IMPACT ASSESSMENT REPORT

BATTERY ENGINEERING RESEARCH LAB

IMPLEMENTING PARTNER: IIT MADRAS

SoulAce
Path to Sustainability

SOULACE CONSULTING PVT. LTD.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

PROJECT OVERVIEW

The IITM–INDUS Battery Engineering Research Lab is a Corporate Social Responsibility (CSR) initiative undertaken jointly by Indus Towers Limited and the Indian Institute of Technology Madras (IIT Madras), formalised through a CSR Agreement executed on 5th January 2023.

The project is titled 'Research & Development for Battery Management System (BMS)' and carries a total CSR contribution of INR 1,20,00,000/- (Rupees One Crore and Twenty Lakhs) for the period November 2022 to March 2024.

The initiative centres on the establishment of a state-of-the-art Battery Engineering Research Laboratory at the Department of Engineering Design, IIT Madras, dedicated to advanced research in electrochemical thermal modelling, thermal analysis, and performance evaluation of cylindrical Lithium-Ion (Li-ion) battery packs.

Research was conducted progressively across four quarters, covering single-cell modelling, multi-chemistry comparative analysis (LCO, NMC, LFP, LMO), Battery Thermal Management (BTM) system design using air-cooling techniques, experimental validation, and the design of a large-format 36P16S battery pack.
All simulations were executed using COMSOL Multiphysics 6.0, employing Newman's Pseudo-2-Dimensional (P2D) model, with twelve cylindrical 21700 Li-ion cells configured in a 6-series/2-parallel (6s2p) arrangement as the baseline pack architecture.

The project also delivered significant human capital outcomes — training M.Tech and B.Tech researchers in battery pack engineering, power management, and thermal management, disciplines that are critically short of skilled professionals in India.

Two academic publications were produced under the project: a conference paper that received the Best Paper Award at ICSPER 2024 (NIT Warangal), and a journal manuscript under review in IEEE Access, affirming the quality and relevance of the research.

The lab is designed to be self-sustaining beyond the CSR funding period, with capacity for research grants, industry-sponsored projects, and professional training programmes, ensuring a long-term multiplier effect on India's battery engineering ecosystem.

PROJECT SNAPSHOT

INR 1.20 Cr CSR Contribution	**16 Months** Project Duration	**4** Battery Chemistries Studied	**7** C-Rate Levels Evaluated
11 Types Battery Analyses Conducted	**2** Academic Publications	**1 Best Paper** Awards Received	**2 Major Units** Equipment Commissioned

Project Title
Research & Development for Battery Management System (BMS)

Simulation Software
COMSOL Multiphysics 6.0 (P2D Electrochemical-Thermal Model)

Implementing Institution
Indian Institute of Technology Madras, Chennai

Battery Configuration
6s2p (12-cell) cylindrical 21700 / 32700 Li-ion packs

Implementing Department
Department of Engineering Design, IIT Madras

Key Equipment
Battery Cycle Tester (100V/100A) + Instron Servo Hydraulic UTM

Project Period
November 2022 – March 2024

Conference Recognition
Best Paper Award — ICSPER 2024, NIT Warangal

Donor
Indus Towers Limited, Gurugram

KEY FINDINGS

NMC Chemistry Delivers Superior Electrochemical Performance

Among the four chemistries tested (LCO, NMC, LFP, LMO), NMC achieved 100% State-of-Charge utilisation at 0.8C–4C rates and the highest battery capacity usage of 8 Ah, consistently operating within safe voltage limits (charging: 4.2V, discharging: 2.2V).

NMC Achieves Best Thermal Performance with Air Cooling

The NMC battery pack demonstrated the most effective heat dissipation — generating 102.5W at 4C rate while maintaining minimum heat accumulation of just 0.0128W. Operating temperature was confined to 21.3˚C–32.8˚C, well within safety thresholds.

LCO Chemistry Offers the Longest Service Life

LCO recorded the longest battery life span of approximately 7.9 years with 2,160 charge-discharge cycles and the lowest capacity fade of 75%, making it the optimal chemistry for applications where longevity and predictable degradation are paramount.

LFP Provides the Best Safety and Stability Profile

LFP chemistry demonstrated the most uniform temperature distribution, lowest thermal runaway risk, and a strong 1,966-cycle life (~6.8 years). Experimental results confirmed simulation accuracy to within 5.6% for SOC and 9.69% for thermal analysis.

Capacity Fade Is the Primary Degradation Mechanism

Capacity fade analysis across all chemistries revealed that cycling stress is the primary driver of degradation, with NMC recording an 80% fade at end-of-life. This finding provides actionable guidance for cycle management and depth-of-discharge optimisation strategies.

Higher C-Rates Substantially Increase Heat Generation

Heat generation was found to scale sharply with C-rate. At 4C, NMC generated 102.5W; at 0.5C, this drops to 0.5W. The 1C rate was identified as the optimal operating condition for LFP modules, balancing performance with minimal heat generation and losses.

Active Air Cooling Is Validated as an Effective BTM Strategy

The air-cooled Battery Thermal Management (BTM) system designed for the 6s2p pack configuration successfully maintained safe operating temperatures across all C-rates and chemistries. Air cooling was found to be simpler, more cost-effective, and sufficient for maintaining pack safety in the studied configurations.

P2D Electrochemical Model Validated Against Experimental Data

The Pseudo-2-Dimensional (P2D) model implemented in COMSOL Multiphysics 6.0 was experimentally verified for LFP chemistry at 0.04C, 1C, and 2C rates. Simulation results matched experimental values with a maximum error of 5.6% (SOC) and 9.69% (thermal), confirming model accuracy.

18P4S LFP Module (72 Cells) Designed and Thermally Characterised

A module-level LFP battery pack with 72 cells in an 18P4S configuration was designed and analysed at 1C and 2C rates. At 1C, the module reached a maximum temperature of 54.1°C; at 2C, this rose to 92.1°C, underscoring the need for active cooling in high-rate discharge scenarios.

36P16S Large-Format Pack Design Initiated for Power Backup Application

Design of a full-scale 36P16S cylindrical LFP battery pack — suitable for power backup in critical infrastructure — was initiated in the final quarter. This represents a significant step toward a deployable, domestically engineered battery solution tailored to India's operational conditions.

KEY IMPACT

World-Class Battery Research Laboratory Established in India

A dedicated, state-of-the-art Battery Engineering Research Laboratory has been created at IIT Madras — one of the first of its kind in India. The lab is equipped with a Battery Cycle Tester (100V/100A, 20kW), an Instron Servo Hydraulic UTM, and COMSOL Multiphysics 6.0, providing end-to-end capability for battery simulation, characterisation, and material testing.

Internationally Recognised Academic Output Generated

The project produced two publications: a Best Paper Award-winning conference paper at ICSPER 2024 (NIT Warangal) and a manuscript under review in IEEE Access. These outputs place IIT Madras on the map as a peer-recognised contributor to global battery engineering research.

Skilled Battery Engineers Trained for India's Clean Energy Sector

M.Tech and B.Tech researchers were trained in highly specialised competencies — P2D modelling, electrochemical thermal simulation, SOC/SOH estimation, battery cycling and material testing — that are directly aligned with the workforce demands of India's electric mobility and energy storage industries.

Indigenous Battery Pack Design Capability Demonstrated

The design of a 36P16S large-format cylindrical battery pack represents a concrete step toward an entirely indigenously engineered battery solution for power-critical applications. This capability supports India's Make in India and Atmanirbhar Bharat goals in the clean energy domain.

National Knowledge Base for Battery Safety and Thermal Management Created

A dedicated, state-of-the-art Battery Engineering Research Laboratory has been created at IIT Madras – one of the first of its kind in India. The lab is equipped with a Battery Cycle Tester (100V/100A, 20kW), an Instron Servo Hydraulic UTM, and COMSOL Multiphysics 6.0, providing end-to-end capability for battery simulation, characterisation, and material testing.

A Self-Sustaining Centre of Excellence Established for Long-Term Impact

The IITM–INDUS Battery Engineering Research Lab has been established with the infrastructure, institutional knowledge, research portfolio, and academic credibility to attract future competitive research grants, industry-sponsored projects, and professional training programmes. The CSR-funded phase has seeded a permanent centre of excellence whose impact will compound well beyond the project period.

01 INTRODUCTION

PROJECT OVERVIEW

This report presents the progress and outcomes of a Corporate Social Responsibility (CSR) initiative jointly undertaken by Indus Towers Limited and the Indian Institute of Technology Madras (IIT Madras). The project, titled “Research & Development for Battery Substitute – Battery Management System (BMS),” was formalised through a CSR Agreement executed on 5th January 2023, with a total contribution of INR 1,20,00,000/- (Rupees One Crore and Twenty Lakhs only) for the period November 2022 to March 2024.

The project centres on establishing a state-of-the-art Battery Engineering Research Laboratory at the Department of Engineering Design, IIT Madras – the IITM–INDUS Battery Engineering Research Lab. This facility is designed to conduct advanced research in electrochemical thermal modelling, thermal analysis, and performance evaluation of cylindrical Lithium-Ion (Li-ion) battery packs for various applications.

ABOUT THE DONOR – INDUS TOWERS LIMITED

Indus Towers Limited (formerly known as Bharti Infratel Limited) is one of India’s largest telecommunications infrastructure companies. Incorporated under the Companies Act, 1956 (CIN: L64201HR2006PLC073821), the company is registered as a Category-1 Infrastructure Provider (IP-1) by the Department of Telecommunications (DoT), Ministry of Communications & IT, Government of India.

The company is engaged in the establishment, operation, maintenance, and provisioning of passive telecommunication infrastructure – including towers – for use by mobile telecom operators who are Licensees under Section 4 of the Indian Telegraph Act. Its registered office is located at 4th Floor, Tower A, Building No. 10, DLF Cyber City, Gurugram-122002, Haryana.

Indus Towers has a strong tradition of corporate social responsibility. As a socially responsible entity, it has consistently benefited socially and economically disadvantaged communities through targeted CSR initiatives, in consonance with Section 135 of the Companies Act, 2013, and the Companies (Corporate Social Responsibility) Rules, 2014. Its CSR investment in the IIT Madras Battery Engineering Research Lab reflects its commitment to advancing clean energy, strengthening India’s infrastructure ecosystem, and contributing to national capacity building in technology and engineering.

ABOUT INDIAN INSTITUTE OF TECHNOLOGY MADRAS

The Indian Institute of Technology Madras (IIT Madras) is a premier academic and research institution constituted by the Government of India under the Institutes of Technology Act, 1961. Located in Chennai, Tamil Nadu, the Institute has consistently been ranked among the top engineering institutions in the country. Its administrative office for industry partnerships is situated at the Alumni & Corporate Relations Office, Centre for Industrial Consultancy and Sponsored Research (IC&SR), IIT Madras, Chennai – 600 036.

IIT Madras is a recognised implementation agency for undertaking CSR projects, as notified by the Ministry of Corporate Affairs (MCA) gazette notification, 2019. The Department of Engineering Design at IIT Madras – the implementing department for this project – has expertise in product design, energy systems, and advanced manufacturing. The department has been at the forefront of research on battery thermal management, electrochemical modelling, and battery pack design for diverse applications including electric vehicles and stationary energy storage.

As the beneficiary and implementing institution, IIT Madras is responsible for the scientific execution of the project, utilisation of CSR funds in accordance with the agreed terms, submission of quarterly and annual utilisation certificates, and ensuring that the lab becomes a self-sustaining facility for research, teaching, and industry upskilling.

PROJECT OBJECTIVES

The IITM–INDUS Battery Engineering Research Lab has been established with the following core objectives:

- Develop and validate electrochemical thermal models for cylindrical Lithium-Ion battery packs (LCO, NMC, LFP, LMO chemistries) to accurately simulate heat generation during charge and discharge cycles under varying C-rates.
- Conduct thermal analysis and performance evaluation of battery packs designed specifically for replicating real-world service conditions.
- Design and demonstrate efficient Battery Thermal Management (BTM) systems to ensure safe operating temperatures, prevent thermal runaway, and extend battery lifespan.
- Enable State-of-Charge (SOC) and State-of-Health (SOH) estimation and lifetime prediction of battery packs through advanced Battery Management System (BMS) development.
- Develop a domestically engineered, defect-free battery pack tailored to Indian environmental and operational conditions, particularly for communication tower power backup.
- Create a world-class teaching and research laboratory facility for B.Tech and M.Tech students in Battery Pack Engineering, Power Management, and Thermal Management.

Upskill undergraduate and postgraduate students as well as industry professionals, building a skilled technical workforce to meet the growing national demand for Battery Pack Engineering expertise.

Enable the lab to become self-sustaining through research grants, industry-sponsored projects, and training programmes, ensuring long-term impact beyond the CSR funding period.

NEED AND RATIONALE FOR THE PROJECT

THE GLOBAL RISE OF LITHIUM-ION BATTERIES AND THE THERMAL MANAGEMENT CHALLENGE

Lithium-ion (Li-ion) batteries have become the foundational energy storage technology of the twenty-first century. Their superior energy density, long cycle life, and declining cost have driven widespread adoption across a broad spectrum of applications – from consumer electronics and medical devices to electric vehicles (EVs), renewable energy grid storage, and industrial power systems. India, as one of the world's fastest-growing economies, is at the centre of this transition, with national programmes such as the Production Linked Incentive (PLI) scheme for Advanced Chemistry Cells (ACC) and the FAME-II initiative for electric mobility placing battery technology at the heart of the country's clean energy future.

Despite this rapid proliferation, a critical and unresolved challenge persists across all battery applications: heat generation during charge and discharge cycles. Elevated internal temperatures cause irreversible capacity degradation, accelerated ageing of electrode materials, and, under extreme conditions, thermal runaway – a self-reinforcing exothermic reaction that poses serious fire and safety risks. Effective Battery Thermal Management (BTM) and intelligent Battery Management Systems (BMS) are therefore not optional enhancements, but essential prerequisites for the safe, reliable, and long-lived operation of battery packs in any application.

DIVERSE SOCIETAL NEEDS DRIVING THE URGENCY FOR BATTERY RESEARCH

The need for advanced battery research in India extends well beyond any single sector. The following areas represent the breadth of societal demand that makes this research initiative both timely and nationally significant:

- Electric Mobility: India's ambitious EV transition requires indigenously developed, thermally robust battery packs that can withstand the country's high ambient temperatures and diverse road conditions. The safety of EV batteries – particularly in two-wheelers and three-wheelers used by low-income commuters – is a direct public safety concern.

- Renewable Energy Storage: Solar and wind energy are inherently intermittent. Battery-based grid storage systems are essential for stabilising supply, enabling round-the-clock power access to rural and peri-urban communities that have historically been underserved by centralised electricity grids.

- Healthcare and Critical Services: Hospitals, diagnostic centres, and cold-chain logistics for vaccine storage increasingly rely on battery backup systems. Failures in these systems can have life-threatening consequences, underscoring the need for batteries with predictable, well-managed lifespans.

- Consumer Electronics and Low-Power Devices: With digital inclusion expanding to hundreds of millions of new users, battery-powered devices – smartphones, tablets, and wearables – represent a direct quality-of-life interface for citizens across income groups.

- Defence and Strategic Applications: Reliable, high-performance battery systems are increasingly critical in unmanned aerial vehicles (UAVs), portable soldier systems, and remote monitoring equipment used in border and disaster-response contexts.

THE NATIONAL GAP: INFRASTRUCTURE, SKILLS, AND INDIGENOUS CAPABILITY

Notwithstanding the scale of India's battery adoption across these sectors, the country faces a structural deficit in the research and human capital infrastructure needed to support it sustainably. There are presently no widely accessible, dedicated academic laboratory facilities in India for the comprehensive electrochemical and thermal characterisation of battery packs under standardised testing protocols. Research-grade simulation tools for electrochemical modelling – such as pseudo-two-dimensional (P2D) thermal models and multi-chemistry comparative frameworks – remain confined to a very small number of institutions, limiting the pace of indigenous innovation.

Equally critical is the acute shortage of trained engineers who understand battery pack design, State-of-Charge (SOC) and State-of-Health (SOH) estimation, capacity fade analysis, and thermal management at the system level. As India's battery manufacturing sector grows, this skills gap risks becoming a binding constraint on the nation's ability to build a self-reliant, globally competitive battery industry – one that does not depend on imported expertise or foreign-designed solutions that are not calibrated to Indian conditions.

THE CASE FOR A DEDICATED BATTERY ENGINEERING RESEARCH LABORATORY

It is in this context that the establishment of the IITM–INDUS Battery Engineering Research Laboratory at the Department of Engineering Design, IIT Madras, through this CSR initiative, constitutes a targeted and high-impact public good. The lab addresses the national need on two fronts simultaneously: advancing the scientific understanding of Li-ion battery behaviour under realistic and varied operating conditions, and creating a pool of trained graduates and professionals who can take this knowledge into India's emerging battery manufacturing, EV, and energy storage industries.

The CSR contribution channelled through this project is therefore an investment not in any proprietary product or commercial interest, but in a shared national capability – a publicly accessible centre of knowledge, testing infrastructure, and skilled human capital that will serve students, researchers, startups, and industries across the full spectrum of India's battery-dependent economy for years to come.

02. RESEARCH **METHODOLOGY**

This chapter describes the methodological framework adopted for conducting the Impact Assessment of the IITM–INDUS Battery Engineering Research Lab. The assessment has been designed to evaluate the outcomes and impact of the CSR initiative undertaken by Indus Towers Limited in collaboration with IIT Madras, across the dimensions of research, infrastructure, human capital development, and broader societal benefit. The methodology is structured to ensure that the findings of this report are grounded in evidence, triangulated across multiple data sources, and presented with the rigour appropriate to a formal impact assessment.

RESEARCH DESIGN

This Impact Assessment is anchored in a Descriptive Research Design. Descriptive research is concerned with systematically describing the characteristics, outcomes, and impacts of a phenomenon or intervention as they exist, without manipulation of variables. It is the most appropriate design for an impact assessment because it allows for a faithful, evidence-based account of what the project has achieved, how it has been executed, and what changes it has produced in the people, institution, and broader ecosystem it has engaged.

The descriptive approach adopted in this report does not seek to establish experimental causation but rather to document, narrate, and interpret the project's trajectory through the lens of its stated objectives. It draws on multiple sources of evidence — written records, quantitative research data, stakeholder testimony, and direct observation — to construct a comprehensive and credible picture of project impact.

Research Design: Descriptive Research — a systematic, evidence-based approach to documenting and interpreting the outcomes, processes, and impacts of the IITM–INDUS Battery Engineering Research Lab as they exist, drawing on multiple data sources for triangulation.

The choice of descriptive research is further supported by the nature of the subject under assessment. The project combines technical research output, physical infrastructure creation, student training, and academic publication — all of which are most effectively captured through description, documentation, and interpretation rather than through experimental or inferential methodologies.

DATA COLLECTION METHODS

The data for this Impact Assessment were gathered through three complementary methods, each designed to capture a distinct layer of evidence. Together, these methods provide a multi-source, triangulated foundation for the findings and conclusions presented in this report.

Method	Purpose	Scope
Secondary Document Review	Collect and analyse formal project records, research reports, and institutional documents	All four quarterly reports, CSR Agreement (MoU), research publications, equipment records
Key Stakeholder Interviews	Capture experiential insights, perspectives, and qualitative impact from individuals directly involved in the project	1 faculty member (Principal Investigator) and 4 research scholars
Physical Inspection of Facilities	Verify the existence, condition, and operability of the laboratory infrastructure created under the project	IITM–INDUS Battery Engineering Research Lab, Department of Engineering Design, IIT Madras

METHOD 1: SECONDARY DOCUMENT REVIEW

The secondary document review constitutes the primary evidentiary base of this Impact Assessment. It involves the systematic collection, reading, and critical analysis of all formal documents generated under and associated with the project. Document review is a recognised and well-established method in programme evaluation and impact assessment, as it provides access to contemporaneous, unmediated records of project activities, decisions, and outcomes.

Documents Reviewed

The following categories of documents were reviewed as part of this assessment:

CSR Agreement (MoU)

The formal Memorandum of Understanding executed on 5th January 2023 between Indus Towers Limited and IIT Madras, establishing the legal, financial, and operational framework of the project. This document was reviewed to understand the agreed objectives, deliverables, funding structure, timeline, and obligations of both parties.

Quarterly Progress Reports (Q1 to Q4)

Four quarterly technical reports submitted to Indus Towers by the research team at the Department of Engineering Design, IIT Madras, covering the periods November 2022–January 2023, April–June 2023, July–September 2023, and October 2023–March 2024. These reports formed the primary technical evidence base for the research findings documented in Chapter 3.

Annual CSR Report

The consolidated annual report for Financial Year 2023–24, providing a summary-level overview of project progress, expenditure, and cumulative outcomes for the full project period.

Research Publications and Conference Proceedings

Published and under-review academic papers generated as outputs of the project, including the conference paper presented at ICSPER 2024 (NIT Warangal) and the journal manuscript submitted to IEEE Access. These documents provided evidence of the academic quality and peer recognition of the research conducted.

- **Equipment Procurement Records**
  Documentation related to the procurement of major laboratory equipment, including the Battery Cycle Tester (IGBT Regenerative Multi-Channel Pack Tester) and the Instron Servo Hydraulic Universal Testing Machine (UTM), used to verify capital investment and lab infrastructure development.

Analytical Approach

The documents were reviewed using a structured content analysis approach. Key information was extracted under the following thematic categories: project objectives and deliverables, research methodology and simulation parameters, technical findings and results, equipment and infrastructure created, student and researcher engagement, academic outputs, and financial utilisation. Cross-referencing across documents enabled the assessors to verify consistency, identify progression over time, and highlight instances of impact.

Where technical data was present (such as battery performance parameters, temperature values, cycle counts, and capacity fade percentages), these were extracted and tabulated for use in the findings chapter. The document review also provided the basis for designing the questions for stakeholder interviews, ensuring the interview process was informed and targeted.

METHOD 2: KEY STAKEHOLDER INTERVIEWS

Stakeholder interviews were conducted to supplement the documentary evidence with experiential, qualitative insights from those directly involved in the day-to-day execution and outputs of the project. Interviews are a critical method in any impact assessment because they capture dimensions of impact that do not readily appear in written records — including perceptions of learning, changes in institutional culture, personal and professional development, and the researchers' own assessment of the significance of their work.

Interview Design and Format

The interviews were semi-structured in nature. A semi-structured format was chosen because it allows the assessor to pursue a defined set of thematic areas while retaining the flexibility to probe interesting or unexpected responses in depth. This format is particularly well-suited to an academic research context, where respondents are knowledgeable, and their detailed reflections are valuable.

A common interview guide was prepared in advance, covering the following thematic areas:

- Background of the respondent's involvement in the project
- Perceptions of the research environment and laboratory infrastructure created
- Technical learning and competency development experienced through participation.
- Challenges encountered during the research and how they were overcome
- Assessment of the significance and quality of the research findings

- Perspectives on the impact of the project on the Department of Engineering Design and IIT Madras
- Views on the long-term sustainability and future potential of the lab
- Any aspects of impact that the respondent considered particularly noteworthy or underappreciated

All interviews were conducted in person at the Department of Engineering Design, IIT Madras. Responses were recorded through detailed notes taken during the interview and consolidated immediately after each session to ensure accuracy. The confidentiality of individual responses was maintained; findings are reported thematically and attributed collectively rather than to specific individuals.

Stakeholder Selection and Profile

Five stakeholders were selected for interview, representing the two primary groups of individuals involved in the project: the academic leader responsible for the research programme, and the research scholars who conducted the technical work under the project.

Interview Sample: A total of 5 stakeholders were interviewed: 2 Faculty Members (one Principal Investigator) and 3 Research Scholars (PhD research Scholars engaged directly in the project).

The stakeholder profiles are described below:

Respondent	Role	Nature of Involvement
Faculty Member (Principal Investigator)	Senior faculty, Department of Engineering Design, IIT Madras	Academic and scientific leadership of the project; responsible for overall research direction, methodology, reporting, and project management. Has been involved from project inception to completion.
Faculty member 1	Faculty Dept. of Engineering Design	Conducted electrochemical thermal modelling of cylindrical Li-ion battery packs; led the COMSOL Multiphysics simulations for LCO and NMC chemistries in the early project phases.
Research Scholar 1	PhD Research Scholar, Dept. of Engineering Design	Responsible for the extended 4-chemistry (LCO, NMC, LFP, LMO) comparative simulations; worked on SOC, SOH, capacity fade analysis and battery lifecycle estimation.
Research Scholar 2	PhD Research Scholar, Dept. of Engineering Design	Led the design and analysis of the 18P4S LFP battery module; conducted experimental validation of the P2D simulation results using the Battery Cycle Tester.
Research Scholar 3	PhD Research Scholar Dept. of Engineering Design	Focused on the design of the large-format 36P16S battery pack; worked on thermal and SOC simulation of the pack and contributed to the conference paper that received the Best Paper Award at ICSPER 2024.

Key Themes from Interviews

While the detailed findings from the interviews are woven into the impact analysis presented in Chapter 3, the following overarching themes emerged consistently across respondents and are noted here as context for the methodology:

Access to World-Class Facilities

All respondents highlighted the transformative effect of having access to high-quality laboratory infrastructure. Before this lab was established, researchers in the department had limited access to dedicated battery testing and simulation facilities. The availability of the Battery Cycle Tester, UTM, and licensed COMSOL Multiphysics software was described as a significant enabler of the quality and depth of research achieved.

Depth of Technical Learning

Research scholars consistently noted that their engagement with this project equipped them with highly specialised competencies — in P2D electrochemical modelling, thermal simulation, battery characterisation, and SOC/SOH estimation — that are directly aligned with the demands of India's emerging battery manufacturing and electric mobility sectors.

Academic Recognition and Confidence

The Best Paper Award received at ICSPER 2024 was cited by research scholars as a significant milestone that validated the quality of their work and enhanced their confidence as researchers. The journal paper under review in IEEE Access was also seen as a mark of international recognition.

National Relevance of the Research

The faculty member and all research scholars expressed a strong sense of purpose regarding the national relevance of their work. The development of battery management systems and thermal management frameworks suited to Indian environmental conditions was seen as a direct contribution to the country's energy security and clean technology ambitions.

Sustainability of the Lab

Respondents expressed confidence that the lab has been set up on a sustainable footing — with physical infrastructure, institutional knowledge, and a growing research portfolio that can attract future funding from competitive research grants and industry-sponsored projects. The CSR-funded phase was described as a critical 'first stage' in the creation of a long-term centre of excellence.

METHOD 3: PHYSICAL INSPECTION OF FACILITIES

A structured physical inspection of the IITM–INDUS Battery Engineering Research Lab was conducted at the Department of Engineering Design, IIT Madras, as part of the data collection process for this Impact Assessment. Physical inspection is an essential component of any infrastructure-related assessment, as it provides direct, first-hand verification of the existence, condition, operability, and utilisation of assets created under the initiative.

Inspection Objectives

The physical inspection was conducted with the following specific objectives:

- To verify that the laboratory infrastructure funded under the CSR initiative has been established as described in the project documentation.
- To assess the condition, operability, and level of utilisation of key equipment procured under the project.
- To observe the physical space, safety arrangements, and overall research environment created at the lab.
- To supplement and cross-validate information gathered through the document review and stakeholder interviews.

Inspection Coverage

The inspection covered all key elements of the laboratory infrastructure, as listed below:

Inspection Item	What Was Observed	Finding
Battery Cycle Tester (IGBT Regenerative, MPT IGBT 100-100-2)	Physical presence, operational status, setup, and connectivity; battery pack testing functionality	Equipment in place and operational. Capable of performing C-rate testing, life cycle evaluation, capacity assessment, and SOC simulation.
Instron Servo Hydraulic Universal Testing Machine (UTM)	Physical presence, condition, material testing setup; compliance with ASTM test standards	Equipment installed and functional. Used for tensile, compression, and fracture toughness testing of battery materials.
Simulation Workstations (COMSOL Multiphysics 6.0)	Availability of licensed simulation software; computing infrastructure supporting P2D modelling	Licenced software installed and actively used for multi-physics battery simulation. Results verified against experimental data.
Lab Space and Safety Infrastructure	Physical layout, workspace organisation, safety labelling, fire and electrical safety provisions, storage for battery materials	Dedicated lab space established within the Department of Engineering Design. Safety provisions appropriate to the nature of battery testing observed.
Research Documentation and Records	Availability of printed and digital research records, quarterly reports, test data, and simulation output archives	Comprehensive research records maintained by the team. Quarterly reports, simulation datasets, and equipment logs available and organised.

Inspection Outcome

The physical inspection confirmed that the laboratory established under the IITM–INDUS CSR initiative is a functional, well-equipped, and actively utilised research facility. The infrastructure is consistent with what was proposed and reported in the project documentation. The equipment is operational, the research environment is purpose-built for battery engineering, and the safety standards observed are appropriate for the nature of the work conducted.

The inspection also validated the narrative provided by the research team during stakeholder interviews regarding the quality and availability of facilities, lending credibility to the impact claims made in this report.

TRIANGULATION AND QUALITY ASSURANCE

A defining feature of this methodology is the triangulation of evidence across the three data collection methods. Triangulation is the practice of verifying and cross-checking a finding or claim against multiple independent sources, thereby strengthening the reliability and credibility of the assessment. In this report:

Research findings derived from the quarterly reports were cross-validated against the data presented in conference and journal publications, ensuring that the technical claims made in this assessment are peer-reviewed and independently substantiated.

Infrastructure claims documented in the project reports were verified through physical inspection, confirming that the equipment and lab facilities described in writing exist and are functional.

Impact narratives from the document review were tested against stakeholder interview responses, ensuring that the impact described in official reports resonates with and is endorsed by those who experienced it directly.

This triangulated approach ensures that the findings of this Impact Assessment are robust, evidence-based, and not reliant on any single source of data. It also strengthens the report's credibility as a formal evaluation instrument for both internal institutional use and external reporting to the donor.

LIMITATIONS OF THE METHODOLOGY

In the interests of methodological transparency, the following limitations of this assessment are acknowledged:

Self-reported data: A portion of the evidence in this report is drawn from project reports prepared by the implementing team itself. While these reports are detailed and internally consistent, they are not independently audited documents. This limitation is mitigated by the cross-validation provided through stakeholder interviews and physical inspection.

Sample size for interviews: Five interview respondents, while appropriate for a project of this scale and nature, represent a relatively small sample. The views expressed are representative of those directly involved in the project but may not fully reflect the perspectives of all students who have used the lab facility or all industry professionals who could eventually benefit from its outputs.

Point-in-time assessment: This assessment captures impact as it stands at the close of the project period (March 2024). Some of the most significant long-term impacts — such as the influence of trained researchers on industry, the citation impact of publications, and the lab's success in attracting future funding — will only become fully apparent over the coming years and are therefore anticipated rather than measured here.

These limitations are inherent to the nature of a CSR impact assessment conducted at project completion and do not detract from the credibility or usefulness of the findings presented in the subsequent chapters.

METHODOLOGY SUMMARY

Aspect	Aspect
Research Design	Descriptive Research
Data Collection Method 1	Secondary Document Review (CSR MoU, quarterly reports, annual report, publications, equipment records)
Data Collection Method 2	Key Stakeholder Interviews (1 Faculty Member / Principal Investigator + 4 Research Scholars)
Data Collection Method 3	Physical Inspection of the IITM–INDUS Battery Engineering Research Lab, Dept. of Engineering Design, IIT Madras
Interview Format	Semi-structured, in-person, conducted at IIT Madras
Analytical Approach	Structured content analysis; thematic coding of interview responses; verification against physical inspection findings
Quality Assurance	Triangulation across all three data sources
Reporting Period Covered	November 2022 – March 2024 (Full project period)

03 KEY FINDINGS

This chapter presents a consolidated assessment of key research findings and the multidimensional impact generated by the IITM–INDUS Battery Engineering Research Lab during the project period from November 2022 to March 2024. The outcomes are evaluated across four primary dimensions: scientific and technical findings, infrastructure and capacity built, academic and human capital development, and broader societal and national-level impact.

OVERVIEW OF PROJECT EXECUTION

The project was executed in four quarterly phases, each building progressively on the findings of the previous. The research trajectory moved from foundational single-cell electrochemical modelling to comprehensive multi-cell battery pack simulation, culminating in the experimental validation of results and the design of large-format battery packs tailored for real-world power backup applications.

Quarter	Period	Primary Focus	Status
Q1 (Nov 2022–Jan 2023)	Oct 23–Mar 24	Lab establishment, literature review, 1D single-cell modelling	Completed
Q2 (Apr–Jun 2023)	Oct 23–Mar 24	Capacity fade analysis, SOC simulation – LCO & NMC	Completed
Q3 (Jul–Sep 2023)	Oct 23–Mar 24	3D battery pack modelling – LCO, NMC, LFP, LMO; air cooling BTM	Completed
Q4 (Oct 2023–Mar 2024)	Oct 23–Mar 24	LFP module design, experimental validation, large-pack (36P16S) design	Completed

KEY RESEARCH FINDINGS

The research was structured around electrochemical thermal modelling of cylindrical Li-ion battery packs using the Pseudo-2-Dimensional (P2D) model, implemented in COMSOL Multiphysics 6.0 software. The findings reported across all quarters are summarised below.

Electrochemical Thermal Modelling – Foundational Outcomes

In the initial phases, a one-dimensional (1D) electrochemical model of a single cylindrical Li-ion cell was developed and validated. This model formed the computational backbone for all subsequent multi-cell and pack-level simulations. The P2D model was selected for its demonstrated accuracy in simulating both charging and discharging scenarios, as established in prior literature and confirmed through the lab's own baseline studies.

Key parameters modelled included electrode length, particle diameter, electrolyte lithium concentration, volume fraction, reference diffusivity, Bruggeman tortuosity, and electrical conductivity for each of the four cathode chemistries. The separator material used across all configurations was Lithium Hexafluorophosphate (LiPF6), with a graphite negative electrode.

Comparative Chemistry Analysis: LCO, NMC, LFP and LMO

A central research contribution of this project is the systematic comparison of four commercially relevant cathode chemistries — Lithium Cobalt Oxide (LCO), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Iron Phosphate (LFP), and Lithium Manganese Oxide (LMO) — in an air-cooled cylindrical battery pack of twelve 21700 Li-ion cells, configured in a 6-series/2-parallel (6s2p) arrangement.

All simulations were conducted at 0.8C discharge rate, 10 Ah battery cell capacity, and 20˚C ambient temperature, with C-rate sweeps from 0.5C to 4C for comprehensive performance mapping.

Parameter	LOC	NMC	LFP	LMO
Nominal Voltage (V)	3.60	3.70	3.20	3.00
Pack Nominal Voltage (V)	21.6	22.2	19.2	18.0
Total Pack Capacity (Wh)	432	444	384	360
Max SOC (%)	95	100	98	95
Max Capacity Used (Ah)	7.5	8.0	7.8	7.4
Temp. Range (˚C)	21.5–34.2	21.3–32.8	21.0–35.5	21.0–35.5
Capacity Fade (%)	75	80	78	77
No. of Cycles	2160	1133	1966	1522
Battery Life Span (years)	7.9	3.9	6.8	5.2

Finding 1: NMC chemistry demonstrated the highest State-of-Charge utilisation (100%) and the maximum battery capacity usage (8 Ah), consistently operating within safe voltage cut-off limits (charging: 4.2V, discharging: 2.2V) across all tested C-rates.

Finding 2: NMC recorded the most effective heat dissipation performance, generating a maximum heat of 102.5W at 4C rate while maintaining minimum heat accumulation of 0.0128W — superior to all other chemistries tested. Operating temperature was confined to the range of 21.3°C to 32.8°C.

Finding 3: LCO chemistry achieved the longest battery lifespan of approximately 7.9 years with 2,160 charge-discharge cycles and the lowest capacity fade of 75%, making it the preferred chemistry for applications demanding longevity over peak performance.

Finding 4: LFP chemistry offered the best balance between cycle life (1,966 cycles, ~6.8 years) and thermal stability, with the most uniform temperature distribution and lowest risk of thermal runaway. This chemistry is particularly suited for safety-critical power backup applications.

State-of-Charge (SOC) and State-of-Health (SOH) Analysis

SOC and SOH estimations were performed for all four chemistries across multiple C-rates (0.5C, 0.8C, 1C, 2C, 3C, and 4C). The NMC battery pack consistently achieved maximum SOC of 100% under 0.8C, 1C, 2C, 3C, and 4C rates, demonstrating the highest charge retention and most efficient energy utilisation among all chemistries tested.

The SOH analysis, combined with capacity fade modelling, revealed that high cycling stress is the primary driver of capacity degradation in NMC electrodes. Mechanical stress induced by repeated intercalation and de-intercalation of lithium ions causes structural changes and electrode degradation over time. This finding has important implications for battery management strategies, highlighting the need for careful cycle management, temperature control, and depth-of-discharge optimisation.

Heat Generation, Accumulation and Dissipation

Thermal analysis across C-rates confirmed that heat generation increases significantly with higher charge/discharge rates. The maximum heat generation and minimum heat accumulation were consistently observed at 4C rate and 0.5C rate respectively, across all four cathode chemistries.

LCO exhibited the highest heat accumulation of 10.2W — the most thermally problematic of all chemistries examined. By contrast, NMC's air-cooling configuration proved highly effective, with the minimum heat generation at 0.5C and 0.8C being approximately 0.5 W and 6.8 W, respectively, and corresponding heat accumulation values of 0.0005 W and 0.0016 W.

These findings validate the design of the active air-cooling Battery Thermal Management (BTM) system as an effective and cost-efficient solution for maintaining safe battery operating temperatures in the modelled configurations.

Capacity Fade and Battery Lifetime Prediction

Capacity fade analysis was conducted to quantify degradation across the battery lifecycle for all four chemistries. The NMC chemistry recorded the highest capacity fade of 80%, resulting in an effective remaining capacity of just 20% at end of life. LCO demonstrated the lowest capacity fade at 75%.

Despite NMC's higher capacity fade, the research concluded that NMC provides the best overall balance of energy performance, temperature management, and charge retention for high-demand applications. The trade-off between cycle life and performance was clearly quantified, providing actionable design guidance for battery pack engineers.

LFP Single-Cell and Module Validation

In the final quarter, the research extended to experimental validation of LFP battery simulations. A single LFP cell was analysed at three C-rates (0.04C, 1C, and 2C), and the simulation results were verified against experimental data, confirming the accuracy of the P2D model for LFP chemistry.

An 18P4S LFP battery module comprising 72 cells was subsequently designed and analysed. At 1C rate, the module achieved a maximum SOC of 100% with an operating temperature of 54.1°C. At 2C rate, the temperature rose to 92.1°C with an SOC range of 50–100%, underscoring the importance of thermal management at elevated discharge rates. The 1C rate demonstrated significantly lower heat generation and losses compared to the 2C rate, confirming the optimal operating condition for LFP modules in power backup applications.

Design of a large-format 36P16S battery pack was initiated and is underway, representing a major stepping stone toward a deployable, domestically engineered battery solution for power-critical applications.

KEY IMPACT

The impact of the IITM–INDUS Battery Engineering Research Lab is assessed across four dimensions: Infrastructure and Laboratory Impact, Academic and Knowledge Impact, Human Capital and Skill Development Impact, and National and Societal Impact.

Infrastructure and Laboratory Impact

The CSR investment has resulted in the creation of a purpose-built, state-of-the-art Battery Engineering Research Laboratory at the Department of Engineering Design, IIT Madras — one of the first of its kind in India dedicated exclusively to battery pack engineering research, certification, and workforce development.

The laboratory is equipped with advanced instrumentation that enables end-to-end research on battery systems:

Equipment	Purpose	Capability
Battery Cycle Tester (IGBT Regenerative, MPT IGBT 100-100-2)	Mechanical testing of battery materials	Voltage: up to 100V; Current: up to 100A; Power: 20kW; 2-channel; C-rate & life cycle tests
Instron Servo Hydraulic UTM Machine	Mechanical testing of battery materials	Tensile, compressive, fracture toughness; ASTM E8, E399, E1820 standard compliance
Instron Servo Hydraulic UTM Machine	Electrochemical thermal simulation	P2D model for multi-chemistry, multi-cell battery pack simulation
Battery Thermal Test Setup	Thermal characterisation under service conditions	P2D model for multi-chemistry, multi-cell battery pack simulation

This infrastructure positions the lab as a recognised facility capable of undertaking battery pack certification, thermal management evaluation, and advanced research. It directly addresses the critical gap identified at the project's inception: the absence of any dedicated battery pack testing and certification facility in India aligned with internationally recognised thermal management test standards.

Academic and Knowledge Impact

The project has generated significant academic output, establishing IIT Madras as a contributing voice in the global battery engineering research community.

Publication 1 (Conference — Best Paper Award): "Thermal Management and SOC Simulation of Li-Ion Battery for Electric Vehicles", International Conference on Sustainable Power and Energy Research (ICSPER) 2024, NIT Warangal, India, March 2024. Received Best Paper Award.

Publication 2 (Journal — Under Review): "Investigation on Thermal Characteristics and Performance of Cylindrical Lithium-Ion Battery Pack using P2D Model with Varied Electrode Chemistries", IEEE Access (Under Review).

These publications represent the first peer-reviewed academic outputs from a dedicated battery engineering research facility in the Engineering Design department at IIT Madras. The Best Paper Award at ICSPER 2024 is a particularly significant recognition, validating the quality and relevance of the research conducted under this CSR initiative.

The body of knowledge produced through the project covers the full spectrum of battery system analysis: electrochemical modelling, thermal analysis, SOC/SOH estimation, capacity fade prediction, and battery lifetime calculation – collectively forming a comprehensive technical reference for battery pack engineers working on Indian environmental and operational conditions.

Human Capital and Skill Development Impact

One of the most enduring impacts of this initiative is the development of a skilled technical workforce in the highly specialised and strategically important field of Battery Pack Engineering. The lab has served as a teaching and training platform for students across B.Tech and M.Tech programmes at IIT Madras.

Category of Impact	Description	Beneficiaries
M.Tech Research Students	Full-time researchers working on electrochemical modelling, thermal simulation, and experimental validation under the project	Graduate researchers at IIT Madras
B.Tech Students	Undergraduate students trained in battery characterisation, simulation tools, and BMS fundamentals through the lab facility	UG engineering students
Practical Competencies	Training on COMSOL Multiphysics, P2D modelling, SOC/SOH estimation, battery cycling equipment operation, and UTM-based material testing	All lab users
Conference Participation	Research presented at national conference – ICSPER 2024 at NIT Warangal, winning Best Paper Award, providing exposure to national research community	Project research team
Industry-Ready Skillsets	Students trained in domains of Power Management and Thermal Management, directly aligned with the needs of India's growing EV, energy storage, and battery manufacturing sectors	Future industry workforce

The project has directly addressed the acute shortage of trained battery engineers in India, a gap identified as critical to the country's clean energy transition and the growth of domestic battery manufacturing. Students trained through this programme are equipped with practical, industry-aligned competencies that are rare in the current Indian engineering education landscape.

National and Societal Impact

The broader societal and national-level impact of the IITM–INDUS Battery Engineering Research Lab extends well beyond the boundaries of this specific CSR project. The work contributes to several of India's most pressing national priorities.

Clean Energy and Energy Security:

- The research provides an indigenous knowledge base for the design and optimisation of Li-ion battery packs suited to India's environmental conditions — characterised by high ambient temperatures and diverse load profiles.
- The validated electrochemical-thermal models enable Indian engineers and manufacturers to design safer, more efficient battery systems without dependence on expensive foreign expertise or proprietary tools.
- The findings on thermal runaway prevention and BTM system design directly contribute to battery safety standards, an area where India is still developing its regulatory framework.

Indigenisation and Manufacturing Readiness:

- The design of a large-format 36P16S cylindrical battery pack represents a significant step toward demonstrating an entirely domestically engineered battery pack solution, aligned with India's Make in India and Atmanirbhar Bharat initiatives
- The LFP battery pack analysis, validated experimentally, provides a deployment-ready template for power backup in safety-critical infrastructure — a domain of national strategic importance.
- Benchmarking of four cathode chemistries (LCO, NMC, LFP, LMO) under Indian conditions enables OEMs and system integrators to make data-driven chemistry selection decisions for specific applications.

Workforce Development at Scale:

- The laboratory infrastructure created under this project has permanence beyond the funding period. It will continue to train engineers, support research projects, and enable industry collaborations, generating a long-term multiplier effect on India's battery engineering talent pipeline.
- The upskilling capability of the lab — covering both academic coursework and industry training programmes — positions IIT Madras to meet the growing national demand for battery engineers as India scales up its electric mobility and grid storage ambitions.

Academic and Institutional Positioning:

- IIT Madras has been positioned as a national centre of excellence in battery engineering, with demonstrated capability in research, simulation, experimental validation, and publication.

- The institute's recognition as an MCA-notified CSR implementation agency, combined with the demonstrable impact of this initiative, strengthens its credibility for attracting future research grants, industry partnerships, and collaborative projects in the battery engineering domain.

IMPACT SCORECARD

The following scorecard provides a concise, evidence-based summary of the project's overall impact across its primary dimensions.

Impact Dimension	Key Metric	Achievement
Research Output	Journal Paper	1 paper under review in IEEE Access
Research Output	Conference Paper	1 paper presented at ICSPER 2024, NIT Warangal
Research Output	Award	Best Paper Award — ICSPER 2024
Technical Coverage	Battery chemistries benchmarked	4 chemistries: LCO, NMC, LFP, LMO
Technical Coverage	C-rates evaluated	0.04C to 5C (7 C-rate levels)
Technical Coverage	Battery analyses conducted	11 types: SOC, SOH, DOD, Voltage, Temp., Capacity, Capacity Fade, Heat Gen., Heat Accum., No. of Cycles, Life Span
Infrastructure	Lab facility established	IITM–INDUS Battery Engineering Research Lab, Dept. of Engineering Design, IIT Madras
Infrastructure	Major equipment commissioned	Battery Cycle Tester (100V/100A) + Instron Servo Hydraulic UTM
Skill Development	Student researchers trained	M.Tech and B.Tech students in battery modelling, simulation & testing
Indigenous pack design initiated	Indigenous pack design initiated	36P16S large-format cylindrical battery pack design underway
Sustainability	Lab self-sufficiency pathway	Capability established for future research grants, industry-sponsored projects, and training programmes

SUMMARY AND FORWARD OUTLOOK

The IITM–INDUS Battery Engineering Research Lab has, over the course of this project, successfully delivered on all its core objectives. It has produced rigorous, validated research on Li-ion battery thermal management and electrochemical behaviour across multiple chemistries; it has built physical infrastructure that will serve the Institute for years to come; it has trained and equipped a cohort of battery engineers equipped for India's energy transition; and it has planted the seed of an indigenous battery pack design capability.

The strategic significance of this work is amplified by its timing. India is at an inflexion point in its clean energy journey — scaling up electric mobility, deploying grid-scale storage, and building indigenous battery manufacturing capacity. The knowledge, tools, infrastructure, and workforce produced by this CSR initiative directly address the foundational gaps that stand between India's battery ambitions and their realisation.

The path forward for the lab includes the completion of the 36P16S large-format battery pack design and validation, the expansion of machine-learning-based SOC prediction models, industry-sponsored testing and certification projects, and the formalisation of a structured training programme for battery engineers from both academia and industry. The foundation laid by this CSR initiative is robust, and the potential for amplified impact in the coming years is substantial.

PROJECT OBJECTIVES: AN ASSESSMENT OF FULFILMENT

The IITM–INDUS Battery Engineering Research Lab was established with eight core objectives. A review of the evidence gathered through this Impact Assessment confirms that all primary objectives were met, and in several instances, the outcomes exceeded the scope originally envisioned.

Objective	Outcome
Develop and validate electrochemical thermal models for cylindrical Li-ion packs (LCO, NMC, LFP, LMO)	Fully achieved. P2D models validated for all four chemistries using COMSOL Multiphysics 6.0, with experimental verification confirming accuracy to within 5.6% (SOC) and 9.69% (thermal).
Conduct thermal analysis and performance evaluation under varying C-rates	Conduct thermal analysis and performance evaluation under varying C-rates
Design and demonstrate efficient Battery Thermal Management (BTM) systems	Fully achieved. Air-cooled BTM system designed and validated for the 6s2p pack configuration. NMC chemistry confirmed as the most thermally efficient under air cooling.
Enable SOC, SOH estimation and battery lifetime prediction	Fully achieved. SOC and SOH estimated for all four chemistries; capacity fade and battery lifespan calculated and benchmarked (LCO: 7.9 years / 2,160 cycles; NMC: 3.9 years / 1,133 cycles; LFP: 6.8 years / 1,966 cycles; LMO: 5.2 years / 1,522 cycles).
Develop a domestically engineered battery pack suited to Indian conditions	Substantially achieved. A 36P16S large-format LFP cylindrical battery pack design was initiated and is underway, representing a significant step toward a deployable indigenous battery solution.
Create a world-class teaching and research lab for B.Tech and M.Tech students	Fully achieved. The IITM–INDUS Battery Engineering Research Lab is operational, equipped, and active as a teaching and research facility at the Department of Engineering Design, IIT Madras.
Upskill students and build a skilled technical workforce	Fully achieved. M.Tech and B.Tech researchers were trained in advanced battery modelling, simulation, and experimental testing — competencies directly aligned with India's growing battery and EV sectors.
Enable the lab to become self-sustaining beyond the CSR period	Well positioned. The lab's infrastructure, research portfolio, academic publications, and institutional credibility provide a strong foundation for attracting future grants, sponsored projects, and training revenue.

Overall Verdict: All eight stated objectives of the project were either fully achieved or substantially progressed by the close of the project period. No objective was left unaddressed. The project delivered on its promise.

04. OECD FRAMEWORK

EVALUATION CRITERIA

Relevance | Coherence | Effectiveness | Efficiency | Impact | Sustainability

The OECD-DAC framework is a globally recognised approach for impact assessments that evaluates development and CSR interventions. It comprises six key criteria: **Relevance, Coherence, Effectiveness, Efficiency, Impact, and Sustainability,** enabling a comprehensive and standardised evaluation of project performance, outcomes, and long-term value.

★★★★★
RELEVANCE

Strong alignment with telecom infrastructure requirements for reliable battery backup systems. The project addresses critical challenges in lithium-ion battery thermal management, enabling safer, more efficient energy storage solutions for telecom tower operations and other emerging energy applications.

★★★★★
COHERENCE

The project demonstrates strong coherence between industry needs and academic research. Collaboration between Indus Towers and IIT Madras aligns with broader priorities in energy storage innovation, telecom infrastructure reliability, and advanced battery engineering research.

★★★★½
EFFECTIVENESS

The project successfully achieved its research objectives through simulation modelling, experimental validation, and comparative analysis of battery chemistries. It generated key technical insights on battery performance, heat generation, and thermal behaviour.

★★★★
EFFICIENCY

CSR resources were effectively utilised to support simulation modelling, laboratory experimentation, and research capacity development. Leveraging IIT Madras' existing research infrastructure enhanced implementation efficiency despite the research's technical complexity

★★★★★
SUSTAINABILITY

The project strengthens long-term research capacity in battery engineering and thermal management systems. The developed models, experimental insights, and laboratory capabilities can support future research, innovation, and technology applications in energy storage systems.

★★★★½
IMPACT

The research contributes to improved understanding of lithium-ion battery thermal behaviour and optimal battery configurations. These insights can inform safer and more reliable battery pack design for telecom infrastructure, with potential applications in electric mobility and renewable energy storage technologies

EVALUATION CRITERIA

Relevance | Coherence | Effectiveness | Efficiency | Impact | Sustainability

Index : 5 Points - Very High ; 4 Points - High ; 3 Points - Moderate ; 2 Points - Low ; 1 Point - Very Low

05. RECOMMENDATIONS

Based on the findings of this Impact Assessment, the following recommendations are made for the continued development of the IITM–INDUS Battery Engineering Research Lab and any future phases of collaboration:

Complete the 36P16S Battery Pack Design and Validation

The large-format LFP pack design initiated in Q4 should be completed, simulated, and experimentally validated. This would produce the first indigenously designed and tested battery pack of this scale in India, and represents the logical culmination of the research programme.

Develop Machine Learning-Based SOC Prediction Models

The project's way-forward identified machine learning as the next frontier for SOC estimation. Collecting SOC data across C-rates and building ML-based predictive models would significantly advance the BMS capabilities developed under this initiative and contribute to the next generation of intelligent battery management.

Extend to Liquid and Hybrid Cooling BTM Systems

The 18P4S module analysis revealed that air cooling alone is insufficient at 2C rates (92.1°C). The next research phase should design and validate liquid cooling and hybrid BTM systems for larger packs, enabling safe high-rate discharge in demanding applications.

Formalise a Battery Engineering Training Programme

The lab's expertise and infrastructure should be leveraged to design and launch a structured, accredited training programme for industry professionals in battery pack engineering, power management, and thermal management — creating a revenue stream that supports lab sustainability while directly addressing India's workforce gap.

Pursue Competitive Research Grants and Industry Sponsorships

The lab's validated research credentials, peer-reviewed publications, and physical infrastructure provide a strong platform for applying to national funding agencies (DST, SERB, MNRE) and engaging with EV OEMs, battery manufacturers, and energy storage companies for sponsored research and certification projects.

Explore Certification and Standards Development Role

India is actively developing its battery certification and safety standards framework. The IITM–INDUS lab, with its validated test protocols and expert faculty, is well positioned to contribute to national standards development and to serve as a recognised testing and certification facility for Indian battery manufacturers.

06. CONCLUSION

The body of research conducted under this project has produced technically rigorous, peer-reviewed, and practically relevant conclusions about the electrochemical and thermal behaviour of cylindrical Lithium-Ion battery packs. The following conclusions are drawn from the full arc of the research across all four project quarters.

On Battery Chemistry Selection

No single battery chemistry is universally optimal — each offers a distinct performance profile that makes it better suited for specific application requirements. The research has produced a clear, quantified framework for chemistry selection based on four independently validated performance dimensions:

NMC is the best-performing chemistry for applications demanding high energy utilisation, peak charge retention, and effective thermal dissipation under air cooling. It operates at 100% SOC and maintains the lowest heat accumulation, but at the cost of the shortest cycle life (3.9 years, 1,133 cycles).

LCO offers the longest operational lifespan (7.9 years, 2,160 cycles) with the lowest capacity fade (75%), making it most appropriate for applications where durability and predictable long-term performance are the primary requirements.

LFP provides the best combination of safety, thermal stability, and longevity (6.8 years, 1,966 cycles). Its experimentally validated low thermal runaway risk and uniform temperature distribution make it the most suitable chemistry for safety-critical power backup applications.

LMO occupies an intermediate position. While it offers adequate performance across all dimensions, it does not lead in any single metric, limiting its advantage over the other three chemistries for specialised applications.

For power backup applications where both safety and service life are critical considerations, LFP emerges as the recommended chemistry. For applications prioritising energy performance and space efficiency, NMC is the preferred choice.

ON BATTERY THERMAL MANAGEMENT

The research confirms that active air cooling is a viable, cost-effective, and sufficient Battery Thermal Management (BTM) strategy for cylindrical Li-ion packs operating at C-rates up to 4C in the 6s2p configuration studied. The validated P2D electrochemical-thermal model provides the analytical foundation for designing BTM systems that prevent thermal runaway, maintain safe operating temperatures, and extend battery lifespan.

The finding that heat generation scales non-linearly with C-rate — from 0.5W at 0.5C to 102.5W at 4C for NMC — has direct design implications for BTM system sizing. For larger-format packs and higher discharge rates (as encountered in the 18P4S module at 2C, where temperatures reached 92.1°C), active liquid cooling or hybrid cooling systems are recommended, providing a clear design decision-tree for battery pack engineers.

On Model Validation and Reliability

The experimental validation of the P2D simulation model against physical battery testing data — achieving a maximum error of 5.6% for SOC analysis and 9.69% for thermal analysis — is a significant technical milestone. It confirms that the modelling framework developed at the IITM–INDUS lab is reliable and suitable for deployment in practical battery pack design and certification workflows. This validated model represents an indigenous computational tool that can reduce Indian industry's dependence on expensive proprietary foreign simulation platforms.

On Capacity Fade and Battery Life Management

Capacity fade was confirmed as the primary degradation mechanism across all four chemistries, driven principally by cycling stress, electrode structural changes, and electrolyte degradation over time. The quantification of capacity fade, cycle counts, and lifespan for each chemistry — under defined C-rate and temperature conditions — provides battery pack designers and fleet operators with actionable data for predicting end-of-life, planning replacement cycles, and optimising depth-of-discharge strategies to extend useful battery life.

Institutional and Societal Conclusions

Beyond the technical outputs, this project has delivered institutional and societal outcomes that are arguably of equal or greater long-term significance.

A Gap in India's Research Ecosystem Has Been Addressed

At the time this project was initiated, India had no dedicated, state-of-the-art research and certification facility for battery packs aligned with international thermal management test standards. The IITM–INDUS Battery Engineering Research Lab directly addresses this gap. It provides Indian researchers, engineers, students, and industry partners with access to world-class infrastructure — physical and computational — for battery characterisation, modelling, and testing. This is a structural contribution to India's research ecosystem that will generate value for years to come.

A PIPELINE OF SKILLED BATTERY ENGINEERS HAS BEEN INITIATED

India's clean energy ambitions — electric mobility, grid-scale storage, renewable integration — all depend on the availability of engineers with deep expertise in battery systems. This project has contributed directly to building that pipeline. Researchers trained under this initiative are equipped with skills that are in acute national demand, and the institutional structures put in place by the lab — coursework, research projects, experimental training — will continue to produce such talent beyond the funded phase.

Indigenous Technology Capability Has Been Seeded

The design of a 36P16S large-format LFP battery pack, based entirely on domestically conducted research using indigenously validated models, is a concrete demonstration that India can develop deployment-ready battery technology without dependence on foreign design expertise. This capability, once fully realised, has the potential to reduce import dependency, lower the cost of battery systems for Indian applications, and contribute to the broader Atmanirbhar Bharat framework in the clean energy domain.

A Model for Impactful CSR in Deep Tech Has Been Demonstrated

This initiative demonstrates what purposeful, well-directed CSR investment in frontier technology research can achieve. By channelling CSR funds into a structured, institutionally anchored research programme at a premier national institution, this project has generated outcomes that are simultaneously scientific, educational, economic, and social in character. The model — CSR funding directed at a specific, nationally relevant research gap, implemented by a world-class institution with strong accountability structures — is replicable and worthy of wider adoption.

Acknowledgement of Partnership

The outcomes described in this report are the product of a genuine and well-functioning partnership between Indus Towers Limited and the Indian Institute of Technology Madras. Indus Towers provided not only the financial resources that made the initiative possible, but also the sustained engagement — through periodic reviews, reporting oversight, and institutional commitment — that kept the project focused and accountable throughout its 16-month duration.

IIT Madras brought to the partnership its most valuable assets: the intellectual capability of its faculty and research scholars, the institutional infrastructure of its Department of Engineering Design, and the credibility of its name — reflected in international publication, peer recognition, and experimental validation of the research produced. The institute fulfilled all its obligations under the CSR Agreement with rigour and integrity.

Together, the two institutions have demonstrated that industry-academia partnership, when built on clarity of purpose and mutual respect, can produce outcomes that neither could achieve alone. This partnership merits continuation and deepening.

The IITM–INDUS Battery Engineering Research Lab stands as a tangible, enduring, and meaningful outcome of a CSR investment made with purpose and executed with rigour. In the space of sixteen months, it has produced validated research, trained researchers, created infrastructure, and generated academic recognition — all in an area of direct national strategic importance.

India is at the threshold of a major transition in its energy systems. The shift to electric mobility, the scaling of renewable energy storage, and the push for energy self-reliance are national imperatives that will define the country's economic and environmental trajectory for decades. At the heart of each of these transitions lies the battery — and at the heart of every reliable, safe, and long-lived battery lies the science of electrochemical engineering, thermal management, and intelligent battery management systems.

This project has placed IIT Madras, and through it India, at the frontier of that science. The knowledge created here, the engineers trained here, and the infrastructure built here will outlast the project that funded them. That is the hallmark of truly impactful CSR.

Final Note: The IITM–INDUS Battery Engineering Research Lab is not the conclusion of a project. It is the beginning of a programme. The foundation has been built with care, competence, and commitment. What is built upon it, in the years ahead, will be the true measure of this initiative's legacy.

SoulAce
Path to Sustainability

SOULACE CONSULTING PVT. LTD.