research & development and ₹80 Cr is assigned for equipment, tools etc.

1.3.3.5 Other potential area

Some potential areas of research in sodium-ion batteries may include:

a. Materials Development: Exploration of new cathode and anode materials that offer improved energy density, cycling stability, and rate capability and research for novel electrolytes and additives to enhance ion conductivity and stability.
b. Electrochemical Kinetics: Understanding the fundamental electrochemical processes within sodium-ion batteries, including sodium intercalation/extraction mechanisms and kinetics.
c. Electrolyte Research: Development of advanced electrolytes that are less sensitive to temperature fluctuations and exhibit improved safety characteristics and development of solid-state electrolytes to mitigate safety concerns associated with liquid electrolytes.
d. Safety and Thermal Management: Research on thermal runaway mechanisms and safety protocols to prevent battery failure under extreme conditions.
e. Environmental Impact and Sustainability: Assessment of the environmental impact of sodium-ion batteries, including the sourcing of materials and end-of-life disposal.

Proposed Research Project- 1.12

Innovation of Solid-State Electrolytes for High Energy Sodium-ion Batteries

1. Gap Analysis & Background
Conventional liquid electrolytes in sodium-ion batteries pose critical challenges such as limited energy density, limited operating temperature range and dendrite formation which compromises battery safety. Solid-state electrolytes are a potential alternative to overcome these limitations. This project focuses on the development of solid-state electrolytes for sodium-ion batteries as they are safer, offer higher energy densities and have higher resistance to dendrite formation as well as degradation.

2. Global Benchmarking
Currently, researchers are meticulously working on fabrication of solid-state electrolytes due to the complexity in manufacturing processes. Recently, sample tests at the laboratories of PowerCo, the Volkswagen Group's battery company, a solid-state battery from QuantumScape achieved more than 1,000 charging cycles while retaining more than 95 percent capacity [36].

3. TRL Level: Starting with TRL-2, deliverable to TRL-5

4. Research Goal
To research and develop novel solid-state electrolyte materials that improve the energy density and safety of sodium-ion batteries.

5. Targets for Project
a. Achieve an ionic conductivity equal to or more than current technologies
b. Produce sodium-ion batteries with an energy density of 200-300 Wh/kg or higher
c. Achieve at least 40 percent growth in cycle life with respect to available technologies
d. Ensure that solid-state batteries meet safety regulation requirements such as thermal propagation, fire resistance, mechanical integrity etc.
e. The cost of the materials used to produce the product must be at least at the commodity level
f. The supply chain for the material must be sourced entirely from India

6. Methodology

a. Benchmark and identify potential solid-state electrolyte materials
b. Develop and optimize synthesis methods for selected materials considering factors like scalability and cost-effectiveness
c. Fabricate electrolyte samples for testing
d. Characterize the samples
e. Assemble small-scale sodium-ion battery prototypes using the developed solid-state electrolytes
f. Conduct thorough testing to assess the performance of prototypes in terms of charge-discharge cycling, capacity measurements, rate capability and thermal stability
g. Analyze the collected data to identify areas for improvements and optimize the electrolyte composition, fabrication methods or battery design if needed

7. Deliverables

a. Solid-state electrolyte materials
b. Battery prototypes with improved energy density
c. Experimental data and analysis
d. Process documentation
e. Scalability plans
f. Manufacturing feasibility report
g. Detailed design and specifications for cells - Pouch, Prismatic and cylindrical cell form factors
h. Target compliance report

8. Impact

a. Due to abundant availability of sodium as raw material in India, the cost per kWh of the batteries will be much lesser as compared to lithium-ion batteries. This will also result in reduced dependency on imports from other countries
b. Successful innovation of solid-state electrolytes will offer enhanced safety in battery technologies
c. Solid-state electrolytes can lead to an increase in performance w.r.t. energy density, cycle life and rate capability of sodium-ion batteries
d. These electrolytes can reduce the degradation of battery components, resulting in longer battery life

9. Indicative list of Execution Agencies

a. Indian Institute of Technology (IIT) Bombay
b. Indian Institute of Technology (IIT), Madras
c. Indian Institute of Technology (IIT), Roorkee
d. University of Pondicherry

10. Timeline: 36 months

11. Estimated Budget: ₹30 Cr
Research & Development: ₹20 Cr
Pilot Manufacturing: ₹10 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence			✓	
Market			✓	
Technology				✓

13. Priority: High

14. Administrative Mechanism

From TRL-2 to 5, research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from industry. Research on solid-state electrolytes recognizes the transformative impact it could have on the performance, safety, and overall capabilities of sodium-ion batteries, making it a strategic and forward-looking investment in advancing battery technology. The Estimated budget of ₹20 Cr is assigned for research and development and ₹10 Cr is assigned for pilot manufacturing.

1.3.4 Aluminium-ion Batteries

Aluminium-ion batteries have shown potential for high charge capacity, low cost and enhanced safety. These batteries operate on the principle of intercalation. Their properties make them promising for energy storage solutions. However, aluminium-ion batteries face challenges in finding stable electrolytes, developing reliable cathode and anode material and improving cycle life and performance. Overcoming these hurdles is crucial for their practical implementation. Research should be focused on addressing these obstacles to make aluminium-ion batteries a more viable and efficient energy storage solution.

1.3.4.1 Current Status & Challenges

Aluminium-ion batteries exhibit potential due to their high energy density, and cost-effectiveness, yet several challenges hinder their widespread adoption. These include the search for a suitable cathode material that offers stability and high capacity, the development of stable electrolytes that enable efficient aluminium-ion transport without dendrite formation, and the need to optimize voltage for higher energy density. Achieving cycling stability, scaling up production while maintaining quality and securing a consistent supply of materials are also significant hurdles. Overcoming these challenges is crucial for the successful commercialization and broad implementation of aluminium-ion battery technology.

Proposed Research Project- 1.13

Research on Aluminium-ion Battery Technology

1. **Gap Analysis & Background**
   Aluminium-ion (Al-ion) batteries are slowly proving to be potential replacements for lithium-ion batteries but these batteries currently face several challenges, such as low energy density, passive film formation, anode corrosion, etc. Hence, there is a need for improved electrode materials to enhance the overall performance and lifespan of these batteries. By leveraging advancements in material science, electrolyte design and electrode architecture, this project seeks to significantly enhance the performance, longevity, and safety of Aluminium-ion batteries, ultimately making them commercially viable for the automotive industry.

2. **Global Benchmarking**
   The initial stages of research on Aluminium-ion battery technology involved coin cell prototypes, but slowly the research is progressing towards prototyping pouch cell formats. The University of Queensland and UniQuest are initiating their expansion of research activities for the Aluminium-ion battery. The University has now made initial battery prototype pouch cells. Initial laboratory tests and experiments have demonstrated that the energy storage capabilities of the Aluminium-ion battery surpass those of the current leading Lithium-ion battery technology in terms of both energy densities and power densities [37].

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-5

4. **Research Goal**
   To develop a stable and high energy density Aluminium-ion battery through novel materials and engineering solutions to address commercial viability and performance limitations.

5. **Targets for Project**
   a. Investigate and develop novel cathode materials and structures to improve the overall energy density (> 350 Wh/kg) and cycle life (>1000 cycles) of Al-ion batteries
   b. Developed cell prototypes should be capable of rapid charging (fully charged in less than 5 minutes)

c. Develop scalable and cost-efficient manufacturing processes to facilitate the commercial adoption
d. The cost of the materials used in production must be at least at the commodity level
e. Preferably, a robust domestic supply chain should exist.

6. Methodology

a. Conduct a thorough review of existing literature on Al-ion battery technology to understand current research, challenges, and opportunities
b. Develop optimized electrode fabrication techniques, focusing on uniform and high-loading electrode structures
c. Investigate novel electrolytes to improve stability and conductivity
d. Manufacture battery prototypes based on developed materials and designs
e. Conduct thorough testing to assess the performance of prototypes in terms of energy density, charge-discharge cycling, capacity measurements, rate capability and thermal stability
f. Continuously refine the battery components and assembly processes based on testing outcomes

7. Deliverables

a. Battery prototypes
b. Materials and component specifications
c. Electrode and electrolyte designs
d. Experimental data and analysis
e. Process documentation
f. Scalability plans
g. Manufacturing feasibility report
h. Detailed design and specifications for cells
i. Target compliance report

8. Impact

a. Due to the abundancy of Aluminium as a raw material in India, successful innovation in Al-ion batteries will reduce the dependency on imports and hence, greatly enhance the economy
b. Improved energy density and faster charging time will contribute to enhanced energy efficiency
c. Enhanced cycling stability and longevity could lead to safer and long-lasting batteries

9. Indicative list of Execution Agencies

a. CSIR-Central Electro Chemical Research Institute (CSIR-CECRI), Tamil Nadu
b. Indian Institute of Space Science and Technology (IIST), Thiruvananthapuram

10. Timeline: 48 Months

11. Estimated Budget: ₹40 Cr
Research & Development: ₹30 Cr
Pilot Manufactruing: ₹10 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence			✓	
Market			✓	
Technology				✓

13. Priority: High

14. Administrative Mechanism
This project is deliverable to TRL-5, hence research institutions and laboratories will participate in developing technologies. This project is an important initiative because innovation in this technology could lead to breakthroughs that address existing limitations, such as cycle life and stability, cost-effectiveness, and reduced dependency on imports and propel the development of high-performance, energy-dense batteries. An estimated

budget of ₹30 Cr is assigned for research on Aluminium-ion battery technology and ₹10 Cr is assigned for pilot manufacturing.

1.3.4.2 Electrode materials

The challenges related to electrode materials in aluminium-ion batteries are multifaceted. One primary obstacle involves the search for cathode materials capable of sustaining reversible aluminium-ion intercalation with structural stability and high energy density. Similarly, finding an anode material that permits efficient aluminium-ion storage without dendrite formation or structural decay during charging cycles is essential. Ensuring compatibility between electrode materials and the electrolyte to prevent side reactions or degradation, along with designing electrode structures that enable rapid ion transport and maintain structural integrity, are also critical areas requiring attention for the advancement of aluminium-ion battery technology.

1.3.4.3. Electrolyte solutions

The challenges linked to electrolytes in aluminium-ion batteries encompass an intricate landscape. One fundamental obstacle involves the development of electrolytes that offer both stability and compatibility, ensuring they interact harmoniously with the anode and cathode materials while preventing detrimental side reactions that could compromise the battery's performance and longevity. Efficient and rapid aluminium-ion transport without dendrite formation is another critical aspect requiring attention. Equally important is the need to create electrolytes that maintain their effectiveness across a wide spectrum of operating temperatures without sacrificing performance or undergoing degradation. Additionally, addressing safety concerns by formulating non-flammable and non-toxic electrolyte solutions remains imperative to mitigate potential hazards associated with battery damage or leakage. Successfully overcoming these challenges is pivotal for advancing and eventually widespread adoption of aluminium-ion battery technology.

1.3.4.4 Manufacturing Process

There are several challenges related to the manufacturing process of aluminium-ion batteries. Precision in electrode material synthesis is vital, demanding controlled structures and compositions to ensure consistent electrochemical performance at scale. Establishing robust assembly methods to stack electrodes uniformly, encapsulate cells effectively and ensure homogenous electrolyte distribution is critical to prevent performance discrepancies between battery units. Adapting electrode coating processes for mass production to maintain uniformity in thickness, porosity, and active material distribution is another challenge. Implementing automated manufacturing procedures and stringent quality control measures becomes essential to sustain consistent product quality, identifying and rectifying any deviations throughout large-scale productions. Addressing these technical challenges is imperative for refining manufacturing processes and ensuring the reliability and efficiency of aluminium-ion battery technology.

1.3.4.5 Other Potential Area

Some potential areas of research in sodium-ion batteries may include:

1. Novel Electrode Architectures: Exploring innovative electrode architectures or designs that minimize the volume changes during charge cycles, thereby reducing mechanical stress and improving overall cycling stability.
2. Scaling Up Production: Developing scalable manufacturing processes and cost-effective electrode and cell assembly techniques to enable mass production is vital for commercial viability.

3. Modelling and Simulation: Advancing modelling and simulation techniques to better understand Aluminium-ion battery behaviour, predict performance, and guide material and system design.

1.3.5 Cell Structure

In the context of EV batteries, the term “cell structure” often refers to as physical formats or shapes of the individual battery cells. The main physical formats of the cells include cylindrical cells, pouch cells, blade cells, prismatic cells, coin or button cells etc. Each type possesses its unique characteristics and challenges.

1.3.5.1 Current Status & Challenges

Different form factors of the battery cells present unique challenges. Cylindrical cells, known for their compact design, face issues related to heat dissipation and maintaining consistent manufacturing quality at scale. Pouch cells, due to their flexible and flat structure, struggle with ensuring structural integrity, especially in demanding applications such as EVs, and require effective thermal management strategies. Prismatic cells with their rectangular shape, encounter challenges in space optimization within battery packs.

Addressing these challenges in each form factor is crucial to enhancing battery technologies, ensuring increased efficiency, safety and performance while meeting the demands of emobility applications. Strategies focused on improving thermal management, structural integrity, manufacturing processes, and recyclability will be key in advancing battery cell technology across these varied form factors.

1.3.5.2 New cell stack-up

The emergence of new cell stack-up configurations in battery technology presents critical challenges. Managing heat dissipation efficiently within these stacked arrangements remains a primary concern to ensure safety and longevity. Implementing robust safety features to prevent thermal runaway and other potential risks, while maintaining uniform temperatures across the stack, is essential. Additionally, complexity of arranging and securing multiple cells within these stacks introduces manufacturing and assembly challenges, demanding standardized, cost-effective assembly process without compromising safety standards.

Achieving uniform performance across all cells, ensuring scalability, and seamless integration into various applications further pose significant hurdles for these new stack-up designs. Addressing these challenges is vital for the advancement of battery technology, particularly in EVs, focusing mainly on safety, thermal management and overall performance enhancements.

1.3.5.3 New innovative cell structure

Proposed Research Project- 1.14

Innovation of Novel Battery Cell Form Factors for Electric Vehicles

1. **Gap Analysis & Background**
   Conventional rigid battery packs which are currently deployed in electric vehicles consist of cells with either of three form factors namely; pouch, cylindrical and prismatic. There is room for improvement in fully utilizing the available space within electric vehicles with these battery packs, which could lead to enhanced design flexibility and overall efficiency. Hence, there is a need for research on novel form factors and/or flexible battery cells which will fully utilise the available space by moulding into unique vehicle designs.

2. **Global Benchmarking**
A South Korean based company-Jenax has been successful in development of a flexible solid-state lithium-ion cell. The cell maintains its power capacity even when fully bent. Panasonic showcased flexible batteries in 2017, with a 0.55mm thickness and a range of capacities of 18, 42, and 65 mAh. Samsung displayed a prototype of thin and flexible batteries with a band-shaped format in 2015 in Seoul. [38]

3. **TRL Level:** Starting with TRL-1, deliverable to TRL-5

4. **Research Goal**
To develop and implement advanced flexible battery cells, focusing on customization for form-factor adaptability and scalability for mass adoption.

5. **Targets for Project**
    a. Investigate and develop novel materials and structures for novel form factors
    b. Developed cell prototypes should have 40 percent improvement of energy density compared to currently available technology
    c. Ensure that developed prototypes meet safety regulation requirements
    d. Develop scalable and cost-efficient manufacturing processes to facilitate the commercial adoption
    e. The cost of the materials used to produce the product must be at least at the commodity level
    f. The supply chain for the material must be sourced entirely from India

6. **Methodology**
    a. Conduct a thorough review of existing literature on flexible battery cells, material science, electrochemical processes etc.
    b. Identify candidate materials with optimum flexibility, energy density, durability and safety characteristics
    c. Engineer small scale prototypes of battery cells using the selected materials
    d. Conduct thorough testing to assess the performance of prototypes in terms of energy density, charge-discharge cycling, capacity measurements, rate capability and thermal stability
    e. Iteratively refine the prototypes based on performance evaluations and feedback
    f. Integrate the developed prototypes into 2-3-wheeler EV architectures and assess the impact on vehicle performance and efficiency
    g. Assess the feasibility of mass production, addressing cost-effectiveness and scalability challenges

7. **Deliverables**
    a. Cell prototypes with novel form factors
    b. Materials and component specifications
    c. Experimental data and analysis
    d. Process documentation
    e. Scalability plans
    f. Manufacturing feasibility report
    g. Detailed design and specifications for cells
    h. Target compliance report

8. **Impact**
    a. Enabling the integration of new form factors of battery cells into electric vehicles will provide automakers with increased design flexibility, allowing for more aerodynamic and space-efficient vehicle designs

9. **Indicative list of Execution Agencies**
    a. CSIR-Central Electro Chemical Research Institute (CSIR-CECRI), Tamil Nadu
    b. Indian Institute of Space Science and Technology (IIST), Thiruvananthapuram

10. **Timeline:** 48 Months

11. **Estimated Budget:** ₹30 Cr
Research & Development: ₹22 Cr
Pilot Manufacturing: ₹8 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence			✓	
Market			✓	
Technology				✓

13. Priority: High

14. Administrative Mechanism

From TRL-2 to 5, research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from industry. Research on novel cell form factors recognizes the transformative impact it could have on the size and shape of the batteries, making it a strategic and forward-looking investment in advancing battery technology. The Estimated budget of ₹22 Cr is assigned for research and development and ₹8 Cr is assigned for pilot manufacturing.

Chapter 2: EV Aggregates

2.1 Introduction

Electric Vehicle (EV) aggregates comprise mainly three fundamental components: batteries, electric motors, and controllers. The electric motor plays an important role as it acts as a primary power source by converting battery electrical energy into mechanical propulsion. The power electronic converters and inverters are required for managing the flow of electricity between the battery, electric motor, and other vehicle systems. The voltage, current and frequency are regulated using power electronics components to deliver power more efficiently. In this process, heat is generated in various parts of EV systems. The thermal management systems are used to regulate the temperature of the battery pack, electric motor, and power electronics devices to maintain optimal performance and safety. All these operations are controlled by the controller of the vehicle which optimizes the vehicle performance using modern software and sensors.

2.2 Current Scenario in India

The Indian Government's FAME II scheme is aimed at reducing dependence on imports and stimulating the domestic EV industry by supporting electric mobility. This scheme is beneficial for manufacturers of EV components [39]. Several Indian startups are actively engaged in developing innovative motors and drivetrain designs to enhance the efficiency and overall performance of EVs. However, the localization of EVs has been particularly challenging due to the nature of components/assemblies and the available ecosystem in India. The unavailability of a hardware manufacturing base in India is pushing OEMs and Tier-1 suppliers for imports. While OEMs have been driving tier-1 localization through limited local value addition on some components, tier-2/3 localization has yet to be achieved. It is important to continue monitoring the development of imported systems such as batteries with advanced chemistry, electric motors, power electronics, and semiconductors. The Indian Government's initiatives that create an enabling local ecosystem coupled with the need for EV OEMs to stabilize and control the ever-growing spend on EV components, will drive localization of the EV supply chain over the next 3-5 years.

2.3 Research Pathway

2.3.1 Electric Motor

The rapid development in the field of power electronics and control techniques has created a space for various types of electric motors to be used in Electric Vehicles. The electric motors used for automotive applications should have characteristics like high starting torque, high power density, higher efficiency, etc.

2.3.1.1 Current Status & Challenges

Various types of motors including permanent magnet synchronous motors (PMSM), Brushless DC (BLDC), induction motors etc. are used in electric vehicles. Each motor has its strengths and weaknesses, and the choice depends on the size and purpose of the vehicle. Electric motors, such as BLDC and PMSM, hold immense promise as they continue to find applications across various industries. Efficiency is a critical aspect, and both BLDC and PMSM motors already offer high efficiency. However, there is still room for improvement, and the future is likely to see efforts aimed at further enhancing efficiency. This could involve the adoption of new materials, innovative designs, and more advanced control algorithms.

2.3.1.2 Winding Material & Design

The choice of materials for winding and the design of electric motors are pivotal factors that significantly influence motor performance. Copper, renowned for its high electrical conductivity, thermal resistance, and magnetic properties, has been a conventional choice in various electromagnetic applications. Alternatively, aluminium wires are used due to their lower mass density and cost. In certain scenarios, an attractive solution arises through the combination of copper and aluminium, manifested as copper-clad aluminium (CCA). CCA offers advantages like reduced weight and cost, rendering it advantageous for high-frequency operations. Moreover, in specialized applications, traditional copper is being substituted by non-metal materials such as carbon nanotubes (CNTs) and graphene. These alternatives offer high conductivity with reduced mass density and the added benefit of a low-temperature coefficient, ensuring stable resistance as temperature changes. The challenges in this field are as follows: strike a balance between electrical conductivity and heat resistance in materials, optimize magnetic properties, and manage weight.

Proposed Research Project- 2.1

Replacement of Copper with Alternative Material or its Alloy for Winding of Electric Motor

1. **Gap Analysis & Background**
   Historically, copper has been the preferred material for electric motor windings due to its superior electrical conductivity. However, its relatively high cost and price fluctuations pose challenges in terms of affordability. To enhance the cost-effectiveness of electric motors, it is imperative to seek out alternatives. One such alternative is aluminium, known for its lower mass density compared to copper. The shift from copper to alternative materials or their alloys offers a promising solution to the challenges. Nonetheless, this transition demands thorough research, innovative design, and rigorous testing to ensure that the new materials meet the required performance and sustainability criteria for electric motors.

2. **Global Benchmarking**
   Globally, in some special applications, there are few references of ongoing research on the replacement of copper by other conducting non-metal such as carbon nanotubes (CNTs) and graphene. These types of windings have the benefit of high conductivity with reduced mass density and also have a low-temperature coefficient. Researchers from the University of Central Florida are currently working on CNTs such as Cu-Al-CNT composite and nanometal interconnected carbon wires [40].

3. **TRL Level:** Starting with TRL-2, deliverable to TRL 5

4. **Research Goal**
   To explore and implement alternative materials or their alloys as substitutes for copper in electric motor windings, aiming to improve performance, reduce costs, mass density and enhance sustainability.

5. **Targets for Project**
   a. To attain manufacturability of novel winding material
   b. Achieve performance and efficiency of the motor with identified alternate material winding comparable to electric motor of copper winding
   c. Reduction in the cost of new winding material such as aluminium or alloy by at least 40% as compared to current copper winding material

6. **Methodology**
   a. Identify and evaluate alternative materials
   b. Develop innovative winding configurations optimized for the selected alternative materials
   c. Analyze the economic implications of using alternative materials
   d. Investigate the environmental impact of alternative materials throughout their life cycle
   e. Conduct comprehensive laboratory testing to evaluate the performance of electric motors made from alternative materials, and compare the findings to those of typical copper windings to determine the viability of the replacements

7. **Deliverables**
   a. A comprehensive report detailing the suitability and performance characteristics of alternative materials

b. A strategy for reducing the manufacturing costs of electric motors through the use of alternative materials, with a cost analysis
c. Development of electric motors with alternative materials
d. Data comparing the performance of electric motors with alternative materials against traditional copper windings
e. Guidelines for development of alternative of copper for the winding material of electric motor
f. Documentation confirming that the project aligns with industry and environmental regulations and standards
g. Detailed design specification for the new winding configuration
h. Cost and Target compliance report

8. Impact

a. Reduction in demand of copper material
b. Utilizing alternative materials instead of copper emerges as a cost-effective option, providing industries reliant on electric motors with the advantage of decreased manufacturing expenditures
c. Reduction in weight and size with increase in efficiency of motor

9. Indicative list of Execution Agencies

a. Indian Institute of Technology (IIT), Gandhinagar
b. Non-Ferrous Materials Technology Development Centre (NFTDC), Hyderabad
c. Indian Institute of Technology (IIT), Delhi

10. Timelines: 36 months.

11. Estimated Budget: ₹ 15 Cr
Research & Development: ₹10 Cr
Pilot Manufacturing: ₹5 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence			✓	
Market		✓		
Technology			✓	

13. Priority: High

14. Administrative Mechanism

Research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from industry. By considering factors such as the need for a thorough cost benefit analysis, the industry readiness for alternative material, potential technical challenges and uncertainties, the project is aimed to research on alternative material for the winding of motors with the estimated budget of ₹15 Cr. An estimated budget of ₹10 Cr is assigned for Research & Development and ₹5 Cr is assigned for pilot manufacturing.

2.3.1.3 Rare-earth Free Permanent Magnets

Rare-earth material has become extremely important to our world of technology owing to their unique magnetic, phosphorescent, and catalytic properties. Permanent magnets (PMs) are crucial in electric motors due to their capacity to maintain a strong magnetic field without external support. The evolution of rare earth-free magnets started with AlNiCo magnets, primarily composed of iron, aluminium, nickel, and cobalt. Hard ferrites, known for being cost-effective permanent magnets, offer an alternative to Alnico magnets. The Remanence (Br) and Coercivity (Hc) values are much smaller in ferrites and AlNiCo and they are also utilized in practice in larger volumes for a multitude of applications. Exploration of rare-earth-free options like FePt, MnBi, FeNi, and Co-rich alloys continues by optimizing both intrinsic and extrinsic magnetic properties. Recently, Iron–Nitrogen system-based compositions have been known to exhibit giant Saturation Magnetization (Ms). Another category of materials worth pursuing are Mn-Al-C and Mn-Bi-X alloys which show promise as they possess decent coercivity. The critical challenge in synthesis of FeN materials is the low decomposition temperature of the nitride [41]. Nitriding of ribbons, wires, foils and powders under pressure has been the only alternative and the metastable magnetic phase fraction has to be increased via innovative processing. However, rare-earth permanent magnets remain prevalent due to their performance and consumer demand. The gap between ferrite and existing magnets will likely lead to diverse approaches in future permanent magnet development.

A research team led by Dr. Jung-Goo Lee and Dr. Tae-Hoon Kim of the Department of Magnetic Materials in the Powder Materials Division at the Korea Institute of Materials Science (KIMS) has developed rare-earth-saving permanent magnets that can replace the 42M-graded commercial magnets while reducing the amount of neodymium (Nd), an expensive rare-earth material, by about 30% [42].

Proposed Research Project- 2.2

Research on Non-Rare Earth Material of Permanent Magnet

1. **Gap Analysis & Background**

   The use of strong magnetic fields is fundamental in various technologies and industries including electric vehicles and consumer electronics. Traditionally, rare-earth magnets, such as neodymium-iron-boron (NdFeB) magnets have been a good choice for achieving high magnetic field strengths due to their exceptional magnetic properties. However, the production and supply of rare-earth materials, which are sourced from a few countries, pose several challenges including price volatility, geopolitical tension and environmental concerns associated with mining and processing. As a response to these challenges, there is a need to explore alternative materials, innovative magnet designs, advanced magnetization techniques and recycling efforts to create efficient and eco-friendly magnet solutions.

2. **Global Benchmarking**

   Researchers propose a new processing method to manufacture non-rare earth bulk magnetic material rich in α-MnBi phase, simplifying the process with fewer steps. By subjecting Mn-Bi composites to multistep High-Pressure Torsion (HPT) processing and magnetic field-assisted annealing, a significant increase in α-MnBi phase content was achieved, reaching up to 70 wt.%. Subsequent deformation steps further refined the phase and grain structure, resulting in homogeneous nanocomposite structures. The process shows potential for industrial applications due to its scalability and the possibility of synthesizing composites with even higher α-MnBi phase content [43].

3. **TRL Level:** Starting with TRL 2, deliverables to TRL 5

5. **Research Goal**

   To identify, develop, and promote the use of non-rare earth materials in the creation of high-intensity permanent magnets, aiming to reduce the environmental impact, enhance resource sustainability, and maintain or improve magnetic performance in various applications comparable to rare earth magnets.

6. **Targets for Project**

   a. Achieve a high magnetic energy product (BHmax) for non-rare earth magnets, comparable to or exceeding that of traditional rare earth magnets
   b. Develop magnets that can maintain their magnetic properties over a broad temperature range, ensuring stability in various applications
   c. Establish suitable processing techniques for shaping and forming non-rare earth magnets, including sintering, hot pressing or other manufacturing methods

d. Develop cost-effective solutions that use non-rare earth materials in a way that is competitive with or cheaper than traditional rare earth magnets

7. **Methodology**

The following tasks are involved in achieving the targets:

a. Identify and evaluate non-rare earth materials and investigate their potential for generating strong magnetic fields
b. Develop innovative magnet designs and configurations that maximize the magnetic field strength generated by the selected non-rare earth materials
c. Conduct extensive laboratory tests to assess the magnetic properties of the selected materials
d. Employ computer-aided design (CAD) and finite element analysis (FEA) tools to optimize magnet geometries to maximize magnetic field strength
e. Assess the economic feasibility of using non-rare earth materials in comparison to traditional rare earth magnets
f. Build prototype magnets using the selected non-rare earth materials and assess their performance in real-world applications

8. **Deliverables**

The following are the proposed deliverables of this activity

a. Providing guidelines for innovative magnet designs and configurations that maximize magnetic field strength
b. Development of guidelines for the manufacturing of non-rare earth magnets, ensuring quality and consistency
c. Production of non-rare earth magnets prototypes and samples for demonstration and testing
d. Presenting data from real-world testing of prototype magnets with non-rare earth materials
e. Comprehensive analysis of the performance of non-rare earth materials compared to traditional rare earth magnets
f. Analyzing the economic implications of using non-rare earth material

9. **Impact**

a. It can lead to significant technological advancement in applications such as electric motors, generators, magnetic bearings and more
b. The identification and use of alternative materials broaden the range of options available to industries, reducing their vulnerability to supply chain disruptions

10. **Indicative list of Execution Agencies:**

a. Non-Ferrous Materials Technology Development Centre (NFTDC), Hyderabad
b. International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), Hyderabad
c. Defence Metallurgical Research Laboratory (DMRL), Hyderabad
d. Bhabha Atomic Research Centre (BARC), Mumbai
e. Indian Rare Earths Limited (IREL), Mumbai

11. **Timelines:** 24-36 months.

12. **Estimated Budget:** ₹ 6 Cr

Research & Development: ₹5 Cr
Pilot Manufacturing: ₹1 Cr

13. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence			✓	
Market				✓
Technology			✓	

14. **Priority:** High

15. **Administrative Mechanism**
This project is deliverable to TRL-5, hence research institutions and laboratories will participate in developing technologies, industries will play a supporting role. The project is given a high priority to align with the strategic goals related to environmental consideration, market competitiveness and demand, technological innovation. The focus of this project is to reduce dependency on rare earth material, advancing technology and fulfilling the market demand. Estimated budget for the project is ₹6 Cr, where ₹5 Cr is assigned for Research & Development and ₹1 Cr is assigned for pilot manufacturing.

2.3.1.4 Motor Design- Stator/Rotor Layout

Well-designed stator and rotor layouts are the key to achieving higher energy efficiency, reduced heat generation, and superior power output. Challenges in motor design, specifically in stator and rotor layout, are essential considerations for optimizing electric motor performance. These challenges include achieving efficient magnetic field generation, minimizing heat generation and energy losses, balancing weight and power density, addressing noise and vibration issues, ensuring scalability and manufacturability, making sustainable material choices and integrating them with control systems. Overcoming these challenges is crucial for creating efficient and adaptable electric motors suitable for various applications.

2.3.1.5 Permanent Magnet Free Motors

Permanent magnet-free motors, including induction motors, switched reluctance motors (SRMs), and wound-rotor synchronous motors (WRSMs) operate without permanent magnets, using electromagnets to create the necessary magnetic field. These motors have a simple and robust design with heat generation in the stator, but they face control complexity and potential noise issues. Wound-rotor synchronous motors (WRSMs) use rotor electromagnet coils to achieve high efficiency and power density, making them suitable for similar applications. Challenges associated with permanent magnet-free motors encompass issues like lower starting torque, complex control requirements, the need for additional switching circuits and noise management in SRMs, thermal management, rotor inertia concerns in SRMs, maintenance requirements, and application-specific challenges. Overcoming these challenges is crucial for harnessing the efficiency and power density benefits offered by these motors in various applications.

In the US, General Motors and start-up Niron Magnetics have announced a partnership to codevelop rare-earth-free permanent magnets. They have disclosed a US $33 million investment into Niron's iron-nitride magnet. However, many experts in magnetics are doubtful about the feasibility of mass-manufacturing an economical magnet free of rare earths that is strong and tough enough for EV propulsion [44].

ZF, a European automotive transmission manufacturer, is developing an electric motor that eliminates the use of permanent magnets. The motor, known as the I2SM (In-Rotor Inductive-Excited Synchronous Motor), transmits the energy for the magnetic field via an inductive exciter inside the rotor shaft. This solution is expected to enable a uniquely compact motor with maximum power and torque density. ZF plans to develop the I2SM technology to production maturity at an unknown date and offer it as an option within its e-drive portfolio [45].

2.3.1.6 Magnet Motors Suitable for Indian Scenario

The use of rare-earth magnets in EV motors and high-efficiency motors is common due to their exceptional performance, but the environmental and geopolitical concerns related to rare-earth mining are significant. In response to these challenges, industries are in process of developing a rare-earth-free platform for electric motor design and production, including motors for EVs. This initiative involves creating intellectual property in hardware, algorithms, and reluctance motor technology that can match conventional motor’s performance across various power levels, with real-time monitoring and control through software platforms. These efforts align with India's "Atmanirbhar Bharat" (self-reliant India) initiative, emphasizing the customization of the EV industry to suit the specific needs of South Asia and similar regions, rather than replicating Western models. This approach illustrates the role of innovation and self-sufficiency in advancing sustainable electric transportation, not only in India but globally.

2.3.1.7 Poly-phase Motors (Multi-Phase)

The Polyphase or multi-phase motors are high-power density motors whose structural design reduces the mass of the motor, without disturbing the flux density distribution through a periodic duty cycle. The high-power density of motors is achieved by proper arrangements of rotor permanent or electromagnet, stator slots and windings. The control of multi-phase motors is more complex than traditional three-phase motors, requiring advanced motor control algorithms and power electronics, by which the cost of the components may increase. Integrating multi-phase motors into existing EVs may require substantial modifications to vehicle design and infrastructure. Multi-phase motors (five-phase or six-phase) motors are still emerging in the EV industry and are not as widespread as traditional three-phase motors. Their adoption depends on the ability to overcome these challenges and demonstrate significant performance and efficiency improvements.

2.3.1.8 Manufacturing Process

The design and material used in the motors are critical for ensuring efficiency and performance. The electric motors used in EVs demand a high level of precision and require strict tolerance control to ensure efficiency and reliability. It is crucial to carefully select the materials, particularly for the components like stator and rotor, as they must possess the right magnetic properties and withstand the rigours of high temperature and stress during operation. Electric Motors often consist of various components sourced from different suppliers, making the supply chain vulnerable to disruptions that can affect production schedules. Overcoming these challenges requires continuous research and development in advanced manufacturing techniques, collaboration with suppliers and research institutions, and a strong commitment to sustainability and maintaining high-quality standards.

2.3.2 Integrated Motor Controller Charger

The Integrated Motor Controller Charger for EVs combines motor control and battery charging in a compact system, streamlining the powertrain for reduced size, making it ideal for EVs with space constraints. This technology enhances EV performance through efficient communication between the motor and battery management system, ensuring precise control and energy efficiency. It allows for convenient charging from various sources, contributing to improved energy efficiency and cost-effective EV solutions. However, developing these integrated units comes with challenges, including thermal management, power density, compatibility, safety, efficiency, interference prevention, scalability, and long-term reliability, all essential for advancing EV technology.

2.3.3 Power Electronics Devices & Technologies

Power electronic devices are fundamental components that enable the efficient control and management of electrical energy within an EV's complex system.

2.3.3.1 Current Status & Implementation in EVs and its Challenges

Power electronics devices like Insulated-Gate Bipolar Transistors (IGBT), Silicon Carbide (SiC) Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET), and Gallium Nitride (GaN) High Electron Mobility Transistors (HEMT) are crucial for managing electrical power in electric vehicles (EVs). Their selection depends on power levels, voltage ratings, and performance requirements in the EV powertrain. With the increasing demand for EVs globally, the power electronics industry has opportunities for innovation and expansion to address emerging challenges and needs [40]. Efficient thermal management is essential to maintain high performance and prevent component damage as power levels increase in EVs. Novel cooling techniques like advanced air cooling, liquid cooling, thermal interface material etc, are being explored to tackle this challenge. Cost reduction in power electronics is a key factor for wider EV adoption. Advances in wide bandgap semiconductors and manufacturing methods have made EV power electronics more affordable, but further cost-reduction efforts are necessary. This includes improvements in materials, production methods, and achieving economies of scale.

2.3.3.2 New Power Electronics Devices

The rapid development of power devices for EVs is challenging chipmakers in the testing of Integrated Circuits (ICs). As transportation networks electrify, this impacts both, the automotive industry and electronic components, particularly power ICs used for voltage control, battery management, and mixed-signal modules. While traditional silicon-based power ICs relied on IGBTs or power MOSFETs, SiC and GaN-based ICs offer advantages such as higher breakdown voltage, mobility, and thermal control. However, challenges persist due to production difficulties, crystal flaws, and high costs. Testing high-voltage, high-current ICs presents unique challenges, including potential risks to testing equipment. The growing semiconductor demand in the automotive industry is driving efforts to address these issues, as SiC and GaN-based ICs require advanced testing environments. These ICs are essential for EVs, including charge station management and battery control, and engineers are innovating to balance high voltage, current, and temperature effects, and reduce testing costs for these advanced power ICs.

Proposed Research Project- 2.3

Research on Toolchain and Equipment for Manufacturing of Power Semiconductor (MOSFET, IGBT, SiC etc.) in India

1. **Gap Analysis & Background**
   Power semiconductor devices, including MOSFETs, IGBTs, and SiC components, are vital components in modern electronics, serving various industries like electric vehicles, renewable energy, telecommunications, and industrial automation. The ability to domestically produce these devices is strategically important for self-reliance and economic growth. India, with its growing electronics and semiconductor industry, is working to establish a robust domestic manufacturing ecosystem for power semiconductors. This research aims to comprehensively analyse this ecosystem in India, covering processes, technologies, supply chains, key industry players, challenges, and opportunities related to power semiconductor production.

2. **Global Benchmarking:**
   The government of India, in 2021, has announced ₹76,000 Cr program for development of semiconductor and display manufacturing ecosystem in India to provide fiscal support to approved applicants for setting up semiconductor fabrication facilities. Tata Electronics Pvt. Ltd, Tata Semiconductor Assembly and Test Pvt. Ltd, and CG Power are among the first applicants for establishing semiconductor fabrication and Assembly, Test, Marking and Packaging facilities (ATMP) facilities in India with government support [46]. The units will focus on producing semiconductor chips for high-performance compute chips with 28 nm technology and power management chips for EVs, telecom, defense, automotive, consumer electronics, display, power electronics, etc. and developing indigenous advanced semiconductor packaging technologies, including flip chip and Integrated System in Package (ISIP) technologies.

3. **TRL Level:** Starting with TRL 2, deliverable to TRL 6

4. Research Goal

Analyse the manufacturing processes involved in producing power semiconductor devices, including wafer fabrication, doping, lithography, etching, and packaging.

5. Targets for Project

a. Achieve higher manufacturing efficiency through process optimization and automation, leading to reduced production costs
b. Develop and integrate advanced materials to improve the performance and efficiency of power semiconductor devices
c. Enhance the voltage and current ratings of power semiconductor devices to meet the demands of emerging applications, such as high-voltage direct current (HVDC) transmission and electric vehicles

6. Methodology

The following tasks are involved in achieving the targets:

a. Conduct a feasibility study to assess the economic, technical, and market viability of the manufacturing facility
b. Analyze the global and domestic market for power semiconductors
c. Identify specialized semiconductor manufacturing equipment
d. Establishment of sample Semiconductor Wafer Fabrication Manufacturing Facilities in India
e. Implement rigorous testing and quality control procedures to meet industry standards

7. Deliverables

The following are the proposed deliverables of this activity

a. Develop a database of components with ratings that are required to cover a range of Power Electronics Control Units (PECU) for mobility
b. Create a stockpile as a buffer till we get indigenous output. This will ramp up the R & D ecosystem to develop many devices based on identified components
c. Development of indignious manufacturing tools and equipments
d. A comprehensive report detailing the economic, technical, and market viability of the manufacturing facility
e. Detailed design plans for the manufacturing facility, including specifications, capacity, utilities, and safety measures
f. Regular reports on the progress of facility construction
g. Commercialization plans
h. Documentation of the development and optimization of semiconductor fabrication processes, including testing and quality control procedures
i. Environmental impact assessments, waste management protocols, and records of eco-friendly practices implemented in manufacturing
j. Skilling plans to disseminate the findings

8. Impact

a. India can become a global hub for semiconductor manufacturing, leading to export opportunities and reduced reliance on imports
b. It can lead to technological advancement, enabling the production of more efficient and advanced semiconductor devices
c. It can contribute to the growth of the R&D ecosystem

9. Indicative list of Execution Agencies:

a. Non-Ferrous Materials Technology Development Centre (NFTDC), Hyderabad
b. Indian Institute of Technology (IIT), Jodhpur
c. Indian Institute of Technology (IIT), Delhi
d. Indian Institute of Technology (IIT), Bombay
e. Indian Institute of Technology (IIT), Madras
f. Semi-conductor Laboratory (SCL), Mohali
g. Continental Device India Pvt. Ltd. (CDIL), New Delhi

10. **Timelines:** 24-36 months

11. **Estimated Budget:** ₹ 250 Cr
    Research & Development: ₹100 Cr (Divided equally between two parties)
    Pilot Manufacturing: ₹150 Cr

12. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market				✓
Technology			✓	

13. **Priority:** Moderate

14. **Administrative Mechanism:**
    Research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from the industry. From TRL-6, industry should take the lead for commercial production. This project is given a moderate priority as the project requires a comprehensive market analysis to understand the current demand in India, a careful consideration of available technologies to identify potential advancement needed, and a gradual infrastructure development to support projects success. The estimated budget for the project is ₹250 Cr. An estimated budget of ₹100 Cr is assigned for Research & Development and ₹150 Cr is assigned for pilot manufacturing.

Proposed Research Project – 2.4

Nucleation and Growth Mechanisms in Semiconductor Material Synthesis and Manufacturability

1. **Gap Analysis & Background**
   India's technology and electronics sectors have experienced substantial growth, becoming vital contributors to the nation's economy and technological advancement. India currently faces dependency on semiconductor imports and lacks a self-reliant semiconductor ecosystem. The growing demand for semiconductor-based devices has highlighted the need for a robust semiconductor ecosystem. India took initiatives such as "Make in India" and "Atmanirbhar Bharat" to emphasize the importance of indigenous semiconductor production. Addressing these challenges requires the establishment of a robust knowledge base, the cultivation of skilled human resources and international support. The project aims to establish a strong foundation in semiconductor material research and manufacturing [47].

2. **Global Benchmarking:**
   Researchers examine the progress and challenges in implementing devices based on ultra-wide bandgap semiconductors. Significant advancements have been made, particularly in silicon carbide (SiC), with demonstrated unit operations for device fabrication and recent improvements in crystal quality. However, crystal growth remains a key challenge across various materials, including diamond, gallium nitride (GaN), and aluminium nitride (AlN). Boron nitride shows promise for certain devices, but hurdles exist in its production. Further research areas include impurity behavior, ion implantation, and metal contacts to advance device fabrication processes and overcome material-specific challenges.

3. **TRL Level:** NA

4. **Research Goal**
   To establish and advance research efforts in the field of semiconductor material synthesis and manufacturability, contributing to technological self-reliance, innovation and industry development.

5. **Targets for Project**
   a. Analyze the demand for semiconductor materials in India and potential areas of growth

b. Cost-benefit analysis to determine the economic viability of semiconductor material production in India
c. Investigate innovative semiconductor material synthesis methods that are efficient, cost-effective and suitable for large-scale production
d. Identify any barriers or incentives that may impact the industry's growth

6. **Methodology**

The following tasks are involved in achieving the targets:

a. Form a multidisciplinary research team with expertise in material science, semiconductor technology and manufacturing processes
b. Facilitate knowledge exchange programs and international research collaborations
c. Advocate for continued support and investment in this field
d. Prepare detailed reports and scientific papers/white papers for sharing research outcomes with the scientific community and industry stakeholders

7. **Deliverables**

The following are the proposed deliverables of this activity

a. Completed collaborative research reports with academic institutions, research organizations and industry partners
b. Field research and financial analysis report
c. Description of materials characterization techniques used in the project
d. Skilled workforce development plan

8. **Impact**

a. India will achieve greater self-reliance in its technology and electronics sectors, contributing to national security and economic stability
b. The research outcomes will enhance India's global competitiveness in semiconductor technology, positioning it as a key player in the global semiconductor industry

9. **Indicative list of Execution Agencies:**

a. India Electronics and Semiconductor Association (IESA), Pune
b. Bosch Automotive Electronics India Pvt. Ltd. Bangalore
c. Continental Device India Pvt. Ltd. (CDIL), New Delhi
d. Semiconductor Laboratory (SCL), Mohali
e. Indian Institute of Technology (IIT), Delhi
f. Indian Institute of Technology (IIT), Chennai

10. **Timelines:** 6 months

11. **Estimated Budget:** ₹0.5 Cr

12. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market			✓	
Technology			✓	

13. **Priority:** High

14. **Administrative Mechanism**

Research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from industry, the project is given a high priority which reflects the recognition that a deep understanding of these fundamental processes is essential for advancing material synthesis technologies. The goal is to comprehend the potential economic benefits that can be derived from advancing the foundational knowledge in semiconductor material synthesis. The estimated budget for the project is ₹0.5 Cr.

2.3.3.3 Wide Bandgap (WBG) Semiconductor Devices

The power electronics industry is addressing limitations in traditional silicon-based devices by focusing on wide-bandgap materials like silicon carbide (SiC), gallium nitride (GaN), and synthetic diamond. These materials offer enhanced voltage, temperature, and frequency capabilities, making them particularly relevant for EVs. While synthetic diamond, GaN, and SiC show promise, cost considerations hinder the widespread adoption of diamond-based devices. SiC metal-oxide-semiconductor field-effect transistors (MOSFETs) are favoured over silicon insulated-gate bipolar transistors (IGBTs) due to their superior performance. However, the integration of SiC devices into the EV industry is still a work in progress, with ongoing efforts to find cost-effective and reliable solutions. Challenges remain in identifying suitable materials for power module packaging. The power electronics sector is evolving to meet the demand for higher efficiency and compactness, with wide-bandgap materials like SiC playing a vital role in the future of power semiconductor devices, especially in EVs. Companies including Infineon Technologies, NXP Semiconductors, and STMicroelectronics are using WBG materials to accommodate the high power and frequencies involved in new power designs for electric vehicles, optoelectronics, and other applications that present severe operating conditions [48].

2.3.3.4 Power Electronics Devices for High Voltage

High-voltage power electronics devices are crucial in EVs, playing a key role in their electrification. EVs are adopting higher voltage levels, exceeding 800 volts, offering benefits like reduced current, lower power losses, and increased energy efficiency. Inverters are essential, converting battery DC power into motor-friendly AC power, efficiently controlling speed and torque. High-voltage systems require effective cooling and thermal management due to increased heat generation. Energy efficiency is vital for extending EV range, necessitating power electronics devices that minimize energy losses during power conversion. Reliability, adherence to regulatory standards, safety certifications, and cost-effective solutions are essential in making EVs competitive. As technology advances, higher voltage in EVs and more efficient, compact power electronics devices will continue shaping the future of electric transportation.

Proposed Research Project- 2.5

Design and Development of a High-Voltage DC Inverter (more than 800V) with Advanced Power Electronics and Control Technologies

1. **Gap Analysis & Background**
   Inverters are electronic devices that convert Direct Current (DC) into Alternating Current (AC) and are used to control and manage the power flow effectively. The development of high-voltage DC inverters is motivated by the increasing demand for efficient voltage conversion in applications like renewable energy integration, industrial automation, and electric vehicles. Recent advancements in power electronics and semiconductor devices have created opportunities to design high-capacity inverters that can synchronize with the grid, enhance energy efficiency, and adhere to stringent environmental and safety standards. Current technologies often fall short in terms of voltage capacity, advanced control methods, and eco-friendliness. Bridging these gaps is pivotal to delivering reliable, energy-efficient solutions that address these challenges and contribute to a sustainable and electrified future.

2. **Global Benchmarking**
   Researchers are working on a new soft-switching DC-DC converter and a high step-up inverter topology for PV systems. The converter offers features like isolation, wide input range, soft switching, and voltage regulation. The inverter utilizes series-connected converter blocks, each capable of generating independent voltage levels.

Theoretical analysis, steady-state waveforms, and experimental results validate the proposed system. Future improvements could focus on enhancing topology, control algorithms, and efficiency [49].

3. **TRL Level:** Starting with TRL 3, deliverables to TRL 8

4. **Research Goal**
To create an efficient, reliable and safe system that can meet the demands of modern high-power applications while contributing to energy efficiency and sustainability.

5. **Targets for Project**
    a. Achieve an Inverter efficiency of more than 94% under full load conditions
    b. Develop an inverter that can operate 800-1200V to accommodate various applications without major design modifications
    c. Incorporate a comprehensive fault protection mechanism
    d. Maximizing the Indian supply chain's Domestic Value Addition by 50%

6. **Methodology**
The following tasks are involved in achieving the targets:
    a. Develop a preliminary conceptual design of the inverter
    b. Create a detailed design of the inverter including schematic, layout and component specification
    c. Design an effective thermal management system to dissipate heat generated during operation
    d. Conduct laboratory testing to verify the inverter's performance
    e. Document the design, testing procedures and results thoroughly

7. **Deliverables**
The following are the proposed deliverables of this activity:
    a. A report detailing the preliminary design concepts and architecture
    b. Documentation of the final inverter design, including schematics, component specification and control algorithms
    c. Prototype of high voltage inverter
    d. Documentation of laboratory tests and validation experiments
    e. Target compliance report

8. **Impact**
    a. Their development can lead to longer driving ranges, faster charging times and improved overall performance
    b. It can lead to reduced energy consumption which makes them valuable components in EVs

9. **Indicative list of Execution Agencies:**
    a. Indian Institute of Technology (IIT), Delhi
    b. The Automotive Research Association of India (ARAI), Pune
    c. Visvesvaraya National Institute of Technology, Nagpur
    d. Indian Institute of Technology (IIT), Bombay

10. **Timelines:** 18 - 24months

11. **Estimated Budget**: ₹ 3 - 5 Cr
Research & Development: ₹1.5 Cr
Pilot Manufacturing: ₹3.5 Cr

12. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market			✓	
Technology			✓	

13. **Priority:** Moderate

14. **Administrative Mechanism:**
 From TRL-2 to TRL-5, research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from industry. From TRL-6, industry should take the lead for commercial production. Due to the unavailability of vehicles with 800 V battery packs in India, this project seems futuristic in nature and hence it has been assigned moderate priority. The estimated budget for the project is ₹3-5 Cr, where ₹1.5 Cr is assigned for Research & Development and ₹3.5 Cr is assigned for pilot manufacturing.

3.3.3.5 Power Electronics Devices for High speed operation

Power electronics devices for high-speed operation, such as silicon carbide (SiC) and gallium nitride (GaN) transistors, are witnessing continuous advancements and application expansions across diverse sectors like EVs, renewable energy and many more. These devices offer rapid switching capabilities and heightened efficiency, outperforming conventional silicon-based counterparts. Yet, challenges persist, including managing thermal dissipation, minimizing switching losses, meeting voltage and current demands, addressing parasitic effects, ensuring long-term reliability, and managing costs. Overcoming these obstacles necessitates sustained research, collaborative industry efforts, and innovative approaches to enhance device performance.

3.3.3.6 Power Electronics for HESS (By-directional DC to DC Convertor)

Power Electronics converters such as DC-DC Bi-Directional converters have seen significant advancements. These converters play a crucial role in managing the energy flow between different storage technologies like batteries, supercapacitors etc. One of the primary goals in power electronics for hybrid energy storage system (HESS) is to improve system efficiency. New converter topologies such as multi-level converters and soft switching techniques aim to reduce energy losses during energy conversion. Developing control strategies that efficiently manage the charging and discharging of multiple storage elements in HESS is still a challenge. On-going research and development efforts aim to further enhance system performance with a focus on emerging technologies like wide-bandgap semiconductors. Overcoming the challenges require interdisciplinary collaboration and a focus on standardization and environmental sustainability to enhance the performance and adoption of HESS.

3.3.3.7 Packaging & Thermal Management for Power Electronics Devices

The packaging and thermal management for power electronics devices in EVs have undergone significant advancements. This includes the exploration of advanced materials, integrated cooling solutions such as liquid cooling, miniaturization for compact design and the utilization of wide band gap semiconductors like SiC and GaN. Innovation in cooling architectures, reliability enhancements through predictive maintenance and the development of intelligent control system contribute to efficient thermal management. Ongoing efforts in simulations and modeling, improvements in thermal interface materials. Challenges persist in achieving high power density while effectively managing thermal issues, prompting researchers to explore novel approaches for a balanced solution.

2.3.3.8 Manufacturing process

There is a notable trend towards adopting advanced semiconductor materials like silicon carbide (SiC) and gallium nitride (GaN) to improve efficiency and performance. Manufacturing processes are becoming increasingly complex, requiring precise control and optimization to ensure high-quality device production. However, challenges persist in material sourcing, process scalability, yield enhancement, packaging, and environmental sustainability. Despite these challenges, there is significant progress in developing innovative solutions and collaborations among industry stakeholders, research institutions, and government agencies. Efforts are focused on improving process efficiency, reducing costs, and enhancing environmental sustainability to meet the growing demand for power electronics devices in various applications such as electric vehicles, renewable energy systems, and data centers.

Proposed Research Project- 2.6

High-Yield Manufacturing process for GaN WBG Semiconductor

1. **Gap Analysis & Background**
   Gallium Nitride (GaN) based devices offer superior performance, especially in high-power and high-frequency applications. Their ability to operate at elevated temperatures and handle high voltages, positions GaN as a key player in the advancement of next-generation electronics. Despite these potential benefits, the manufacturing of GaN semiconductors presents several challenges such as material quality, difficulty in achieving stable p-type doping, and substrate mismatch. Currently, substrates like silicon (Si), silicon carbide (SiC), and sapphire are used, which have impeded the scalability and cost-effectiveness of GaN devices. While SiC is more mature than GaN in terms of substrate technology and offers better thermal and lattice matching . To overcome these challenges, there is a need to develop scalable, cost-effective manufacturing processes aiming to unlock the broad application of GaN technology.

2. **Global Benchmarking**
   In specific applications, Gallium Nitride (GaN) is favored for its elevated electron mobility, reduced die size, and increased power density. However, it encounters challenges such as substrate limitations for GaN epitaxy, crystalline defects, and polarity issues. Addressing these hurdles, researchers at Nagoya Institute of Technology in Japan utilized silicon (Si) as a substrate. Employing various techniques, including Metal-Organic Chemical Vapor Deposition (MOCVD), molecular beam epitaxy (MBE) and hydride vapor phase epitaxy (HVPE) they successfully obtained an epitaxial layer with improved crystal quality without cracks [50]. Similarly, researchers from Qilu University of Technology (Shandong Academy of Sciences), Jinan, China reported that GaN devices can be integrated on Si Substrates by applying techniques like MOCVD, MBE and HVPE. Amongst which, the epitaxial layer grown by MOCVD technology has the advantages of low surface roughness, high purity, and easy mass production [51].

3. **TRL Level:** Starting with TRL-2, deliverable to TRL 5

4. **Research Goal**
   To optimize manufacturing processes, elevate crystal quality using advanced epitaxial growth, investigate innovative p-type doping approaches and improve overall process uniformity.

5. **Targets for Project**
   a. Establish manufacturing procedures that consistently produce GaN Wide Bandgap (WBG) semiconductors of high quality with minimal deviations
   b. Improve crystal quality through advanced epitaxial growth techniques, aiming for uniformity and enhanced performance
   c. Investigate and implement innovative p-type doping strategies for GaN WBG semiconductors to achieve stable and efficient doping
   d. Investigate various dielectric materials and deposition processes to optimize the gate dielectric interfaces, aiming for improved stability and performance

6. **Methodology**
   The following tasks are involved in achieving the targets:
   a. Evaluate various substrate materials (e.g., silicon carbide, sapphire) for their impact on GaN material quality
   b. Systematically optimize growth parameters, including temperature, pressure, and precursor flow rates, to achieve uniform and high-quality GaN layers
   c. Experiment with different doping concentrations and techniques to develop stable and efficient p-type doping strategies for GaN WBG semiconductors
   d. Investigate various dielectric materials and deposition processes for optimizing the gate dielectric interface

e. Utilize electrical characterization methods to assess the impact of interface modifications on device performance
f. Develop accelerated reliability testing protocols to simulate long-term device operation

7. Deliverables

The following are the proposed deliverables of this activity:

a. Comprehensive documentation outlining optimized manufacturing processes for high-yield GaN Wide Bandgap (WBG) semiconductors
b. Detailed report highlighting improvements in crystal quality and uniformity achieved through advanced epitaxial growth techniques
c. Report on successful p-type doping methods, including materials, concentrations, and deposition techniques
d. Report on the optimization of gate dielectric interfaces, outlining materials, deposition processes, and performance improvements.
e. Development and documentation of accelerated reliability testing protocols
f. Comprehensive cost analysis document, outlining the economic viability and competitiveness of the developed manufacturing processes
g. Regular reports on project reviews, feedback sessions, and recommendations for continuous improvement in manufacturing processes

8. Impact

a. The project's outcomes are expected to advance GaN Wide Bandgap (WBG) semiconductor technology, contributing to enhanced performance, reliability, and versatility
b. Improved manufacturing processes will position GaN WBG technology as a more competitive option in the semiconductor market, offering higher yields and cost-effectiveness
c. The project's advancements are expected to encourage the broader adoption of GaN technology across various sectors like phones, electronic power systems, wireless devices, and the upcoming 6G networks.

9. Indicative list of Execution Agencies:

a. Non-Ferrous Materials Technology Development Centre (NFTDC), Hyderabad
b. Semi-conductor Laboratory (SCL), Mohali
c. Indian Institute of Science (IISc), Bangalore

10. Timelines: 60 months

11. Estimated Budget: ₹150 Cr
Research & Development: ₹90 Cr
Pilot Manufacturing: ₹60 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence				✓
Market		✓		
Technology			✓	

13. Priority: High

14. Administrative Mechanism:

Research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from industry. The project is crucial for technological advancement, particularly in power electronics and high-frequency applications. Improving GaN manufacturing processes enhances properties like high electron mobility, wide bandgap, thermal stability, which results in improving energy efficiency, sustainability and electronic system miniaturization. The estimated budget for the project is ₹150 Cr, where ₹90 Cr is assigned for Research & Development and ₹60 Cr is assigned for pilot manufacturing.

2.3.4 Thermal Management of Batteries, Motors & Power Electronics Devices

2.3.4.1 Current Status & Challenges

Thermal management systems are essential for EVs to ensure battery safety and optimize energy utilization. It has cooling, heating, and insulating features to assure the proper operating conditions for EV systems including the powertrain, batteries, and power electronics devices. Traditional air-cooling systems are user-friendly but struggle to effectively handle heat, while active thermal management systems are efficient but come with drawbacks like high power consumption and cost. Research indicates that conventional cooling methods are inadequate for high-capacity EV systems. Emerging alternatives like phase change material cooling and direct liquid cooling are gaining attention. Heat pipe cooling and liquid cooling are also promising but face challenges like diminishing coolant effectiveness over time, electrical conductivity issues, and the risk of leaks. For instance, a hybrid cooling system that combines active and passive thermal management systems is being explored to minimize energy consumption while effectively managing heat.

2.3.4.2 New Thermal Management System

In the early stages of EV development, air cooling was a popular choice for thermal management due to its simplicity, cost-effectiveness, and ease of maintenance. However, it has limitations in handling high heat dissipation demands. Liquids, with their better thermal conductivity and heat capacity, have proven more effective in managing temperature. Direct liquid cooling is emerging as an advanced thermal management solution for next-generation EVs. Emerging alternatives like phase change material cooling and advanced direct cooling are gaining attention, particularly considering the increasing energy density of EV batteries. Recommended coolants for immersion cooling, chosen based on their key properties, encompass a range of options like dielectric fluid, hydro-fluoro-ethers, hydrocarbons, esters, mineral oils, silicone oils, water-glycol mixtures etc. but the liquid cooling brings complexities related to coolant evaporation and condensation, coolant flow distribution, increased pump losses with viscous coolants, higher costs, greater fluid weight, and material compatibility issues. Further in-depth research is needed to determine the best approach for implementing thermal management systems in future EVs, especially for batteries and propulsion systems.

Proposed Research Project- 2.7

Novel Thermal Management System for Battery Pack

1. **Gap Analysis & Background**
With the global shift towards renewable energy, electric vehicles and increased reliance on battery-based solutions, the efficient and safe operations of these battery packs are of paramount importance. Controlling and dissipating heat generated during charging, discharging, and other operations is vital for improving battery performance, extending lifespan, ensuring safety and supporting rapid-charging capabilities. The primary objective of this project is to develop a novel thermal management system that excels in efficiently dissipating heat, maintaining batteries within optimal temperature ranges and improving overall battery performance.

2. **Global Benchmarking**
Researchers from Germany and China have developed a prototype of a high-voltage battery pack for electric vehicles (EVs), incorporating a hybrid thermal management system with an innovative hybrid cooling plate (HCP). By integrating active cooling with phase change material (PCM), the HCP design minimizes liquid leakage risks and allows for easy installation and customization with various PCMs. Mechanical enhancements, including the use of a mandrel, improve compression at the pack level. Custom control strategies demonstrate effective cooling performance under different discharge conditions, maintaining the battery pack temperature below 35˚C and ensuring temperature uniformity [52].

3. **TRL Level:** Starting with TRL 2, deliverables to TRL 5

4. **Research Goal**

To design, develop and test a novel thermal management system that enhances the thermal performance and overall efficiency of battery packs in electric vehicles and energy storage systems.

5. **Targets for Project**
   a. Optimize the manufacturing process to minimize production costs, including assembly and labour expenses
   b. Minimize the risk of thermal runaway and thermal-related safety issues
   c. Ensure that the system is scalable to various battery pack sizes and configurations
   d. Strive to reduce the overall cost of the thermal management system compared to existing solutions while maintaining or improving performance

6. **Methodology**

The following tasks are involved in achieving the targets:
   a. Develop conceptual designs for the thermal management system
   b. Create computational models to simulate the thermal behaviour of the battery and the proposed thermal management system under different operating conditions
   c. Build a prototype of the novel thermal management system, incorporating the selected components and design concepts
   d. Conduct extensive laboratory testing and experiments to evaluate the performance of the prototype under controlled conditions
   e. Conduct field tests and validation in real-world EVs to assess the system's performance, durability, and user satisfaction

7. **Deliverables**

The following are the proposed deliverables of this activity:
   a. Detailed engineering design, specifications, schematics and technical drawings
   b. A physical prototype of the novel thermal management system
   c. Comprehensive data from laboratory testing and experiments
   d. Target compliance report

8. **Impact**
   a. By maintaining batteries within optimal temperature ranges, the system can extend the lifespan of battery cells
   b. Reduced charging times encourage the use of electric vehicles by enabling longer EV trips, reducing range anxiety
   c. It can lead to significant cost savings for consumers
   d. It enhances battery safety by preventing overheating

9. **Indicative list of Execution Agencies**
   a. Indian Institute of Technology (IIT), Delhi
   b. The Automotive Research Association of India (ARAI), Pune
   c. Visvesvaraya National Institute of Technology, Nagpur
   d. Indian Institute of Technology (IIT), Bombay

10. **Timelines:** 18-24 months

11. **Estimated Budget**: ₹13 - 15 Cr

Research & Development: ₹10 Cr
Pilot Manufacturing: ₹5 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market			✓	
Technology				✓

13. Priority: Moderate

14. Administrative Mechanism

Research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from industry. By considering the factors like effectiveness of existing thermal management solutions, the maturity of emerging technologies, and potential integration challenges, the project is given moderate priority with an estimated budget of ₹13-15 Cr. An estimated budget of ₹10 Cr is assigned for Research & Development and ₹5 Cr is assigned for pilot manufacturing.

Proposed Research Project – 2.8

India-Centric identification of Phase Change Material for Thermal Management System

1. **Gap Analysis & Background**

In contrast to traditional thermal management systems such as air-cooled and liquid-cooled system, phase change materials (PCMs) stand out due to its lightness, compactness and high efficiency. PCMs exhibit the ability to absorb or release significant latent heat while maintaining a nearly constant temperature. The escalating demand for PCMs highlights the requirement for a robust ecosystem in India. Strategic initiatives like "Make in India" and "Atmanirbhar Bharat" underscore the emphasis on indigenous production. To meet this demand, it is required to establish a strong knowledge foundation, the cultivation of skilled human resources, and government support. The project is oriented towards a comprehensive exploration of the availability of phase change materials in India.

2. **Global Benchmarking**

Globally, PCMs for various applications commonly include organic compounds such as paraffin and its hydro compositions, as well as inorganic compounds like nitrate salts, carbonate salts, hydroxide salts, chloride salts, and sulphate salts. Presently, these materials are imported into India from various countries. To promote indigenous production, researchers from KPR Institute of Engineering and Technology in Coimbatore, India, introduced a hybrid solution by infusing paraffin with nanoparticles, specifically a combination of nano-SiO_2 and nano–CeO_2. The outcomes revealed significant improvements in the thermal storage characteristics of paraffin, making the system well-suited for low-temperature solar thermal applications [53].

3. **TRL Level:** Starting with TRL-2, deliverable to TRL 5

4. **Research Goal**

Development of a self-sustaining ecosystem for Phase Change Materials (PCMs) in thermal management systems, minimizing reliance on imports and promoting indigenous production.

5. **Targets for Project**
   a. Identify and select a diverse range of PCMs suitable for varied thermal management application in India
   b. Assess the thermal performance, stability and phase change characteristics of the PCMs
   c. Evaluate the suitability of PCMs for specific industries in India, considering unique thermal challenges and requirements
   d. Strive to reduce the overall cost of the thermal management system compared to existing solutions while maintaining or improving performance

6. **Methodology**
   a. Establish criteria for selecting PCMs considering thermal properties, phase change temperatures and compatibility with Indian climatic conditions

b. Create computational models and simulate to assess thermal stability, latent heat storage capacity and phase change characteristics
c. Monitor and analyse the real-world performance of PCMs under varying temperature and environmental conditions
d. Develop guidelines for the integration of PCMs into existing thermal management system, addressing industry specific needs
e. Conduct a comprehensive cost benefit analysis to determine the economic feasibility
f. Identify gaps in current research and propose areas for future exploration and improvements in India-centric PCM technologies

7. Deliverables

a. Guidelines for effectively integrating PCMs into diverse thermal management systems
b. Results from laboratory experiments including thorough assessments of thermal performance, stability analyses and phase change characteristics of selected PCMs
c. Document outlining recommendations for future research endeavours, identifying gaps and suggesting areas for further exploration in India-centric PCM technologies.

8. Impact

a. The project is expected to contribute to technological advancements in thermal management systems, introducing innovative solutions through the effective identification and application of PCMs
b. It has the potential to enhance energy efficiency in various industries, resulting in a reduction of overall energy consumption
c. It can lead to significant cost savings for consumers
d. It enhances battery safety by preventing overheating

9. Recommended Execution Agencies

a. National Chemical Laboratory (NCL)
b. Indian Institute of Technology (IIT), Madras
c. Non-Ferrous Materials Technology Development Centre (NFTDC), Hyderabad

10. Timelines: 36 months

11. Estimated Budget: ₹ 30 Cr
Research & Development: ₹25 Cr
Pilot Manufacturing: ₹5 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market		✓		
Technology			✓	

13. Priority: High

14. Administrative Mechanism

Research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from industry. The project supports for National Initiatives and promotes indigenous technological solutions, which can be a cost saving for industries. The estimated budget for the project is ₹30 Cr, where ₹25 Cr is assigned for Research & Development and ₹5 Cr is assigned for pilot manufacturing.

2.3.5 Motor Control Unit

The performance and efficiency of electric powertrains are achieved by advanced motors and motor controllers. Currently, India has been relying on imports for motor controllers. The biggest concerns in EV motor control include requirements for higher efficiency, which are also related to the need to extend EV range. One of the biggest challenges in EV motor control is to achieve higher efficiency at high speeds. As the motor speed increases, efficiency deteriorates due to an increase in frequency of sinusoidal current signals which makes it difficult for motor controllers to track. Additionally, due to an increase in the speed, frequency, and amplitude, the back-emf also increases, further hampering the motor efficiency.

Proposed Research Project- 2.9

Enhancing Efficiency in High-Speed Electric Vehicle Propulsion Systems through Motor Control Optimization

1. **Gap Analysis & Background**
   Electric vehicles (EVs) rely on motor control units to regulate speed, torque, and efficiency. However, maintaining efficiency at higher speeds presents challenges and they affect crucial parameters like range optimization, performance, thermal management, and regenerative braking. Addressing these challenges requires advancements in motor control algorithms, power electronics, thermal management, and vehicle integration. Through research in this area, the aim is to enhance EV efficiency and performance, contributing to the transition towards sustainable transportation solutions.

2. **Global Benchmarking**
   Researchers from the University of Technology Sydney, Australia, are implementing motor control systems for electric vehicles using Field-Oriented Control (FOC) and Model Predictive Control (MPC) methods. It discusses motor modelling, hardware configuration, and practical considerations such as field-weakening control and overmodulation to address load variations. Experimental comparisons between FOC and MPC methods demonstrate fast and stable torque responses with minimal torque ripple within rated power. Overall, the reviewed motor controller offers flexibility for different motor types, making it suitable for electric vehicle applications [54].

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-5

4. **Research Goal**
   To enhance the efficiency and performance of electric vehicles by addressing challenges associated with maintaining optimal motor control unit operations at higher speeds.

5. **Targets for Project**
   a. Optimize power electronics components such as inverters and converters to improve efficiency at higher speeds
   b. Integrate the motor control unit with the battery management system (BMS) to optimize power delivery and maximize efficiency across varying speed profiles and driving conditions
   c. Explore methods to optimize regenerative braking systems for higher-speed operation, capturing more kinetic energy to extend vehicle range
   d. Validate and fine-tune control algorithms, power electronics designs, and thermal management solutions through simulation

6. **Methodology**
   The following tasks are involved in achieving the targets:
   a. Optimize motor control algorithms tailored for high-speed operation, leveraging techniques such as field-oriented control (FOC) or direct torque control (DTC)
   b. Optimize power electronics components, including inverters and converters, to maximize efficiency at higher speeds
   c. Validate the developed algorithms, power electronics designs, thermal management solutions, and integration strategies through a combination of simulation studies
   d. Evaluate the performance of the optimized motor control unit through comprehensive testing under various operating conditions, including steady-state and dynamic scenarios

7. Deliverables

The following are the proposed deliverables of this activity:

a. Documentation of optimized motor control algorithms, including detailed descriptions, flowcharts, and implementation guidelines
b. Design specifications, schematics, and simulation results for optimized power electronics components such as inverters and converters
c. Development of control algorithm and communication strategies of motor control unit with different electrical and electronics components
d. Documentation of integration protocols and control strategies for seamless integration of the motor control unit with the battery management system (BMS)
e. Comprehensive data and analysis from simulation studies and experimental testing, validating the performance of developed algorithms and components
f. Detailed evaluation reports highlighting the performance of the optimized motor control unit under various operating conditions
g. Cost and Target compliance report

8. Impact

a. Enhancing the efficiency of motor control units at higher speeds can lead to significant energy savings, extending the range of electric vehicles and reducing overall energy consumption
b. By maximizing energy efficiency and optimizing regenerative braking systems, electric vehicles can achieve longer driving ranges on a single charge, addressing one of the key barriers to widespread adoption
c. The research outcomes can drive advancements in motor control and power electronics, benefiting not only electric vehicles but also other applications such as renewable energy systems and industrial automation
d. Efficiency improvements may lead to cost savings for electric vehicle manufacturers and consumers through reduced energy consumption, maintenance, and operational costs over the vehicle's lifespan

9. Indicative list of Execution Agencies

a. Indian Institute of Technology (IIT), Madras
b. The Automotive Research Association of India, Pune
c. Indian Institute of Technology (IIT), Delhi

10. Timelines: 24 months

11. Estimated Budget: ₹ 2.5 Cr
Research & Development: ₹2 Cr
Pilot Manufacturing: ₹0.5 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market		✓		
Technology			✓	

13. Priority: Moderate

14. Administrative Mechanism:

Research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from the industry. By considering factors such as extension in EV range, energy conservation and technological progress the project is aimed to optimize motor control efficiency for high-speed EV with an estimated budget of ₹2.5 Cr. An estimated budget of ₹2 Cr is assigned for Research & Development and ₹0.5 Cr is assigned for pilot manufacturing.

2.3.6 Vehicle Control Unit

A Vehicle Control Unit (VCU) is an electronic control unit that manages a vehicle's subsystems. The VCU ensures that the vehicle operates efficiently and safely by monitoring critical systems such as battery health, motor temperature, and state of charge. Currently, VCUs are yet to get standardized in terms of hardware and software so that they will be able to fit into any vehicle system. As of now, every company has VCUs with its software and hardware architecture. This would change the VCU market scenario in the future. However, one of the primary challenges is to ensure reliable and high-speed communication with powertrain controllers and intelligent and robust control of the vehicle powertrain to coordinate driving modes.

2.3.7 Battery Management System

The Battery Management System (BMS) plays a crucial role in optimizing battery performance and safety across various sectors such as consumer electronics, electric vehicles, and renewable energy storage. However, accurately estimating battery conditions presents challenges due to limited data availability, imperfect models, and the unpredictable behaviour of batteries. To overcome these obstacles, researchers and engineers are leveraging smart sensor technology, advanced algorithms, and efficient data storage solutions. Despite concerted efforts, accurately predicting battery conditions remains difficult, particularly in demanding scenarios. Nonetheless, ongoing advancements in intelligent batteries and advanced technologies are transforming battery state estimation methods, ultimately enhancing accuracy even in complex and extreme conditions.

2.3.8 DC-DC Converter

DC-DC converters have made significant strides in efficiency and size reduction, propelled by advanced semiconductor technologies such as SiC and GaN transistors. These innovations enable improved energy conversion efficiency, compact designs, and higher power densities. They are increasingly versatile and capable of accommodating wide input voltage ranges, critical for renewable energy and electric vehicle applications. Digital control methods further enhance performance, facilitating features like adaptive control. Despite these advancements, challenges remain in optimizing efficiency at light loads, ensuring rapid response to load changes, and managing electromagnetic interference. Ongoing research focuses on refining control strategies, compensation techniques, and EMI mitigation approaches.

2.3.9 Inverter

Advancements in inverter technology, fueled by innovations in semiconductor devices like SiC and GaN transistors, have led to highly efficient and compact designs. In the EV sector, ongoing developments focus on meeting the increasing demands for higher power density, improved efficiency, and enhanced thermal management, resulting in longer driving ranges and faster charging times. Conversely, industrial motor drives rely on inverters to control the speed and torque of AC motors across various applications. Despite these advancements, challenges persist in optimizing inverter efficiency under partial load conditions and addressing electromagnetic interference (EMI) issues. Additionally, in energy storage systems, there are obstacles in optimizing control algorithms and managing bidirectional power flow. Thus, while significant progress has been achieved, further efforts are needed to overcome these challenges and enhance performance across diverse applications.

2.3.10 DC Switch Gear

The present status of DC switchgear showcases ongoing advancements and widespread adoption across various sectors, including renewable energy, electric vehicles, and data centres. Key priorities include enhancing efficiency, reliability, safety, sustainability, and compliance with regulations. Research and development endeavours are directed towards improving performance and exploring novel applications, underscoring the dynamic nature of the field. Standardized solutions are needed to address compatibility issues between different EV models and charging stations, stemming from variations in charging protocols and connector types. Moreover, scaling up DC charging infrastructure to meet the rising demand from the growing adoption of electric vehicles presents logistical and cost-related hurdles. Overcoming these challenges necessitates concerted efforts in research, innovation, and collaboration to propel the advancement of DC switchgear technology.

2.3.11 Hybrid Energy Storage System

2.3.11.1 Current Status & Challenges

Hybrid energy storage systems (HESS), combining different energy storage technologies such as batteries, and supercapacitors are gaining attention for their ability to provide a balanced solution that combines high energy density with fast response time. Research efforts are ongoing to enhance the design, efficiency and overall performance of HESS. This includes exploring new materials, advanced control strategies and innovative system configurations. In EVs, HESS is being explored to address the dual requirements of high power for accelerating and regenerative braking and high energy density for extended range. Advanced control systems and technology integration with renewables are key focus areas for research and development.

Chapter 3: Materials & Recycling

3.1 Introduction

Recycling is the process of transforming used or discarded materials into new products, aiming to utilize less energy, reduce the consumption of fresh raw materials, and protect the environment. It plays a crucial role in sustainable waste management by reducing landfill waste, cutting greenhouse gas emissions, and conserving natural resources. Recycling can be categorized into three categories viz reduce, reuse, and recycle.

3.2 Current scenario of Domestic Materials and Recycling of Materials used in various systems for eMobility

In India, approximately 90% of used batteries are either processed by the unorganized industry or end up in landfills and garbage dumps. This poses a risk to human safety in addition to being an environmental issue. The Government of India (GoI) released the draft regulations for battery recycling called Battery Waste Management Rules 2022. This management rule outlines a minimum of 90% materials recovery by 2027. The NITI-Aayog also predicts that India's EV battery recycling market is set to expand to 128 GWh by 2030 [55].

3.3. Research Pathways

3.3.1 Materials Used in Li-ion Chemistries

3.3.1.1 Current Status & Challenges

Lithium-ion batteries can be a safety hazard if not properly engineered and manufactured because they have flammable electrolytes that, if damaged or incorrectly charged, can lead to explosions and fires. Research has been under way in the area of non-flammable electrolytes as a pathway to increased safety based on the flammability and volatility of the organic solvents used in the typical electrolyte. At present, there are only two types of commercialized anode materials: those based on carbon and the oxide spinel Li4Ti5O12. The use of a low potential intercalation electrode avoids the cycling and safety issues associated with dendrite formation on lithium anodes undergoing recharge, which have stymied their use in rechargeable batteries. Current research on electrodes for Li ion batteries is directed primarily toward materials that can enable higher energy density of devices. For positive electrodes, both high voltage materials such as LiNi0.5Mn1.5O4 and those with increased capacity are under development.

However, development of materials for lithium ion chemistries poses several challenges. To overcome this Nano structuring works best when used on materials with low reactivity, such as LiFePO4 and Li4Ti5O12, which have now been commercialized. A Nano approach also appears to have some merit for silicon anodes, which are in an advanced stage of development. In addition to silicon, new high-energy density electrodes such as layered-layered oxide composites, high voltage spinel's, conversion materials, and multivalent redox compounds including but not limited to silicates have recently emerged on the battery landscape. Recently, many investigations have gone into revolutionary novel nanoarchitectures to enlarge the capacity and lifespan of the LIBs. Among kinds of candidates, graphene has emerged as one of the most foremost contenders.

Proposed Research Project – 3.1

Research on Competitive Manufacturing Methods of Graphene

1. **Gap Analysis & Background**
Graphene is a compound of a single layer of carbon atoms linked in a hexagonal pattern with superior properties of tensile strength, thermal and electrical conductivity, and corrosion resistance. In India, the manufacturing of graphene material is gaining significance due to its potential applications in automotive electronics, energy storage, and other industries. There are several methods for manufacturing graphene; the Chemical Vapor Deposition (CVD) method is the most widely used. With this method, high quality and excellent conductivity of graphene can be achieved as compared to others. But this method faces challenges such as scalability, cost, and environmental impact. To overcome this challenge, research must focus on novel methods with cost-effective processes, including the use of locally available resources and energy-efficient techniques.

2. **Global Benchmarking**
Globally, the Chemical Vapor Deposition (CVD) procedure is adopted to produce high-quality monolayer and a few layers of graphene; however, mass manufacturing with the CVD approach is challenging. To overcome this problem, researchers are working on novel manufacturing methods for the mass production of graphene. For example, researchers from Virginia Tech have developed a novel one-pot production process for graphene production. The process requires only one acid and no oxidants, which greatly simplifies production compared to current methods [56]. The Indian Institute of Technology, Patna, developed a way to produce graphene using a plasma gun that they hope is scalable while still producing high-quality material [57].

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-5

4. **Research Goal**
To research on novel Graphene manufacturing methods that are capable of scaling up for large-scale production, allowing for faster and more cost-effective manufacturing, and are sustainable and environmentally friendly compared to existing methods.

5. **Targets for Project**
    a. Investigation and development of novel method for synthesizing graphene with enhanced efficiency, yield, cost effective, and easily scalable for mass production
    b. Optimization of energy consumption during the manufacturing process to enhance overall sustainability and reduce environmental impact
    c. Facilitation through documentation for adoption of the manufacturing method across industries by addressing compatibility issues and demonstrating its practicality and benefits

6. **Methodology**
    a. Conduct a comprehensive review of existing graphene synthesis methods and identify challenges in current approaches
    b. Conduct a cost-benefit analysis to assess the economic feasibility of the novel method compared to existing approaches
    c. Design and implement energy efficient processes, considering operational costs associated with graphene production
    d. Integration of automation and control systems to enhance precision, reduce human error, and ensure consistent product quality
    e. Ensure that the manufactured graphene is compatible for the application of battery cells
    f. Develop robust quality control protocols to ensure the reliability and consistency of the graphene produced through the novel method
    g. Optimization of the novel manufacturing method based on feedback from experiments, adjusting parameters to enhance performance
    h. Develop and implement safety protocols for handling graphene materials, addressing potential health and environmental risks

7. Deliverables

a. Novel manufacturing process parameters
b. Manufacturing feasibility report
c. Novel manufacturing process equipment
d. Detailed design and specification
e. Target compliance report

8. Impact

a. Enhance the commercial viability of graphene by reducing production costs, making it a more attractive material for widespread adoption across industries
b. Simulate economic growth by creating opportunities for new businesses and industries centred around the production and application of graphene material

9. Recommended Execution Agencies

a. Indian Institute of Technology (IIT), Roorkee
b. Indian Institute of Science (IISc), Bangalore
c. Nonferrous Materials Technology Development Centre (NFTDC), Hyderabad

10. Timeline: 60 Months

11. Estimated Budget: ₹100 Cr
Research & Development: ₹80 Cr (Divided equally between two parties)
Pilot Manufacturing: ₹20 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence	✓			
Market			✓	
Technology				✓

13. Priority: High

14. Administrative Mechanism
This project is deliverable to TRL 5. It is forecasted that the prototype product developed by research institutions will be transferred to industries for commercial production. The development of scalable manufacturing methods can potentially reduce production costs, making graphene more economically viable and customization for widespread use in various industries. The estimated budget of ₹80 Cr is allocated for research and development and ₹20 Cr is assigned for pilot manufacturing.

3.3.1.2 Cathode materials

Electric vehicle (EV) batteries utilize diverse cathode materials such as Lithium Nickel Cobalt Aluminium Oxide (NCA), Lithium Nickel Manganese Cobalt Oxide (NMC), and Lithium Iron Phosphate ($LiFePO4$), which pose safety concerns due to thermal runaway reactions. Ensuring EV safety requires robust battery designs. Moreover, high-performance cathode materials like NCA and NMC, which rely on costly elements, contribute to increased EV battery expenses. Additionally, the environmental impact of cathode material production and disposal underscores the importance of sustainable manufacturing and recycling approaches.

3.3.1.3 Anode materials

Anode materials are essential in lithium-ion batteries for electric vehicles (EVs), influencing performance, energy storage capacity, and overall efficiency. EV lithium-ion chemistry employs various types of anode materials. Unlike graphite anodes, which have limited capacity and safety concerns, alloy anodes and their combinations are used to mitigate these issues. Moreover, alloy anodes demonstrate outstanding processing traits and high charge-discharge capacity, indicating potential for advancing lithium-ion battery (LIB) technology.

3.3.1.4 Electrolytes

A recent advancement in electrolyte technology is the utilization of Room Temperature Ionic Liquids (RTILs), which mitigate flammability and volatility issues associated with organic electrolytes. To address environmental contamination and flammability risks linked with liquid electrolytes, solid polymer electrolytes (SPEs) are emerging as promising alternatives, employing materials like poly(oxyethylene) (POE) to enhance battery safety. Furthermore, battery technology advancements include the adoption of ceramics as electrolytes, such as Lithium Super Ion Conductors (LiSICONs) and glassy materials, resulting in enhanced conductivities. Efforts to enhance ceramic electrolyte conductivity aim to achieve performance levels comparable to liquid electrolytes. Another critical factor impacting Li-ion battery performance is the Solid Electrolyte Interphase (SEI), a passivation layer formed at electrode surfaces from electrolyte decomposition products.

3.3.1.5 Cell & battery casing

Automobile industries frequently employ aluminium for crafting vehicle body parts and essential components like battery housings due to its lightweight nature and unique qualities such as corrosion resistance, high strength, excellent machinability, and versatility in manufacturing techniques. This makes aluminium an ideal material for EV battery box design. Similarly, stainless steel is commonly chosen for EV battery boxes due to its superior machining properties, strength, rigidity, and suitability for complex geometries, making it beneficial for electric car battery enclosures. Fiber-reinforced composites and thermoplastics are emerging as promising materials for EV battery boxes due to their lightweight, high strength, durability, and resistance to heat and fire, offering advantages over traditional metals and alloys in terms of weight reduction and cost-effectiveness. Despite these alternatives, aluminium remains predominant in EV battery box designs, reflecting its established reliability and widespread usage in the automotive industry, while other materials represent a growing trend as manufacturers seek further weight reduction in electric vehicles.

Proposed Research Project – 3.2

Research on Novel Material Composition for Battery pack and Cell Casing

1. **Gap Analysis & Background**
   Battery protection and monitoring are a necessity with Li-ion battery packs to protect them from overvoltage and load impact during crashes/accidents. To avoid damages by side-impact and pole-impact load cases, the EVs are equipped with battery housing systems. The cell casing of an battery is responsible for providing crash-safe battery protection against electric shock and fire dangers. This project is focus on research on novel material composition for battery pack and cell (prismatic, pouch and cylindrical) casing to ensuring robust protection for the battery cells against external impacts, vibrations, and thermal events to prevent the risk of fire or explosion.

2. **Global Benchmarking**
   The range of materials for developing EV battery cases is growing, and are addressing issues of weight, assembly and even condensation. Globally, EV production incorporates various thermoplastic materials for components such as battery modules, and battery enclosures. Novelis Introduces new design innovations with second Generation Aluminium Intensive Battery Enclosure Solution for Electric Vehicles [58].Notably, a plug-in hybrid EV manufactured in china uses a thermoplastic polypropylene compound for its battery case cover instead of aluminium, resulting in significant weight savings [59]. A design known as "cell-to-pack" eliminates the intermediate module stage and inserts the cells right into the pack. This design is currently being produced by BYD. The battery cell, the vehicle chassis, the electric powertrain, and thermal management are all integrated via cell-to-chassis technology.

3. **TRL Level:** Starting with TRL-3, deliverable to TRL-5

4. **Research Goal**
To research on novel material composition for battery pack and cell casing to enhance the need for a lightweight casing, durability, vehicle efficiency, range, robust protection, and thermal management

5. **Targets for Project**
    a. Develop novel material that enhance the safety of battery packs by providing better protection of cells against physical damage, thermal runaway, and fire hazards
    b. Design novel material that withstand mechanical stress, corrosion, and environmental factors ensuring long-term durability and reliability under various operating conditions
    c. Investigate lightweight materials that maintain structural integrity while reducing the overall weight of the battery pack, thereby improving vehicle efficiency and extending range

6. **Methodology**
    a. Conduct a comprehensive review of existing literature related to battery pack casing and identify gaps, potential areas for innovation
    b. Identify candidate materials based on their properties and suitability for battery pack casing
    c. Develop new materials or modify existing ones to meet the desired properties, this may involve chemical synthesis, formulation of composites, surface modification, and nanomaterial incorporation
    d. Characterize the physical, chemical, and mechanical properties of the developed materials using various analytical techniques
    e. Fabricate prototype battery pack and cell casing using the developed materials through suitable manufacturing processes
    f. Conduct comprehensive testing of prototype battery pack casing under simulated operating conditions
    g. Validate the performance, safety, and reliability of production ready through rigorous testing and certification processes

7. **Deliverables**
    a. Detailed design and specification
    b. Developed Prototype
    c. Target Compliance Report
    d. Performance testing results

8. **Impact**
    a. Development of novel material will enhance the overall performance of the battery pack, leading to increased energy density, longer lifespan and improved safety
    b. Innovative materials can provide a competitive edge in the market, especially if the new casing material offers superior characteristics compared to existing solutions.

9. **Recommended Execution Agencies**
    a. Indian Institute of Technology (IIT), Roorkee
    b. Indian Institute of Science (IISc), Bangalore
    c. Nonferrous Materials Technology Development Centre (NFTDC), Hyderabad
    d. Indian Institute of Technology (IIT), Bombay
    e. Indian Institute of Technology (IIT), Madras

10. **Timeline:** 24 Months

11. **Estimated Budget**: ₹10 Cr
Research & Development: ₹8 Cr (Divided equally between two parties)
Pilot Manufacturing: ₹2 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence			✓	
Market				✓
Technology			✓	

13. Priority: Moderate

14. Administrative Mechanism

This project is deliverable to TRL 5. It is forecasted that the prototype product developed by research institutions will be transferred to industries for commercial production. The development of new novel material composition can potentially ensure robust protection, making material more economically viable and customization for widespread use in various industries. The estimated budget of ₹10 Cr is allocated for research and development and ₹2 Cr is assigned to pilot manufacturing.

3.3.1.6 Efficient Manufacturing process

a. Raw materials like lithium salts, electrode active materials (e.g., lithium cobalt oxide, lithium nickel manganese cobalt oxide), binders, electrolytes, and separators undergo sourcing and processing, which may include purification, mixing, blending, and chemical treatment to achieve desired composition and properties.

b. Electrodes are created by applying active materials onto current collectors (aluminium for cathode, copper for anode) using methods such as slurry casting, doctor-blade coating, or electrodeposition. Precise control of coating thickness and uniformity is vital for enhancing battery performance.

c. The electrodes, separator, and electrolyte are assembled into a cell under controlled conditions, often with automated equipment to maintain consistency and minimize contamination. Cell design and assembly methods may vary based on the battery architecture and application needs.

d. Assembled cells undergo a formation process, which includes initial charging and discharging cycles to activate electrode materials, stabilize electrolyte, and establish desired electrochemical properties. This process also aids in early identification and mitigation of defects or performance issues in manufacturing.

e. During manufacturing, strict quality control measures are in place to monitor material properties, dimensional accuracy, and performance characteristics. Diverse testing techniques like electrochemical testing, microscopy, and spectroscopy are utilized to ensure adherence to specifications and standards.

3.3.2 Materials used in Electric Motors

3.3.2.1 Current Status & Challenges

Electric motors play a crucial role in fostering a sustainable and energy efficient future. However, the advancement of these motors poses distinct challenges. Primary challenge is to overcome weight issues and maintain optimal efficiency in electric motors. Researchers have investigating many different materials in recent years, including carbon fiber and polymer-based composites. Improving the design of components and evaluating the use of advanced materials in electric motors overcomes many of the issues with current technologies.

3.3.2.2 Core materials

Electric motors in EVs utilize various core materials for improved performance and efficiency, chosen based on magnetic properties, thermal conductivity, and mechanical strength. Silicon steel is commonly used due to its high conductivity, low loss, corrosion resistance, and cost-effectiveness, ideal for larger machines where energy efficiency is crucial. Nickel alloys offer enhanced heat resistance, suitable for applications in high-temperature environments like rotary converters. Cobalt alloys, with higher magnetic permeability, are well-suited for large DC machines, effectively managing eddy current losses. Thin-gauge electrical steels are easy to assemble, making them suitable for limited-space installations or replacements without disrupting operations.

3.3.2.3 Insulation materials

Insulation materials are vital components in electric motors for electric vehicles (EVs), safeguarding electrical integrity and preventing short circuits. Commonly used materials include paper and pressboard, offering moderate thermal resistance but susceptibility to moisture and limited mechanical strength. Plastics and rubber, like PVC, PE, and rubber, are preferred for their superior insulation capabilities and enhanced mechanical strength, though they can degrade at high temperatures. Mica, renowned for its exceptional electrical insulation properties and high-temperature resistance, is often reinforced with materials such as glass, resins, or ceramics to enhance performance. Ceramics and glass provide effective insulation and high-temperature resistance, but lack mechanical flexibility, making them suitable for motors operating in extreme temperature conditions.

3.3.2.7 Casing materials

Fiber reinforced plastics (FRP) present an opportunity to lighten electric motors by substituting certain components, thereby reducing overall weight. FRP materials enhance both mechanical properties and electrical conductivity. Thermosetting FRP materials offer exceptional resistance to heat and chemical corrosion. Soft magnetic composites (SMC) are employed to achieve a high power-to-weight ratio while reducing manufacturing expenses. Phenolic composite materials (PCM) prove advantageous in replacing numerous metallic parts with a single integrated component. This integration not only decreases assembly time but also facilitates faster maintenance. Polymer housings offer manufacturing ease compared to aluminium housings.

3.3.2.8 Efficient Manufacturing process

Efficient manufacturing of electric motors relies on carefully chosen materials that balance performance, cost-effectiveness, and environmental sustainability. Key materials include high-performance permanent magnets like neodymium-iron-boron (NdFeB), optimizing motor efficiency and power density, prized for its electrical conductivity. Copper is utilized in windings to reduce losses, and enhance power transmission. Aluminium's lightweight properties make it ideal for motor housings and rotor cages, aiding energy efficiency and heat dissipation. Steel and iron provide mechanical strength and magnetic properties in motor components, with specialized electrical steel reducing losses. Composite materials, such as fiber-reinforced plastics (FRP), offer strength while reducing weight, while soft magnetic materials minimize losses in motor cores. Insulation materials, including polymers and ceramics, protect against short circuits and enhance efficiency. These materials collectively drive advancements in electric motor efficiency, contributing to reduced energy consumption and improved performance in electric vehicles and beyond. Ongoing innovations in material science promise further enhancements in motor efficiency and sustainability.

3.3.3 Recycling of Li-ion batteries

Lithium-ion batteries are rechargeable energy storage devices that have gained widespread use due to their high energy density, long cycle life, and versatility. However, as these batteries reach the end of their useful life, there is a pressing need for efficient recycling. The recycling of lithium-ion batteries is crucial for several reasons, including reducing environmental impact, conserving valuable resources, and minimizing waste.

3.3.1.1 Current Status & Challenges

Lithium-ion batteries have become an essential component of modern life, powering everything from smartphones to electric vehicles. However, the rapid growth in lithium-ion battery production has also led to an increase in end-of-life batteries that require proper disposal or recycling.

The global battery recycling market is reported to be worth USD 26.9 billion in 2023 and is projected to grow significantly to USD 54.3 billion by 2030 [60]. In terms of battery recycling capacity, Centre for Study of Science, Technology and Policy (CSTEP) reported, around 0.4 GWh lithium-ion batteries were available for recycling in India in 2020. Now India is aiming to scale up to 128 GWh by 2030. Several technologies are employed in the recycling of lithium-ion batteries including, mechanical separation, Hydrometallurgical Processes and Pyrometallurgical Processes. While these technologies are effective, they can be energy-intensive and produce emissions, which raises concerns about their environmental impact.

The recycling of lithium-ion batteries is a critical component of achieving a sustainable and environmentally responsible energy future. Despite progress, significant challenges persist, such as low recycling rates, technological limitations, and regulatory gaps. Addressing these challenges will require collaborative efforts involving government, industry stakeholders, and researchers to ensure that lithium-ion batteries are recycled efficiently, preserving valuable resources, and reducing environmental impact.

3.3.1.2 Recycling value chain

The lithium-ion battery recycling value chain constitutes a complex and multifaceted system involving several key stakeholders and processes. As the demand for lithium-ion batteries continues to grow, understanding the intricacies of recycling these batteries becomes imperative for ensuring sustainability and resource conservation.

Several challenges hinder the efficiency and sustainability of the lithium-ion battery recycling value chain. The primary concern is Battery Heterogeneity, wherein a wide variety of battery chemistries, sizes, and shapes complicates the sorting and processing of used batteries. Additionally, safety risk associated with lithium-ion batteries during collection, transportation, and recycling pose significant challenges. Achieving high rates of resource recovery, especially for materials like cobalt and lithium, is challenging due to the complexity of battery chemistries. Furthermore, ensuring compliance with recycling regulations and standards can be complex and costly.

3.3.1.3 Recycling techniques

In recycling techniques, three primary methods are predominantly used i.e. mechanical Recycling, Hydrometallurgical recycling and Pyrometallurgical recycling. Mechanical recycling facilitates the recovery of plastics, aluminium, copper and black mass. Batteries undergo mechanical disassembly using specialized equipment, involving cutting, shredding, or crushing them into smaller pieces. The goal is to expose internal components without triggering thermal runaway or fires. The Hydrometallurgical technique employs acid or alkali leaching to recover various metal compounds. The reclaimed chemicals can be utilized to produce the building blocks for brand-new cathode. This technique offers high metal recovery efficiency, complete recovery at lower temperatures, and flexible disposal. Pyrometallurgical recycling utilizes high-temperature furnaces to extract valuable metals from battery components through smelting. This method is effective in recovering metals like cobalt, nickel, and copper.

In recent years, the direct recycling technique has gained popularity for recycling Lithium-ion batteries (LiB). With a significant amount of embedded energy retained within the cathode particle structures, used cathode material from LIBs can be treated electrochemically or physiochemically. This process restores the damaged structure and electrochemical properties, allowing it to be reused either directly as new cathode materials or as precursors for the preparation of new electrodes.

Proposed Research Project – 3.3

Research Novel Recycling Processes other than Hydro/Pyro Metallurgy Processes

1. **Gap Analysis & Background**
   Lithium-ion batteries (LIBs) have gained widespread popularity due to their excellent electrochemical performance, including high stability, compact size, lightweight construction, and high-power output. However, the disposal of spent LIBs presents remarkable challenges, as they contain toxic substances and electrolytes that can release harmful gases and vapours into the environment, posing risks to human health and air quality. Currently, the primary industrial approach for LIB recycling relies on pyrometallurgical processes. However, this method consumes high amounts of power and results in the emission of hazardous and corrosive gases. Alternatively, the hydrometallurgical process involves organic acid and inorganic acid leaching and poses challenges in reusing expensive organic leaching agents. To overcome this challenge, there is a need to discover novel recycling processes that enhance resource recovery, minimise environmental impact, and comply with regulatory standards.

2. **Global Benchmarking**
   Globally, hydrometallurgy and pyrometallurgy methodologies are deployed as the dominant methods of recycling, but there are several challenges in hydro and pyro, such as environmental concerns, operational costs, and energy consumption. To overcome these challenges, researchers are working on a cost-effective novel recycling process. Currently, research is ongoing on the whole-process electrolysis (WPE) battery recycling concept, in which the electrochemical properties of the spent battery's active material are delicately considered. Electrochemical techniques are applied in all the procedures of the recycling process. Waste reactant generation is significantly diminished by replacing the use of redox agents with a solid-state electrolysis process [61].

3. **TRL Level:** Starting with TRL-1, deliverable to TRL-5

4. **Research Goal**
   To research and develop a sustainable and cost-effective novel recycling process for batteries that enhances resource recovery, reduces environmental impact, and complies with regulatory standards.

5. **Targets for Project**
   a. Design and development of recycling process which includes minimizing the environmental impact, reducing emissions, energy consumption, and overall ecological footprint
   b. Evolution of a recycling process that can be scaled up to handle increasing volumes of used batteries, and accommodating future growth in demand for recycling services
   c. The cost of Setup and implementation of recycling method must be at least at the commodity level
   d. Innovation of efficient technology for the efficient separation of materials in batteries, enhancing the overall effectiveness of the recycling method

6. **Methodology**
   a. Conduct an extensive review of existing literature on battery recycling methods to identify gaps, challenges, and potential areas for innovation
   b. Conduct a detailed analysis of various types of used batteries to understand their composition and variability
   c. Investigate optimal conditions for the recycling process, considering factors like temperature, pressure, and reaction times to maximize material recovery and minimize energy consumption
   d. Develop safe and effective methods for handling and neutralizing hazardous materials present in batteries, ensuring compliance with safety regulations
   e. Conduct pilot-scale tests to validate the effectiveness of the developed recycling process under controlled conditions
   f. Implement quality control measures to ensure the recovered materials meet industry standards, with a focus on purity and suitability for reuse in battery manufacturing

g. Perform a life cycle assessment to evaluate the environmental impact of the recycling process, such as energy consumption, emissions, and resource utilization

7. Deliverables

a. Detailed design and specification
b. Technology integration guidelines
c. Equipment needed for novel recycling processes
d. Life cycle assessment results
e. Target compliance report

8. Impact

a. This novel method will boost the recycling industry in India, and making a significant difference globally
b. Reduction in environmental pollution and resource depletion by minimizing the need for new raw materials

9. Recommended Execution Agencies

a. Central Power Research Institute (CPRI), Bangalore
b. Indian School of Mines, Dhanbad
c. Centre for materials for Electronics Technology (CMET), Hyderabad

10. Timeline: 60 Months

11. Estimated Budget: ₹40 Cr
Research & Development: ₹25 Cr (Divided equally between two parties)
Pilot Manufacturing: ₹15 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence	✓			
Market			✓	
Technology				✓

13. Priority: High

14. Administrative Mechanism

This project is deliverable to TRL 5; hence research institutions will participate in developing technologies. The development of novel recycling processes can play a pivotal role in creating a more sustainable, cost effective, and responsible approach to managing the lifecycle of batteries. Aligning with global efforts to address climate change and promote responsible resource management. The estimated budget of ₹25 Cr is allocated for research and development and ₹15 Cr is assigned for pilot manufacturing.

3.3.1.4 Economic analysis of battery recycling

Lithium battery recycling offers substantial environmental and resource conservation benefits. However, the economic viability of recycling operations depends on various factors, such as collection and transportation costs, recycling technology efficiency, commodity prices, and government incentives. A comprehensive economic analysis is crucial for investors, policymakers, and industry stakeholders to make informed decisions regarding lithium battery recycling initiatives. As technology advances and recycling processes become more efficient, the economic viability of recycling is likely to improve, contributing to a more sustainable energy future.

There are several challenges in conducting an economic analysis of battery recycling. One key challenge is the minimal value of the recovered materials from Li-ion batteries. Although, materials like lithium, cobalt, nickel, and other can be extracted and reused to make new batteries. However, their market values are often too low to make recycling economically feasible. Another challenge arises from the lack of consistent and standardized recycling processes for Li-ion batteries, due to their diverse chemistries and designs, hinders economies of scale and increases costs. However, there are possible solutions, including implementing policies to boost demand for recycled materials, and creating standards and certification for recycling procedures. Further research and development in these areas could enhance the economic viability and sustainability of Li-ion battery recycling in the long term.

3.3.1.5 Adoption challenges

Adopting efficient recycling procedures for lithium-ion batteries comes with several challenges the primary concern is to create standardized recycling procedure capable of effectively handling different dimensions, chemistries, and shapes of batteries. While lithium-ion batteries should be recycled, the recycling process itself can impact the environment due to energy consumption and the use of potentially hazardous chemicals. Globally researchers are investigating ways to develop novel recycling techniques that are more beneficial to the environment.

3.3.4 Second life of batteries

3.3.4.1 Current Status & Challenges

Batteries that can no longer be used in vehicles can be utilized to power EV charging stations. Globally, automotive lithium-ion battery demand accounted up to 340 GWh in 2021, more than twice the level of 2020. As a result, the market for second-life batteries increased, reaching a demand of 7 gigawatt-hours for utility-scale storage. By 2025, the supply of second-life batteries will reach 1 GWh/year and will exceed the demand for lithium-ion batteries for utility-scale storage [62]. This demonstrated how popular EVs are becoming. Even while EVs hold out the prospect of a more sustainable era of transportation, finding appropriate and efficient ways to recycle end-of-life batteries and give them a second life is a priority.

Several challenges occur in the second life of the battery. The primary challenge is a variety of battery pack designs available in the market, each with a different size, electrode chemistry, and format, raising the concern and cost of recycling. The usage of different battery chemistries, sizes, and designs by different manufacturers makes it challenging to develop standardized systems for reusing batteries. Globally, researchers have implemented a standardized system to store battery details from manufacturing to recycling. Presently, in India, research is focusing on developing a battery Aadhaar system, which includes details about the manufacturer, supplier, material composition, durability, performance, and recycling of batteries.

Proposed Research Project – 3.4

Development of Battery Aadhaar System

1. **Gap Analysis & Background**
   A battery Aadhaar is a digital record that contains data about every battery available on the market, including details about the manufacturer, localization, material composition, durability, performance, and recycling information. Currently, in Europe, one of the main ongoing projects is the battery passport financed by the German government [63]. India needs such kind of technology/system to localize and enable appropriate traceability and transparency in data so that battery manufacturers, consumers, and recyclers may make well-informed decisions. This project proposes to develop the battery Aadhaar in the Indian context and aims to address by providing a comprehensive digital record of a battery's life cycle, from raw material extraction to manufacturing, usage, and recycling or disposal.

2. **Global Benchmarking**
   Global Battery Alliance (GBA) conceptualized the Battery Passport as a framework to increase transparency across the battery value chain. The GBA's Battery Passport is unique as it is a key instrument for implementing a

global vision of sustainable, responsible, and circular battery value chains based on data that is standardized, comparable, and auditable. Its ultimate goal is to provide end-users with a quality seal, based on the battery's sustainability performance, according to reporting rules agreed upon by stakeholders from industry, academia, non-governmental organisations and government.

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-5

4. **Research Goal**
Development of the battery Aadhaar standardized system or protocol to improve sustainability, efficiency, and safety in battery manufacturing, usage, and recycling by providing detailed information about each battery's composition, usage history, and end-of-life management.

5. **Targets for Project**
   a. Development of a unique numeric barcode for each battery that contains the data and description about the battery manufacturing year, lithium import, electrode materials, cell localization, manufacturing history, battery chemistry, battery capacity, manufacturing location and battery potting etc. This information will be more convenient to recyclers for streamlining the recycling process.
   b. Development of multi-party private permissioned blockchain which is restricted to ensure data security and privacy
   c. Design and development of data analytics and machine learning to predict maintenance or replacement of batteries which helps in preventing unexpected failures
   d. Development of industry standards for battery Aadhaar to guarantee data consistency and interoperability among various manufacturers and systems

6. **Methodology**
   a. Identification of different types of batteries and devices for data storage and assigning a unique identifier to each battery, such as serial number, RFID and barcode Code
   b. Establish protocols for collecting real time data on temperature, voltage, charge cycles, and battery usage
   c. Determine a software programme to manage and store battery data
   d. Implement security precautions to protect confidential battery details
   e. Develop regular battery maintenance programmes based on usage and manufacturer recommendations
   f. Provide instructions and documentation for users to refer to while utilizing the system
   g. Thoroughly test the system and continuous monitoring of the system's functioning and making necessary adjustments.
   h. Recommendation of a mandatory system through regulation

7. **Deliverables**
   a. Functional Battery Aadhaar prototype
   b. Guidelines for operating the Aadhaar System
   c. Guidelines for integrating different batteries with battery Aadhaar
   d. Target compliance report

8. **Impact**
   a. Battery Aadhaar can become a vital tool for companies striving for sustainability, compliance, and consumer trust.

9. **Indicative list of Execution Agencies**
   a. Indian Institute of Science (IISc), Bangalore
   b. Tata Consultancy Services (TCS)
   c. Infosys Limited
   d. Wipro
   e. HCL Technologies
   f. Indian Institute of Technology (IIT), Bombay
   g. Indian Institute of Technology (IIT), Madras
   h. Indian Institute of Technology (IIT), Delhi
   i. CSIR - Central Electro Chemical Research Institute (CSIR- CECRI)
   j. National Chemical Laboratory (NCL)

k. Centre for Materials for Electronics Technology (C-MET)
l. The Automotive Research Association of India (ARAI)

10. **Timeline:** 18 Months

11. **Estimated Budget:** ₹0.8 Cr
Research & Development: ₹0.6 Cr
Pilot Manufacturing: ₹0.2 Cr

12. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence	✓			
Market			✓	
Technology			✓	

13. **Priority:** High

14. **Administrative Mechanism**
This project is deliverable to TRL 5; hence research institutions and industries will participate in developing technologies. This project has been assigned high priority, due to the significant need for digital data storage, transparency, traceability, and localization of batteries. Determination of these parameters will aid in second-life applications as well as the recycling and management of batteries. The estimated budget of ₹0.6 Cr is assigned for research and development and ₹0.2 Cr is allocated for pilot manufacturing.

3.3.4.2 Infrastructure Requirement of Second Life of Battery

The infrastructure requirement for the second life of batteries involves several steps as follows:

1. Establish a robust collection mechanism to locate and collect the spent batteries safely from collection points to recycling facilities.
2. Acquire equipment for evaluating the capacity and condition of used batteries to determine their suitability for a second life.
3. Establish quality control methods to ensure that reconditioned batteries fulfil performance and safety standards.
4. Implement appropriate waste management and environmental protection measures to handle hazardous materials safely.
5. Implement methods for monitoring and reporting the environmental impact, energy savings, and social benefits of the recycling program.
6. Implement a standardized hardware and software integration for second-life applications.

Proposed Research Project – 3.5

Standardizing Hardware and Software Integration for Second Life Applications of EV Battery

1. **Gap Analysis & Background**
In the midst of the expanding electric vehicle (EV) market, the integration of retired EV batteries into second-life applications is hampered by the lack of standardized hardware and software solutions. This project addresses this critical issue by focusing on the standardization of integration processes, emphasizing compatibility and safety. The goal is to establish industry-wide standards, safety protocols, and efficient software systems to streamline the integration of diverse EV battery models, thereby encouraging a more consistent and sustainable approach to second-life EV battery applications.

2. Global Benchmarking

SANY's first intelligent battery swapping system for heavy trucks begins with docking and includes a series of automated actions such as QR code scanning, automatic vehicle unblocking, battery replacement, and vehicle locking. The entire procedure is completed in less than five minutes, demonstrating remarkable efficiency and minimal downtime [64]. Qnovo's software has specific use cases for battery energy storage systems (BESS), both with first and second-life batteries, helping asset managers understand the true battery capacity and remaining useful life of each battery cell.. The advantages of adaptive charging, built-in intelligence, and predictive analytics can also be utilized [65].

3. TRL Level: Starting with TRL-2, deliverable to TRL-5

4. Research Goal

To develop comprehensive standards and protocols for seamless hardware and software integration, ensuring compatibility and safety in the repurposing of diverse EV battery models for second-life applications.

5. Targets for Project

a. Develop a standardized hardware interface that accommodates various EV battery models, ensuring compatibility during integration
b. Establish industry-wide communication protocols to facilitate data exchange between repurposed EV batteries and management systems
c. Develop a testing framework to assess the interoperability of integrated EV batteries, enabling manufacturers to certify compatibility

6. Methodology

The following tasks are involved in achieving the targets:

a. Collaborate with EV manufacturers, battery integrators, regulatory bodies, and other stakeholders to gather insights, requirements, and feedback on integration challenges and needs
b. Collection of data and analysis of various EV battery models, including specifications, communication protocols, and performance characteristics
c. Based on the data analysis, develop a standardized framework for hardware interfaces, communication protocols, and software integration. Ensure compatibility among different EV battery models
d. Collaborate with safety and regulatory authorities to establish comprehensive safety guidelines for handling and repurposing EV batteries. Ensure compliance with industry safety standards
e. Design and develop software solutions for monitoring, managing, and optimizing second-life EV battery performance
f. Build prototypes of standardized integration systems and software. Conduct testing to validate their performance, safety, and efficiency

7. Deliverables

The following are the proposed deliverables of this activity

a. Communication protocols
b. Software solutions
c. Documentation
d. Developed Prototype
e. Design and Specifications
f. Target compliance Report

8. Indicative list of Execution Agencies

a. Indian Institute of Science (IISc), Bangalore
b. CSIR - Central Electro Chemical Research Institute (CSIR- CECRI)
c. National Chemical Laboratory (NCL)
d. Centre for Materials for Electronics Technology (C-MET)
e. KPIT Technologies
f. Qpi Volta Technologies

9. Timelines: 18 months

10. **Estimated Budget:** ₹0.85 Cr
    Research & Development: ₹0.6 Cr
    Pilot Manufacturing: ₹0.25 Cr

11. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence			✓	
Market			✓	
Technology				✓

12. **Priority:** Moderate

13. **Administrative Mechanism**
    This project is deliverable to TRL 9; hence research institutions and industries will participate in developing technologies. This project has been assigned moderate priority due to the concept and sales of EVs and their batteries being in its nascent stage and hence the solution for end of life battery management is advantageous to the country. The estimated budget of ₹0.6 Cr is assigned for Research and Development and ₹0.25 Cr is assigned for pilot manufacturing.

3.3.5 Recycling of Magnetic Materials

The global demand for rare-earth magnets has surged in recent years, driven by the rapid growth of industries. However, the production of these magnets is associated with significant environmental and geopolitical concerns, due to their reliance on scarce and often environmentally damaging resources. In this context, magnet reuse and recycling hold immense promise by facilitating the recovery of valuable magnetic materials during production and also from end-of-life products and industrial waste streams. The research is focused on magnet reuse and recycling for new applications.

Proposed Research Project – 3.6

Magnet Reuse and Recycling and Its Impact on Developing Magnets for New Applications

1. **Gap Analysis & Background**
   In today's rapidly advancing technological landscape, magnets play an indispensable role in countless applications, especially in electric mobility motors. As India seeks to establish itself as a global technology and innovation hub, the effective management of critical resources, including rare-earth magnets, becomes increasingly vital. Magnet production involves powder metallurgy techniques, resulting in material wastage during manufacturing. There is a need to produce net or near net shape manufacturing technique to improve the efficiency of the magnet manufacturing process. Considering above point, magnet reuse and recycling have emerged as innovative solutions with the potential to address not only resource scarcity but also process efficiency. This will drive the development of magnets for not only mobility but also new applications in India.

2. **Global Benchmarking**
   The global demand for rare-earth magnets has surged in recent years due to rapid industrial growth. However, their production raises significant environmental and geopolitical concerns due to reliance on scarce and often environmentally damaging resources. In this context, magnet reuse and recycling hold immense promise, as they enable the recovery of valuable magnetic materials from both production processes and industrial waste streams. US company Okon Recycling is using the direct recycling method for end-of life magnets, which involves demagnetizing, dismantling, harvesting and prepping rare earth magnets to be reused. Its output is “hundreds of tonnes of rare earth magnets per year” and recycled magnets are often reused in a similar product by the original equipment maker (OEM) [66].

3. TRL Level: Starting with TRL-2, deliverable to TRL-5

4. Research Goal

Research and explore innovative techniques for refurbishing magnetic material powders and used magnets to meet the performance requirements of diverse applications.

5. Targets for Projects

a. To establish safe and easy dismantling practices of magnets
b. Investigate methods to efficiently recover and recycle rare-earth and other valuable materials from discarded magnets
c. Explore the design and utilization of recycled magnets for emerging technologies, such as next-generation motors using recycled magnets
d. Develop a comprehensive magnet characterization facility which covers the spectrum starting from material collection, characterization, manufacturing, and complete testing of magnetic materials

6. Methodology

The following tasks are involved in achieving the targets:

a. Identify sources of used magnets, and collect and sort magnets by type, size, and composition
b. Inspect the condition of the magnet and test its properties
c. Dismantle the magnets, separate different materials and process the separated magnet materials to recover the individual elements
d. Purify and refine the recovered materials into a usable form
e. Perform quality control tests on the newly manufactured magnets to ensure they meet performance and safety standards
f. Set up a Pilot plant to process magnets which will also include production at a small scale

7. Deliverables

The following are the proposed deliverables of this activity

a. Establish a small division in the existing magnet research and development facility
b. Specifications of magnet reuse and recycling
c. Target compliance Report

8. Indicative list of Execution Agencies

a. CSIR - National Institute for Interdisciplinary Science and Technology (NIIST), Thiruvananthapuram
b. CSIR-Advanced Materials and Processes Research Institute, Bhopal
c. Non-Ferrous Materials Technology Development Centre (NFTDC), Hyderabad
d. International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), Hyderabad

9. Timelines: 18-24 Months

10. Estimated Budget: ₹ 15 - 20 Cr

Research & Development: ₹15 Cr (Divided equally between two parties)
Pilot Manufacturing: ₹5 Cr

11. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence			✓	
Market			✓	
Technology				✓

12. Priority: High

13. Administration Mechanism

This project is deliverable to TRL 8; hence, research institutions and industries will participate in developing technologies. This project is prioritized at a high level to reduce the dependencies on imports. Magnet is produced using powder metallurgy techniques and these techniques create wastage of material during manufacturing. This project enables the recovery of valuable magnetic materials during production and also from end-of-life products and industrial waste streams. The estimated budget of ₹15 Cr is assigned for research, development and ₹5 Cr is assigned for pilot manufacturing.

Chapter 4: Charging & Refueling

4.1 Introduction

The charging of EVs has sparked a surge in innovation, with advancements aiming to enhance charging efficiency and convenience. The charger receives power from the local grid electricity supply and transfers it to the control system and wired connection to the EV. The development of chargers requires factors like charger capacity, compatibility with different EV models, and integration of smart grid technology for load management and demand response. Electric vehicles can be charged using three primary methods i.e., conductive charging, inductive charging, and the battery swapping technique. In India, the most common charging technology is conductive charging, often known as plug-in (wired) charging. The specifications for conductive charging rely on various elements, including the type of vehicle, battery capacity, charging strategies, and power ratings [67].

Inductive charging involves wireless electric transmission, requiring auxiliary devices like high-frequency transformers, supervisory control, data acquisition, and vehicle alignment monitoring systems, resulting in high overall costs. Battery swapping stations facilitate the exchange of depleted batteries with fully charged ones, involving the collection, storage, and provision of voltage support and regulation during peak load periods. At present, research is focused on inductive or wireless charging systems, which are considered more efficient and safer as compared to conductive charging.

4.2 Current Scenario in India

India aims to a achieve 30% electric vehicle usage by 2030, with a target of 4 lakh charging stations by 2026. According to NITI-Aayog 2021 reports, there are 2000 charging stations exist in India currently. There is a plan to install stations every 3 km in cities and every 25 km on highways [55]. The government of India (GoI) initiated the National Electric Mobility Mission in 2020 to increase electric vehicle usage and introduced Faster Adoption and Manufacturing of Hybrid EVs (FAME) to reduce costs and boost sales.

In 2017, the Ministry of Heavy Industries (MHI) launched two chargers named Bharat AC 001 & Bharat DC 001with modifications relevant to Indian climate conditions. The AC 001 is essentially for low power usage and lacks communication protocols between EV and charger. Meanwhile, the DC 001 utilizes the Controller Area Network (CAN) protocol for communication between Charger and the EV battery management system. Different EV charging levels are used for charging a vehicle as mentioned in Table 3.

Table 3: Different EV Charging Levels

Specification	Level 1	Level 2	Level 3
Charging Power	1.4 kW – 1.9 kW	3.1kW - 19.2kW	20kW – 350kW
Charger Type	Onboard-Slow Charging	Onboard - Semi-Fast Charging	Offboard Charger Fast Charging
Charge location	Residential	Private and Commercial	Commercial
Power Supply	120/230Vac, 12A - 16A, Single-Phase	208/240Vac, 12A - 80A, Single Phase/split phase	300-800Vdc, 250-500A Three-Phase

4.3 Research Pathways

4.3.1 Static Wireless Charging Technology

The static wireless charging System charges electric vehicle batteries in a static mode using inductive charging. It easily replaces plug-in chargers, and avoiding safety issues such as electric shocks. The wireless charging system consists a transmitter and receiving coil. AC current passes through mutual induction, gets converted to DC using power converters and charges the vehicle's battery as shown in Figure 6.

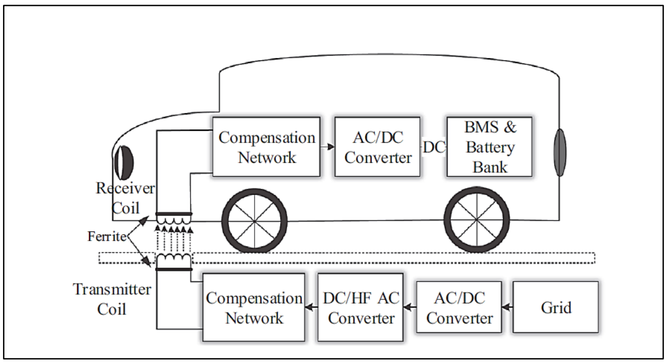

Figure 6: Block Diagram of Wireless Charging System

4.3.1.1 Current Status & Challenges

The wireless charging system offers advantages over plug-in chargers, but it faces challenges related to health, safety, finances, and limitations in power range that need to be addressed. Prototypes and lab experiments have been developed for various EV power ranges. Internationally many institutions and industries are working on wireless charging system, for example, ElectReon has been developed the static wireless charging technology and successfully implemented the technology on public roads in Israel, Sweden, Germany, and Italy [68].

In India, conductive chargers are currently used to charge a vehicle. These chargers come with different charging protocols such as Combined Charging System (CCS), CHAdeMO, Type 1 and Type 2 each with a certain power range. Since each vehicle possesses different charging connectors; there is a concern about the unavailability of each charging protocol in each station; and there are also safety hazards due to human interference. To overcome these concerns, integrating a wireless charging system into electric vehicle becomes crucial, eliminating the need for human interference between vehicle and charger. This charging system helps M & N category vehicle (Passenger vehicles and Trucks) drivers to charge their vehicles without any difficulties. Presently, research is focused on high-power wireless charging systems with efficiencies comparable to conductive charging.

Proposed Research Project – 4.1

Research on High Power Density Static Wireless Charging System

1. **Gap Analysis & Background**
Modern technologies like wireless power transmission have the advantages of convenience and flexibility as well as the capacity to support completely automated charging. Wireless charging is feasible despite possible risks to electromagnetic interference or cyber security, as compared to conductive charging systems which require heavy gauge cables and can cause electrical or ergonomic concerns. In the scenario of plug-in AC EV chargers, much of the heavy lifting is managed by the vehicle's on-board charger. However, with wireless charging, the vehicle does not need an onboard charger, reducing the charging complexity on the vehicle itself. This project proposes to carry out a high-power density wireless charging system which transfers up to 200 kW with efficiency lying in the range of 90 - 94% and is suitable for all vehicles irrespective of charging protocols.

2. **Global Benchmarking**
Wireless EV charging technology is interoperable, convenient, and harder to vandalise compared to traditional public charging units. Currently, the power delivery for passenger EVs via wireless charging is achieved at 11 kW by WiTricity. For commercial vehicles, approximately 200 kW on average is achieved by a few players, such as Momentum Dynamics, Wave, and Tesvolt, and is only made possible due to innovative coil designs and larger surface areas of the pads [69]. India has developed a 1.5 kW (30A@48V) static wireless charger [70].

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-5

4. **Research Goal**

   To study and design a high-power density wireless charging system which transfers up to 200 kW with efficiency in the range of 90 - 94% to enhance performance, flexibility, and energy management.

5. **Targets for Project**
   a. Implement increased misalignment tolerance and thermal safety measures to achieve an efficiency between 90 – 94%, comparable to conductive charging
   b. To address non-standard battery voltages by exploring wireless communication protocols
   c. Design optimization of magnetic coils for high power density
   d. Development of foreign object detection systems to prevent unintended charging or interference
   e. Ensure the system's long-term reliability by designing it to tolerate challenging environmental factors

6. **Methodology**
   a. Benchmarking across different standards.
   b. Define performance criteria to maximize efficiency
   c. Design and development of a wireless charging subsystem based on optimized design proposed by relevant standards
   d. Design and development of magnetic coils to improve the power density
   e. Develop a mechanism enabling the EV to be automatically placed and aligned with the charging pad for efficient power transmission
   f. Design and implement a high-power inverter and rectifier to convert AC to DC
   g. Implement a communication protocol to enable user involvement and manage the charging process
   h. Testing and validation, including interoperability and safety checks

7. **Deliverables**
   a. Functional charger prototype with an efficiency of 90 - 94 %
   b. Guidelines for integration
   c. Draft standards along with detailed communication protocols
   d. Detailed design and specification
   e. Target compliance report

8. **Impact**
   a. Wireless charging can bring user convenience and compatibility without compromising on efficiency

9. **Recommended Execution Agencies**
   a. Indian Institute of Technology (IIT), Madras
   b. Visvesvaraya National Institute of Technology (VNIT), Nagpur
   c. Indian Institute of Technology (IIT), Kanpur
   d. Indian Institute of Technology (IIT), Delhi
   e. The Automotive Research Association of India (ARAI), Pune

10. **Timeline:** 36 Months

11. **Estimated Budget**: ₹20 Cr

    Research & Development: ₹10 Cr (Divided equally between two parties)

    Pilot Manufacturing: ₹10 Cr

12. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence	✓			
Market			✓	
Technology			✓	

13. **Priority**: High

14. Administrative Mechanism

This project is deliverable to TRL 5, it is envisaged that the prototype product developed by research Institutions shall be transferred to industries for commercial production. Currently, in India, the industries are only working on the production of conductive chargers. Wireless charging is a new technology which is more convenient as compared to conductive charging. Hence, the industry may be associated with the functional prototypes and guidelines right from the beginning with technical specifications. The estimated budget of ₹10 Cr is assigned for research and development and ₹10 Cr for pilot manufacturing.

4.3.1.2 Coil design & materials for transmitting & receiving coil

Two types of wireless charging coils, polarized and non-polarized. Polarized pads generate perpendicular and parallel flux components, while non-polarized pads produce only perpendicular flux components. The design of wireless transmitter and receiver utilizes various planar coil shapes like circular, rectangular, and hybrid arrangements in non-polarized pads to enhance performance and address misalignment issues between transmitter and receiver pads.

Designing and developing the transmitting and receiving coils for a wireless charging system poses several challenges. One of the primary challenges is potential misalignment between the transmitting and receiving coils. To overcome this issue, wireless charging systems must allow for some tolerance to maintain efficient charging. Heat generation is another significant challenge for coils and other components while charging, consider implementing heat dissipation mechanisms to prevent overheating and ensure safe operation. The effects of mounting metallic objects in EV wireless charging setups cannot be neglected. Consequently, it requires careful design to prevent interference from moving parts and foreign object debris between the transmitting and receiving charging pads of EVs. To improve the overall performance, safety, and longevity of charging system, researchers are presently focusing on investigating these issues through advancements in various types of material for heat dissipation and shielding purposes.

4.3.1.3 Power electronics devices & technology

Static wireless charging involves several 'power electronic devices' to enable efficient and safe wireless charging. Implementing power electronics in wireless charging systems poses various challenges. The primary concern is that inverters generate high-frequency AC waveforms, creating an oscillating magnetic field around the charging pad or coil using semiconductor devices like Insulated-gate bipolar transistors (IGBT), Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET), and Silicon Carbide (SiC) MOSFET. IGBTs are widely used for high-power applications. It is typically challenging to run at a frequency higher than 20 kHz due to the physical constraints of IGBT. However, MOSFET devices can operate at high frequencies, but their power output is typically minimal. Silicon carbide (SiC technologies enable higher power levels and frequencies (up to 100 kHz theoretically) compared to conventional MOSFETs due to low switching loss and good thermal behavior.

In the infrastructure side or transmitting side of AC-DC converter, the switching frequency increases at the induction that creating high-frequency electromagnetic interference (EMI) or electromagnetic compatibility which becomes a challenge. Thermal management of power electronic devices is critical due to the heat generation during operation, necessitating measures to prevent overheating and device degradation. Another technical challenge lies in creating efficient bidirectional power electronics capable of converting DC power from EV batteries into grid AC power (V2G) or DC power for storage in another EV (V2V). A far-field wireless charging system is beneficial to charging the vehicle irrespective of parking slots and at a distance without human interference between vehicle and charger. Currently, a prototype of this charging system has been developed globally. In India, the research regarding far-field wireless charging systems is focused on efficient power electronic devices as it can contribute the sustainability and increased availability.

Proposed Research Project – 4.2

Research on Far-Field Wireless Power Transfer System

1. **Gap Analysis & Background**
The Far-field wireless power transfer system uses three technologies such as magnetic resonant coupling, Electromagnetic/ microwave/ Radio Frequency radiation, and laser power beaming. Devices used in magnetic coupling technology, such as tuned wire coils and lumped element resonators, produce magnetic induction across a distance of a few meters, typically 4 to 10 times the coil diameter. Microwave radiation uses antenna arrays and rectenna devices that can operate at distances ranging from a few meters to kilometers. Laser technology uses a laser emitter and a photovoltaic receiver, which can transfer power up to kilometers. Nowadays, India is using conductive charging, which has charging protocols like CCS, CHAdeMO, and Type 2 which has a limited cable distance. There is an opportunity to create wireless charging technology irrespective of charging protocols which eliminates the need for human interference and makes charging more convenient. This project proposes to develop a far-field wireless power transfer system at a distance of 100m to achieve better charging availability and power transfer rate.

2. **Global Benchmarking**
Research is currently being conducted by Lockheed Martin on the wireless charging of UAVs (unmanned aerial vehicles) and has successfully charged UAVs over long distances [71]. Kyoto University developed two types of wireless charging of the EV with microwave, one is a short-distance system with a range of 2-3m and the other is a mid-distance system [72]. The National Aeronatics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) has reported experimental data on a Microwave wireless Transfer (MPT) system. The system demonstrated DC to microwave conversion efficiencies of 69%, 95%, and 82% in different tests.   . However, outdoor experiments with long-distance MPT technology are far from achieving this efficiency. For example, JPL's outdoor experiment at 1.54 km showed a system efficiency of only 6, 7%, mainly because the microwave beam capture efficiency was only 11.3% [73].

3. **TRL Level:** Starting with TRL-1, deliverable to TRL-5

4. **Research Goal**
To study and develop a far-field wireless charging system covering a 100 m distance in parking lots with efficiency between 60 - 80% to enhance convenience, and improve overall system performance.

5. **Targets for Projects**
    a. Determine the appropriate technology to achieve efficiency with ranges between 60 – 80% to make wireless charging competitive with wired options
    b. Enhancing the system's capacity to continue transferring power effectively even in situations where the vehicle and charging station are not perfectly aligned
    c. Implementation of a wireless communication and control system for monitoring the charging process, which will include power delivery, vehicle identification, and safety protocols
    d. Implementation of a weather resistance system that can operate effectively under various weather conditions

6. **Methodology**
    a. Determine the desired range and power levels for the system
    b. Select appropriate technology for efficient energy transfer over long distances
    c. Design a receiver system that is capable of converting energy into electrical power effectively
    d. Implement a safety regulation to avoid causing injury to living organisms
    e. Develop efficient converters to optimize energy conversion
    f. Implement a communication system for data exchange between the transmitter and receiving units
    g. Testing and validation including interoperability and safety

7. Deliverables

a. Functional Charger prototype with efficiency of 60 – 80%
b. Guidelines for integration
c. Design and Specification
d. Target compliance report

8. Impact

a. Far-field wireless charging can reduce the requirement for significant charging infrastructure, including charging stations and cables, making EV adoption more feasible in various locations

9. Indicative list of Execution Agencies

a. Indian Institute of Technology (IIT), Delhi
b. Indian Institute of Technology (IIT), Madras
c. Visvesvaraya National Institute of Technology, Nagpur
d. The Automotive Research Association of India (ARAI), Pune

10. Timeline: 36 Months

11. Estimated Budget: ₹10 Cr
Research & Development: ₹5 Cr (Divided equally between two parties)
Pilot Manufacturing: ₹5 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence		✓		
Market				✓
Technology				✓

13. Priority: High

14. Administrative Mechanism

This project is deliverable to TRL 5; hence research institutions will participate in developing technologies. Due to the coil-based wireless charging systems being currently under development in India, the development of Far-field wireless charging system is a future scope. Far field wireless charging offers a more convenient and flexible way to charge electric vehicle. Hence it has been assigned with the estimated budget of ₹5 Cr for research & development and ₹5 Cr is assigned for pilot manufacturing.

4.3.1.4 Cost-competitive methods

The cost competitiveness of a static wireless charging system for electric vehicles (EVs) depends on factors like technology, manufacturing scale, and efficiency. The various cost-competitive methods for the development of static wireless charging systems are as follows:

a. Advancements in materials science may lead to the creation of more cost-effective components for wireless charging systems, including coils and power electronics.
b. Enhance the design of the charging coil for optimal efficiency and minimize energy loss using simulation tools to optimize power transfer.
c. Smart charging systems can optimize charging schedules based on electricity prices, grid demand, and other factors, thereby reducing overall charging costs for users.
d. Enhance the management of power grid balancing for grid stability and load control.

4.3.1.5 Manufacturing process

The manufacturing process for static wireless charging system involves several steps, including:

a. The development of a wireless charging system, including both transmitter and receiver, requires careful consideration to ensure compatibility and efficiency.

b. These coils are made of high-quality copper or aluminium with different shapes and sizes. In the manufacturing process of primary and secondary coils, it is crucial to ensure that the coils are wounded, insulated, and calibrated to meet the system's requirements.
c. Assembly of Power electronic devices including inverters and converters, is essential to manage the power flow effectively.
d. Integration of a control system for communication, safety, and system monitoring
e. For safety concerns, components must be shielded in a protective housing to safeguard them from environmental hazards. Additionally, implementing foreign object detection helps to prevent accidents.
f. Investigating the functionality of individual components to ensure proper alignment between the transmitter and receiver is crucial, and testing for electromagnetic interference and insulation also plays a pivotal role in the system's development.

4.3.1.6 Infrastructure Requirements (As per Indian Context)

The infrastructure requirements for static wireless charging are as follow:

a. The installation of a transmitting pad underneath the road and a charging pad specifically for electric vehicles requires proper road infrastructure availability.
b. Wireless charging stations are typically installed in designated areas like parking spaces, garages, malls, hotels, etc.
c. The infrastructure for charging stations must prioritize safety, incorporating grounding systems, insulation, and protective measures to prevent accidents, protect users from electromagnetic interference, and ensure user comfort.
d. Charging stations require consistent, significant power from renewable energy sources, grid connection, or a combination of both for sustainable solutions.
e. Isolated transformer must be installed with all related substation equipment including safety appliances.
f. Coils are essential for inductive power transfer in charging stations and devices, with proper positioning and design for safe and effective energy transfer.
g. Tie up with online network service providers to enable advance online booking of charging slots by EV owners.

4.3.2 Dynamic Wireless Charging Technology

Dynamic wireless charging allows EVs to charge on the motion, from which vehicles need not stop to refuel or recharge. Instead, they receive a constant stream of energy across an air gap while the vehicle is in motion. Dynamic wireless technology consists of a transmitter and receiving coil of the same size. These coils have their compensation circuit. In this type, the receiver coil is coupled with one coil from the transmitter, so only the closest transmitter to the receiver can be excited. When the vehicle moves away from the excited transmitter coil, the excitation can be turned off. This leads to improved efficiency and reduces the leakage magnetic field around the system. This charging system needs many compensation components, inverters and transmitter coils which leads to high costs. To reduce this cost, the system can be designed to have a string of coils sharing the same power electronic converter.

4.3.2.1 Current Status & Challenges

Researchers are working to advance dynamic wireless EV charging to make EV use more convenient, cost-effective for consumers & viable at highway speeds. Currently in India, IIT Dhanbad has developed a model of hybrid renewable energy driven by a bidirectional wireless charging system that ensures the charging of EVs in static as well as dynamic conditions. The Oak Ridge National

Laboratory's (ORNL) dynamic charging system, currently under development, also facilitates the electrification of heavy-duty trucks. According to ORNL's Electric Drives [74]. Research Group, these large trucks currently necessitate extensive battery packs, which increase both weight and cost. However, by implementing dynamic wireless charging, particularly on highways, the required onboard battery capacity can be reduced, simultaneously mitigating range anxiety.

Proposed Research Project – 4.3

Research on Dynamic Charging System for EV

1. **Gap Analysis & Background**
Dynamic (conductive/wireless) charging of electric vehicles (EVs) can significantly eliminate range anxiety while reducing the required onboard battery capacity. This system is designed to improve the convenience provided by EVs and also address range anxiety, by enabling charging while in motion, potentially extending driving distances without the need for frequent stops at charging stations. This system typically involves embedding charging infrastructure within roadways or using overhead charging mechanisms to transfer power to EVs as they travel, ensuring seamless and efficient charging without the need for manual intervention by the driver.

2. **Global Benchmarking**
The Department of Energy (DOE) and Oak Ridge National Laboratory (ORNL) are working to advance dynamic wireless EV charging to make its use more convenient, cost-effective for consumers, and viable for speed limits on the highways. The goal is to integrate high-efficiency wireless charging technology with the nation's power grid and maintain charging power for high-speed applications. The ORNL has developed dynamic wireless EV charging technology and has licensed it to Brooklyn-based HEVO. The license includes ORNL's unique polyphase electromagnetic coil and the Oak Ridge Converter.

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-5

4. **Research Goal**
Development and adoption of dynamic (conductive/wireless) charging system for optimizing performance, ensuring safety, and promoting widespread integration into existing infrastructure.

5. **Targets for Project:**
   a. Ensuring the ways to maximize the efficiency of power transfer between the road infrastructure and vehicle to minimize energy loss and improve system performance
   b. Designing systems that can be deployed across various transportation networks, and adapted to different types of vehicles
   c. Implementing robust safety measures to prevent accidents or hazards associated with charging while driving
   d. Design the system to be scalable, accommodating different power levels and adapting to various types of roads and traffic conditions
   e. Implementation of user-friendly features, such as automatic alignment and efficient charging initiation, to enhance the overall experience for EV owners

6. **Methodology**
   a. Conduct a thorough review of existing literature on dynamic wireless charging, focusing on technological advancements and challenges
   b. Develop conceptual design and define the system architecture for the dynamic charging systems. Specify the components, subsystems, and interactions involved in the charging infrastructure, including power electronics, and alignment mechanisms
   c. Modelling and simulating virtual prototype of the dynamic charging system with various operating conditions to evaluate system performance, efficiency, and safety
   d. Conduct a comprehensive safety and reliability analysis to evaluate potential risks, such as electromagnetic interference, thermal effects, and mechanical failures
   e. Build a physical prototype for experimental testing and validation.

7. Deliverables

a. Detailed design and specification
b. Target compliance report
c. Functional Prototype
d. Guideline for integration

8. Impact

a. Vehicles can charge while in motion, reducing the need for frequent stops and extending their range.
b. Dynamic charging systems can be integrated into existing road networks. This can lead to more efficient use of space and resources compared to building and maintaining traditional charging stations.

9. Recommended Execution Agencies

a. Indian Institute of Technology (IIT), Madras
b. Visvesvaraya National Institute of Technology, Nagpur
c. Indian Institute of Technology (IIT), Delhi
d. Indian Institute of Technology (IIT), Bombay
e. Indian Institute of Science (IISc), Bangalore

10. Timelines: 36 Months

11. Budget: ₹20 Cr
Research & Development: ₹10 Cr (Divided equally between two parties)
Pilot Manufacturing: ₹10 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence		✓		
Market				✓
Technology				✓

13. Priority: Moderate

14. Administrative Mechanism

The prototypes shall be developed by research Institutions and the lab scale technology can be transferred to industries for commercial production. Currently, in India, the prototypes of static wireless charging systems have been developed at limited power (1.5 kW to 5 kW). Therefore, it is a high-priority project as its successful deployment shall reduce the time spent in recharging the vehicle and will reduce the weight of the vehicle due to the reduced size of the battery. Hence it has been assigned with the estimated budget of ₹10 Cr for research & development and ₹10 Cr is assigned for pilot manufacturing.

4.3.2.2 Coil design & materials for transmitting & receiving coils

Wireless charging couplers, including transmitter and receiver coils, must have high misalignment tolerance, interoperability, high power transfer efficiency, low cost, efficient thermal management and adhere to standard recommendations. Non-Polarized pads (Circular, square, hexagonal, and rectangular) are appropriate for static wireless power transfer. Polarized pads (DD- Double D Pad, DDQ- Double D Quadrature Pad, and BP- Bipolar Pad) are ideal for dynamic wireless power transfer. Designing for transmitting and receiving coils faces challenges such as shielding. High-power wireless charging requires efficient shielding, specific materials such as aluminium, ferrite, and nickel-iron soft ferromagnetic alloy etc. and efficient heat dissipation to maintain optimal performance and prevent overheating.

4.3.2.3 Infrastructure Requirements

a. The installation of multiple transmitting pads in the ground requires specific road infrastructure availability.
b. Electric vehicles need to be equipped with receiver coils, which are usually placed on the vehicle's undercarriage.
c. Communication infrastructure should be integrated to control power delivery and monitor the charging process.
d. Infrastructure should include various safety systems, such as emergency shutdown mechanisms, and fault detection.
e. To ensure the reliability and performance of the charging system, implement a maintenance and monitoring system.
f. Consider integrating charging systems to smart grid technologies, to optimize energy distribution and management.
g. Payment and billing system should be implemented for users to pay for the energy they consume.

4.3.3 Adaptive Charging Technology

The Adaptive Charging System for Electric Vehicles is a revolutionary technology that enhances the efficiency, convenience, and sustainability of electric vehicle charging. This system is a smart, versatile platform that utilizes advanced algorithms, data analytics, and real-time communication to optimize the charging process for electric vehicles. The Adaptive Charging System adjusts charging speed based on user schedule, grid capacity, and EV's state of charge, making it a key feature. This dynamic approach ensures optimal energy consumption for electric vehicles (EVs) and prevents grid overloads during peak demand periods [75].

The Adaptive Charging Network is a cyber-physical system made up of five interconnected subsystems: The information system, which gathers data and computes control actions; the sensor system, which collects data from the physical system; the actuation system, which regulates each vehicle's charging rate; and the physical system (electrical infrastructure), which provides power to the EVs, and drivers, who provide data to the system and decide when their vehicles are available to charge.

4.3.3.1 Current Status & Challenges

The Indian government has set an ambitious target of achieving 4 lakh charging stations by 2026. Currently, India is developing a DC conductive fast charger with output ranging from 30kW to 240 kW power [40]. Fast Charging stations, with their high charging loads, pose challenges such as a rise in peak load demand, voltage instability, and reliability issues. Thus, an adaptive charging system can help to balance the grid load and decrease stress on the electrical system as the number of EVs on the road increases. Adaptive charging has the potential to make EVs more cost-effective, reliable, and sustainable by addressing grid stability concerns, range anxiety, and high charging prices.

However, the development of adaptive charging systems poses several challenges. The primary concern is it requires extensive data collection and processing, including user preferences, charging patterns, and grid information, which needs to be safeguarded against cyber threats while maintaining user privacy is crucial. Localized grid congestion might emerge as a challenge, particularly during peak charging hours when more EVs are put on the road. In order to prevent overload on local transformers and distribution networks, adaptive charging systems must effectively control grid capacity. Additionally, adaptive charging systems need to ensure compatibility with various types of electric vehicles and battery chemistries.

Proposed Research Project- 4.4

Research on Adaptive Charging Techniques

1. Gap Analysis & Background

Adaptive charging techniques play a vital role in supporting the adoption of electric vehicles and ensuring their convenience and sustainability through better thermal management, charging algorithms, and software implementation. While charging an EV is still slower than filling a petrol tank, it can be simpler and faster than existing EV charging due to these techniques. However, Fast Charging poses several challenges, one of which is that charging a battery in extremely hot or cold temperatures might deteriorate its condition. To overcome this challenge, this project aims to use adaptive charging techniques between the vehicle and charger, which monitor the temperature of the battery, charging performance, balancing grid stability, and efficient energy management.

2. Global Benchmarking

One of the main concerns about plug-in charging is that constantly charging an EV battery to its maximum capacity or exposing it to extreme temperature conditions during charging can strain the battery. To overcome this concern, adaptive charging ensures that energy is provided when genuinely needed and not as a default charging method. Qnovo has developed adaptive charging, which provides safe Fast Charging in all weather Fast Charging and identifies rare battery defects, preventing thermal events [76]. Exponent Energy India has also developed 15-minute rapid charging technology using HVAC (Heating, Ventilation, Air-Conditioning) [76].

3. TRL Level: Starting with TRL-2, deliverable to TRL-5

4. Research Goal

To study and analyse adaptive charging techniques that optimise the charging process to improve charging speed by 30 to 40 % without compromising the battery life, grid conditions, and user experience which contribute to a more sustainable transportation system and safety.

5. Targets for Project

a. Design and development of adaptive charging techniques for different power ranges of EVs, battery chemistries, and charging protocols
b. Design and optimize the software that interacts with charging stations to manage the scheduling of charging
c. Develop a sophisticated liquid cooling system that efficiently dissipates heat generated during the charging of the vehicle which increases the charging speed and life of the battery
d. Design and implement the charging algorithms which include voltage and current limit set by the charger, grid demand, state of charge (SOC) and temperature of the EV battery, and limitation of the on-board charger

6. Methodology

a. Defining the specific requirements of a fast charger for the Indian context, such as power output, charging speed, and heat generation rate
b. Establish the thermal management objectives, such as the maximum allowable temperature for critical components
c. Select the proper liquid cooling components; they should be made for applications requiring high power and temperature
d. Develop adaptive charging algorithms and simulate them in controlled environments to ensure their performance under various scenarios
e. Develop user interfaces for the adaptive charging system so that EV owners and charging station operators can communicate with it
f. Install temperature sensors at strategic locations inside the charger to monitor the temperature of critical components
g. Collaborate with the providers of charging infrastructure to incorporate adaptive charging technology into charging stations
h. Include safety features to prevent overheating, such as alarms and emergency shutdown procedures
i. Testing and validation including interoperability and safety

7. **Deliverables**
    a. Developed product and demonstration on 2&3 wheelers, passenger cars, and trucks etc.
    b. Testing reports
    c. Guidelines for integration
    d. Design and Specification
    e. Target compliance report

8. **Impact**
    a. Adaptive charging can optimize the efficiency of the charging process by balancing the charge rate to the battery's state and the capacity of the charging infrastructure
    b. Adaptive chargers can communicate with the grid to prevent charging during high-demand hours, this helps to balance the load on the electrical grid and reduce the need for expensive grid upgrades

9. **Indicative list of Execution Agencies**
    a. Indian Statistical Institute (ISI), Kolkata
    b. Chennai Mathematical Institute (CMI), Chennai
    c. The Automotive Research Association of India (ARAI), Pune

10. **Timeline:** 36 Months

11. **Estimated Budget:** ₹10 Cr
    Research & Development: ₹7 Cr (Divided equally between two parties)
    Pilot Manufacturing: ₹3 Cr

12. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence	✓			
Market			✓	
Technology			✓	

13. **Priority:** High

14. **Administrative Mechanism**
    Research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from the the industry. This project is prioritized to adopt charging rates based on grid conditions, forecasting demand, optimizing charging schedules, heat dissipation during charging, and identifying efficient charging patterns that impact the performance, safety, and overall capabilities of Fast Charging. Estimated budget of ₹7 Cr is assigned for research and development and ₹3 Cr is allocated for pilot manufacturing.

4.3.3.2 Cost-competitive methods

The cost-competitive methods for adaptive charging systems involve several steps, including:

1. Implementing adaptive charging features using the current infrastructure may be cost-effective and less expensive than creating new stations with communication components and software updates.
2. Existing charging stations would need to be equipped with smart meters and communication modules to facilitate real time data exchange between the EVs and charging stations.
3. Strengthen the existing grid infrastructure to handle the variable loads introduced by adaptive charging. This may include upgrading transformers, substations, and distribution lines to ensure they can accommodate the increased and fluctuating demand.

4. Cloud computing can centralize data processing and decision-making, simplifying individual charging stations and reducing hardware requirements, ultimately lowering their cost.
5. Develop charging stations with simple hardware that focuses on key features to support adaptive charging and reduce manufacturing costs.

4.3.4 New Communication Protocols for Charging Infrastructure

Communication protocols play a vital role in the functioning of EVs and their charging infrastructure. They enable interoperability, ensuring effective communication between devices, systems, and networks. Communication between the vehicle and charger using a Pulse Width Modulation (PWM) signal can be done with the Control Pilot (CP) which is included in the charger connector. CP indicates the different states of charging like vehicle connected, charging allowed, ventilation, Charger shutdown, and error.

4.3.4.1 Current Status & Challenges

India follows the Open Charge Point Protocol (OCPP) which is an open-source protocol that provides a communication link between the EV charging station and the central management system. India has adopted the OCPP version 1.5 and it was also specified that if a higher version of OCPP is used then it should be compatible with OCPP 1.5. The functions performed by OCPP 1.5 are authentication, reservation of charger, start and end of charging, state of charge (SoC) level, depth of discharge (DoD) level of the battery, maximum allowable current limits, type of connector and charging type.

4.3.4.2 Identify the threat of cyber-attacks

A modern electric vehicle requires a Fast Charging infrastructure, which is possible through power line communication. Fast chargers can fully charge vehicle batteries quickly as the internet protocol is stacked on top of it to carry power packs and to make payments automatically based on power consumption. Vehicle to Grid (V2G) will allow a vehicle to communicate with a charging station which poses several cybersecurity threats to the vehicle. The primary concern is, that hackers steal personal information from the charging station network, including payment data, email addresses, and phone numbers. EV charging stations can be programmed to record incorrect charging times, which allows hackers to receive free electricity. A combination of apt technical and policy measures is required for protection against these types of cyber threats. It is essential to be aware of the potential vulnerabilities and to take adequate security measures to avoid cyber-attacks.

4.3.4.3 New or advanced communication protocols to address cyber security challenges

Implementing strong encryption algorithms and authentication protocols can safeguard data transfer between EVs, charging stations, and central management systems. To mitigate cybersecurity attacks, employ secure communication channels such as Virtual Private Networks (VPNs) or Transport Layer Security (TLS) protocols which create an additional layer of protection. Segregate the charging station network from other networks to minimize the potential impact of a cyberattack. To prevent unauthorized access, Intrusion Detection and Prevention Systems (IDPS) can continuously monitor charging station networks for any suspicious activities.

4.3.4.3 Adoption challenges & opportunities

One of the major uses of communication protocols is that they can help facilitate the development of standardized charging infrastructure and can have a significant impact on the Indian electric vehicle ecosystem in the ways of interoperability, advanced features, and cost savings.

With the adoption of interoperable protocols such as OCPP and OCPI, charging stations from different manufacturers can communicate with each other, making it easier for EV drivers to access charging infrastructure. Interoperability is critical for the development of a robust charging network. Communication protocols such as Open Smart Charging Protocol (OSCP) allow for advanced features such as load balancing, real-time demand response, and renewable energy integration. Standardized charging infrastructure can develop charging stations that are compatible with different management systems, reducing costs associated with proprietary systems. EV owners can also benefit from the availability of standardized charging infrastructure, reducing the need to invest in multiple charging cables and adapters.

Proposed Research Project – 4.5

Research on Wireless Communication Protocols for EV

1. **Gap Analysis & Background**
   Communication protocols are a method for transferring data among distributed modules via a serial data bus or employing wireless. Currently, in India, plug-in chargers using wired Control Pilot (CP) & Proximity Pilot (PP) as communication between the charger and the vehicle. Nowadays, Wireless charging technology for EVs has become an active area of research and development. Such a charging system requires low latency and it establishes reliable communication between the EV and the Electric vehicle supply equipment (EVSE) to optimize power transfer efficiency. This project proposes research on wireless communication protocols to enhance reliability, security, and efficiency.

2. **Global Benchmarking**[1]
   Researchers have proposed some experimental test platforms consisting of EV and EVSE emulators and a Raspberry Pi 3 with a WLAN module for wireless communication. The approach was applied in the case of a wired charging EV and was limited to the authentication phase [77].

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-5

4. **Research Goal**
   Studying and analysing robust and efficient wireless communication protocols for seamless interaction between electric vehicles and chargers, focusing on enhancing reliability, security, and efficiency.

5. **Targets for Project**
   a. Design the communication protocol to ensure compatibility between different vehicles and chargers, regardless of manufacturer or model, to enable widespread adoption and seamless integration into existing infrastructure.
   b. Establishment of robust communication links between vehicles and chargers to ensure consistent and reliable charging sessions without interruptions or errors.
   c. Implementation of strong encryption and authentication mechanisms to prevent unauthorized access to the charging system.

6. **Methodology**
   a. Conduct a comprehensive review of existing literature, focusing on current technologies challenges, and opportunities.
   b. Define the specific requirements considering factors like interoperability, reliability, security, efficiency, and alignment tolerance.
   c. Develop a conceptual design for the wireless communication protocol based on the identified requirements.

[1] Electric vehicle communication controller (EVCC) and supply equipment communication controller (SECC) are the main components in the wireless communication scenario. The EVCC and SECC are electronic systems that manage communication protocols and control energy flow between EVSE and EV.
The AC voltage signal (simulating battery signal) is sensed by the DSP kit via an analog GPIO with a sampling time. The DSPs Analogue Digital Converter (ADC) converts the voltage to digital data. Then data is sent to the raspberry Pi via I2C bus. The Rasberry Pi acts as a master and the DSP kit as the slave. The Rasberry Pi (client) uses TCP/IP protocol to send I2C data to a distant Rasberry Pi (server). The server then transfer the data through I2C to DSP kit for energy flow control.

d. Utilization of simulation tools and modelling techniques to evaluate the performance of the proposed protocol under different scenarios, including different charging conditions.
e. Implement a prototype of the wireless communication protocol focusing on key functionalities such as data exchange, authentication, error handling, and power transfer control.
f. Conduct thorough testing and validation of the prototype protocol to assess its performance, reliability, and security.

7. Deliverables

a. Detailed design and specification
b. Target compliance report
c. Developed product
d. Guideline for integration

8. Impact

a. Wireless communication protocols eliminate the need for physical cables and connectors, simplifying the charging process and making it more convenient.

9. Recommended Execution Agencies

a. Indian Institute of Technology (IIT), Madras
b. Visvesvaraya National Institute of Technology, Nagpur
c. Indian Institute of Technology (IIT), Delhi
d. Indian Institute of Science (IISc), Bangalore

10. Timelines: 36 Months

11. Budget: ₹10 Cr
Research & Development: ₹6 Cr (Divided equally between two parties)
Pilot Manufacturing: ₹4 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence	✓			
Market			✓	
Technology			✓	

13. Priority: High

14. Administrative Mechanism

Research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from the industry. This project is prioritized to adopt wireless communication protocols between charger and vehicle to enhance convenience, reliability and security. Estimated budget of ₹6 Cr is assigned for research and development and ₹4 Cr is assigned for pilot manufacturing.

Way Forward

The transition to eMobility necessitates a comprehensive approach to ensure successful implementation. The way forward involves enhanced research and development focusing on next-generation energy storage, advanced EV aggregates, and sustainable materials and recycling methods. Concurrently, robust infrastructure development is critical, including a widespread and reliable charging network and smart grid integration to optimize energy usage. Policy support in the form of incentives, subsidies and regulatory frameworks will accelerate market adoption, while public private partnerships can allocate resources and drive innovation. Engaging consumers through awareness campaigns and incentives alongside developing educational programs and workforce training, will further promote adoption. Establishing mechanisms for monitoring progress and incorporating feedback will ensure the roadmap's dynamic adoption to evolving technological and market conditions. By following these steps, India can lead in the global eMobility revolution, driving economic growth, and reducing environmental impact.

Annexure A: Identified Research Projects in the Area of Hydrogen

A.1 Introduction

Electric vehicles are more efficient and environment friendly with low or zero emission compared with conventional internal combustion engine-based gasoline vehicles. Fuel Cells are considered a promising technology because of several key advantages they offer, such as; zero emissions, higher energy density, fast refuelling, long range and reduced dependence on rare minerals. Apart from EV powertrain components, the typical FCEV consists of a fuel cell (FC) stack, hydrogen storage, cooling circuit, Balance of Plant (BOP) and DC-DC converter.

A.2 Current Scenario in India

Fuel cell (FC) technology in India is gaining attention and support as a potential clean energy solution. Various research institutes, universities, government agencies as well as private companies are working on various aspects of FC technology such as material research, on-board hydrogen storage, on-board hydrogen generation, balance of plant, component manufacturing, etc. Below are the certain developments in the specific area:

a. Vehicle pilot projects initiated by GoI: [78]
   i. NTPC Vidyut Vyapar Nigam Ltd, (NVVN) is setting up a pilot project and it targets the operation of five hydrogen fuel cell-based electric buses between Delhi and Leh. NVVN along with NTPC Ltd. would be developing the hydrogen generation and dispensation facility which will be fed through Renewable Energy, making it a truly zero-emission initiative. The pilot project is being executed by NVVN with financial support from the Ministry of New & Renewable Energy, Government of India.
   ii. Tata Motors has won the IOCL tender to provide 15 hydrogen FC buses.

b. Vehicle R&D in the advanced stage: [79]
   i. Union Minister Dr. Jitendra Singh unveils an indigenously developed Hydrogen Fuel Cell Bus developed by KPIT-CSIR in Pune.
   ii. Olectra Greentech Limited, in association with technology partner Reliance, has developed a hydrogen FC bus which is a carbon-free alternative to traditional public transport. Single hydrogen fill allows the bus to travel up to 400 kms.
   iii. A commercial vehicle manufacturer in India Bharat Benz has been working towards its first intercity bus concept, powered by hydrogen fuel cell technology, for quite a long time. Now, the company in partnership with Reliance unveiled the heavy luxury commercial vehicle based on this technology at the 4th Energy Transitions Working Group meeting under India's G20, which was held in Goa's Taleigao.
   iv. Tata Motors received a road-worthiness certificate for its upcoming hydrogen-powered buses.

c. Regulations:
   Based on the development of fuel cell vehicles globally, the AISC panel has been constituted to formulate the Automotive Industry Standard for type-approval of compressed gaseous hydrogen fuel cell vehicles. This standard is AIS157 (Safety and procedural requirements for type-approval of compressed gaseous hydrogen FC vehicles).

A.3 Research Pathways

A.3.1 Fuel Cells Technology

A.3.1.1 Current Status & challenges

The current status of FCEVs shows promise in terms of clean energy. However, fuel cell technology is currently facing challenges related to:

a. Hydrogen Production and Infrastructure: A major challenge is the production, storage, and distribution of green hydrogen as a fuel. In the current scenario, Hydrogen is mostly derived from fossil fuels, which offsets some of the environmental benefits of fuel cells. Developing sustainable and cost-effective methods for producing and distributing hydrogen is crucial.
b. Cost: Fuel cell systems, especially those based on precious metals like platinum, can be expensive to manufacture. Efforts are ongoing to reduce costs through material innovation and manufacturing processes.
c. Durability and Lifespan: Ensuring the long-term durability and reliability of fuel cell systems is important for commercial applications. Degradation of fuel cell components over time can impact their efficiency and performance.
d. Size and Weight: Fuel cell systems need to be compact and lightweight for various applications, especially in transportation. Achieving high power density and miniaturization is a challenge.
e. Safety: Hydrogen is highly flammable, and safety concerns related to its production, storage, and use need to be thoroughly addressed.
f. Policy and Regulations: Clear regulations and policies are necessary to promote the adoption of fuel cell technology and to address safety, infrastructure, and emissions concerns.
g. Public Awareness and Acceptance: Educating the public about fuel cell technology and its benefits is essential for its wider acceptance and integration into various sectors.

In Europe, several initiatives have been taken to promote fuel cell technology which include a Hydrogen Strategy under the European Green Deal, emphasizing clean hydrogen production [80]. The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) facilitates public-private collaboration for research & development [81]. The European Clean Hydrogen Alliance fosters industry, public and civil society collaboration to support the development of hydrogen and fuel cell technologies [82]. Whereas, in the United States, Department of Energy (DOE) is working closely with its national laboratories, universities, and industry partners to overcome critical technical barriers to fuel cell development [83].

A.3.1.2 India centric, efficient, cost-effective fuel cell

To manufacture cost-efficient fuel cells in India, a multifaceted approach is needed. This includes substantial investment in research and development, fostering national and international collaborations and promoting innovative designs and materials. Local material sourcing and scaling production can significantly reduce costs while building a skilled workforce and adhering to standardized manufacturing processes will ensure quality and consistency. By taking these measures, India can establish itself as a competitive player in the clean energy and transportation sectors by manufacturing cost-efficient fuel cells for a sustainable future.

A.3.1.3 Manufacturing process

Manufacturing processes for fuel cell technology face many challenges, including the need for precision and consistency in producing delicate and complex components, such as the fuel cell stack and its catalyst layers. Ensuring high-quality and uniform materials for critical components, such as membranes and electrode materials, is crucial. Scaling up production while maintaining cost effectiveness can be challenging, as economies of scale are yet to be fully realized in fuel cell manufacturing. Additionally, the development of efficient and sustainable methods for producing hydrogen needs significant attention to ensure a consistent supply chain. Addressing these challenges is essential to make fuel cell technology more accessible and competitive in various applications.

Proposed Research Project- A.1

Research on Design Optimization of Bipolar Plates of Fuel Cell Stack

1 Gap Analysis & Background

Bipolar plates, supply hydrogen and air to the Membrane Electrode Assembly (MEA), remove water and conduct current between cells and also provide mechanical support. Flow fields on the bipolar plates are critical to ensure the adequate availability of hydrogen and air throughout the stack. There exist efficient flow field options which perform satisfactorily in an individual or small stack assembly. However, in higher capacity FC stacks, there are challenges related to the non-uniform distribution of hydrogen and air which leads to lower power output.

2 Global Benchmarking

Design of a bipolar plate greatly affects the hydrogen mass fraction and power density. Square baffled channel, rectangular baffled channel, double serpentine geometry etc. are some of the bipolar plate design geometries on which researchers are currently working on. Square baffled plate design demonstrates 22.6% increase in hydrogen mass fraction and 12.11% increase in power density. Rectangular baffled design and parallel baffled design are comparable to square baffled design whereas double serpentine design is the least performing amongst the others. [84]

3 TRL level: Starting with TRL-2, deliverable to TRL-7

4 Research goal

To optimize the design of bipolar plate to achieve higher performance in terms of fuel adequacy to MEA, water removal, eliminate leakages and evaluate manufacturability for higher capacity FC stacks.

5 Targets for Project

a. To demonstrate that the fuel cell stack delivers rated output for greater than 90 percent of the time
b. Reduce the cost of BOP by over 20 percent
c. Proposed bipolar plate shall be efficient in terms of adequacy of fuel for electrochemical reaction and be feasible for manufacturing

6 Methodology

The following tasks are involved in achieving the targets:

a. Determine the bipolar plate requirements
b. Benchmark global practices for bipolar plate designs and manufacturing
c. Determine the capacity of the stack for which plates have to be designed
d. Design and CFD analysis of various options
e. Manufacturing of at least 3 suitable prototypes
f. Assembling the FC stack
g. Integration and validation

6. Deliverables

a. Best-suited design of bipolar plate for automotive application FC stack
b. Design validation testing reports
c. Guidelines for manufacturing
d. Commercialization plan
e. Target compliance report

7. Impact

a. Optimized bipolar plate designs can lead to enhanced fuel cell performance, increased efficiency, improved durability and corrosion resistance
b. Cost-effective manufacturing

8. Indicative list of Execution Agencies

a. Center for Fuel Cell Technology (CFCT-ARCI)
b. Ministry of New and Renewable Energy (MNRE)/National Green Hydrogen Mission
c. National Chemical Laboratory (NCL), Pune

d. Indian Institute of Technology, Delhi (IITD)
e. The Automotive Research Association of India (ARAI), Pune
f. Indian Institute of Technology, Madras
g. Indian Institute of Technology, Ropar (IITRPR)

9. **Timeline:** 24 to 36 months

10. **Estimated Budget:** ₹20 Cr
Research & Development: ₹10 Cr
Pilot Manufacturing: ₹10 Cr

11. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market			✓	
Technology			✓	

12. **Priority:** High

13. **Administrative Mechanism**
From TRL-2 to 5, research institutions/labs and academia will take the lead in developing technologies, with support, engagement, and commitment from the industry. From TRL-6 onwards to TRL-7, the industry should take the lead for commercial production. Prioritizing this project at a high level recognizes the immediate impact it can have on advancing fuel cell technology by resolving affecting factors such as conductivity, durability, and weight leading to improved efficiency and longer lifespan of the fuel cell system. Estimated budget of ₹10 Cr is assigned for research & development, and ₹10 Cr is allotted to pilot manufacturing.

A.3.1.4 Robust supply chain

Establishing a robust supply chain faces multifaceted challenges. Ensuring a stable supply of critical materials like platinum for catalysts and high-performance polymers for membranes is essential, as these materials are often expensive and subject to supply risks. Expanding hydrogen production and distribution infrastructure is vital to ensure a consistent source of fuel for fuel cell applications, this may require significant investment. Also, developing standardized components and production processes to facilitate interchangeability and reduce costs across supply chain is challenging. Coordinating global supply chains for fuel cell components can be complicated, given the need for collaboration among various manufacturers, suppliers, and stakeholders, all while meeting stringent quality and performance standards.

A.3.2 Membrane Electrode Assembly (MEA) for Fuel Cells

MEA plays a pivotal role in FCEVs. It consists of a proton-conducting membrane sandwiched between two electrode layers. In FCEVs, hydrogen and oxygen react at these electrodes generating electricity, water and heat. The membrane selectively allows protons to pass through, facilitating the electrochemical process. MEA's efficiency and durability are crucial for the overall performance of FCEVs, influencing factors such as power output and lifespan. Advances in MEA technology contribute significantly to enhancing the feasibility and sustainability of hydrogen-powered transportation.

A.3.2.1 Current Status & challenges

Several challenges surround membrane electrode assemblies in fuel cell technology. Durability remains a primary concern, as MEAs are susceptible to degradation over time due to factors like chemical exposure, temperature fluctuations and mechanical stress. Achieving cost-effectiveness poses another hurdle, as MEA production often involves expensive materials like platinum catalysts.

Additionally, water management within the MEA is critical for optimal performance, requiring intricate design considerations to balance hydration levels. Addressing these challenges is essential for the widespread adoption of fuel cell technology, necessitating ongoing research and innovation in MEA development.

A.3.2.2 Electrode Materials

Electrode materials in MEAs face notable challenges in fuel cell applications. One key concern is the scarcity and cost of platinum, a common catalyst used in electrodes. Developing alternative, earth-abundant catalysts is crucial to reduce reliance on expensive materials. Additionally, electrode durability is a persistent issue, as chemical and electrochemical reactions during fuel cell operation can lead to degradation over time. Optimizing the balance between performance and cost, while ensuring long-term stability, presents a complex challenge in advancing electrode materials for MEAs. Ongoing research should focus on addressing these obstacles and pave the way for more sustainable and economically viable fuel cell technologies.

A.3.2.3 Novel materials

Indian researchers are actively exploring non-precious metal catalysts to replace or reduce the reliance on expensive materials like platinum. Transition metal oxides, nitrogen-doped carbon and other innovative compounds show promise in enhancing catalytic activity while addressing cost concerns. In addition to catalysts, advancements in proton-conducting membranes are noteworthy. Proton Exchange Membranes (PEM) play a critical role in facilitating the movement of protons during the electrochemical reactions within fuel cells. Novel materials, including high-temperature-resistant polymers and composite structures, are being researched to improve the durability and efficiency of PEMs.

A.3.2.4 Flow field

Optimizing flow field in fuel cells poses challenges centered on achieving uniform reactant distribution across electrodes to prevent performance degradation and uneven wear. Designing an efficient flow field requires a delicate balance to manage water content effectively. Achieving the right equilibrium between maintaining adequate hydration for proton conductivity and avoiding flooding is crucial. More research needs to be focused on these challenges by exploring innovative flow field designs and materials, aiming to enhance fuel cell efficiency, longevity and overall reliability.

A.3.2.5 Energy-efficient fuel cell stack

Developing an energy-efficient fuel cell stack faces multifaceted challenges. One primary concern is optimizing the balance between operating temperature and performance, as higher temperatures can enhance reaction kinetics but also lead to increased material degradation and energy losses. Ensuring uniformity in gas distribution and temperature across the stack is crucial to prevent localized variations that can impact overall efficiency. Additionally, managing thermal gradients and heat dissipation within the stack poses a significant challenge, influencing not only performance but also durability of materials. Addressing these complexities requires ongoing research to design innovative stack configurations, materials and thermal management strategies to unlock the full potential of fuel cell systems.

A.3.2.6 Cost-competitive domestic materials

Developing cost-competitive domestic materials for MEAs in India encounters several challenges. One primary hurdle is the affordability and availability of critical components like catalysts. Precious metals such as platinum, commonly used in MEA catalysts, can contribute significantly to the overall cost. Finding or developing alternative, more cost-efficient catalyst materials is crucial for making fuel cell technology economically viable in the Indian context. Additionally, ensuring a stable Indian supply chain for these materials poses a challenge, as fluctuations in availability can impact production costs and hinder scalability.

A.3.2.7 Manufacturing Process

The manufacturing process of MEAs faces significant challenges, primarily centered around cost, scalability and precision. Achieving consistent quality while minimizing production costs remains a delicate balance, especially concerning materials like catalysts that can be expensive. Scaling up production to meet the demand of widespread fuel cell adoption poses challenges in maintaining uniformity and efficiency across large-scale manufacturing facilities. Precision in assembling MEA components, including proton-conducting membranes and electrode layers, is crucial for optimal performance while adding complexity to the manufacturing process. Addressing these challenges requires continuous advancements in manufacturing technologies, materials and quality control measures to ensure cost-effectiveness and reliability in the production of MEAs for fuel cells.

A.3.3 Electrolyte for Fuel Cells

In FCEVs, the electrolyte plays a crucial role in enabling the electrochemical reactions that convert hydrogen into electricity to power the vehicle. Often utilizing proton exchange membranes (PEMs), these electrolytes facilitate the movement of protons between anode and cathode, allowing for the efficient generation of electric current. The specific characteristics of electrolytes significantly impact the performance and efficiency of FCEVs, influencing factors such as power output, durability, and overall driving range.

A.3.3.1 Current Status & Challenges

Challenges associated with electrolytes for fuel cells in FCEVs revolve around achieving a delicate balance between performance and durability. Proton exchange membranes (PEMs), which are commonly used as electrolytes face challenges related to maintaining optimal proton conductivity while ensuring long-term stability in varying operating conditions. Issues such as membrane dehydration, chemical degradation, and sensitivity to impurities in hydrogen fuel can impact overall fuel efficiency. Additionally, ensuring cost-effectiveness without compromising performance remains a significant challenge, as advanced materials capable of meeting stringent FCEV requirements often come with elevated production costs. Overcoming these challenges requires ongoing research and development to identify robust and cost-efficient electrolyte solutions.

A.3.3.2 Electrolytes Materials

The challenges associated with electrolyte materials in FCEVs are diverse. Finding materials that can resist chemical degradation, remain stable over extended periods and perform consistently in the automotive environment is a significant hurdle. Additionally, the cost and scalability of advanced electrolyte materials, such as high-performing polymers or alternative solid-state electrolytes, present challenges for widespread FCEV adoption. Overcoming these obstacles requires continual research efforts to develop electrolyte materials that simultaneously meet performance demands, durability criteria and economic feasibility.

Proposed Research Project- A.2

Research on Novel Membrane Materials and Structures for Enhanced Fuel Cell Efficiency

1. **Gap Analysis & Background**
   Currently, fuel cells offer a promising alternative to their low environmental impact and high efficiency. However, existing membrane materials and structures face limitations such as low conductivity, susceptibility to degradation, and high costs. This project seeks to explore advanced membrane materials and structures capable of overcoming existing challenges, thereby unlocking the full potential of fuel cells as a clean and efficient energy source.

2. **Global Benchmarking**
   A steady supply of hydrogen to the cells and simultaneously controlling the release of electrical energy is vital for the efficient performance of the fuel cell. Research is focused on enhancing cell performance by replacing the materials being used in order to improve properties and reduce operating temperatures. In order to enhance its electrochemical performance, research is carried out on different materials for electrodes such as Polyvinylidene difluoride and stainless steel: PVDF/SS, Carbon nanotube filled Polytetrafluoroethylene: CNT/PTFE, Ti_4O_7 etc. and electrolytes (perfluoro sulfonic acid: PFSA).

3. **TRL Level:** Starting with TRL-3, deliverable to TRL-5

4. **Research Goal**
   To investigate and implement advanced membrane materials and improved structural designs to optimize fuel cell performance and efficiency.

5. **Targets for Project**
   a. Investigate and develop novel membrane materials with at least 40 percent improvement in conductivity
   b. Developed membranes should be 60 percent more durable than currently available membrane technology
   c. Develop scalable and cost-efficient manufacturing processes to facilitate the commercial adoption
   d. The cost of the materials used to produce the product must be at least at the commodity level
   e. The supply chain for the material must be sourced entirely from India

6. **Methodology**
   a. Conduct a thorough review of existing literature on fuel cell membrane technology to understand current research, challenges, and opportunities
   b. Develop and synthesize novel membrane materials using appropriate manufacturing techniques and perform material characterization to analyse their properties
   c. Fabricate membranes with varying compositions, thicknesses, and structures
   d. Optimize fabrication parameters to achieve desired membrane properties and performance characteristics
   e. Conduct electrochemical tests to assess membrane conductivity, ion transport and fuel cell efficiency. Evaluate membrane durability and stability under simulated operating conditions
   f. Develop computational models and simulations to predict membrane performance and validate model predictions against experimental results for further optimizations
   g. Scale up the synthesis and fabrication processes to produce membranes at a larger scale

7. **Deliverables**
   a. Membrane Prototypes
   b. Integrated fuel cell demonstrations
   c. Material specifications
   d. Membrane synthesis protocols
   e. Experimental data and analysis
   f. Computational models
   g. Process documentation
   h. Scalability plans

i. Manufacturing feasibility report
j. Detailed design and specifications for cells
k. Target compliance report

8. Impact

a. Development of more durable novel membrane materials and structures can significantly enhance the efficiency of fuel cells
b. By optimizing membrane materials and fabrication processes, the project can potentially lower the production costs of fuel cell technology

9. Indicative list of Execution Agencies

a. Centre for Fuel Cell Technology (CFCT-ARCI)
b. Ministry of New and Renewable Energy (MNRE)/National Green Hydrogen Mission
c. National Chemical Laboratory (NCL), Pune
d. Indian Institute of Technology, Delhi (IITD)
e. The Automotive Research Association of India (ARAI), Pune
f. Indian Institute of Technology, Madras
g. Indian Institute of Technology, Ropar (IITRPR)

10. Timeline: 48 Months

11. Estimated Budget: ₹25 Cr
Research & Development: ₹15 Cr
Pilot Manufacturing: ₹5 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market			✓	
Technology			✓	

13. Priority: High

14. Administrative Mechanism

This project is deliverable to TRL-5, hence research institutions and laboratories will participate in developing technologies. Prioritizing this project at a high level recognizes the immediate impact it can have on advancing fuel cell technology by resolving affecting factors such as durability and weight leading to improved efficiency and longer lifespan of the fuel cell system. Estimated budget of ₹15 Cr is assigned for research & development, and ₹5 Cr is assigned for pilot manufacturing.

A.3.3.3 Manufacturing process

Manufacturing electrolytes for FCEVs entails challenges in optimizing production processes for scalability, cost efficiency and quality control. Achieving uniformity and precision in the fabrication of proton exchange membranes (PEMs) or other electrolyte materials demands advanced manufacturing techniques. Scaling up production while maintaining consistent quality can be intricate, especially considering the sensitivity of electrolytes to impurities and the need for precise ion transport. Moreover, the complexity of assembling multiple layers and components within the electrolyte poses challenges in maintaining high standards of performance and reliability during mass production. Addressing these manufacturing challenges requires ongoing advancements in technology, process optimization, and quality assurance methodologies to ensure reliable and cost-effective production of electrolytes for FCEVs.

A.3.4 Onboard Hydrogen Storage

A.3.4.1 Current Status & challenges

Hydrogen storage in Fuel Cell Electric Vehicles (FCEVs) presents unique challenges for the automotive industry. One key challenge is the need for high-pressure tanks that can safely store hydrogen. These tanks need to possess good strength while being lightweight. Moreover, achieving competitive driving ranges comparable to conventional petrol and diesel vehicles is challenging due to hydrogen's lower energy density by volume compared to gasoline or diesel, necessitating larger or higher-pressure tanks.

Additionally, building an extensive network of hydrogen refuelling stations is crucial to provide FCEV drivers with convenient access to fuel, but it requires substantial investment and coordination among stakeholders. Ensuring hydrogen purity, reducing costs, enhancing safety, and addressing durability concerns further complicate the development and adoption of FCEVs.

Efforts to overcome these challenges include advancements in materials science to improve tank design, the development of lightweight and durable storage materials, the expansion of refuelling infrastructure, and continued research into safety measures. Education and outreach to consumers also play a vital role in addressing misconceptions and fostering acceptance of FCEVs as a clean and practical transportation option. Ultimately, successful hydrogen storage solutions in FCEVs will rely on a multi-faceted approach that combines technological innovations, infrastructure development, and public awareness efforts.

A.3.4.2 Storage Cylinder

Fuel cell electric vehicles face numerous challenges related to hydrogen storage cylinders. These cylinders must withstand high-pressure storage often between 350-700 bar, demanding the use of strong and lightweight materials. Ensuring the safety of these high-pressure cylinders in the event of accidents and crashes is of paramount importance. Moreover, maintaining hydrogen purity, managing temperature fluctuations, and achieving cost-effective production are crucial considerations. Addressing these challenges through ongoing research and technological advancements is vital to promote the widespread adoption of FCEVs.

A.3.4.3 Sub-ambient Storage methodology

Sub-ambient storage methodology in FCEVs refers to a specialized approach for storing hydrogen at temperatures lower than room temperature. This method is primarily used to increase the density of hydrogen storage. However, there are challenges that need to be addressed. These challenges include the need to optimize the weight of the energy-intensive cryogenic equipment, potential efficiency offsets due to energy consumption during liquefaction, and the importance of effective thermal insulation to prevent hydrogen from returning to a gaseous state. Material compatibility is another issue that needs to be addressed to ensure that materials do not become susceptible to hydrogen embrittlement. Cryogenic hydrogen storage can experience boil-off losses as a small amount of hydrogen vaporizes even with good insulation. Managing and minimizing these losses is important for increasing and maintaining efficiency.

Many international research institutes are working on storing hydrogen in the form of Liquid Organic Hydrogen Carriers. The European Union has funded the Ship-aH2oy project to develop and demonstrate a zero-emission propulsion technology using green hydrogen from liquid organic hydrogen carriers (LOHC) on a megawatt scale [85] [86].

Proposed Research Project- A.3

Liquid Organic Hydrogen Carriers (LOHC) Storage Technology for Fuel Cell Electric Vehicles

1. **Gap Analysis & Background**
The progress of fuel cell electric vehicles is hindered by a major challenge of on-board hydrogen storage due to the low energy density of gaseous hydrogen. This project aims to overcome this challenge by exploring novel on-board storage technology for storing Liquid Organic Hydrogen Carriers (LOHC) as a promising alternative which is to be deployed in Fuel Cell Electric Vehicles.

2. **Global Benchmarking**
Liquid organic hydrogen carrier (LOHC) systems store hydrogen through covalent bonds. Role of different catalyst materials for hydrogen productivity and LOHC stability is being studied. Although, the performance of a LOHC dehydrogenation unit is also strongly dependent on the applied reactor configuration, density functional theory techniques are used to determine adsorption energies and identify steps in LOHC conversion processes. Multiple energy storage technologies have been researched on and LOHC is an emerging technology preferred over other technologies like RHFC for its higher volumetric and gravimetric hydrogen storage densities, Higher energy stored on investment (ESOI), Energy returned on investment (EROI) and lower energy embodied cost. Industrial implementation of the LOHC technology has started but is still in development phase. [87]

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-5

4. **Research Goal**
To develop Liquid Organic Hydrogen Carriers (LOHC) storage technology as a viable and sustainable solution for on-board hydrogen storage in Fuel Cell Electric Vehicles (FCEVs).

5. **Targets for Project**
   a. Achieve a minimum target of 80 percent efficiency for the conversion of organic carriers into hydrogen
   b. Achieve a 20 percent improvement in energy density for LOHC storage
   c. Ensuring the safety of the storage technology under various operating conditions
   d. Investigating scalability and practicality for implementation in FCEVs
   e. Addressing compatibility issues with existing FCEV infrastructure
   f. The cost of the materials used to produce the product must be at least at the commodity level
   g. The supply chain for the material must be sourced entirely from India

6. **Methodology**
The following tasks are involved in achieving the targets:
   a. Benchmark global LOHC technologies
   b. Identify and synthesize suitable LOHC for hydrogen storage and procurement of the materials for prototyping
   c. Measure the energy density of selected LOHC and compare it to traditional hydrogen storage methods
   d. Develop and optimize chemical or thermal processes for efficiently releasing hydrogen from LOHC
   e. Construct a prototype storage system and conduct enhanced safety testing to evaluate the stability and safety under various conditions
   f. Conduct comprehensive testing and validation of the prototype under real-world conditions
   g. Analyze the data collected throughout the project to draw conclusions about the feasibility
   h. Assess the scalability of the technology and its compatibility with existing FCEV infrastructure

7. **Deliverables**
The project's deliverables encompass the development of efficient and safe LOHCs, alongside the creation of prototype FCEVs employing these carriers. Infrastructure expansion plans and target compliance reports will also be provided as an integral component of the project's outcomes.

8. Impact

a. LOHCs have the potential to offer higher energy density compared to gaseous hydrogen
b. LOHCs will mitigate concerns related to hydrogen gas leakage
c. Liquid carriers can potentially reduce energy losses during transportation and storage

9. Indicative list of Execution Agencies

a. Indian Institute of Technology, Madras
b. Ministry of New and Renewable Energy (MNRE)/National Green Hydrogen Mission
c. Indian Institute of Technology, Roorkee (IITR)
d. Indian Institute of Technology, Bombay
e. Indian Institute of Technology, Guwahati
f. The Automotive Research Association of India (ARAI), Pune
g. Indian Institute of Science, Bangalore
h. National Institute of Technology, Rourkela (NITR)
i. CSIR- National Environmental Engineering Research Institute (NEERI)

10. Timelines: 24 months

11. Estimated Budget: ₹15 Cr
Research & Development: ₹10 Cr
Pilot Manufacturing: ₹5 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market			✓	
Technology				✓

13. Priority: High

14. Administrative Mechanism

This project is deliverable to TRL-5; hence research institutions and laboratories will participate in developing technologies, and industries will play a supporting role. Prioritizing this project at a high level recognizes its role in advancing the feasibility and practicality of hydrogen as a clean energy carrier for fuel cells, contributing significantly to the development and commercialization of FCEVs. The estimated budget of ₹10 Cr is assigned for research & development and ₹5 Cr is allotted to pilot manufacturing.

A.3.5 Hydrogen (H2) Generation & Storage

Hydrogen generation and storage are fundamental aspects of FCEVs, playing a vital role in their clean energy ecosystem. Efficient and scalable hydrogen production methods, coupled with advanced storage technologies, are crucial for realizing the practicality of FCEVs. Challenges in this domain include cost, efficiency and sustainability, particularly in transitioning away from traditional fossil fuel-dependent methods like steam methane reforming to greener alternatives such as electrolysis powered by renewable energy.

Hydrogen poses its own set of challenges, revolving around achieving high energy density, safety and practicality. Various storage methods, including compression, liquefaction and solid-state storage, each come with their own complexities. Efficiently storing hydrogen at high volumetric and gravimetric densities while ensuring safety during handling, transportation and use presents a significant challenge. Advancements in material science and engineering are crucial for developing storage solutions that strike a balance between energy density, cost-effectiveness, and safety.

Addressing these challenges requires ongoing innovation and research to make hydrogen generation and storage viable and scalable solution for FCEVs.

A.3.6 Balance of Plant (BOP) for Fuel cell vehicle

A.3.6.1 Current Status & challenges

The Balance of Plant for FCEVs has seen notable advancements but it continues to struggle with several critical challenges. Enhancing the efficiency and cost-effectiveness of BoP components such as compressors, heat exchangers, and pumps remains paramount to boost overall FCEV performance and affordability. Also, ensuring the durability and reliability of materials in BoP components under the demanding conditions of FCEVs is another concern. Moreover, scaling up manufacturing capacity for key components like hydrogen tanks and fuel cell stacks is essential to meet growing demand. And, integrating and optimizing these components seamlessly into FCEV designs for real-world conditions is another challenge.

Proposed Research Project- A.4

Development of New Sealing Methods for Components Deployed in BoP

1. **Gap Analysis & Background**
   The efficient and safe operation of FCEVs depends on the reliability of the components within the Balance of Plant (BoP). Due to factors such as small molecular size and high permeability of hydrogen, high operating temperatures and pressures etc. There is a need for advanced sealing methods within the BoP components. Seals play a major role in maintaining the integrity of critical interfaces, preventing leaks and ensuring long-term safety and efficiency. This project aims to address these challenges by developing innovative and robust sealing methods.

2. **Global Benchmarking**
   Products such as preformed inlay gaskets have been used traditionally for the sealing of components of BoP. But as it required manual insertion, it wasn't suitable for high volumes. Sealing methods were researched for fuel cell stacks as well as BoP in the FCEVs. These include low gas permeable materials, polyurethane based products. Polyurethanes have proved to be a superior alternative for many traditional sealing methods like laser welding for joining and sealing two half shells of metallic bipolar plates. Elastomers are used to seal various components in BoP due to their chemical resistance, thermal stability and ability to hold off against multiple operating conditions.

3. **TRL Level:** Starting from TRL-2, deliverable to TRL-6

4. **Research Goal**
   To develop innovative sealing methods for components deployed in the Balance of Plant of FCEVs to enhance their reliability, safety and efficiency.

5. **Targets for Project**
   a. Develop innovative sealing techniques to improve the longevity and durability of BoP components
   b. Ensure that the developed sealing methods meet or exceed industry and regulatory standards for safety and performance
   c. Minimizing maintenance requirements and associated costs by 20 percent
   d. Aim to lower the overall cost of FCEVs by designing more cost-effective sealing methods
   e. The supply chain for the material must be sourced entirely from India

6. **Methodology**
   The following tasks are involved in achieving the targets:
   a. Identify critical sealing challenges within the FCEV Balance of Plant components
   b. Review and benchmark existing research on sealing methods and materials

c. Evaluate and select sealing materials that can withstand high-pressure hydrogen, extreme temperatures and mechanical stress
d. Conduct material testing for compatibility, durability and performance
e. Create prototypes and perform tests and simulations to assess the sealing performance under various conditions
f. Continuously refine the sealing methods based on testing results and feedback
g. Develop a plan for scaling up production for implementation of new sealing methods in commercial FCEVs

7. Deliverables

a. Physical prototypes of components with new sealing methods
b. Specifications and performance characteristics of selected sealing materials
c. Data from controlled testing and simulations
d. Recommendations for performance optimization
e. Cost analysis report
f. Scale-up plan
g. Target compliance report

8. Impact

a. Reduced risk of leaks and improved durability and reliability of Balance of Plant
b. Reduced dependency on foreign companies for specialized components
c. Cost-effective sealing solutions will lower production and maintenance costs

9. Indicative list of Execution Agencies

a. Center for Fuel Cell Technology (CFCT-ARCI)
b. Indian Institute of Technology, Bhuvaneshwar (IITBBS)
c. Ministry of New and Renewable Energy (MNRE)/National Green Hydrogen Mission
d. National Chemical Laboratory (NCL), Pune
e. Indian Institute of Technology, Delhi (IITD)
f. Indian Institute of Technology, Bombay
g. Vikram Sarabhai Space Center (VSSC), Thiruvananthapuram
h. Indian Institute of Technology, Ropar (IITRPR)

10. Timelines: 24- 36 months

11. Estimated Budget: ₹15 Cr
Research & Development: ₹10 Cr
Pilot Manufacturing: ₹5 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence			✓	
Market			✓	
Technology				✓

13. Priority: Moderate

14. Administrative Mechanism

This project is deliverable to TRL-6, hence research institutions and laboratories will participate in developing technologies with support and feedback from industries. This project has been assigned moderate priority due to established sealing techniques but it is important as it acknowledges the potential for improvement in terms of preventing leaks and ensuring long-term safety and efficiency. An estimated budget of ₹10 crores is assigned for research & development and ₹5 Cr is allotted to pilot manufacturing.

A.3.6.2 Manufacturing process

Manufacturing Balance of Plant components for fuel cell electric vehicles presents several challenges. Ensuring consistent quality and performance of critical components like hydrogen tanks, pumps, and thermal management systems is essential to maintain vehicle safety and efficiency. Scaling up production needs significant investment in specialized manufacturing facilities and skilled labour. The supply chain for vital components, such as electrolysers and fuel cells, needs to be robust and reliable to avoid production bottlenecks. Overcoming these challenges is essential for the widespread adoption of FCEVs.

Proposed Research Project- A.5

Design and Development of Components Deployed in Balance of Plant

1. **Gap Analysis & Background**
   The efficient operation of FCEVs relies on the Balance of Plant. This project aims to advance the state of FCEV technology by focusing on the improvement and innovation of critical BoP components. These components play a critical role in the overall efficiency, performance, and durability of FCEVs. Currently, besides fuel cell stacks which are imported, manufacturers are also buying complete packages along with BoP. Hence, there is a requirement to work analogously on the design and development of components used in BoP.

2. **Global Benchmarking**
   A concerted effort is taken worldwide by various countries and multinational companies for development of fuel cell system. Research targeting indicative efficiency of the vehicle is being conducted which is currently between 50-60%. Various Indian companies have been working on innovative technologies and processes for development of components in BoP. Testing equipment are available for determination of performance curves of compressors and membrane humidifiers, simulation of intake air and ambient temperature, etc.

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-7

4. **Research Goal**
   To advance the performance, efficiency, and affordability of FCEVs by designing and developing innovative components for their Balance of Plant.

5. **Technology Targets**
   a. Achieve a minimum of 10% increase in the overall energy conversion efficiency of FCEVs through development of improved BoP components
   b. Increase the mean time between failures of critical BoP components to ensure long-term durability
   c. Attain a reduction in size and weight of the BoP components to enhance fuel efficiency and performance
   d. The supply chain for the material must be sourced entirely from India

6. **Methodology**
   a. Conduct a comprehensive review of existing FCEV BoP components and technologies to identify areas for improvement
   b. Define specific performance, efficiency, safety, and cost requirements for the new components
   c. Generate innovative design concepts for each targeted component
   d. Use computer-aided design and simulation tools to assess feasibility and performance of proposed designs
   e. Build functional prototypes for lab testing as well as testing in real-world conditions
   f. Assess the performance of prototypes in terms of efficiency, durability, and safety
   g. Continuously iterate the designs based on test results until the components meet or exceed defined requirements
   h. Test the compatibility and integration of new components with existing FCEV BoP systems to verify seamless operation

i. The transition from prototyping to full-scale production of improved components

7. Deliverables

a. Detailed design specifications including schematics, dimensions, and materials
b. Functional prototypes of improved components
c. Testing and performance reports
d. Bill of Materials (BOM) and cost analysis reports
e. Integration documentation
f. Diversification plan
g. Manufacturing guidelines for production
h. Target compliance report

8. Impact

a. Improved components will lead to more efficient energy conversion in FCEVs
b. Lower manufacturing costs and increased durability can make FCEVs more cost-competitive

9. Indicative list of Execution Agencies:

a. National Institute of Technology, Rourkela (NITR)
b. CSIR- National Environmental Engineering Research Institute (NEERI)
c. Ministry of New and Renewable Energy (MNRE)/National Green Hydrogen Mission
d. Indian Institute of Technology, Hyderabad (IITH)
e. Jawaharlal Nehru Center for Advanced Scientific Research, Jakkur, Bangalore
f. Indian Institute of Science, Bangalore
g. The Automotive Research Association of India (ARAI), Pune
h. Indian Institute of Technology, Kharagpur (IITK)
i. Indian Institute of Technology, Delhi (IITD)
j. Larsen & Toubro (L&T)
k. Bharat Heavy Electricals Ltd.
l. Thermax Ltd.
m. Siemens Ltd.

10. Timelines: 18-24 months

11. Estimated Budget: ₹25 Cr
Research & development: ₹15 Cr
Pilot manufacturing: ₹10 Cr

12. Risks:

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization				✓
Obsolescence			✓	
Market			✓	
Technology				✓

13. Priority: High

14. Administrative Mechanism:
This project is deliverable to TRL-7, hence research institutions and laboratories will participate in developing technologies while industry will play a supporting role. This project is given a high priority, in order to initiate design, development and manufacturing of BOP components in India and reduce/terminate the dependency on imports. It will also result in significant cost-reduction of FCEVs in India. The estimated budget of ₹15 Cr is assigned for research & development and ₹10 Cr is assigned for pilto manufacturing.

A.3.7 Hydrogen-fueled linear generators

A.3.7.1 Current Status & Challenges

Hydrogen-fueled linear generators are an active research and development topic, driven by the clean energy focus and the versatility of hydrogen as a fuel. The technology involves converting linear motion directly into electrical power and is being explored for diverse applications including backup power. Ongoing efforts are directed at optimizing efficiency, integrating with the evolving hydrogen infrastructure and hydrogen storage and transportation. Challenges in the development include efficiency optimization, material compatibility and cost effectiveness. Overcoming these challenges demands researchers and industry players to advance technology, establish robust infrastructure and navigate regulatory complexities for the successful implementation of hydrogen-fueled power generation.

A.3.7.2 Different types of linear generators

Currently, there are various types of hydrogen fueled linear generators in different stages of development and exploration. These include hydrogen fuel cells, hydrogen internal combustion engines, hydrogen piston linear generators, Stirling engines and pneumatic linear generators. Challenges across different types of hydrogen fueled linear generators include addressing efficiency and emissions in hydrogen fuel cells, combustion efficiency and component durability in hydrogen internal combustion engines, optimizing piston motion in hydrogen piston linear generators, enhancing thermal efficiency and material compatibility in sterling engines, managing combustion stability and reliability in free piston linear generators, optimizing thermoacoustic engine efficiency in linear free-piston Stirling engines. Some of the common challenges include hydrogen storage and infrastructure development, safety considerations and regulatory compliance. Ongoing research and development aim to optimize their performance, efficiency and scalability for various applications.

A.3.7.3 Potential of Linear Generators in Electric Vehicles

There has been ongoing research into linear generators as potential range extenders or auxiliary power units in electric vehicles. Linear generators offer the advantage of converting linear motion directly into electrical power. These generators in EVs could be used for range extension by converting mechanical energy from motion into electrical energy to charge the battery. Some prototype demonstrations and experimental vehicles have incorporated linear generators to harness energy during vehicle motion, particularly utilizing vibrations or oscillations. The ongoing research is focused on achieving high efficiency, designing compact and durable generators, managing vibrations for consistent power, ensuring cost effectiveness and integrating into EV architecture.

A.3.7.4 Manufacturing process

The current state of hydrogen-fueled linear generator manufacturing demonstrates progress in clean energy solutions but faces significant challenges. Manufacturers are actively researching and developing these generators for various applications, including power generation and transportation. However, challenges such as material selection, manufacturing complexity, limited hydrogen infrastructure, efficiency optimization, high cost, and regulatory compliance persist. Addressing these challenges necessitates collaborative efforts and innovation across material science, manufacturing processes, and hydrogen infrastructure development to unlock the full potential of hydrogen-fueled linear generators as clean and sustainable energy solutions.

A.3.8 Communication Protocols for H2 Filling Station

A.3.8.1 Current Status & Challenges

The Society of Automotive Engineers (SAE) developed fuelling protocol J2601 for light-duty HFCEVs to ensure safe vehicle fills while maximizing fuelling performance. Both the fuelling methods provide fast fuelling of HFCEVs within minutes, but the MC formula method takes advantage of active measurement of precooling temperature to dynamically control the fuelling process and thereby provide faster vehicle fills. According to SAE J2799, the station fuelling nozzle may contain a communications receiver and the vehicle may contain a communications transmitter. The vehicle Insurance Regulatory and Development Authority (IrDA) communications system may use the SAE J2799 protocol to transmit the measured temperature and pressure of the compressed hydrogen storage system on the vehicle to the hydrogen dispenser.

A.3.8.3 Design of Communication System for H2 Filling Station

Designing a communication system for an H2 filling station involves various considerations to ensure efficient operation, safety, and reliability. Understanding the layout and components of the station, including storage tanks, dispensers, compressors, safety sensors, and control systems, is essential. Internal communication between these components is crucial for monitoring and control. External communication with control centres, emergency services, and customers may also be necessary for payment processing and status updates. For communication within the station, wired options like Ethernet or fibre-optic cables provide reliable, high-speed connections. Wireless technologies such as Wi-Fi, cellular networks, or DSRC are suitable for mobile components or remote monitoring.

Safety standards and protocols must be met to prevent accidents and ensure safe operation. Integration with control systems enables real-time monitoring and control, while remote access allows operators to monitor performance and address faults from a central location. Secure access controls and encryption protect against unauthorized access and cyber threats. For customer interaction, communication interfaces like touch screens or mobile apps facilitate filling initiation, payments, and status updates. Emergency response communication channels enable quick reactions to incidents such as leaks or fires. Establishing protocols for troubleshooting ensures prompt resolution of communication issues to minimize downtime.

Proposed Research Project – A.6

Research on Communication Protocols for H2 Filling Station

1. **Gap Analysis & Background**

   Fuel Cell Electric Vehicles (FCEVs) rely on hydrogen gas as their fuel, undergoing a reaction with oxygen from the air within a fuel cell to generate electricity, with water vapor as the sole emission. This technology presents numerous benefits, such as zero tailpipe emissions, extended driving ranges, and quicker refuelling times in comparison to battery electric vehicles. The widespread use of Fuel Cell Electric Vehicles (FCEV) relies on a dependable hydrogen fuelling infrastructure. Hydrogen filling stations are central to this infrastructure, offering FCEV owners a safe and convenient refuelling option. However, designing and operating these stations pose technical hurdles, particularly regarding communication protocols. This project proposes communication protocols to enhance safety, efficiency, and fuelling time.

2. **Global Benchmarking**

   Typical approaches for fuelling vehicles with gaseous hydrogen operate under safety standards set by SAE International, for example, SAE J2601 (Fuelling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles) and SAE J2799. The fuelling process of hydrogen is not much different than gasoline. But as hydrogen is supplied at high pressure and is extremely volatile, a connection between vehicle receptacle and pump must be watertight. The hydrogen is dispensed through a nozzle controlled by a valve which regulates the flow rate of gas at required pressure. There is no electronic intervention in the refuelling process and the time required to refuel is more than in conventional gasoline fuelling stations. Some of the market leaders in hydrogen fuel stations are Linde, Nel, and Air Liquide which are constantly working on providing the best infrastructure and hassle-free hydrogen refuelling experience. [88]

3. **TRL Level:** Starting with TRL-2, deliverable to TRL-5

4. **Research Goal**
To research and design a communication protocol tailored specifically for hydrogen (H2) filling stations, with the objective of optimizing operational efficiency, ensuring safety, and promoting seamless integration with existing and future hydrogen fuelling infrastructure for FCEVs.

5. **Targets for Project**
   a. Create protocols facilitating rapid and dependable data exchange between FCEVs and hydrogen filling stations, ensuring effective communication
   b. Incorporate sensors and monitoring systems into the communication protocol for real-time tracking of fuelling metrics like pressure, temperature, and flow rate
   c. Develop communication protocols with inherent fault tolerance mechanisms and redundancy features to minimize disruptions caused by communication errors or equipment failures
   d. Establish standards to encourage interoperability among diverse FCEV models and hydrogen filling station setups, fostering seamless communication and compatibility throughout the hydrogen fuelling infrastructure

6. **Methodology**
   a. Perform an in-depth analysis of the communication needs between FCEVs and hydrogen filling stations, identifying the essential parameters to be exchanged.
   b. Review existing communication protocols and standards relevant to hydrogen fuelling
   c. Based on the requirement analysis, develop a specialized wireless communication protocol for hydrogen filling stations, outlining message formats, data exchange methods, error management protocols, and security measures.
   d. Create a prototype of the new communication protocol, potentially requiring software development for both FCEV and filling station equipment to showcase the protocol's feasibility and functionality.
   e. Perform thorough testing and validation of the prototype communication protocol in both simulated and real-world environment
   f. Document the new communication protocol, including specifications, implementation guidelines, and best practices

7. **Deliverables**
   a. Detailed design and specification
   b. Target compliance report
   c. Functional Prototype
   d. Guideline for integration

8. **Impact**
   a. Developing new protocols will encourage technological innovation within the industry, driving progress and advancements in hydrogen fuelling infrastructure and technology.

9. **Recommended Execution Agencies**
   a. Indian Institute of Technology, Madras
   b. Indian Institute of Science, Bangalore
   c. Ministry of New and Renewable Energy (MNRE)/National Green Hydrogen Mission
   d. Indian Institute of Technology, Roorkee (IITR)
   e. Indian Institute of Technology, Bombay

10. **Timelines:** 24 Months

11. **Budget**: ₹15 Cr
    Research & Development: ₹10 Cr
    Pilot Manufacturing: ₹5 Cr

12. **Risks:**

Risk Type	NIL Risk	Low Risk	Medium Risk	High Risk
Industrialization			✓	
Obsolescence		✓		
Market			✓	
Technology			✓	

13. **Priority:** High

14. **Administrative Mechanism**
    This project is deliverable to TRL-5, hence research institutions and laboratories will lead in developing technologies while industry will play a supporting role. This project is given a high priority, in order to initiate the design and development of communication protocols which will result in convenient communication with various vehicles. The estimated budget of ₹10 Cr is assigned for research & development and ₹5 Cr is allotted to pilot manufacturing.

A.3.8.4 Design of Communication System for H2-based Vehicles

Developing a communication system for H2-based vehicles entails several critical factors to ensure operational efficiency, safety, and dependability. Primarily, it involves establishing seamless communication between H2 vehicles and various infrastructure components like filling stations, traffic signals, and roadside units, enabling real-time access to essential information such as refuelling options and traffic conditions. Additionally, facilitating communication among H2 vehicles themselves enhances safety through V2V communication, enabling timely warnings about hazards and coordinated manoeuvres. Telematics systems play a crucial role by remotely monitoring vehicle performance, including fuel levels and diagnostics, which aids in predictive maintenance and fleet optimization. Integrating communication capabilities with onboard navigation systems offers drivers route guidance to nearby refuelling stations and real-time traffic updates. Moreover, enabling H2 vehicles to send distress signals during emergencies ensures prompt assistance, while remote diagnostics allow technicians to address vehicle issues remotely, minimizing downtime and repair costs. User-friendly communication interfaces, like smartphone apps or in-car displays, empower drivers to monitor vehicle status, schedule maintenance, and access remote services, enhancing overall user experience and vehicle management efficiency.

A.3.8.5 Adoption process

The adoption process for communication protocols in H2 filling stations follows a structured approach to ensure smooth integration and efficient operation. It starts with assessing the station's communication needs, considering factors like dispenser quantity and integration with external systems. Extensive research is then done to select a suitable protocol based on reliability, scalability, and compatibility. Pilot testing in a controlled environment allows for problem/defect identification and system fine-tuning. A detailed integration plan must be developed for seamless integration with existing infrastructure. Staff undergo thorough training to understand protocol features and troubleshooting. Rigorous testing ensures functionality, reliability, and security compliance post-implementation. Continuous monitoring ensures alignment with emerging technologies and standards, allowing for ongoing optimization.

Annexure B: Details of Panel Members and Contributors

CGeM ADVISORY COMMITTEE

SN	Name, Designation, and Organisation	Role
1	Prof. Ajay K. Sood, Principal Scientific Adviser, Government of India	Chairman
2	Dr. Parvinder Maini, Scientific Secretary, Office of PSA	Member
3	Prof. Karthick Athmanathan, Honorary PSA Fellow and Professor of Practice, Indian Institute of Technology (IIT), Madras	Member
4	Dr. Preeti Banzal, Adviser/Scientist 'G', Office of PSA	Member-Secretary

CGeM WORKING COMMITTEE

SN	Name, Designation, and Organisation	Role
1	Dr. Preeti Banzal, Adviser/Scientist 'G', Office of PSA	Chair
2	Prof. Karthick Athmanathan, Honorary PSA Fellow and Professor of Practice, Indian Institute of Technology (IIT), Madras	Vice-Chair
3	Sh. Suresh Kumar Kunhikannan, Scientist 'F' (Retd.)	Member
4	Sh. S. A. Sundaresan, Vice President (EV and eMobility Solutions), M/s. Ashok Leyland Ltd.	Member
5	Dr. Jabez Dhinagar, Senior Vice President–Vehicle, OLA Electric Technologies Pvt. Ltd.	Member
6	Prof. C. S. Shankar Ram, V. Ramamurti Faculty Fellow, Indian Institute of Technology (IIT), Madras	Member
7	Prof. Sagar Mitra, Department of Energy Science and Engineering, Indian Institute of Technology (IIT), Bombay	Co-opted Member
8	Prof. R. V. Ravi Krishna, Department of Mechanical Engineering, Indian Institute of Science (IISc), Bangalore	Co-opted Member
9	Dr. Kaushal Kumar Jha, Centre for Battery Engineering and Electric Vehicles (C-BEEV)	Co-opted Member
10	Prof. Kannan L, Centre for Battery Engineering and Electric Vehicles (C-BEEV)	Co-opted Member

11	Dr. Malobika Karanjai, Scientist' F', International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI)	Co-opted Member
12	Dr. K. Balasubramanian, Director, Nonferrous Materials Technology Development Centre (NFTDC)	Co-opted Member
13	Sh. Abhijit B. Mulay, Deputy Director, Automotive Research Association of India (ARAI)	Member- Secretary
14	Dr. Sneha Malhotra, Chief Technology Officer, Office of PSA	Co-opted Member
15	Sh. Shubham Agrawal	Member – Convener

PROJECT MANAGEMENT ASSISTANCE UNIT (ARAI)

SN	Name, Designation, and Organisation
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Annexure C: Budget Distribution for R&D and Pilot Manufacturing

Buckets & Topics		Range of Technology Readiness Level- Start TRL to End TRL	Budget for R&D (INR Crores (Cr))	Budget for Pilot Manufacturing (INR Crores (Cr))	Total Estimated Cost (INR Crores (Cr))
Energy Storage Cells	Semi-Solid Electrolytes for Lithium-ion Batteries	2 to 8	20	5	25
	Research on Advanced Liquid Electrolytes for Lithium-ion Batteries	2 to 5	2	1	3
	Solid-State Electrolytes for High Energy Lithium-ion Batteries	2 to 8	40	10	50
	New Paradigm Separators for Lithium-ion Batteries	2 to 5	20	10	30
	Highly Accelerated Testing of Cells	2 to 6	5	15	20
	AI Enabled Cell Chemistry Discovery System	2 to 5	10	-	10
	Innovation of Lithium-Sulfur Battery Technology	2 to 4	40	20	60
	Surface Engineering and Material Synthesis of Anode Materials via Dry Coating for Enhanced Energy Storage in Sodium Ion Batteries	2 to 5	15	5	20
	Optimizing Cathode and Anode Electrolyte Interfaces for Enhanced Performance in Sodium-Ion Batteries	2 to 7	6	2	8
	Design and Development of Manufacturing Line and Equipment for Next Generation Battery Chemistries	2 to 5	20	80	100
	Innovation of Solid-State Electrolytes for High Energy Sodium-ion Batteries	1 to 5	20	10	30
	Research on Aluminium-ion Battery Technology	2 to 5	30	10	40
	Novel Fire Suppressant Materials for High Energy Lithium-ion Batteries	2 to 5	8	2	10
	Innovation of Novel Battery Cell Form Factors for Electric Vehicles	1 to 5	22	8	30
EV Aggregates	Replacement of Copper with Alternative Material or its alloy for Winding of Electric Motor	2 to 5	10	5	15
	Research on Non-Rare Earth Material of Permanent Magnet	2 to 5	5	1	6
	Research on Toolchain and Equipment for Manufacturing of Power Semiconductor (MOSFET, IGBT, SiC etc.) in India	2 to 6	100	150	250
	Nucleation and Growth Mechanisms in Semiconductor Material Synthesis and Manufacturability	NA	0.5	-	0.5

	Design and Development of a High-Voltage DC Inverter (more than 800V) with Advanced Power Electronics and Control Technologies	3 to 8	1.5	3.5	5
	High-Yield Manufacturing Process for GaN WBG Semiconductor	2 to 5	90	60	150
	Novel Thermal Management System for Battery Pack	2 to 5	10	5	15
	India-Centric identification of Phase Change Material for Thermal Management System	2 to 5	25	5	30
	Enhancing Efficiency in High-Speed Electric Vehicle Propulsion Systems through Motor Control Optimization	2 to 5	2	0.5	2.5
Materials & Recycling	Research on Competitive Manufacturing Methods of Graphene	2 to 5	80	20	100
	Research on Novel Material Composition for Battery pack Casing	3 to 5	8	2	10
	Research Novel Recycling Processes other than Hydro/Pyro Metallurgy Processes	1 to 5	25	15	40
	Development of Battery Aadhaar System	2 to 5	0.6	0.2	0.8
	Standardizing Hardware and Software Integration for Second Life Applications of EV Battery	2 to 5	0.6	0.25	0.85
	Magnet Reuse and Recycling and its Impact on Developing Magnets for New Applications	2 to 5	15	5	20
Charging & Refuelling	Research on High Power Density Static Wireless Charging System	2 to 5	10	10	20
	Research on Far-Field Wireless Power Transfer System	1 to 5	5	5	10
	Research on Dynamic Wireless Charging System	2 to 5	10	10	20
	Research on Adaptive Charging Techniques	2 to 5	7	3	10
	Research on wireless communication protocols for EV	2 to 5	6	4	10
Total Budget (in INR Cr)			**669.200**	**482.450**	**1151.650**

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