DEPARTMENT OF HEAVY INDUSTRY
GOVERNMENT OF INDIA

TIFAC

R&D PLAN FOR TECHNOLOGY PLATFORM ON ELECTRIC MOBILITY_

NATIONAL MISSION FOR ELECTRIC MOBILITY

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सत्यमेव जयते
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TIFAC

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भारत सरकार

Minister of
Heavy Industries & Public Enterprises
Government of Ind ia

अनंत ग. गीते
ANANT G. GEETE

MESSAGE

A vibrant manufacturing sector is key to economic growth and employment generation. The Make in India initiative of the Government of India is an apt step towards this. The automobile industry is a major contributor in the manufacturing sector. While with rising growth and prosperity demand for automobiles is expected to grow unabated, it is essential to ensure that such growth is sustainable from the viewpoint of environment as well as energy security. Electric Mobility is definitely a promising alternative for the road transport sector to replace conventional fossil fuel based automobiles.

The Faster Adoption of Hybrid and Electric Vehicles in India (FAME India) Scheme initiated by the Government under the National Mission on Electric Mobility (NMEM) aims to bring about electric mobility in the country in a phased and systematic manner, backed by future-oriented policies to catalyze growth of electric mobility. Promotion of electric mobility largely depends on development of competence in manufacturing of electric vehicles, its components and supporting infrastructure.

The R&D Plan for the National Mission on Electric Mobility brought out by the Department of Heavy Industry is expected to play a key role of being a common reference point among various stakeholders regarding the roadmap towards achieving the desired technological competency in electric mobility in the country.

I congratulate the Technology Information, Forecasting and Assessment Council (TIFAC) for its contributions towards preparation of this document bringing together a large number of experts from industry, R&D institutions, academia, Government and other stakeholders. I hope this document will be instrumental in setting forth an effective R&D ecosystem for electric mobility in the country, in which a synergistic collaboration among all stakeholders strives towards achieving the identified goals.

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भारी उद्योग एवं लोक उद्यम
भारत सरकार

स्वच्छ भारत
एक कदम स्वच्छता की ओर

MESSAGE

Initiatives on electric mobility meet two important objectives of the Government of India – one, thrust on manufacturing sector, and two, promotion of clean technologies. The Ministry of Heavy Industry and Public Enterprises has already delineated a plan for promoting India into a higher echelon in the global automobile market by introducing the Automotive Mission Plan 2026 (AMP–2026).

FAME India Scheme introduced by the Government of India under the National Mission on Electric Mobility (NMEM) can have a major contribution towards achieving the leadership position in the automotive sector, that AMP 2026 envisages. NMEM targets annual sale of 6 million plus hybrid and electric vehicles in India by 2020.

Achieving this kind of target requires policy measures to encourage all stakeholders. It also calls for development of indigenous capability for devising cost-effective holistic solutions for all the challenges related to electric mobility spanning the entire gamut of electric vehicles ecosystem. It is in this context that technology holds a great significance.

I am pleased that the Department of Heavy Industry has provided adequate emphasis on technology development under the FAME India Scheme, and also instituted a detailed study that has come out in the form a R&D Plan for the National Mission on Electric Mobility. I hope that this document, compiled by the Technology Information Forecasting and Assessment Council (TIFAC), will play the necessary catalytic role in forging strong alliances among the stakeholders to develop technologies that accelerate promotion of electric mobility in the country.

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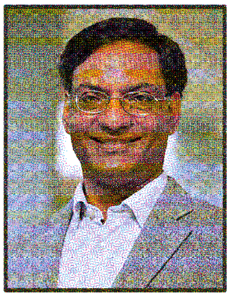
Ministry of Science and Technology
Department of Science and Technology



Message

Advances in Science and Technology have improved quality of life and boosted productivity and competitiveness of the industry. But at the same time, increased consumption of energy and natural resources has created adverse effect on environment, threatening the long term sustainability of the civilization. Hence the world today is looking for cleaner and sustainable alternatives, and a major thrust of technology developments in modern times is towards enabling sustainable development. In the transport sector, electric mobility is one such promising alternative.

The National Mission on Electric Mobility (NMEM) has taken up the ambitious plan of promoting electric mobility in India. Along with steps towards demand creation and infrastructure roll out, technology development is one important aspect in such an initiative. Technology development for electric and hybrid electric vehicles is a complex process, requiring technology innovations in various levels - vehicle, its subsystems and even the ecosystem supporting the vehicles. It may require non-sequential development approaches and involvement of multiple stake-holders. It is always beneficial to have a clear understanding of the technology pathways and priorities in such an initiative.

The R&D Plan for the National Mission on Electric Mobility prepared by TIFAC is aimed at fulfilling this critical need. I hope that this document will be an important reference for the R&D community and will impart momentum to R&D efforts on electric mobility in India.

(Ashutosh Sharma)

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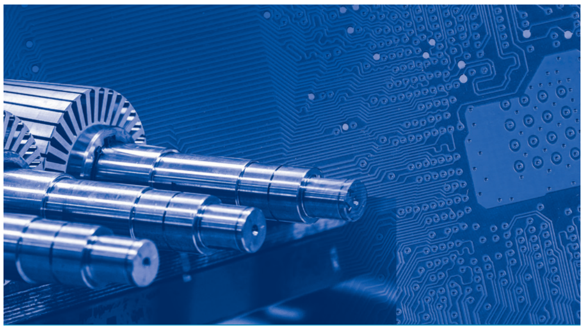

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MOTORS AND DRIVES

PREAMBLE

Rising economic growth, population growth and societal needs have caused exponential increase in transportation demand. For a rapidly developing country like India, energy demand and emissions from the transportation sector is a major issue to be addressed. Transport sector in India is responsible for more than 90% of the crude oil consumption in the country. Inadequate road infrastructure, densely populated cities and congested traffic implies that high level of penetration of conventional automobiles in future will be unsustainable. Thus India needs more sustainable solutions for mobility. Electric mobility, along with greater focus on public transport, is definitely a promising candidate in this regard.

As a technology think tank, TIFAC has been at the forefront of developing technology roadmaps for the country. Over the years TIFAC has developed expertise in technology foresight in various sectors of the economy. After Technology Vision 2020 during mid-1990s, TIFAC has further prepared Technology Vision 2035 for the country recently. One of the major prerogative identified under the Technology Vision 2035 is safe and speedy mobility. The Technology Vision 2035 sets a target of reducing emission in the transport sector by half and at the same time doubling energy efficiency by 2035. Alternative propulsion technologies, and particularly electric mobility can contribute towards achieving this target.

From the global perspective, saving our earth from the menace of global warming and associated catastrophic effects requires mitigation actions in terms of promoting clean technologies. Most countries in the world have agreed to reduce energy and emission intensity of their economy. India has committed to pursue implementa-

Dr. Anil Kakodkar, Chairman, Governing Council, TIFAC

tion of clean energy technologies during the Paris convention in 2015. Under the National Solar Mission, India is aggressively promoting utilization of solar energy. Clean technologies for road transportation is another crucial step forward towards sustainability.

Electric mobility brings with it a paradigm shift. Interaction between the energy sector and the transport sector is redefined. A new set of natural resources are demanded. Possibility of utilization of renewable energy in the transportation sector is opened up. New sets of standards need to be developed. Moreover, technological solutions to several challenges to electric mobility need to be addressed. Identification of technology priorities taking into account country-specific needs is thus important, as it is important for stakeholders to work towards a common set of goals in a coherent manner.

This will require catalyzing a vibrant innovation ecosystem for electric mobility R&D in the country, in which academic/research institutions, industry and financial institutions work with vertical and horizontal interactions at multiple levels. All the players in the innovation chain need to be linked to each other. To make this happen, an efficient structure of the R&D ecosystem needs to be defined, along with R&D targets and priorities.

The Collaborative Automotive R&D (CAR) initiative coordinated by TIFAC during 2003-2010 promoted the culture of consortia research in the automotive field.

The present effort of preparing the Detailed R&D Plan for the Technology Platform under the National Mission on Electric Mobility is based on these foundations. TIFAC benefited from the network of automotive researchers, both from academia/ R&D institutions and industry.

I hope that this document will help to establish an effective R&D ecosystem for electric mobility in the country, and will catalyze innovations that helps India to secure a leadership position in the field of electric mobility.

GENESIS & KEY CONTRIBUTORS

In recent times major focus in the transport sector globally have been emission reduction and improvement in fuel economy. This has set a trend towards increasing electrification of the transport sector. For India electric mobility has further significance. As a nation committed towards sustainability, India has set its goal for reducing emissions and promoting clean technologies. India's huge import bill for petroleum products makes it imperative to search for alternatives to fossil fuels. The National Mission on Electric Mobility (NMEM) is a timely initiative in this context.

The Mission has given great importance to Technology Development. The Department of Science and Technology participates in the Mission to implement the Technology Platform on Electric Mobility. An essential prerequisite for such a technology porgamme is a well planned technology roadmap featuring R&D priorities, pathways to achieve them, and a well designed R&D ecosystem involving industry, component industry, R&D labs and academic institutions. Considering these, the Department of Heavy Industry made a request to DST to prepare a detailed project report for the technology programme under NMEM.

As a technology think tank TIFAC has been involved in preparation of technology foresight and technology assessment reports and roadmaps. TIFAC has over the years developed a vast network involving experts form industry, academia and government. TIFAC also has linkages with international technology foresight organizations. All these helped TIFAC to take up the challenge of delineating technology pathways for electric mobility in India.

This report has benefited from extensive consultation held by Department of Heavy Industry (DHI) even before the report was commissioned, Discussions in the NMEM Working Group on R&D set the directions for the subsequent efforts. The NMEM Working Group on R&D constituted a subgroup on Battery and BMS and another on Power Electronics and Motors. TIFAC was a participant in the Working Group on R&D as well as these subgroups. Then a project was granted by the Department of Heavy Industry to TIFAC to prepare this detailed R&D Plan. During the process of preparing this R&D plan also, the TIFAC team benefited from advices from members of the NMEM Working Group on R&D, such as Mr. Chetan Kumaar Maini and Mr. Mukesh Bhandari.

A large number of experts from vehicle manufactures, component manufacturers, R&D institutions, academia and Government have contributed immensely towards shaping this R&D Plan. For the specific purpose of putting together an initial outline of the R&D Roadmap, a core-group was set up by the NMEM Workging Group on R&D. This core-group was led by Mr. Sajid Muabashir and included Mr. Manik Narula, Mr. Ravindran, Mr. Shivam Sabesan, Mr. Sourav Rohilla, Mr. Anand Deshpande, Dr. Saptarshi Ghosh, Mr. Kartik Gopal, Mr. Prasanta Sarkar, Mr. Arun Pratap Singh and Mr. Arghya Sardar.

Prof. Prabhat Ranjan, Executive Director, TIFAC

The initial outline draft put together by this group went through detailed discussions in various brainstorming sessions during the next few years. People who led these discussions and provided valuable guidance include Dr. Arun Jaura, Mr. VG Gujrathi, Mr. Bidya Bijoy Bhaumik, Dr. Vijayamohanan K Pillai, Dr. K Balasubramanian and Dr. DP Amalnekar. These brainstorming sessions helped TIFAC in working out details of the R&D Ecosystem and implementation strategy for the technology priorities. Representatives of the three major industry associations - Society of Indian Automobile Manufactures (SIAM), Automotive Component Manufactures Association (ACMA) and Society for Manufacturers of Electric Vehicles (SMEV) actively participated in the brainstoming sessions and other discussions. The SIAM Frontier Technology Group led by Dr. Tapan Kumar Sahoo also reviewed the document and provided valuable feedbacks,

Mr. Sajid Mubashir has been a constant source of encouragement, support and advice to the TIFAC team and also spent a lot of time to edit the chapters. He is also the principle contributor of the chapter on Charging Infrastructure.

During preparation of the final draft the TIFAC team received valuable inputs form Mr. Prasanta Sarkar, Prof. Siddhartha Mukhopadhyay, Dr. Ramaswamy, Prof. Anindya Deb, Dr. R Gopalan, Dr. N Kalaiselvi, Dr. S Gopukumar, Dr. ZV Lakaparampil and Mr. Srinivas Kudligi, We wish to thank Prof. Siddhartha Mukhopadhdyay, Dr. ZV Lakaparampil and Dr. S Venugopal who spent significant amount of efforts to review the draft. Their constructive comments were extremely valuable for this report.

The report was discussed in the Inter-Ministerial Technology Advisory Committee on Electric Mobility (IM-TAG) a couple of times in detail. All members of IM-TAG provided valuable inputs. Particularly guidance of Prof, Ashok Jhunjhunwala and Dr. G. Sundararajan helped to steer the R&D plan towards right direction.

Officials from the Department of Heavy industry namely Mr. Ambuj Sharma, Mr. Vikram Gulati, Mr. Niraj Kumar and Mr. Praveen Agarwal have offered their support and guidance. Former Secretary of DHI Shri Girish Shankar and Joint Secretary Shri Visvajit Sahay extended their encouragement and support to TIFAC.

This document could not have seen daylight without the efforts of TIFAC Scientists Mr. Arghya Sardar and Mr. Suresh Babu Muttana, who have drafted this report by integrating all the knowledge and insights emerging out of the the brainstorming sessions as well as studies on global trends. It is the drafting team at TIFAC which is mainly responsible for the final contents of this report.

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

ACRONYMS

AC	Alternating Current
A	Ampere
ACCOMPLICE	Affordable Composites for Lightweight Car Structures
ACIPM	Alternating Current Interior Permanent Magnet Machine
AFM	Axial Flux Permanent Magnet Machine
Ah	Ampere-hour
AHSS	Advanced High Strength Steel
AMT	Automated Manual Transmision
APEEM	Advanced Power Electronics and Electric Machine
ARAI	Automotive Research Association of India
ARCI	International Centre for Powder Metallurgy and New Materials
ARCP	Auxiliary Resonant Commuted Pole
ARPA-E	Advanced Research Projects Agency-Energy
ARS	Auxiliary Resonant Snubber
ASF	Audi Space Frame
ASRTU	Association of State Road Transport Undertakings
ASTM	American Society for Testing and Materials
BARC	Bhaba Atomic Research Centre
BEV	Battery Electric Vehicle
BHEL	Bharat Heavy Electricals Limited
BIL	Battery in Loop
BIW	Body in White
BL:DC	Brushless Direct Current
BMS	Battery Management System
BMS	Battery Electric Vehicle
CAD	Computer Aided Design
CAFE	Corporate Average Fuel Economy
CAGR	Compounded Annual Growth Rate
CAN	Controller Area Network
CAR	Collaborative Automotive R&D

CDAC	Centre for Development of Advanced Computing
CEERI	Central Electrical Engineering Research Institute
CeNSE	Centre for Nano Science and Engineering
CFRP	Carbon Fibre Reiforced Plastics
CGCRI	Central Glass and Ceramics Research Institute
CMET	Centre for Materials for Electronic Technologies
CNG	Compressed Natural Gas
CoE	Centre of Excellence
CPSR	Constant Power Speed Range
CS	Charge Sustaining
CSC	Cell Supervision Circuit
CSI	Current Source Inverter
CSIR	Council of Scientific and Industrial Research
CSTEP	Centre for Science and Technology Policy
CVT	Continuously Variable Transmission
D-LFT	Direct Long Fibre Thermoplastics
DC	Direct Current
DC	Direct Chilled
DCA	Dynamic Charge Acceptance
DCPM	Direct Current Permanent Magnet Machine
DEC	Diethyl Carbonate
DeITY	Department of Electronics and Information Technology
DISCOM	Distribution Companies
DLB	Direct Lead Bonding
DMC	Dimthyl Carboante
DMC	Dough Molding Compound
DSP	Digital Signal Processor
DSPM	Doubly Salient Permanent Magnet Machine
DTC	Direct Torque Control
EC	Ethylene Carbonate

ECM	Engine Control Module
ECU	Electronic Control Unit
EMC	Electromagnetic Compatibility
EMF	Electromotive Force
EMI	Electro-Magnetic Interference
EMI	Electro Magnetic Induction
EML	Electrical Machines Limited
EMS	Electro-Magnetic Susceptibility
EOL	End of Life
ERDA	Electrical Research and Development Association
ESR	Equivalent Series Resistance
eV	Electron Volt
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FAME	Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India
FCEV	Fuel Cell Electric Vehicle
FET	Field Effect Transistor
FOC	Field Oriented Control
FPGA	Field Programmable Gate Array
GFRP	Glass Fibre Reinforced Plastics
GVW	Gross Vehicle Weight
HAL	Hindustan Aeronautic Limited
HALT	Highly Accelerated Life Test
HEV	Hybrid Electric Vehicle
HIL	Hardware in Loop
HSS	High Strength Steel
IACS	Indian Association of Cultivation of Sciences
ICE	Internal Combustion Engine
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
IEC	International Electrotechnology Commission
IGBT	Insulated Gate Bipolar Transistor
IICT	Indian Institute of Chemical Technology

IIEST	Indian Institute of Engineering Science and Technology
IISc	Indian Institute of Science
IIT	Indian Institute of Technology
IPM	Interior Permanent Magnet Machine
ISO	International Organization for Standardization
ISRO	Indian Space Research Organization
JNRDDC	Jawaharlal Nehru Aluminium Research Development and Design Centre
kg	kilogram
kV	kilo Volt
kW	kilo Watt
kWh	kilo Watt hour
LAPM	Lightweight Automotive Materials Programme
LCV	Light Commercial Vehicle
LiB	Lithium ion Battery
MMC	Metal Matrix Composite
MOS	Metal Oxide Semiconductor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MOST	Media Oriented System Transport
NaMPET	National Mission for Power Electronics Technologies
NATRIP	National Automotive Test and Research Infrastructure Project
NCA	Nickel Cobalt Aluminium Oxide
NEDC	New European Driving Cycle
NFTDC	Non-Ferrous Technology Development Centre
NiMH	Nickel Metal Hydride
NIT-K	National Institute of Technology Karnataka
NMC	Nickel Manganese Cobalt Oxide
NMEM	National Mission on Electric Mobility
NMITLI	New Millenium India Technology Leadership Initiative
NML	National Metallurgical Laboratory
NSTL	Naval Science Technological Laboratory

NTU	Nanyang Technological University
OEM	Original Equipment Manufacturer
OSTLER	Optimised Storage Integration for the Electric Car
OSTLER	Optimized Storage Integration for the Electric Car
PAN	Polyacrylonitrile
PBT	Polybutylene terephthalate
PC	Propylene Carbonate
PCRA	Petroleum Conservation Research Association
PCU	Power Control Unit
PE	Power Electronics
PET	Polyethylene Theraphthalate
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PIC	Power Integrated Circuit
PMBLDC	Permanent Magnet Brushless DC
PMSM	Permanent Magnet Syncrhonous Machine
PP	Poly Propylene
PRDCL	Parallel Resonant DC Link
PSU	Public Sector Undertaking
PURIM	Polyurethane Resin Infusion Molding
PWM	Pulse-Width Modulation
QRDCL	Quasi-Resonant DC Link
RDCL	Resonant DC Link
REE	Rare Earth Elements
REEV	Range Extended Electric Vehicle
RESS	Rechargeable Energy Storage System
RFM	Radial Flux Machine
RMS	Root Mean Square
RPWM	Random Pulse-Width Modulation
RTM	Resin Transfer Molding
S3C	Software Standard for Small Car
SACHV	Sine Amplitude Converter High Voltage
SALVO	Structural Analysis of Hybrid Materials Concept for Lightweight Vehicles
SCR	Silicon Controller Rectifier

SEI	Solid Electrolyte Interphase
SIL	Software in Loop
SMC	Sheet Molding Compound
SOC	State of Charge
SOC	System on Chip
SOF	State of Function
SOH	State of Health
SPS	Spark Plasma Sintering
SRDCL	Series Resonant DC Link
SRM	Switched Reluctance Machine
SSF	Semi-Solid Forming
SUV	Sports Utility Vehicle
SynRM	Synchronous Reluctance Machine
TEGDME	Tetra Ethylene Glycol Dimethyl Ether
TIM	Thermal Interface Material
TPEM	Technology Platform on Electric Mobility
TPM	Transfer-molded Power Module
TRL	Technology Readiness Level
ULSAB	Ultra Light Steel Auto Body
UPS	Uninterruptible Power Supply
US DoE	United States Department of Energy
V	Volt
V2G	Vehicle to Grid
VARI	Vacuum Assisted Resin Infusion
VHDL	VHSIC Hardware Description Language
VSI	Voltage Source Inverter
VVVF	Variable Voltage Variable Frequency
WBG	Wide Band Gap
Wh	Watt-hour
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
xEV	All types of electric drive vehicles
ZEBRA	Zero Emission Battery Research Activity
ZEV	Zero Emission Vehicle

01 INTRODUCTION

01 BACKGROUND

India is currently among the top 10 countries with vehicle and component manufacturing capabilities. This growth was achieved in 30 years, compared to more than hundred years in Germany and US, and 70 years in Japan. But the technology capabilities are still to mature. The vehicle companies have developed excellent design & product development capabilities, and about half dozen hybrid and electric vehicles have already been launched, since the Mission has been announced. The larger automobile companies have also established dedicated research teams for hybrid and electric vehicle development, and are building up their research facilities.

The component manufacturers have, in the past, imported technologies through joint ventures; and gained significant competitiveness through "frugal engineering"- which are shop floor innovations that are aimed at conservation of resources and improvements in productivity. The component sector has been growing very consistently for nearly 30 years now, but has a shallow technology base.

While the automotive companies in India are chasing up the growth curve to reduce the gap with developed countries, the large domestic market is in their favour. They source many IC engine vehicle technologies from Tier-1 companies to keep up with new trends and evolving consumer preferences. Yet the future growth at this level is not assured, as new competition is emerging from electronics and electrical technologies, which is the weak underbelly for the Indian automotive sector.

Globally, a number of models of Hybrid EVs are being offered by the mainstream manufacturers, and many well-established vehicle brands plan a full conversion to hybrids. For example the Volkswagen has announced that eventually, their entire portfolio of 40 vehicle models will be converted to electric drive, in future. It is expected that by 2020, the xEV (EV & HEV, collectively) would be a mainstream choice for the customer globally. This has changed the technology base very significantly. One obvious pain area is the lack of technology and manufacturing capabilities of lithium ion batteries in the country. From 2010 onwards there is widespread use of these batteries by global OEMs.

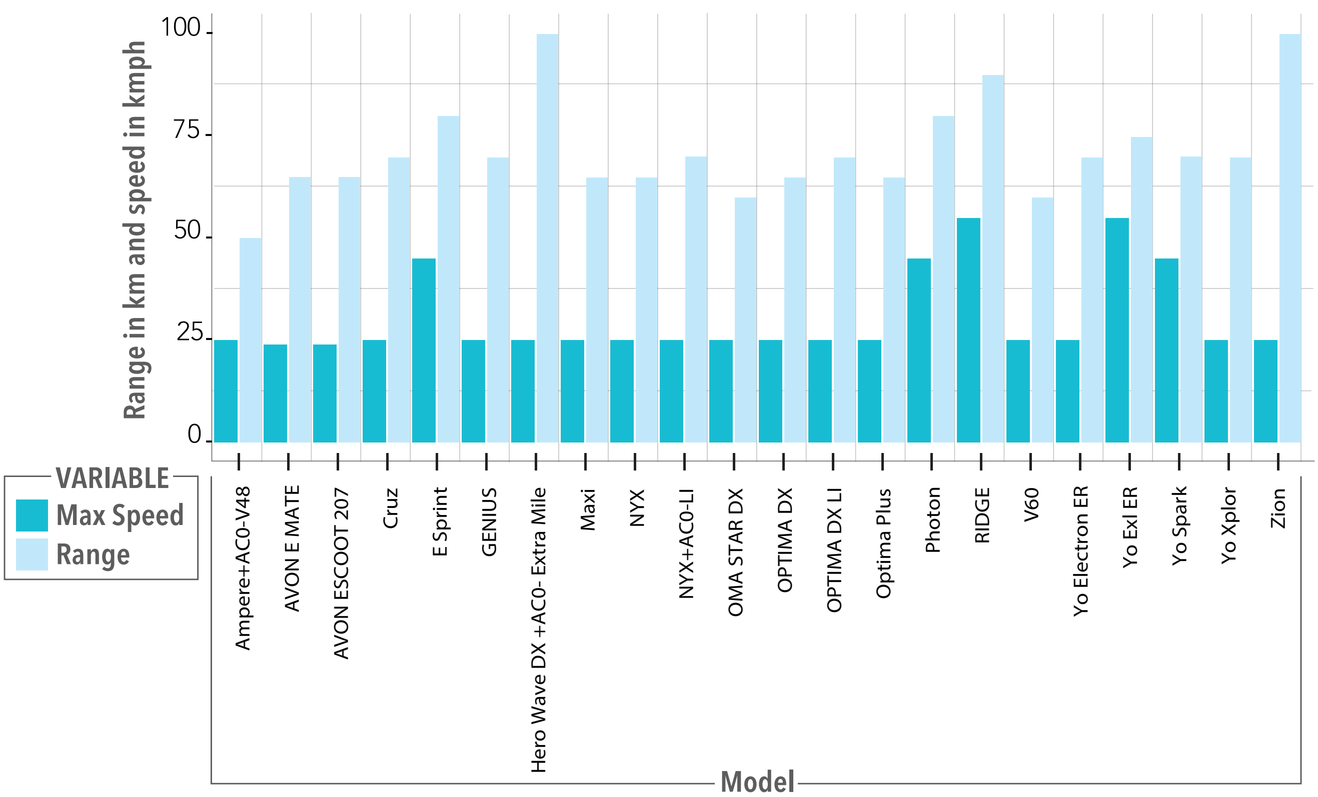
An efficient transportation system enhances the price competitiveness of the country's economy by being able to deliver Goods & Services over long distances at low cost, and enable consumers, employees, entrepreneurs and others to commute easily between production and consumption centers. For xEVs, there are technology challenges to overcome to meet these requirements effectively.

A short assessment of the global market for electric-drive vehicles is given below, and it sets the ground for discussing the capability gaps in India. The intent of the National Mission on Electric Mobility (NMEM) is to promote "Make-in-India" of Electric-Drive Vehicles & Components.

1.1 TWO WHEELER EV MARKET

China is the largest electric two wheeler (E2W) market with sales of 20 million/ year, and has a total E2W population of 120 million. Japan is next biggest market for E2W. Till recently Pedelecs (cycle E2W with battery assist) had the maximum sales. Pedelec E2Ws use batteries with energy storage between 0.2-0.6 kWh, motor power of 150-250 W, and are priced between $700-$2,000.

FIGURE 1.1: TWO WHEELERS UNDER **FAME**



The market is now shifting to e-motorcycles and e-scooters and use of lithium-ion battery is increasing rapidly. Overall in Asia Pacific, between 2012-18, the use of Li-ion batteries is expected to grow in e-scooters (@CAGR 10.4%) and e-motorcycles (@CAGR 11.3%). In Japan, Li-ion battery is expected to be used in all e-motor cycles by 2015, and in 37% of e-scooters in 2018.

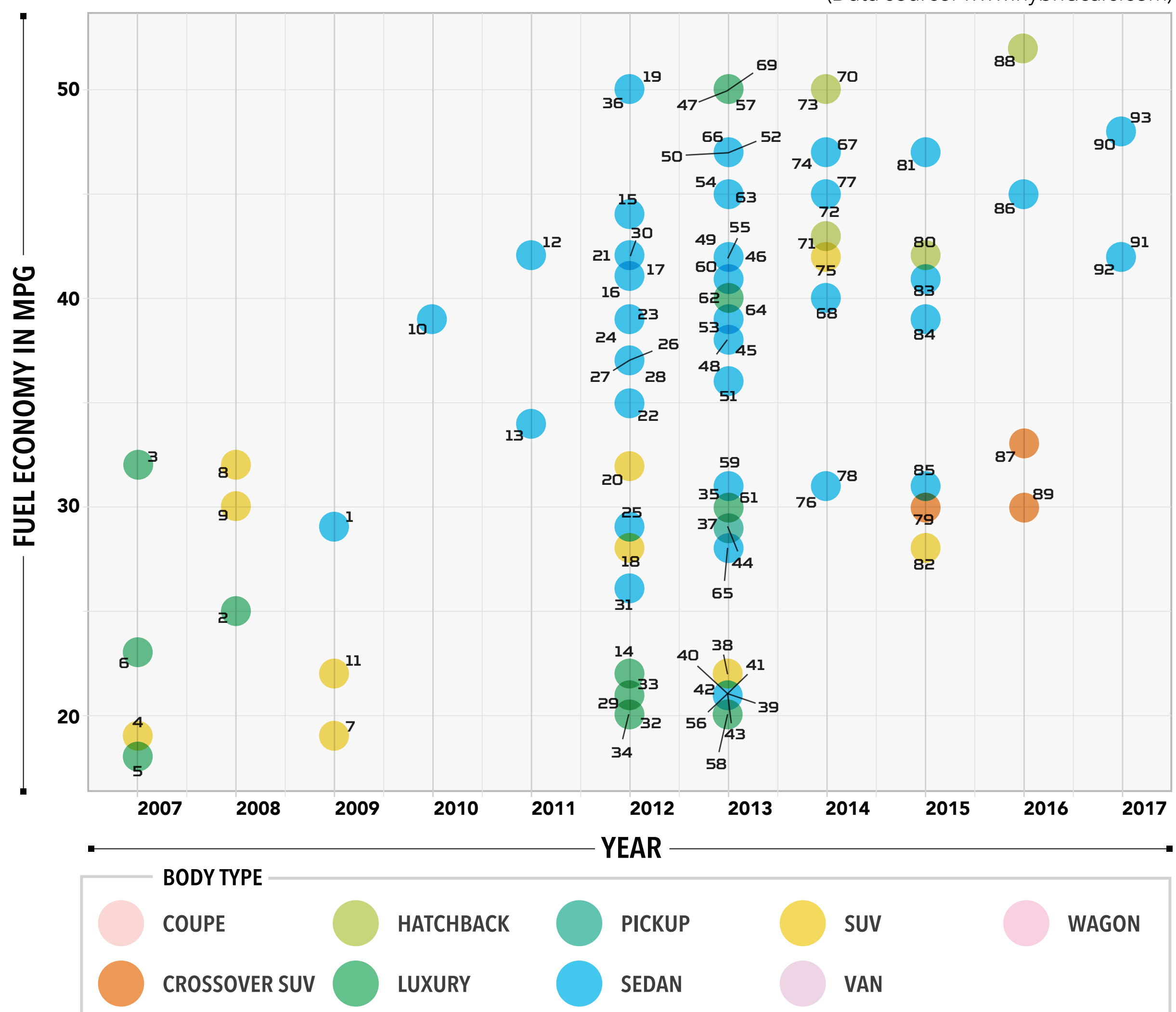
In India, there are approximately 15 electric two wheeler manufacturers (e-scooters and e-bikes) among which Heroelectric, BPG, BSA, TVS and EKO are the lead manufacturers. During the year 2016, it was reported that 20,000 units of two-wheeler were sold till June.

Approximately 2,50,000 e-rickshaws are operating in six major states including Delhi-NCR, Bihar, West Bengal and Orissa, mostly as last mile connectivity options. Most of them use imported lead acid battery. Recently some established vehicle manufacturers such as Hero Electric have ventured into this segment.

1.2 PASSENGER CARS

Hybrid Electric Vehicles (HEV) were introduced in 1997 and global sales of hybrid models from Toyota alone crossed 10 million in January 2017.

FIGURE 1.2: HYBRID CARS (Data source: www.hybridcars.com)



1. Chevrolet Malibu Hybrid
2. Lexus RX 400h
3. Mercury Mariner Hybrid
4. Chrysler Aspen Hybrid
5. BMW X6 Hybrid
6. Lexus GS 450h
7. Dodge Durango Hybrid
8. Mazda Tribute Hybrid
9. Saturn Vue Green Line Two-Mode
10. Mercury Milan Hybrid
11. Mercedes ML 450 Hybrid
12. Honda Civic Hybrid
13. Nissan Altima Hybrid
14. Audi Q5 Hybrid
15. Honda Civic Hybrid
16. Toyota Camry Hybrid
17. Lexus CT 200h
18. Toyota Highlander Hybrid
19. Toyota Prius Liftback
20. Ford Escape Hybrid
21. Honda Insight
22. Lexus HS 250h
23. Ford Fusion Hybrid
24. Lincoln MKZ Hybrid
25. Buick LaCrosse eAssist
26. Hyundai Sonata Hybrid
27. Kia Optima Hybrid
28. Honda CR-Z Hybrid
29. Porsche Cayenne S Hybrid
30. Toyota Prius v
31. BMW ActiveHybrid 5
32. Lexus LS 600h L
33. Mercedes S400HV Hybrid
34. BMW ActiveHybrid 7
35. Lexus RX 450h
36. Toyota Prius c
37. Buick Regal
38. Volkswagen Touareg Hybrid
39. Chevrolet Tahoe Hybrid
40. GMC Yukon Hybrid
41. Cadillac Escalade Hybrid
42. Chevrolet Silverado Hybrid
43. GMC Sierra Hybrid
44. Infiniti M35h Hybrid
45. Acura ILX Hybrid
46. Toyota Prius v
47. Toyota Prius c
48. Hyundai Sonata Hybrid
49. Lexus CT 200h
50. Ford C-MAX Hybrid
51. Kia Optima Hybrid
52. Ford Fusion Hybrid
53. Lexus ES Hybrid
54. Lincoln MKZ Hybrid
55. Honda Insight
56. Porsche Cayenne S
57. Toyota Prius Liftback
58. Lexus LS 600h L
59. Lexus GS 450h
60. Toyota Camry Hybrid
61. Lexus RX 450h
62. Toyota Avalon Hybrid
63. Volkswagen Jetta Hybrid
64. Ford C-Max Hybrid
65. BMW ActiveHybrid
66. Ford Fusion Hybrid
67. Honda Accord Hybrid
68. Lexus ES 300h
69. Toyota Prius c
70. Toyota Prius Liftback
71. Ford Fusion Hybrid
72. Ford C-Max Hybrid
73. Toyota Prius c
74. Honda Accord Hybrid
75. Toyota Prius v
76. Lexus GS 450h
77. Honda Civic Hybrid
78. Infiniti Q50 Hybrid
79. Lexus RX 450h Review
80. Lexus CT 200h Review
81. Honda Accord Hybrid
82. Toyota Highlander Hybrid
83. Toyota Camry Hybrid
84. Toyota Avalon Hybrid
85. Infiniti Q50 Hybrid Road
86. Volkswagen Jetta Hybrid
87. Toyota RAV4 Hybrid
88. Toyota Prius Review
89. Lexus RX 450h
90. Honda Accord Hybrid
91. Ford Fusion Hybrid
92. Kia Optima Hybrid
93. Honda Accord Hybrid
94. Buick LaCrosse eAssist

Trends observed in commercially available and concept HEV cars are as follows:

- European manufacturers focus on upper and sports class (segments E+F+S)
- Asian OEMs introduce HEVs mainly in middle class segment (C+D), also including the Toyota Prius as Full- and Plug-In Hybrid Electric Vehicle
- US-American manufacturers prefer the SUV segment (J) for HEV market penetration

Large luxury cars and Sport Utility Vehicles offer opportunity for improvements in overall energy efficiency through electrification of powertrain. Very few hybrid vehicles are in the small car segment.

Hybrids (exemplified by Toyota Prius) have reached good market penetration in some advanced countries, and the combined sales of EV & REEV have now reached 100,000/month. Yet it is still considered a nascent/ niche market, that is maintained through various Government support programs (direct and indirect incentives). A lot of improvement is expected in xEVs to make them competitive in terms of cost, performance, and convenience, and there is continued research activity across the world to achieve improvements in all the subsystems of the vehicle.

Worldwide cumulative sales of Toyota gasoline hybrid vehicles (Generations I, II and III) passed the 10 million mark as of the end of January 2017[1]. HEV combine both internal combustion engine and electric motors, and the battery is kept charged continuously by the on-board generator. In Hybrids, there is cost increase due to addition of batteries, electric motors, chargers and power electronics equipment. Some weight is saved through an optimized IC engine, and vehicle body is light-weighted to some extent. Plug in hybrid electric vehicles (PHEV) are similar to hybrid vehicles in terms of architecture, but have provision for charging the battery from external electricity source.

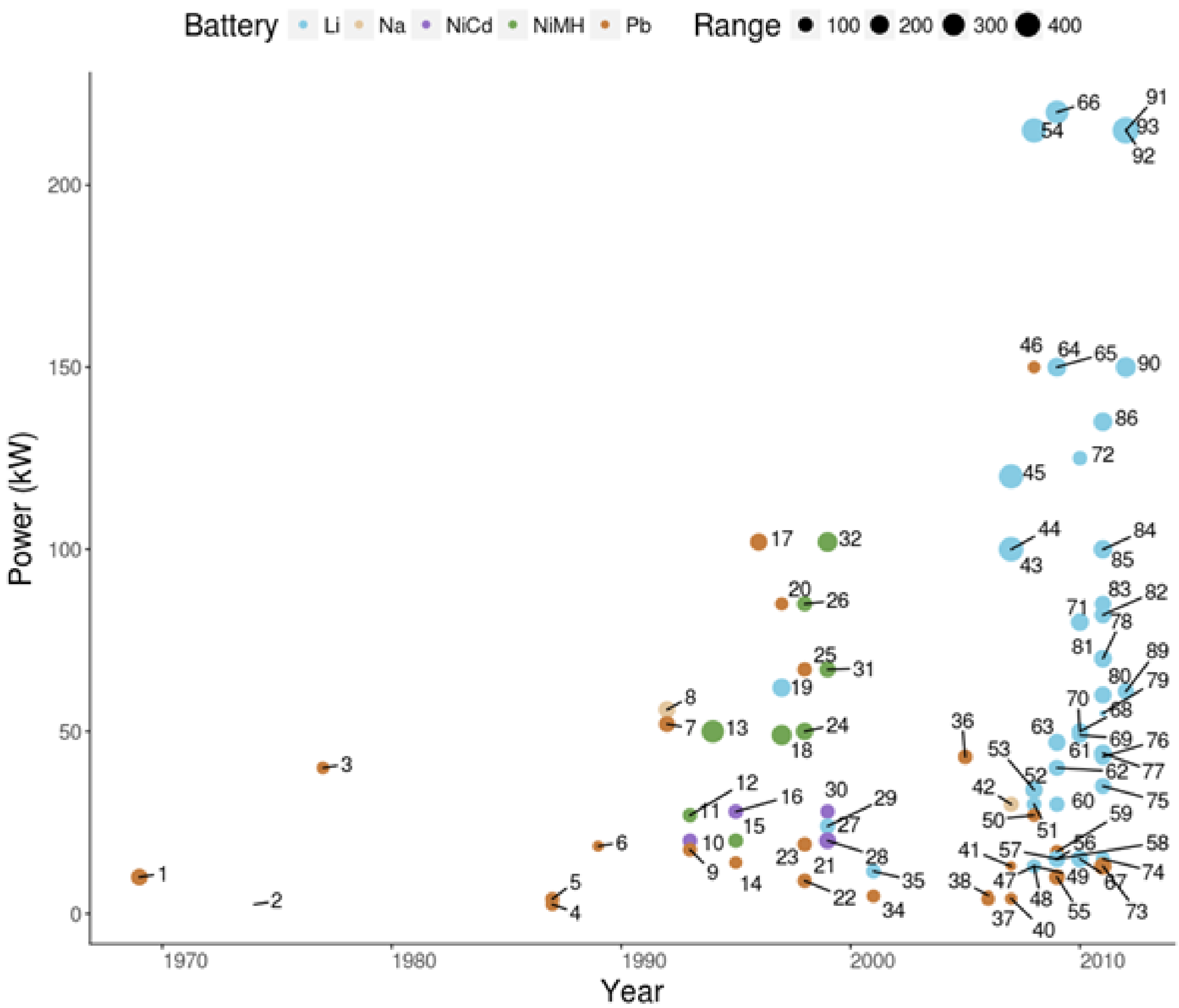
The GM Chevrolet Volt Range Extended EV (REEV) (price: $34345) launched in 2009, Nissan Leaf EV (price: $ 21510) launched in 2011, and the Tesla Sports car (price for Tesla Model S: $69900 - $105000). "Leaf" is the highest selling EV car. Electric Vehicles (EV) are more expensive mainly due to the high cost of the Battery. In March 2016, Tesla has unveiled Model 3, its first mass market electric vehicle, at a price of $35000. It is expected to be available in market in 2017. General Motors is also working on introducing a mass market electric passenger car Chevvy Bolt EV in 2017. Range extended electric vehicles (REEV) are electric vehicles with a small internal combustion engine to run an on-board generator, used only when extended range is required.

Due to very high production costs of batteries, high net weight and relatively low energy density per kWh, the battery electric vehicles worldwide have mainly been limited to the small segments (A and B). Range of pure electric vehicles is generally limited to 150 km to 200 km.

Thus, EV is essentially meant for city operations. It is noted that the 1908 Fritchle Electric and the popular 2010 Nissan Leaf have a similar 100 miles range. Though there has been vastly improved capability of the modern EV in terms of efficiency, speed, power, and battery capability, there is also much enhanced expectations now in comfort and drivability/ performance, which require many new sub-assemblies. The stricter regulations for these high speed vehicles require a very sturdy body. The high electronics content also consume a lot of energy. Thus the weight and energy requirements have also increased and the EV driving range has not improved much.

1. As per data obtained from www.toyota-global.com

FIGURE 1.3: BEV CARS



1. Enfierld 8000
2. Chloride Citicar
3. Oka NEV ZEV Lucas
4. CityEl
5. CityEl
6. FVW Golf CityStormer
7. Bertone Blitz
8. Ford Ecostar
9. VW Golf CityStromer
10. Citreon AX
11. Chrysler TEVan
12. Chrysler TEVan
13. Solectria Sunrise
14. Subaru Minivan 200
15. Citreon Saxo
16. Citroen Berlingo
17. General Motors EV1
18. Honda EV Plus
19. Nissan Ultra
20. GM S-10
21. CityCom Mini-El
22. GEM car
23. RenaultExpress Electric
24. Toyota RAV4 EV
25. Ford Ranger EV
26. GM S-10
27. Peugeot 106
28. Myers Motor NmG
29. Hypermini
30. Peugeot Partner
31. Ford Ranger EV
32. General Motors EV1
33. Dynasty IT
34. G-Wlz
35. Cree SAM
36. Commuter Cars Tango
37. NICE Mega City
38. ZAP Xebra
39. CityCar
40. The Kurrent
41. Kewet Buddy
42. Smart ED
43. Phoenix sut
44. Phoenix sut
45. ZAPI OBVIO 828E
46. AC Propulsion eBox
47. ZENIN
48. REVAi
49. REVAi
50. Stevens Zecar
51. Lumeneo SMERA
52. Think City
53. Think City
54. Tesla
55. Chana Benni
56. Tazzari Zero
57. Micro-Velt Fiat 500
58. Micro-Velt Fiat Panda
59. Zytel Gorilla Electric
60. Citroen Ci ev'ie
61. Smart ED
62. Subaru Stella EV
63. Mitsubishi iMiEV
64. BYD e6
65. Mini E
66. Venturi Fetish
67. Wheego Whip LiFe
68. Gordon Murray T-27
69. Ciroen C Zero
70. Ford Transit Connect EV
71. Nissan Leaf
72. BYD F3M
73. REVA NXR
74. Renault Twizy
75. Peugeot iOn
76. Fiat Doblo
77. Kangoo Express Z.E.
78. Ford Tourneo Connect EV
79. Tata Indica Vista EV
80. Renault ZOE
81. Renault Fluence ZE
82. Volvo C30 Drive Electric
83. Skoda Octavia Green E Line
84. Ford Focus Electric
85. CODA Sedan
86. Saab 9-3 ePower
87. Toyota RAV4 EV
88. Honda Fit EV
89. Hyundai BlueOn
90. Lightning GT
91. Tesla Model S
92. Tesla Model S
93. Tesla Model S

However, a significant number of concept BEV cars are in the sports class (S), e.g., Mercedes-Benz SLS AMG Electric Drive, the Audi R8 E-Tron and Tesla Roadster, which offer a larger range, and better performance. All these vehicles have quite large batteries and very light body construction, using aluminium and carbon fibre. These vehicles are too expensive for the Indian market.

Fuel cell electric vehicles are the promised alternative to on-board energy storage (Battery EV). Research has been underway for several decades now, and the first road-worthy fuel cell hybrid electric plug-in car was introduced in 2007 by Ford. However, they are mainly concept vehicles and commercial introduction of fuel cell vehicles have not been possible, although very recently Toyota has launched first fuel cell vehicle meant for commercial market.

1.3 COMMERCIAL VEHICLES

Currently, series hybrid powertrain topology has been used commercially for transit city buses. The buses manufactured by Scania, MAN Lion, ETS, Tata Series Hybrid Bus (EMT Madrid) and Daimler AG's Orion series hybrid buses achieved 25-35% improvement in fuel economy over standard diesel buses.Typically, the parallel hybrid powertrain is more energy efficient in higher average speed driving and series hybrid achieves higher efficiency in stop-and-go urban driving. Tata Star bus CNG Electric Bus use parallel architecture and obtained 25-30% improvement in fuel economy. Volvo 7700 Hybrid bus achieves 30% improvement in fuel economy and 50% less NOx emissions. In terms of price, there is no significant difference between parallel and series hybrid electric buses.

FIGURE 1.4

FOUR WHEELERS UNDER **FAME**

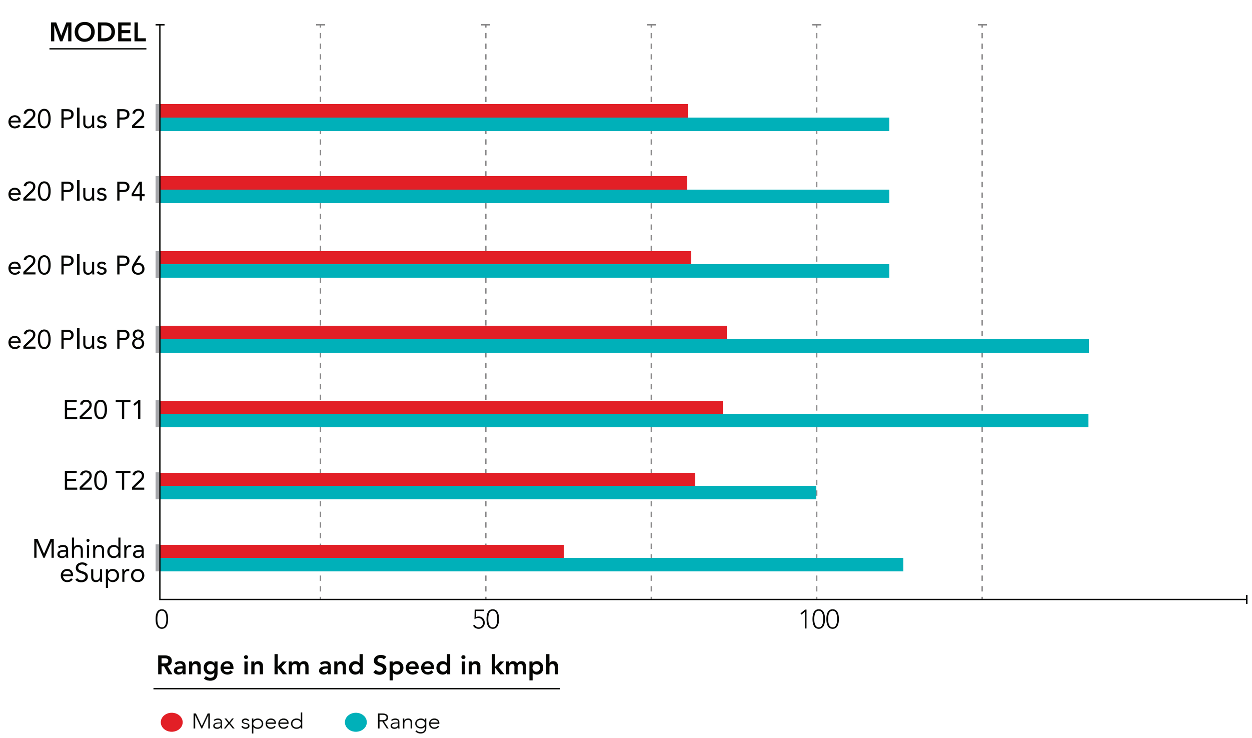
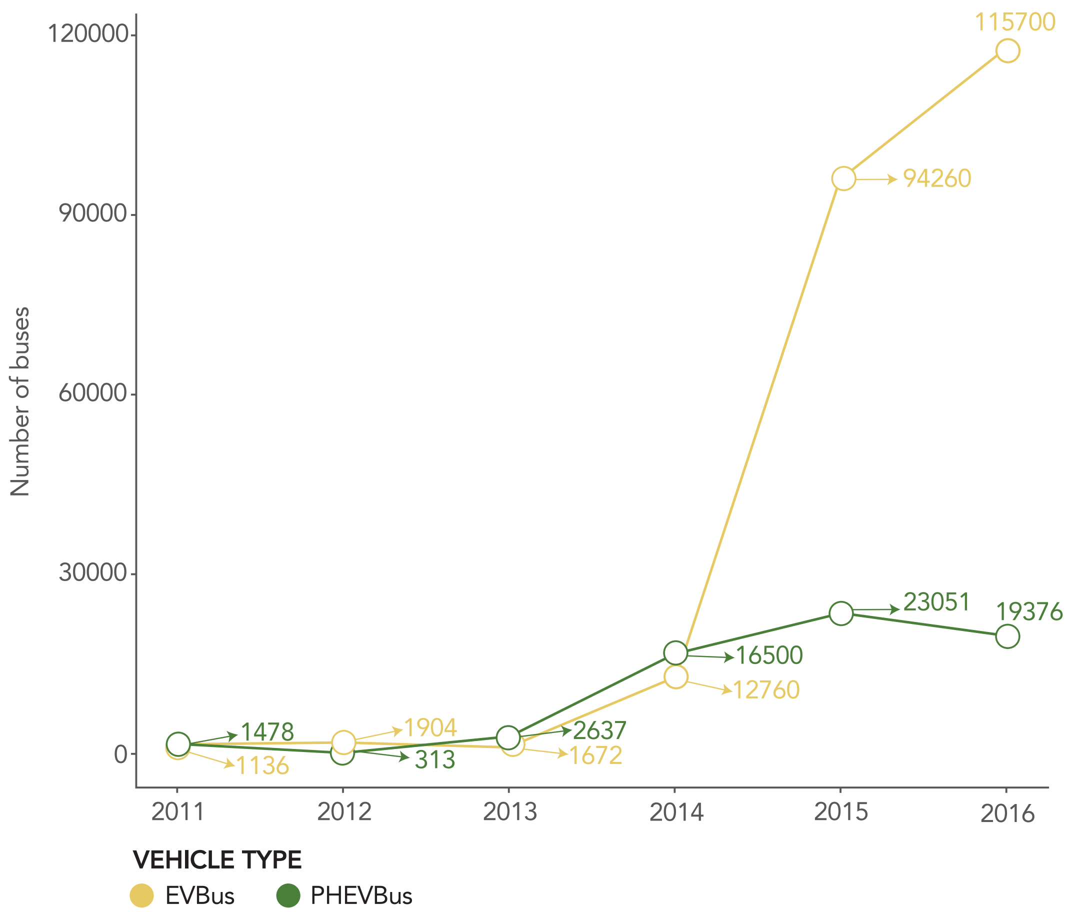


FIGURE 1.5: xEV BUS SALES IN CHINA



Full size electric buses became commercially available recently. The recent development in battery technology has increased the potential of electric buses to be viable solution for mass public transport. However, battery technology has not been mature enough in terms of durability, costs and energy density for a breakthrough of large scale commercialization of electric city buses. The constraint of range limitation can be managed comparatively easily in case of electric buses as compared to passenger vehicles, if the fleet is well managed in terms of charging and route planning. BYD Electric Transit Bus and EcoRide BE35 battery electric Bus of Proterra are commercially available. K9 BYD Electric Bus series integrates renewable energy (Solar PVs) on the roof.

Ashok Leyland HyBus series plug-in hybrid bus offers 20-30% more fuel efficiency, compared to the buses powered by CNG. Volvo 7900 Plug-in Hybrid saves as much as up to 80% in fuel consumption and reduces CO_2 emissions by the same amount.

Significant research has been carried out on fuel cell electric (FCEV) buses. FCEV buses offer range similar to diesel buses. However, due to lack of market maturity in terms of capital costs and fuel infrastructure, they are not fully confirmed in vehicle use. In addition, they are expensive (twice that of a battery electric vehicle), requires dedicated infrastructure and are less durable. FCEV buses are the most expensive electric buses available in the market, with average manufactured price of $ 2 million.

FIGURE 1.6: xEV BUSES IN EUROPE

(Based on data from European Alternative Fuel Observatory)

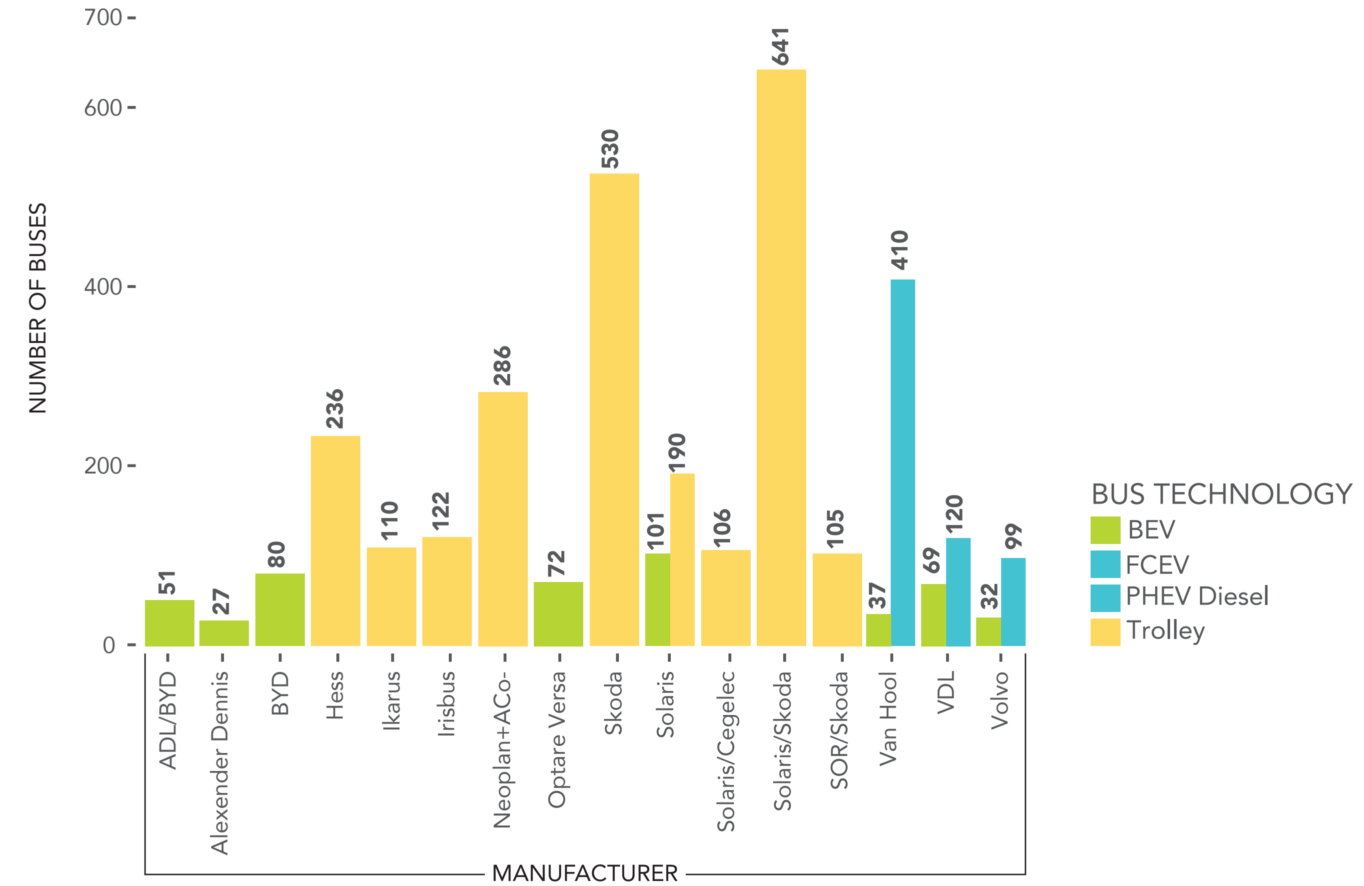
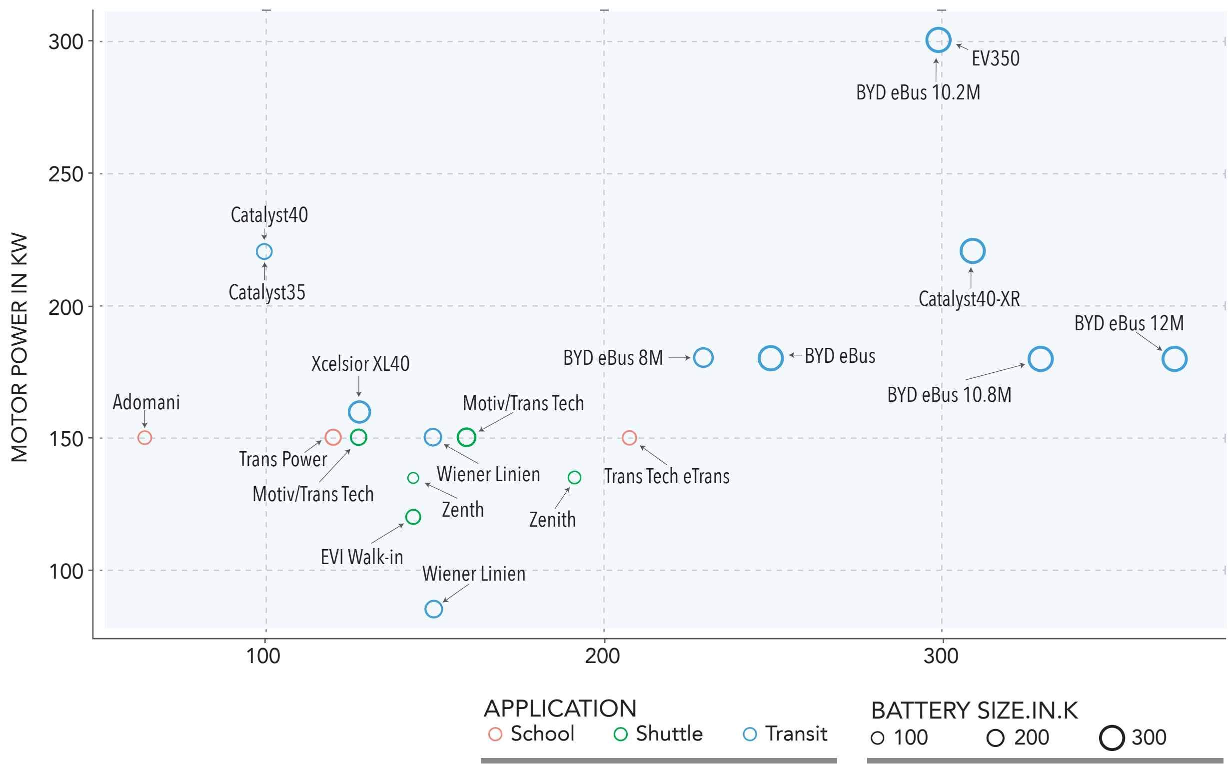


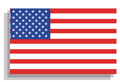
FIGURE 1.7: ELECTRIC BUS



02 NATIONAL PROGRAMMES

Globally, the turning point is considered to be the decision in September 1990 of the California Air Resources Board (CARB) to adopt the Zero Emission Vehicles (ZEV) norms. Initially, the portion of the new regulations that dealt with the ZEVs required that 2% of all passenger cars and light trucks sold in the state by every major car manufacturer must emit zero exhaust emission, beginning with the 1998 models. The percentage of ZEVs was to increase to 5% in 2001 and to 10% in 2003. This technology/ regulatory forcing was apparently resisted by the industry, so the electric mobility did not grow well.

In recent years, the situation has changed dramatically as a result of the Global Climate Change concerns (notably the IPCC report & UN Conventions/ Treaties) and the desire to reduce the fossil fuel demand through large-scale electrification of the light-duty vehicle



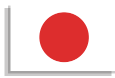
UNITED STATES

Cumulative ev Stock in 2012

71,174

National Target

1,000,000 by 2020



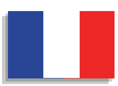
JAPAN

Cumulative ev Stock in 2012

44,727

National Target

20% of vehicle sales by 2020



FRANCE

Cumulative ev Stock in 2012

20,000

National Target

2,000,000 by 2020

CHINA

Cumulative ev Stock in 2012

11,573

National Target

5000,000 by 2020

UNITED KINGDOM

Cumulative ev Stock in 2012
8,183

National Target
15,000,000 by 2020

NETHERLAND

Cumulative ev Stock in 2012
6750

National Target
1,000,000 by 2025

GERMANY

Cumulative ev Stock in 2012
5555

National Target
1,000,000 by 2020

SWEDEN

Cumulative ev Stock in 2012
1285

National Target
6000 by 2015

PORTUGAL

Cumulative ev Stock in 2012
1862

National Target
750,000 by 2020

DENMARK

Cumulative ev Stock in 2012
1388

National Target
200,000 by 2020

SPAIN

Cumulative ev Stock in 2012
787

National Target
250,000 by 2014

FINLAND

Cumulative ev Stock in 2012
271

National Target
80,000 by 2020

fleet. Most developed countries have prepared roadmaps for the electrification of transport systems and have well funded programs that provide consumer incentives to offset the increased cost of the electrified vehicles to create the pilot domestic markets, and support to new technology developments, manufacturing of key component (like batteries) and for incubation of specialist/ startup companies. Many countries have set ambitious targets for electric vehicle penetration:[2]

2. Yong et al; A Review of the state-of-the-art technologies of electric vehicle, its impacts and prospects; Renew-able and Sustainable Energy Reviews, 49(2015), 365-385

The leading vehicle manufacturers now compete on the basis of technology leadership in electric-mobility. Toyota, GM, Renault-Nissan, Volkswagen, BMW, Daimler, Honda etc., and their suppliers now fully dominate the EV & HEV market. Most niche companies have given way to the dominant automobile companies, and only technology leaders like Tesla Motors remain as exclusively EV companies today.

Toyota started its Hybrid Electric Vehicle program in 1997 in response to the Kyoto Summit, where Japan had taken a lead in pushing the world towards mandated CO_2 reduction targets. The Nissan and Renault had taken an early stand for EV development. Although a late entrant, the Volkswagen has announced that all their 40 vehicle models will not be converted to electric-drive vehicles. Many leading OEMs are implementing technology programs for Fuel Cell technologies, linked to their national programs. All of this combined has created an ecosystem for Tier-1 companies like Denso, Bosch, Siemens etc. to run major component development programs for electric mobility, and that has provided a momentum of its own.

The global OEMs and their suppliers have prepared long term technology road-maps - some are focused on the Hybridization route from HEV to PHEV or REEV, while others like Renault-Nissan took a direct route to developing EV platforms, and some like Toyota seem to believe in Fuel-Cell vehicles for the future. The automotive sector has emerged as the largest R&D spender in recent years, in the US and Europe, perhaps due to this paradigm shift.

The objective of the FAME India scheme is the long term energy security, and sustainable growth of the transportation systems. The entry strategy into this rapidly evolving market segment is provided by the Consumer Incentives and Promotion of Supply Side Activities, and the long term capabilities will be enhanced through the Charging Infrastructure & Technology Platforms.

03 TECHNOLOGY HOTSPOTS

3.1 BATTERY

Since traction battery need to supply energy for a sustained period of time, deep Cycle batteries are used. The commercially available technologies at present are Lead Acid, Ni-MH and Lithium ion.

Pb-Acid batteries are most commonly used in EV2Ws and EV3Ws due to its wide spread availability, reasonable performance at low cost. Advanced Pb-Acid batteries have been developed in order to overcome some of the pit falls of the conventional lead-acid battery mainly for use in HEVs. Some of them like Carbon-foam based and Bipolar Battery offer potential for widespread use in 3W taxis.

NiMH batteries have a greater power and energy density (compact & lower mass), provide longer cycle life at lower cost of ownership than that of lead acid. They have been under development since 1970s, hence have been the battery of choice for many of the HEV models that include the Toyota Prius, Honda Civic and the Honda Insight types. They are no longer considered suitable, in the presence of Lithium ion battery. However, there are some efforts to revive other Nickel based battery like the NiZn system etc.

Lithium-ion batteries have several advantages (higher energy & power density, longer cycle & calendar life, absolutely maintenance free, no memory effect, operation at any SOC unlike issues of partial SOC operation with Pb-Acid system, >90% round trip efficiency, very low self discharge rate, low reversible heat dissipation, manufacturability in wide variety of formats) over lead acid and Ni-MH batteries. Based on the present trends, it is apparent that the lithium-ion is the most preferable option available, while pursuing long term efforts in the emerging options.

In the short term significant improvement in the specific energy/ energy density of batteries to provide ideal driving ranges for PHEVs and BEVs is not expected to happen. Better integration of batteries and making them abuse tolerant should be short term priority.

3.2 ELECTRIC MACHINES & POWER ELECTRONICS

Early day electric vehicles used the battery power mainly for traction, but in modern cars, there are a host of auxiliary systems such as power windows, entertainment systems, dashboard instruments, air-conditioning, wipers etc. Advances in power electronics have made these possible, and today even the conventional vehicle is largely dependent on power electronics devices. For electric and hybrid electric vehicles, power electronics hold even greater significance.

Energy Management is critical to the success of modern day xEVs. For Battery Electric Vehicles, the challenge is to maximize the range using the limited on-board energy storage while meeting power demands as per the driving pattern. This requires high efficiency of traction drive as well as that of all energy conversion processes. The need for higher efficiency and better maintainability have led to the use of AC traction motors, which require power electronics devices for their control. Quicker charging of electric vehicles is made possible with power electronics. Hybrid electric vehicles require elaborate energy management strategy – for the optimum shifting among multiple sources of energy, which includes utilizing the braking power to recharge the on-board battery pack.

Power Electronics is used to change the magnitude of current/voltage and/ or frequency of electrical power to suit various applications in the electric-drive vehicle. The use of cost-effective, high-efficiency Static Power Electronic Converters (with no moving parts) have made electric propulsion more practical. Various types of converters include AC-DC converter (referred to as converters) for battery charging, DC-DC converters for changing the voltage to appropriate level for powering the motor and auxiliaries. DC-AC conversion, i.e. inverters, are required for powering the motor. The Power Converters are manufactured using Power Semiconductor Devices which differ from the typical (control) electronic devices as they have to withstand high voltage and high current ratings and fast turn-on and turn-off characteristics. Achieving high efficiency, power density and thermal tolerance are the main thrusts for power electronics in xEV applications.

Among various types of motors, DC Motor, Induction Motor and Permanent Magnet Brushless DC Motor (BLDC) or Permanent Magnet Synchronous Motor (PMSM) have mainly been used. DC Motors are not used anymore due to maintainence issues. New topologies such as Switched Reluctance Motor and Synchronous Reluctance Motor are also being pursued.

3.3 WEIGHT REDUCTION

Significant mass reduction can be achieved when high density steel in vehicle components can be replaced with lower density material such as Advanced High Strength Steels (AHSS), aluminum, magnesium or composites. They require high level of engineering design for the products or components to meet required strength and rigidity. Other issues are end-of-life consideration for re-manufacture or recyclability. In EV the battery may weigh 15%-35% of the vehicle[3] . So the higher cost of light weight material may be offset by the reduction in the cost of battery needed in the vehicle.

The high strength steel body technologies like Hydro-forming, Tailor-welded blanks, Hot-forming and Laser Welding are widely used today to gain weight reduction of upto 15% in Body in White. Aluminum alloys are used extensively in high end cars for more weight reduction and better performance. Honda NSX was the first production car with an all-aluminum body, chassis, suspension, and engine. Audi A8 flagship car was designed as all-aluminium from the outset, and later it expanded to the full Audi lineup. Recently, there are dramatic examples like Land Rover reduced by 420 kg, the Ford F-150 Pickup Truck – the most popular vehicle in the US for 3 decades - is being reduced by 15% (700 pounds)[4] .

3. Besselink et al, 2010; Design of an efficient, low weight battery electric vehicle based on a VW Lupo 3L ; EVS-25 Shenzhen, China, Nov. 5-9, 2010

4. Ford's Trade-In: Truck to Use Aluminum in Place of Steel ; The Wall Street Journal; www.wsj.com

02
CHARGING INFRASTRUCTURE

01
CURRENT TRENDS AND CHALLENGES

Charging infrastructure is an essential component of the ecosystem of plug-in electric vehicles. Unsatisfactory specific energy of the battery and long charging time have been the critical bottlenecks for promotion of electric vehicles. Issues of range anxiety, battery pack size, and charging infrastructure are inter-related. Availability of adequate number of charging facilities may be able to reduce the burden of on-board energy storage system, however, with a likely increase in infrastructure cost. Hence a right balance between the infrastructure requirement and battery pack cost is required.

Compatibility and safety are major issues associated with electric vehicle charging infrastructure. Apart from this, in future charging infrastructure may need to play an important role in terms of offering flexibility of flow of energy, and would be required to possess adequate intelligence to support technologies such as vehicle-to-grid (V2G) systems.

Impacts on the distribution grid is another issue to be considered while discussing charging infrastructure for electric vehicles. The impacts are in terms of additional power demand on the grid, power quality, and impact on the grid assets.

TABLE 2.1: 'TYPE' REFERS TO SOCKET, INLET, PLUG & CONNECTOR DESIGNS IN IEC 62196

TYPE 1	SAE J1772-2009 (US standard); used for single phase energy transfer; uses power line communications for control functions between EVSE & EV.
TYPE 2	VDE-AR-E 2623-2-2 (European Standard); based on IEC 61851; supports single and 3-phase energy trans-fers
TYPE 3	EV Plug Alliance

TABLE 2.2: 'MODE' IN EU CHARGING STANDARDS REFERS TO POWER LEVEL & COMMUNICATION / CONTROL SIGNALS THAT INFLUENCES THE ENERGY TRANSFER BEHAVIOR

TYPE 1	Slow charging from a household-type socket-outlet
TYPE 2	Slow charging from a household-type socket-outlet with an in-cable protection device. It has protective earth and a control pilot function
TYPE 3	Slow or fast charging using a specific EV socket-outlet with additional protection function installed (charging station socket is dead if no vehicle is present), and it allows for an integration into smart grid scenarios
TYPE 4	Fast charging using an external charger. Using DC Fast Charging allows for considerably higher currents, up to 400 A. Connectors require a range of control and signal pins to ensure operation for fast charging

At present most plug-in electric vehicles depend on conductive charging technology. The inductive charging, though used in 1990s for GM EV1, did not find favour due to comparatively low efficiency. However, in recent years, encouraged by some better results based on so called strongly coupled magnetic resonance theory, wireless power transfer technology is gaining growing interests because of advantages such as no exposed wires, ease of charging and safe transmission of power in adverse environmental conditions. But, such systems require further developments before commercial use. Wireless charging technology opens up the possibility of charging the vehicle while on the move. Another option that has been explored and demonstrated is battery swapping technology.

FIGURE 2.1: SLOW CHARGER INSTALLATIONS

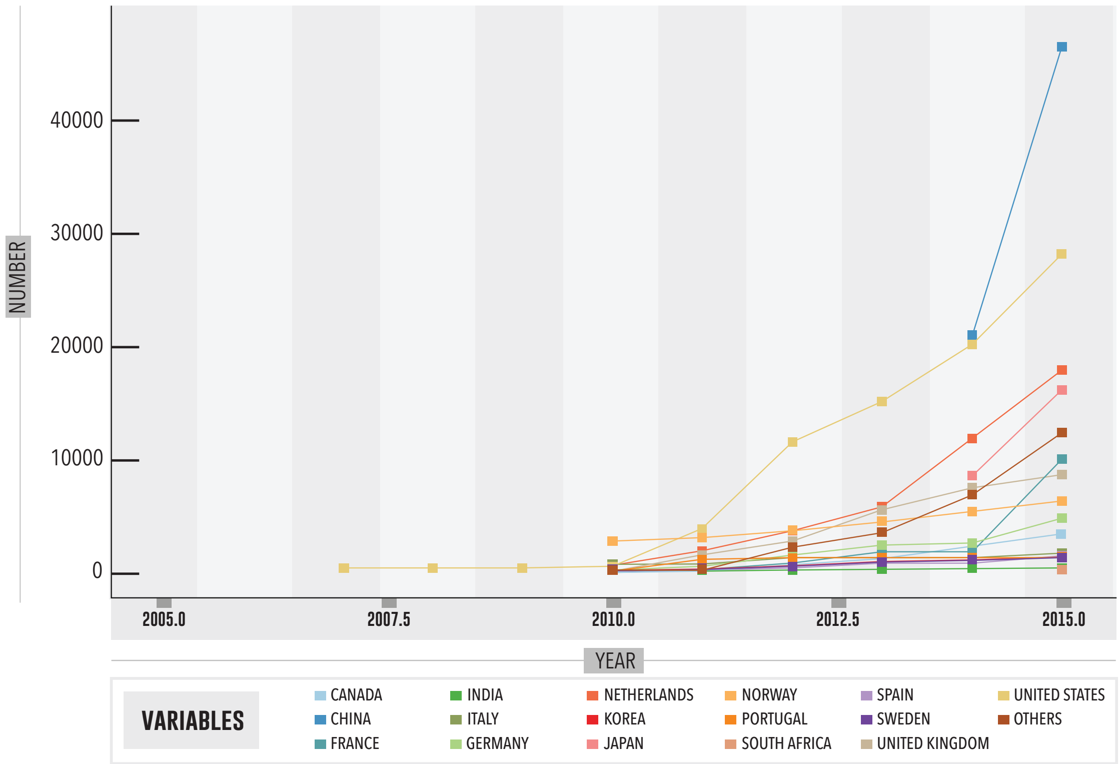


TABLE 2.3: CHARACTERISTICS OF xEVs IN INDIA

VEHICLE CATEGORY	TYPE	DRIVETRAIN VOLTAGE LEVELS (V)	DRIVETRAIN POWER LEVELS (KW)	BATTERY CHEMISTRY	BATTERY CAPACITY	DRIVING RANGE (KMS)
2W	BEV	48V - 72V	<2 kW	Pb acid & LiB	1-2 kWh present; 3-4 kWh future	50-100
3W	BEV	48V - 72V	<7 kW	Pb acid & LiB	5 - 10 kWh	50-100
SMALL 4W	Mild, strong, PHEV, BEV	48V - 72V	19 kW - 60 kW	LiB	10 – 15 kWh for BEV's; <5 kWh for PHEV's	100-200
LARGE 4W	Mild, strong, PHEV, BEV	>300V	~80 -100 kW for BEV	LiB	25-50 kWh for BEV's	100-200
MINI-BUSES	Mild, strong, PHEV, BEV	>300V	~50-60 kW for BEV	LiB	25-50 kWh for BEV's	50-100
CITY-BUS	BEV + overhead charging	>300V	>100 kW	LiB & others	100 kWh	50-100

All Plug-in EV variants (BEV, PHEV, REEV) will have on-board AC chargers (normal power) which convert the supply current into dc voltage appropriate for the vehicle battery pack. The Electric Vehicle Supply Equipment (EVSE) has been specified in competing ways by standards agencies. The Mission should develop affordable charging equipment for widespread deployment.

India offers large market for xEV, but it is very cost sensitive as well. There is possibility of large fleet/commercial mobility vehicles also. Hence a large deployment of public charging outlets is called for.

Single phase 230 V charging (~3.3 kW, 16 amps) will be adequate for regular home charging of 2W, 3W & 4W.

3-phase AC charging (11 - 22 kW, 16-32 amps) will be required for (a) High Performance Cars & BEV Buses, and (b) Extreme climate battery heating or cooling, and for cabin conditioning – additional phase can provide power to heating/cooling elements without degrading battery charging current.

1.1 INFRASTRUCTURE POLICY

Stakeholders will be electricity utilities & charging station operators, equipment suppliers, data and network managers.

Policy Interventions will include the specification of EVSE standards, as well as regulatory and legislative provisions to set up widespread charging facilities at homes, offices and public areas.

Regulatory amendments may be required to facilitate the commercial business of xEV charging, standards and safety precautions and facilitating installation of the charging equipment by apartment blocks and office buildings. There will be an emphasis on setting up of Public Charging Stations for fleet operations

TABLE 2.4: POLICY ACTIONS

AGENCY	ROLE	POLICY INTERVENTION REQUIRED
Utilities	Generating and distributing energy Billing the end-user for consumption Smart Grid management	Provision for retail "sales" by entrepreneur owned charging stations.
Property Partner	Provides space for the charging station infrastructure. This may include public institutions and cities like parking lots, railway stations, airports etc; retailers or shopping complexes; hotels	MoUD regulations for providing charging facilities in parking lots.
Charging station manufacturer	To create the infrastructure hardware necessary for charging EV batteries	Standardization; supply side incentives; government purchase scheme/ incentives.
Charging station retailer & Installation service provider	Operating the charging stations	Develop Business Model for catalyzing entrepreneurship in setting up charging station network
Charging Infrastructure Management Solution provider & Network operator	Managing integration of equipment from multiple vendors, updating equipment; billing information. Runs a network of charging stations offering service to customers either on membership or one time use basis	Technology Platform activities, Standardization & framing of appropriate regulations
Wireless communication service provider	Charging station availability and reservation, real-time smart charging, user/ car authentication and authorization, battery monitoring and remote control	Technology Platform activities, Standardization & framing of appropriate regulations. Link to Smart Grid forums/ agencies.

and for quick top-up charging by individual consumers. Where possible, attempt should be made to link the charging infrastructure to renewable energy generation systems.

1.2 CHARGER & EVSE CAPABILITIES

1.2.1. Vehicle side

All EVs shall connect to the charger though a predefined connector that carries the power and the protocol connections. Cars should accept a standard dc voltage input (for e.g., 48V) and must have the circuit to do the standard charging profile for battery in the car. A local display in the car in order to display state of charge, time to charge as well as time to replace battery indication will be necessary.

1.2.1. Charger behavior

The Charger should deliver a fixed DC output voltage with a limited Power Rating (e.g., 48v & 1000W). When deriving power supply from the grid, it should not worsen harmonic impurities on power lines, and specifications must provide for : Efficiency > 90%; THD< 10 % & Power Factor > 0.9. The charger must have overload capabilities and should automatically disconnect in case of an overload or tamper.

There should be some communication/ information exchange between the vehicle and the charging station to ensure appropriate charging suitable for the battery in its present condition, and also from the requirement of the business model. Communication for information exchange, and safety and cyber security aspects need to be considered while designing charging infrastructure and enabling their networks.

1.2.3. Communication Standards

Communication interface with the EV charging infrastructure is important for billing, demand response and utility perspective. The international standard available for information exchange between e-Vehicle and charging infrastructure (ISO / IEC 61851) and for vehicle to grid communication (ISO / IEC 15118) is to be studied along with Open Charge Point Protocol (OCPP) for communication between EV charging station and central management system.

02 DEPLOYMENT STRATEGY

2.1 EV CHARGING IN RESIDENTIAL AREAS

Standard household power sockets with power limiting power cables or dumb cheap AC chargers may become widespread. Charging devices at homes will be owned by EV owner. First right to parking in apartment parking lot with charging infrastructure should be of electric vehicles.

In future, when large number of EVs get sold, the uneven geographical distribution of EV population may result in higher capacity utilization of the transformers in specific geographic areas. Harmonic distortion can affect transformer currents. Transformers generally begin to fail catastrophically when they are loaded beyond 180%. The spatial patterns in the EV roll-out also have to be monitored, in order to assess potential impact on the distribution feeders at the EV charging spots (in terms of kW, kWh & power quality)

2.2 COMMERCIAL CHARGING FACILITIES

Public Charging Stations owned by place owners (like Petrol Pumps) or service providers (like Commercial Parking Lots) will be AC chargers up to 22 kW with communication interface and smart meters could be thought of. Second Sale of electricity in India is permitted only for Electricity Distribution Licensees; hence further clarifications to permit resale of electricity by entity other than distribution licensee should be given. The proliferation of Public Charging Stations will facilitate widespread use of EVs. The Utility can assess the load demand at Public Charging Stations more easily, compared to residential charging.

The entity creating charging infrastructure may have to be either permitted to take license from the appropriate commission or will have to operate as a Franchisee of the area's Electricity Distribution Licensee. It will encourage even the way-side restaurant owner to have a stake in keeping the charging infrastructure and parking bays in good fettle. Charging infrastructure entities may be exempted under Section 14 of Electricity Act, 2003. The Automobile Companies may be permitted to operate services on lease basis for SEZs, IT /ITES Companies, Industries etc.

One of the issues that may arise for chargers at different places (e.g., residence, railway stations, commercial centres, campuses etc) is that it may lead to unlawful drawal of electricity due to the tariff differential. Such aspects will have to be considered when designating appropriate locations for EV charging points and tariffs (DISCOMS may approach respective Regulatory commissions for creating specific tariff category for EV charging stations).

Fleet Charging Facilities: Entrepreneur/ Franchisee model should be considered for Battery-Pump/ Battery-Bank Model that cater to Taxi and Auto-rickhaw fleets, where function of Utility could be to supply electricity. Specification need to be worked out for Common Format for such facilities that may be set up in collaboration with Oil Marketing Cos (OMC), Battery Cos and Utilities operating in a particular region. In case of public charging stations, it is a challenge to interface them directly with the level voltages (MV) while keeping the harmonics at acceptable levels, due to the multi megawatt power levels. Hence appropriate charging devices have to be specified for Public Charging Facilities.

DC Fast Charging Stations network has to be promoted in major urban locations and highways. Utility may be allowed to set up and operate charging stations. Their existing infrastructure will make it easier to roll-out the charging stations network, and it will be easier for the government to regulate the stations owned and operated by utilities.

TABLE 2.5: CHARGING STATION MODEL

MODEL	ROLE OF DISCOM	RESPONSIBILITY FOR INVESTMENT		LAND OWNERSHIP	POSSIBLE TARIFF POLICY
		DISCOM	OPERATOR/ FRANCHISEE		
Model 1 (Power Supplier Model)	Supply power to operator	NA	100% capital investment + investment	Land owning agen-cy. Lease/ rent paid by the operator	Separate EV tariff on Time of Use (ToU) basis
Model 2 (Franchisee Model)	Installs charging station on sharing basis and supplies power	70% capital investment	30% capital invest-ment	Franchisee	Separate EV tariff on Time of Use (ToU) basis
Model 3 (Lease Model)	Installs charging station on lease basis and supplies power	5 years lease based charging stations	NA	Land owning agen-cy	Separate EV tariff on Time of Use (ToU) basis

Possible payment settlement options which could be offered to EV users are:

- Prepaid cards issued by DISCOMs/third parties
- Credit/Debit cards
- Cell phone credits
- Cash option
- Mobile wallets
- Reward points etc.

Different Business Models will require different payment settlement options. For example, E- Rickshaw fleet might prefer cash settlement and high end residential customer may opt for credit/debit card and loyalty/reward points for charging in shopping malls.

Model standard operating practices (SOP) for charging infrastructure may be developed.

2.3 PREFERENTIAL TARIFF FOR EV CHARGING

Based on the inputs from stakeholders like India Smart Grid Forum, some policy options that came up are as follows:

For home users, there could be two categories (which are commonly used in the United States):

- Home and EV on Time of Use (ToU): EV charging costs are incorporated into customer's total household electric bill. Only single meter is used for billing purpose.
- Only EV on Time of Use (ToU): Customer can opt to have in-home charging station on a separate meter which will keep EV charging costs distinct from the rest of the home. Unlike our other residential rate plans, the EV rate plans will not be tiered. There will be two separate meters one for home and other for EV charging.

Considering that there are a larger number of Two/Three Wheelers in India, the proposed charging options are recommended at:

TABLE 2.6: CHARGING OPTIONS

VEHICLE CATEGORY	CHARGING OPTIONS
Two wheelers	May be allowed to charge from normal plug points at residential tariffs at home and other commercial/industrial establishments at tariffs applicable to those establishments – no separate tariff for electric two wheelers
Three wheelers	May be able to charge only at public charging stations (special plug points) which can have a separate tariff – some cases the city governments can even subsidize electricity cost for charging e-rickshaws to promote clean public transport and reduce pollution within the city
Four wheelers	May be able to charge only from EV charging stations (special plug points) at home, offices and other public charging stations for which special tariffs may be designed by respective DISCOMS and SERCS considering the local priorities of each state/city/town
Electric Buses and other large public/goods transportation vehicles	Only from public charging stations (Special Plug Points)

Again the electricity tariff for charging of electric buses and other goods transportation vehicles could have special tariff as considered appropriate by the local authorities, DISCOMs and State Electricity Regulatory Commissions (SERCs). Fast chargers may be provisioned for Buses.

EV charging station: Use of differential pricing for different times of day and night may be promoted. Separate tariff category may be created for electric vehicle charging through public infrastructure which may be dynamic and concessional based on grid situation. Necessary Regulatory approval may be obtained for separate EV tariffs. DISCOMs to take up this matter with respective SERCs and State Governments. Use of differential pricing for different times of day and night may be promoted.

The pricing of the EV charging could be control mechanisms to manage the peak demand at a location. Time of Day (TOD) tariff or real time pricing mechanism will encourage more charging in off peak hours and thus improve the load-factors for some locations. Differential pricing can also control the number of vehicles being charged.

2.4 SMART CHARGING OPTIONS

In the long term, a large population of Plug-in EVs can assist the utilities to balance the grid with the possibility of EVs giving back energy to the grid at high demand periods.

The solutions to deploy will include:

- Demand response programs (smart charging and V2G to address peak electricity use, grid reliability),
- Grid balancing (matching supply with demand, integration of variable renewable generation)
- Electricity cost management (demand charge reduction, ToD and dynamic prices)
- Technologies and tools for customers and utilities (charging availability, time required, range, interoperability standards).

In the case of V2G, the charge/ incentive maybe based on net electricity consumption by the EV owner. However, there could be possibility of higher tariff rate in case of vehicle to grid energy transfer, to promote such technologies.

03 CHARGING STANDARDS

Development of the following are necessary for electric vehicle charging ecosystem in India:

- Standards and connectors for charging devices and connectors
- A Technology Platform for design & development of the charging devices, EVSE, plugs and sockets, Communications & Billing Platform etc.

3.1 AC CHARGING SYSTEMS

Typically, the xEVs will have an on-board charger to draw power from the power line at home or office, to recharge the xEV's battery pack. The on-board unit has a rectifier circuit to transform AC from the electrical grid to direct current suitable for the battery. Safety, reliability and user-friendliness are the major requirements for electric vehicle charger connectors. Charger/ Vehicle Communications is an important factor in ensuring the safety, reliability and efficiency of the charging process.

3.1.1. Available Standards

The dominant AC charger standards are listed below. Although the AC standards permit upto 60A to 80A current, the actual implementation are at considerably lower level.

- Society of Automotive Engineers (SAE) standard J1772 -2009 ; uses "Yazaki connector" and power levels up to 240V / 80A
- International Electrotechnical Commission (IEC) standard VDE-AR-E 2623-2-2; uses "Mennekes connector" and power levels up to 3@400V/63A.

3.1.2. AC Chargers Standards in India

The following two AC Public Charging specifications have been adopted in the Mission.

- Public charging EVSE's to carry 230 V, 15 A IEC-60309 industrial socket with an optional energy meter and RFID pre-paid card reader for payment, authentication, monitoring and control. Socket itself costs only a few hundred rupees, low cost approach to large scale penetration. Vehicles may carry charging cable with in-line RCD. The IEC-60309 socket has industrial (water-proof) versions suitable for outdoor use and are manufactured in India.
- Public charging EVSE with 230 V, 15 A IEC 60309 socket as well as a IEC 61851 Type-2 socket. Allows bidirectional energy transmission. The charging cable is equipped with two identical plugs. The "control pilot" contact enables data communication. While it can be used to 3 kW (fast) charge 2-wheelers and smaller 4-wheelers also, this connection is meant for high power levels that use 3 phase AC charging up to 400 V.
- In a workshop conducted by ARAI to discuss AC and DC charging standards to be adopted under this Mission, it was recommended that IEC 61851 can be adopted as the base standard, as it is widely used internationally.

3.2 DC CHARGING SYSTEMS

For 4W and larger vehicles, direct-current quick-charging systems provide a rapid means for recharging. It converts AC to high-current DC of about 500 V to charge the xEV battery to 80 % in less than 20 minutes. (DC connection, > 22 kW, > 32 amps). The fast charger accesses the Vehicle ECU to get information on battery voltage, current and temperature, and sends the optimum charging current by varying the power output to match the battery's state and ability to accept the charge. The Fast Charger costs nearly five times the cost of Level II AC charger.

3.2.1. Available Standards

There are four competing standards for DC fast charging, out of which the Mission decided to study CHAdeMO and China GB/T Standards, to choose a suitable standard. The SAE & EU version of fast chargers were found unsuitable for Indian situation.

CHAdeMO: Capable of up to 125 A current; voltages up to 500 V supported.

The CHAdeMO protocol connector is specified by the Japan Automobile Research Institute (JARI) G105-1993. The charging station has a dedicated transformer, and provides a maximum current of up to 50 kW (which is the optimal for fast charging of Lithium ion battery).

- Connector has 10 contacts: two large connectors for providing DC current and rest provide analog and digital communications for charging management and control.
- There is high level of data communication, using CAN bus protocol. An insulation check is conducted before charging, and the coupler is locked during charging via a mechanical latch as well as an electrical lock.
- To ensure protection from electrical shock, an isolation transformer separates the power system from the battery system. A leakage current monitoring device is also installed.
- CAN based communication protocol

China GB/T 20234: Supports up to 250 A and up to 700 V; Connectors available to support up to 250 A.

Open standard, CAN based communication protocol

COMBINED CHARGING SYSTEM (CCS) was developed by SAE. It adds DC Fast Charging to the existing AC Connectors, and put them into a common plug that can be used both at AC and DC charging outlets. It reuses the control & communication pins of the Type 1 and Type 2 systems used in AC charging for DC charging as well. The CCS in Europe and US have different shape and size for the Connector/Socket/Inlet (Type 1 in US & Type 2 in Europe). However there may not be much merit in such a multi-purpose large (expensive) connector under Indian conditions.

EN 62196-3 (EUROPE): Supports up to 200 A current, voltages up to 600V. Connectors from manufacturers are available only up to 150 A. PLC based communication protocol

US SAE J1772 COMBO: Supports up 200-450 V, up to 90 kW. Not applicable for India as input AC voltages are different in the US.

TABLE 2.7: COMPARISON OF DC FAST CHARGING STANDARDS

PARAMETER	CHADEMO	IEC COMBO	CHINA GB
Safety [1]	IP 67; 3 interlocks	IP 67; 3 interlocks	IP 67; 2 interlocks
Voltage range supported	Up to 500 V	Up to 600 V	Up to 700 V
Current range	Up to 125 A	Up to 200 A [2]	Up to 250 A
Station-side Connector Cost	High	Medium	Low
Reliability (>10,000 cycles)	Y	Y	Y
Vehicle socket Footprint	Medium	High	Medium
Communication protocol	CAN	PLC	CNA

[1] Chademo & IEC has a mechanical interlock in addition to software interlocks and 'pin-contact' check.
[2] Connectors from suppliers only available up to 150 A.

04 CHARGER DEVICE DEVELOPMENT

Development of low voltage charging infrastructure is essential in India considering that two and three wheelers dominate the electric vehicle market in the present scenario. Many of these vehicles use lead acid battery. However, it is expected that in future, there will be more use of lithium ion battery.

Development of communication protocol between the charging infrastructure and the control centre as well as the different charging stations is also necessary.

Regarding grid related development, stability of the grid while supporting a large number of electric vesicles, and bidirectional capability of the grid (Vehicle to Grid) are important issues.

4.1 LOW VOLTAGE DC CHARGER

The sub-category of 70/140A DC Charging is for 2W, 3W & hybrid kits fast charging needs. A specific low cost connector for 2W would be needed. The Connector proposed for 4W should work for 3W also; should specify the voltage range for connectors along with current. This category of DC charger can also be used for standalone solar charging stations, specifically developed for the purpose of charging small EVs.

4.2 HIGH VOLTAGE DC CHARGER

There are two categories of EVs to be considered in India. xEVs with lower voltage (48–72 V) drive-trains and high currents (200 A for 1C rate charging) and xEV's with higher voltage and lower current systems.

Since a single unit to cater to entire voltage and current range can be more expensive, the Mission could specify DC Fast Charger stations at 2 power levels:

- Stations capable of up to 200 A, up to 100 V, 15 kW power output. Lower power level stations less likely to face local distribution transformer capacity challenges.

- Stations capable of up to 200 A, up to 500 V, 50-60 kW power output.

The output power can be delivered through a connector to an EV only after the vehicle has been positively identified through a communication protocol either directly using the in-vehicle telematics or through the connectivity through the charging station.

The charger must have overload capabilities and may automatically disconnect in case of an overload or tamper.

4.3 EV BUS CHARGING SYSTEMS

The Mission has placed particular importance to the introduction of electric-drive in Public Transportation Buses. A few prototypes of HEV, PHEV and EV buses were demonstrated by the domestic manufacturers over the last 5 years, but they have not been able to firm up definite commercialization plans due to the higher costs.

TABLE 2.8 : SUGGESTED CHARGING INFRASTRUCTURE ROLL OUT

PHASE	AC CHARGING SOCKETS WITH RFID CARD READER	AC CHARGING EVSE WITH TYPE 2 SOCKETS	LOW POWER DC FC STATIONS	HIGH POWER DC FC STATIONS
Phase 1 Pilots	200 (50 x 4 cities)	0	50 (25 x 2 cities)	0
Phase 2 Build up* supported	2,000 (200 x 10 cities)	250 (25 x 10 cities)	250 (25 x 10 cities)	60 (15 x 4 cities)
Phase 3 Mass adoption	12,000 (300 x 40 cities)	4,000 (100 x 40 cities)	2,000 (50 x 40 cities)	600 (15 x 40 cities)
Total charging points	14,200	4,250	2,300	660
Estimated Cost per unit	INR 25,000	INR 50,000	INR 5,00,000	INR 15,00,000
Infrastructure setup costs (Crore INR)	35.5	21.25	115	99

Total Infrastructure Setup Cost estimate (Crore Rs.) 270.75. * Tier 1 cities could have 2x of Tier 2 city installations.

For example, the HEV buses would cost nearly three to four times that of a diesel or CNG bus, under the current circumstances, where the supply chain for the EV components has not developed in the country. The largest cost item is the Lithium ion Battery, which by itself will have a cost equivalent to that of a regular low floor bus! Hence, the strategy to conserve the battery is critical to roll out xEV buses in large numbers.

One option is to develop an xEV bus system that can replenish its battery charge at bus-stops. Novel ideas are solicited from the stakeholders for this, including overhead charging in the vicinity of the bus-stop (100m approach, at the bus-stop, and 100m while moving away); quick / partial swapping of battery; DC fast charging en-route etc.

EVs can be leveraged as energy storage devices for behind the meter applications by EV owners as well as virtual power plants by DISCOMs for grid support. This will require necessary regulation and policies for EVs to pump energy into grid.

Model standard operating practices (SOP) for charging infrastructure may be developed. Separate tariff category may be created for electric vehicle charging through public infrastructure which may be dynamic and concessional based on grid situation. Necessary regulatory approval may be obtained for separate EV tariffs. DISCOMs to take up this matter with respective SERCs and State Governments

Use of differential pricing for different times of day and night may be promoted. Differential pricing may be applied for locations that may see concentration at some time during the day and rest of the day very lean load. Example: EV chargers at or around cinema halls or malls where people would be away for 3 hours, might see shortage of spots and past cinema/mall hours those spots would be little or unused. To control the number of vehicles one could use differential pricing in these places. Differential pricing for EV charging could also help renewable energy integration – subsidized rates when surplus generation from RE resources on the grid.

Different Business Models will require different payment settlement options. For example, E- Rickshaw fleet might prefer cash settlement and high end residential customer may opt for credit/debit card and loyalty/reward points for charging in shopping malls.

Vehicle to Grid technologies may be considered and an EV owner may be charged with or incentivized on net consumption (import-export) basis.

Multiple ownership options may be allowed, including 3rd party deployment of charging infrastructure. Different business models have been tried in different countries with various combinations of a Battery Leasing and Battery Swap model executed through Charging Infrastructure solely owned by a Battery Supply Company and operated by the Battery Supply Company, Land provided by Oil Marketing Companies (OMC)/any other local land owner. Here the role of the DISCOM may be limited to provide electricity to Charging Infrastructure.

There are international standards available for information exchange between EV and power charging infrastructure and connectors (IEC 61851-1-2010 and 62196-3-2014) and for vehicle to charging station communications (ISO/IEC 15118 using Home Plug Green PHY over Power Line Communications), which can be adopted in India. The recent work of IEC 61851/62196 focuses on direct current (DC) fast charging.

There are international standards for enabling communication and networking of charging station infrastructure such as Open Charge Point Protocol (OCPP), which can be adopted in India.

There are international standards for enabling grid connectivity for demand response and price communications such as Open Automated Demand Response (OpenADR), which can be adopted in India.

Estimate of support required

Of the 3 phases, it is proposed that the Government may fund the full costs of Phases 1 and 2 to ensure large scale penetration of charging stations in the country. Phase 3 and beyond can be on a Public-Private-Partnership model with 50% funding from Government. Thus, total expenditure from Government funding is as follows:

TABLE 2.9: GOVERNMENT INVESTMENT IN CHARGING INFRASTRUCTURE (CRORE INR) 150.75 (~$25.1 M)

CHARGING STATION TYPE	PHASE 1 INVESTMENT	PHASE 2 INVESTMENT	PHASE 3 INVESTMENT
AC Charging Sockets with RFID card reader (Cr Rs.)	0.50	5.00	15.00
AC Charging EVSE with Type 2 Sockets (Cr Rs.)	0.00	1.25	10.00
L120.00ow Power DC FC Stations (Cr Rs.)	2.50	12.50	50.00
High Power DC FC Stations (Cr Rs.)	0.00	9.00	45.00
Sub-total per Phase (Cr Rs.)	3.00	27.75	120.00

Technology Development

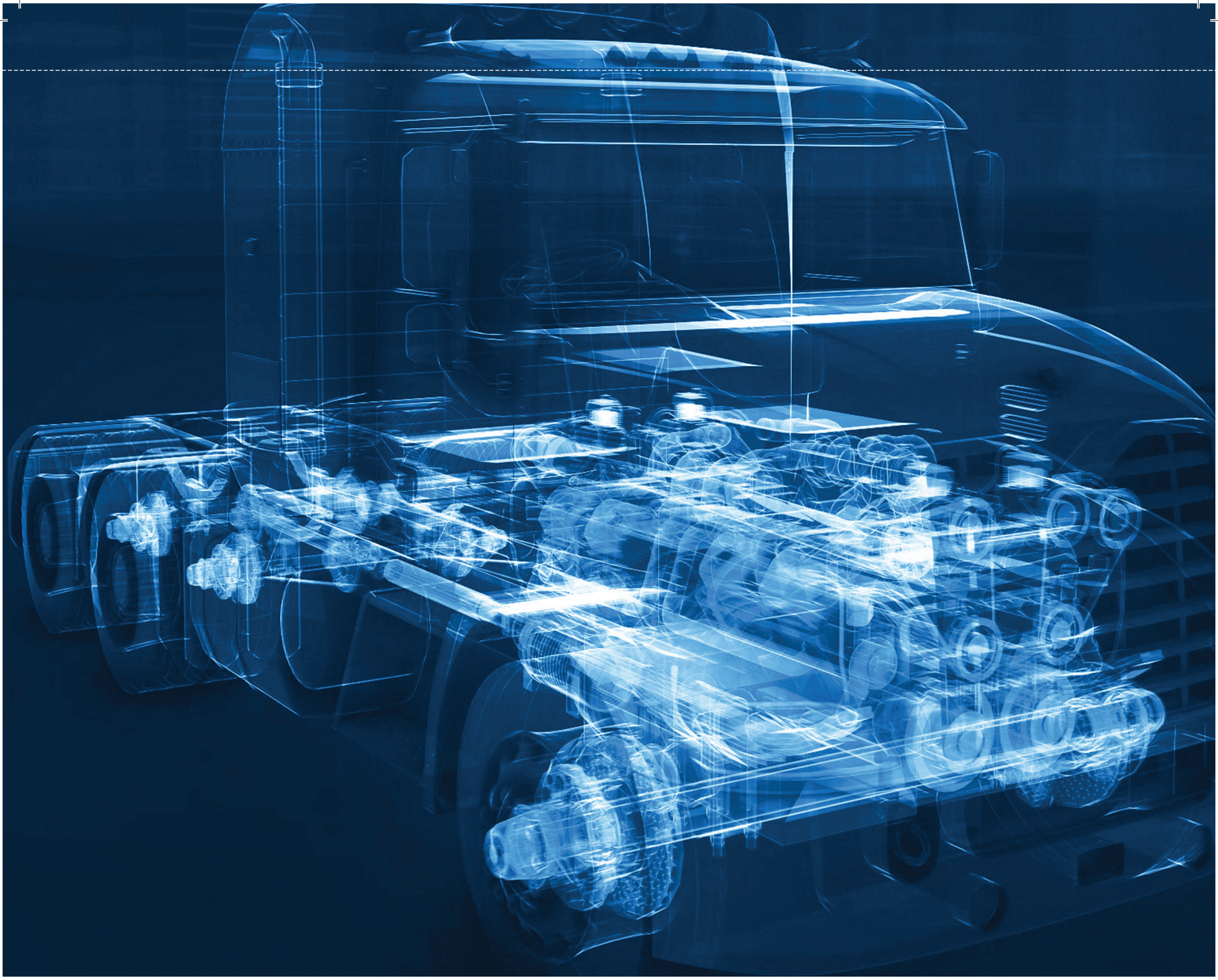
Technology development of electric vehicle chargers and grid interface issues may be taken up under the TPEM-4, Motors and Power Electronics.. This is covered in chapter 5 of this report.

03
VEHICLE SYSTEMS INTEGRATION AND LIGHTWEIGHTING

01 INTRODUCTION

The goal of Vehicle Systems Integration is to meet the desired vehicle targets through a holistic integration of the six major subsystems: Mechanical Systems, Thermal systems, Electrical Systems, Energy Storage System, Electronic systems and Controller networks. The process begins with defining each subsystem and its relation to other subsystems, followed by a dynamic analysis to ensure the desired performance of the integrated system. After confirming this, the prototype subsystems can be built. Systems Integration considerations are also influenced by the specific strategy for addressing range limitation, performance, cost and charging time.

Electric Vehicles (EV) require large on-board energy storage systems, which are currently quite expensive; but due to higher efficiency



of the electric drivetrain, the running expenses are low for EVs. The focus is on conserving energy withdrawal from the battery. The EV can be developed with a totally new design paradigm, but only a few of the current EVs have been 'purpose designed'; and most EV models maintain designs from the conventional vehicle platforms.

Hybrid Electric Vehicles (HEV) achieve improved fuel efficiency by downsizing the IC engine and adding an electric drive train, along-with complex electronic control for the optimum utilization of both the power sources. As a result, HEV cost 20%-50% higher than comparable IC engine vehicles (depending on type of hybridization). The best current HEV commercial technology is exemplified by the Toyota Prius HEV, which has highly integrated electro-mechanical systems with two electric machines and a special gear box for torque distribution. The HEV control system coordinates between multiple power sources and possible paths for energy-flow to obtain optimum fuel economy and performance.

The relative size of the IC engine reduces from Hybrid EV, Plug-in Hybrid EV to Range Extended EV. IC engine components are completely absent in BEV. Each of them offer different system integration challenges.

The Electric Drive System (in both EV & HEV) is composed of traction motor, control system (including motor drives, controllers), transmission, and wheel unit. The performance of the vehicle has significant dependence on the drive motor and its control.

Control System integrates the accelerator pedal, brake, stop, forward, reverse, neutral, steering wheel, and other signals. The key actions involve signal processing in the control unit followed by input to the motor drive to control the drive motor speed and torque, and transmission device then driving the wheels.

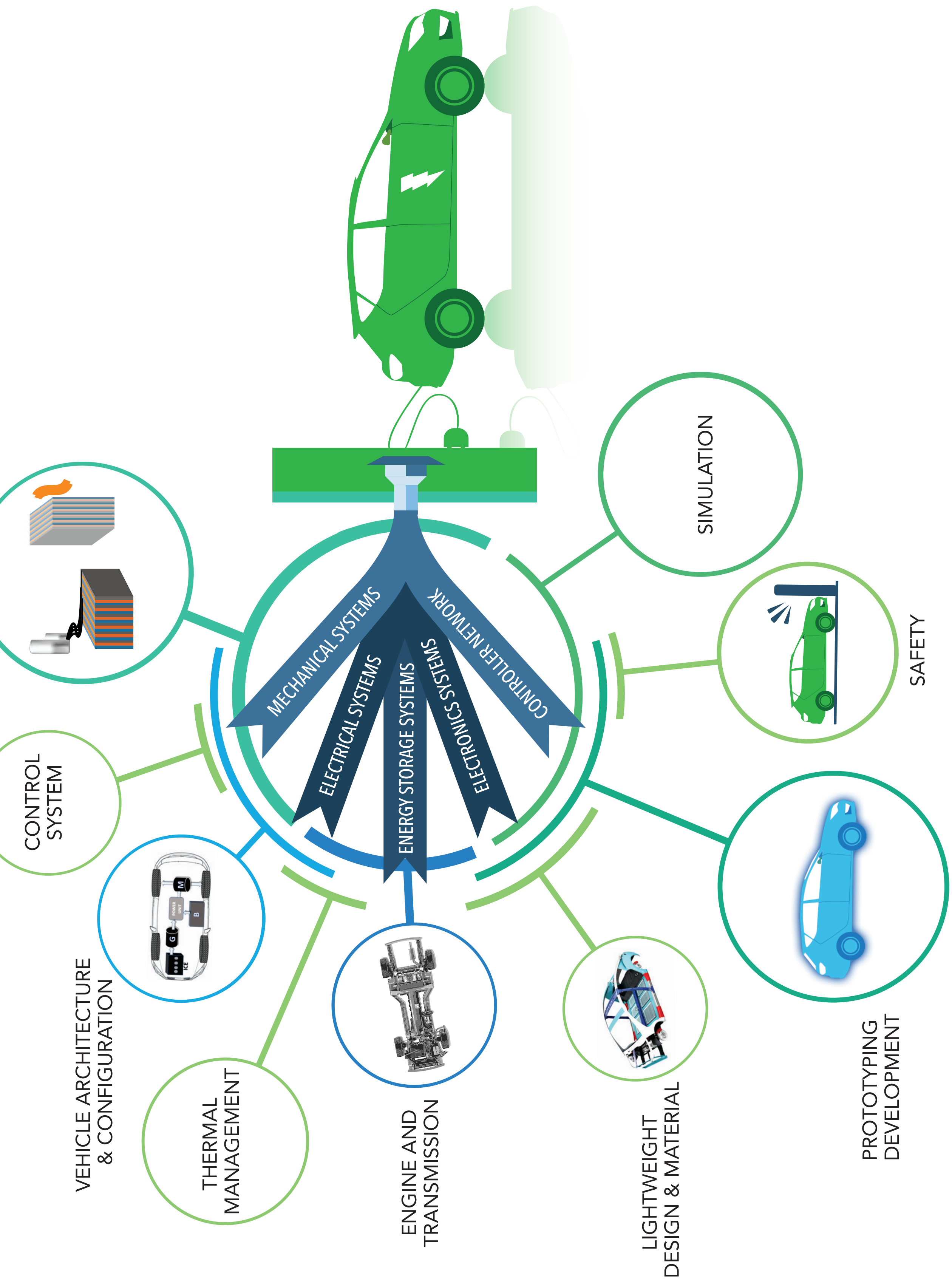
The vehicle's **Energy Management System** (EMS) collects operations-data on each subsystem, conducts monitoring and diagnosis functions, provides charging control, displays residual energy etc. The electrical power systems is specifically managed by Battery Management System (BMS), which monitors the battery parameters like voltage, current, temperature, discharge status, depth of discharge and avoids overcharge, over-discharge and voltage imbalance.

Various trade-offs have to be considered to get an optimized solution. The subsystems will have to be compact, with high power density and optimized thermal management, while complying to safety standards. The battery pack and the controllers have to be packaged efficiently. Even cables, connectors, fuse boxes, power distribution boxes and safety switches can create packaging and EMI/EMC challenges. The efforts to integrate, assemble, dismantle and service the subsystems can be expensive and complex from a software and hardware perspective. The trend is to go for mechatronics and electronics integration to get smaller packages. It increases reliability through better functionality, manufacturability and testability.

The electronic content in the modern (conventional, IC engine) car is already formidable due to the many "intelligent-subsystems" with their own control electronics, packed in engine compartment. Their integration and verification for safe and reliable vehicle operation has already become a challenge. In developing EV & HEV, the issues are more complex due to the interaction between electrical and mechanical components. It is quite difficult to predict the interactions among many vehicle components and systems due to the complex new power-train designs and the dependence on embedded software. A modeling environment (for working with model of components and embedded software) is needed, for the Systems Integration work for the xEVs. This can reduce development time and cost, and enhance penetration of xEVs.

> Efficient and intelligent integration of subsystems is critical to achieve desired vehicle attributes. There is significant scope for R&D efforts on drive train architecture, mechatronic integration, control, thermal management, light-weighting, safety etc.

FIGURE 3.1


PACKAGING
CONTROL SYSTEM
VEHICLE ARCHITECTURE & CONFIGURATION
THERMAL MANAGEMENT
ENGINE AND TRANSMISSION
LIGHTWEIGHT DESIGN & MATERIAL
PROTOTYPING DEVELOPMENT
SAFETY
SIMULATION
MECHANICAL SYSTEMS
ELECTRICAL SYSTEMS
ENERGY STORAGE SYSTEMS
ELECTRONICS SYSTEMS
CONTROLLER NETWORK

02 TECHNOLOGY TRENDS

2.1 xEV DRIVETRAIN

2.1.1 BEV Drivetrain Configuration

Table 3.1 summarizes various configuration of BEV drivetrain. One-motor based EV powertrains have been favoured, since they can maximize the utilization of existing mechanical systems in conventional ICE vehicles. This configuration essentially requires a differential to split generated torque to the wheels, enabling the wheels to be driven at different speeds when vehicles turn corners. Use of a single level reduction gear along with high speed electric motor can achieve a wide range of output characteristics and reduce size of the motor.

In Cascade type configuration, the differential gear is removed. Two motors are installed on body side and have joints provided to transmit power to the wheels to give a function equal to the differential. This is also called as the direct drive type.

From conventional type to four-wheel direct drive type, the power-train gets increasingly compact. 2014 Subaru XV Crosstrek Hybrid is an all-wheel drive vehicle. Tesla Model S is an all-wheel drive electric vehicle with two motors - one rear and one front. 2014 Mitsubishi Outlander PHEV is also a 4 wheel drive vehicle.

The wheel hub motor concept has the advantages of removal of gearbox, clutch, drive-shaft or differential, thereby contributing towards the weight reduction and energy efficiency. The direct drive in-wheel motors can provide greater flexibility to vehicle designers. But in case of wheel hub motor the unsprung masses are substantially increased, thereby reducing driving dynamics and comfort. The tyres become too heavy, causing driving discomfort, at least at higher speed and on uneven surfaces. New concepts try to solve this problem by using light weight material and new suspension concepts. In the two-motor based system, each of the two wheels gets speed and torque from the respective individual motors and dedicated converters. The mechanical transmission path is reduced. Whereas this system simplifies the mechanical structure, there is an increased complexity in electrical components and controllers.

Protean Electric has designed and developed an in-wheel electric drive system for hybrid, plug-in hybrid and battery electric light-duty vehicles. It is a fully integrated, direct-drive solution that combines in-wheel motors with an integrated inverter, control electronics and software.

TABLE 3.1: VARIOUS CONFIGURATIONS OF BEV DRIVETRAIN

ONE MOTOR TYPE EV POWER TRAIN	TWO/ FOUR MOTOR TYPE EV POWER TRAIN
(A) CONVENTIONAL TYPE The constituents of the EV propulsion system are a differential (D), a gearbox (GB), a clutch (C), and an electric motor (M). This configuration is similar to an ICE vehicle with rear-engine-front-wheel drive, where the ICE is replaced by an electric motor	D) NO DIFFERENTIAL TYPE In this configuration two motors are individually connected to each of the front wheels through mechanical fixed gearing and the differential is eliminated.
(B) NO TRANSMISSION, RF DRIVE This features Rear-engine-Front-wheel (RF) drive. However a fixed gear (FG) is used instead of a clutch and gearbox. Thus this configuration is also similar as the conventional IC engine power train.	(E) IN WHEEL TYPE WITH FIXED GEAR (FG) This type is similar to the no-differential type in (d), except different location of the electric motors. Electric motors are embedded in wheels for the in-wheel type. Two motors are fixed to the wheel side with reduction gears provided to drive the wheel
(C) NO TRANSMISSION, FF DRIVE It features Front-engine-Front-wheel (FF) drive. The electric motor is placed in the front, together with fixed gearing, and differential. This configuration is similar to ICE vehicles with front-engine-front-wheel drives	(F) IN WHEEL TYPE WITHOUT FIXED GEAR (FG) Mechanical gearing is completely removed for this type. The vehicle speed directly depends on the motor speed. Rear wheels and motors are integrated so that rotations can be caused directly without resort to gear. Four wheel direct drive configuration allows electric steering.

2.1.2 HEV: Degree of Hybridization

Micro Hybrid or Stop Start

Micro hybrids or Stop Start improve fuel economy by around 5-6% through minimization of engine idling loss. The engine is stopped whenever the vehicle comes to a halt, and is started instantly when the driver steps on the gas pedal. It is a low cost, near term option that gives good benefit in city driving.

There are two variants:

- The alternator is modified with a bidirectional belt/ pulley system. This integrated-starter-generator can produce limited amount of motoring torque, enough to crank a small engine.
- The belt-driven alternator is replaced with an electric machine that serves both as a generator and a motor. Thus when the engine runs, the electric machine acts as a generator, and charges a separate 36-V battery. When the engine needs to be started, the electric machine draws power from the battery, applies its torque via the accessory belt, and cranks the engine.

A micro-hybrid does not have provision for electric power assist or regenerative braking, technically this is not a hybrid system.

Mild Hybrid
It has stop-start function, regenerative braking and modest electric-only propulsion to provide fuel economy gain up to 35%. Mild HEV systems utilize a 36V/ 42 V battery and a belt-alternator system or integrated starter-generator. Honda's Integrated Motor Assist system used in Insight, Civic and new Accord models are good examples.

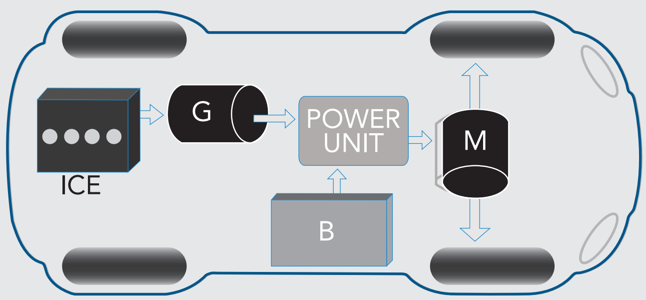
Full Hybrid
Full-HEV can offer a fuel economy benefit of 60% and can run on battery power, or on engine power or a combination of both. Some full-HEV models use the fuel-efficient Atkinson Cycle engine, instead of conventional piston engine. It achieves fuel-thrifty operations by using electronic control to get a greater expansion of the fuel-air mixture in the cylinder. It has a reduced maximum power, however in HEV, the electric motor can make up for this power loss.

Full HEVs require a large high voltage battery pack. System level efficiency can be enhanced by using the battery run accessories like power steering, air conditioning, water, oil pump and fan. Decoupling these accessories from the engine enables them to run at a constant speed, or being switched off.

2.1.3 HEV Powertrain Architecture
Figure 3.2 shows various architecture of HEV drivetrain. Every power train topology has specific advantages and disadvantages, and no clear trend can be identified in this regard. It is expected that most of these topologies will coexist in near future. The most used power train architecture globally throughout the years has been the parallel one, followed by the combined architecture. In terms of regional analysis of HEV architecture, it has been observed that European OEMs heavily focus on the parallel HEV power train architecture whereas Asian car makers use mainly the combined system. One notable example is Toyota HEVs.

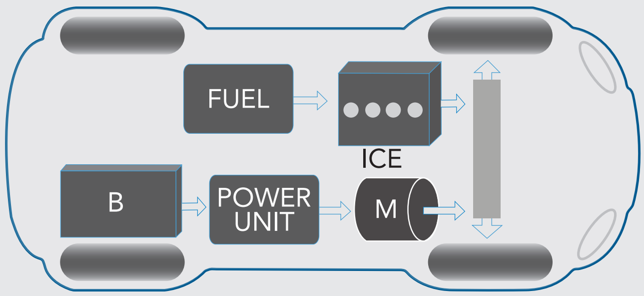
FIGURE 3.2
VARIOUS ARCHITECTURE OF HEV DRIVETRAIN

SERIES HYBRID



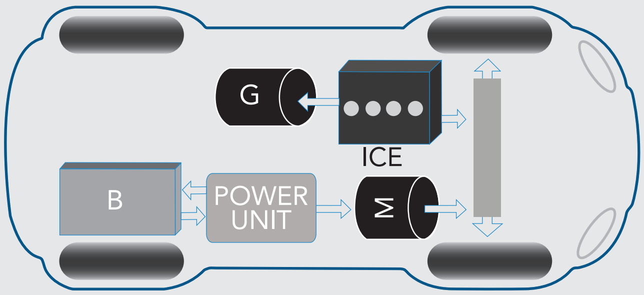
- Preferred in heavy-duty vehicles. No mechanical link between the IC engine and the wheels.
- A single reduction gear can be utilised, reducing complexity.
- The size of the IC engine can be reduced significantly
- High efficeintly, optimal engine, operating points and simpler transmission is possible
- Separate motor and generator
- Suitable for stop and go traffic

PARALLER HYBRID



- Both electrical and internal combustion systems are connected to the mechanical transmission
- Multiple operation modes possible
- Complex transmission design

SERIES-PARALLEL HYBRID



- A power-split device is used to optimally deploy the dual sources of power for any driving conditions
- The TOYOTA Hybrid Synergy Drive System is leading implementation of this system

2.1.4 Plug-in Hybrid

The PHEV uses larger battery and higher power electric motor, the engine and mechanical systems are downsized. They charge from grid power. PHEV has three possible operational modes – electric vehicle (charge depleting), blended and charge sustaining (CS). While it gives larger savings in emission and fuel consumption, the PHEV is also the costliest HEV variant. But since the battery and electronic component prices have been steadily dipping, they may have a large market in future.

Unlike the HEV, the PHEV battery will undergo deep discharging and it must be designed to have large energy capacity for the specified EV range, and its minimum state of charge (SOC) should designed considering the Charge Sustaining (CS) mode of operation, to meet the cycle life requirement. In 2005 Daimler-Chrysler built the first prototype PHEV Mercedes Benz Sprinter van. Toyota is a leading developer of PHEV.

A recent variant of the plug-in hybrid electric vehicle is the **Range-Extended Electric Vehicle (REEV)**. In this type of vehicles, a small internal combustion engine is provided just to provide additional range, when the battery runs out of charge. However, in REEV, there is no Charge Sustaining mode of operation.

2.2 VOLTAGE CLASSES OF xEVs

High Voltage (HV) systems provide many advantages, including improved fuel economy. To ensure passenger safety, certain minimum electrical isolation has to be maintained between the HV system and body/ chassis. Loss of insulation on electric powered vehicles is one of the more common failure modes. The automotive industry has adopted 60 volts as the threshold for HV and any voltage higher than this requires special considerations from the OEMs. The testing and diagnostic challenges associated with high voltage systems need to be understood.

For most hybrid and electric vehicles, the HV component family typically includes the battery pack, power inverter, electric-machines, dc-dc converters, and electric air conditioning compressor. There are various international and national standards dealing with protective measures. Especially standards dedicated to electrically propelled road vehicles are ISO 6469-3 and ISO 26262. Currently no standard is available for voltage ranges greater than 60 V DC in vehicles.

The DC-link voltage is the key design parameter for all the different drivetrain architectures. The voltage level for the DC-link vehicle bus is commanded by the main source of electrical energy in the system (high voltage battery). This dependency leads to severe limitations for the drivetrain architecture design, the component layout (especially the EM) as well as the energy management and control strategy.

To overcome this limitation, a high voltage DC to DC converter could be used to decouple the ESS voltage level from the vehicle DC-bus voltage level and gain an extra degree of freedom to be leveraged for system design, control and energy management. A well-known example for such a kind of separation between ESS voltage level and vehicle DC-bus in certain drive situation is the Toyota Prius since its second generation.

One major challenge for high voltage architecture is to take care of the variation of cell voltages. Typically, a high voltage pack requires a large number of cells in series. The voltage level of the cells may vary based on SOC. Accordingly, there could be wide variation of pack voltage. For example, a lithium ion cell could be rated at 3.2V and its maximum voltage could be 4.2 V. If 100 such cells are connected in series, pack voltage may vary between 320V to 420V. This fact underlines a major problem in designing a high voltage vehicle drivetrain.

Apart from this, the currently used semiconductors for devices like VSI are usually rated only for a maximum input DC-link voltages up to 450 V. The same is true for components like electric machines. At higher DC-link voltages components like electric machines need to be double checked and re-designed if necessary to achieve sufficient insulation requirements.

2.3 CONTROL

2.3.1 Electric Vehicle Control

Electric vehicles are essentially energy management machines. Since range of the vehicle is the main constraint, the controller needs to perform energy management efficiently, besides controlling the performance for smooth driving for comfortable riding. The controller enables an optimum balance of maximum speed, acceleration, performance and traveling range per charge.

An energy management system is needed to control the flow of power and to maintain adequate reserves of energy in the storage devices.

The most critical aspect of control of EV is the control of motor. Excellent performance of electric motor in motion control is an advantage for electric vehicles. The quick, accurate and easily comprehensible torque generation capability of electric motor enables fast and precise motion control. Motor can also be small enough to be attached to each wheel.

AN ELECTRIC VEHICLE CONTROL SYSTEM COMPRISE OF THE FOLLOWING SUB-SYSTEMS:

- **VEHICLE MANAGEMENT SYSTEM (VMS)**
- **BATTERY MANAGEMENT SYSTEM (BMS)**
- **AUTO DISCONNECT MODULE (ADM)**
- **MOTOR CONTROL UNIT (MCU)**

Traditional control algorithms like PID cannot meet the requirements of EV control. Generally Pulse Width Modulation (PWM) control is used for dc motor. Variable-voltage variable-frequency (VVVF), field-oriented control (FOC), and direct torque control (DTC) are used for induction motor. For PMSM, generally vector control and direct torque control strategies are used. Many modern high-performance control technologies, such as adaptive control, fuzzy control, artificial neural network and expert system are being used in EV controllers.

AC to DC conversion is required for the energy storage system of electric vehicles. Traditionally ac-dc converters are made of diodes and thyristors, and have the disadvantage of generation of harmonics and reactive power.

Some desirable features of the electric vehicle controllers are:

- Provision for a regenerative control function to save energy in battery and hence enhance the driving range per charge;
- Self diagnostics and restoration from failure;
- Scalable to function expansion;
- Comprehensive protection functions, including over-temperature protection, over- voltage and under-voltage protection, over-current protection, short-circuit protection, motor-lock protection, and protection for control unit, main switch and security, etc.

Development of high computing capability microprocessor such as DSP has enabled performing complex control on electric vehicles. In recent years most of the motor control applications have been dominated by software based solutions implemented in DSPs (Digital Signal Processors). These are characterized by low cost and ease of programming. However, with the increasing computational, functional and timing specifications of modern vehicular applications, DSP solutions are facing difficulties. For complex and time-critical applications involving multi-motor control, the sequential processing of the single-core DSP based solutions result in decrease in the controller bandwidth. Multi-core DSPs add costs and interconnection complexity.

Thus, Field Programmable Gate Arrays (FPGA) is emerging as an option to offload time-critical tasks from the DSPs, or even replace the DSPs control platform by a System on Chip (SOC) based on FPGAs. Due to high processing speed, execution times of the motor control algorithm is reduced. Parallel architecture and ability to handle multiple complex algorithms simultaneously in hardware make FPGAs suitable for xEV drive system applications such as VVC and motor control. The parallelism and modularity features also open up new possibilities to incorporate multi-motor control in a single chip. However, the main challenge for FPGA technology has been its high unit cost and designing time/ learning curve. Typically codes are written directly in hardware description languages, like Verilog or VHDL.

2.3.2 Hybrid Electric Vehicle Control

In HEV there are two energy sources, and one main task of the HEV control is to coordinate among these and find an optimum path for the conversion of energy. Depending on the driving situation, drive-train configuration and objective of the control strategy, the vehicle may use power from one or both of these sources at a particular time. Accordingly, the HEV drive-train has to interact with the braking systems, battery charge and discharge systems, combustion engine control, transmission and cabin controls.

All these require that the HEV control system has a Central Controller or Vehicle Management Unit. The top level monitoring of vehicle acceleration, deceleration, braking, clutch control, motor control and battery state etc. is performed by the Central Controller. It manages communication with the sub-system controllers through input and output signals.

Among the subsystem controllers, the important ones are:

- Engine Management System: Power and energy management of the engine
- Motor Management System: Speed control of the electric motor
- Battery Management System: State of charge, state of health and state of function of the battery

HEVs require many new electronic control units (ECU) not present in IC engine vehicles to control the electric motor, power inverter, battery, and driver information systems. Apart from that, even the existing systems of the IC engine vehicle like the engine control module and transmission control are also changed.

The HEV control system has to respond to the stimulus provided by the driver (such as braking and acceleration) and select the optimal operations among the five possible modes - motor only, engine only, power assist, recharge and regenerative - while taking into account the multiple data inputs on the current state of the vehicle (such as component temperatures, battery voltage, current, and state of charge)

In the power assist or recharge mode the HEV Control Strategy determines the engine power, motor power and transmission gear ratio to achieve the desired objectives of maximizing the fuel economy and minimizing emissions, while maintaining the expected performance.

The control strategy of HEV provides the intelligence that makes the components work together as a system. The hardware configuration and the power control strategy are designed together. Although hardware configuration dictates to some extent what control strategies make sense, there is still a wide spectrum of control strategies for each hardware configuration.

Individual components may be controlled by mechanical or electrical means. Mechanical Control includes clutches, throttles controlled by the accelerator pedal and dials on the dashboard, as well as other controls activated mechanically by the driver from the car's interior. In Electrical Control the on-board computers and software activate the relays and other electromechanical systems to perform the desired functions.

A primary function is to monitor and control the state of the batteries, to maintain the efficient working life of the batteries. The design approaches for the Energy Management System can be classified into four categories:

- Rigorous mathematical optimization methods with a comprehensive performance index or cost function (e.g. Sequential Quadratic Programming)
- Dynamic Programming Approach
- Intelligent Control Techniques

Static Optimization Methods focus on reducing the total energy costs. This method optimizes the power split between the two energy sources used, and requires relatively less computational effort. Dynamic Optimization Methods are considered superior as they assess the dynamic nature of the system to realize the optimal power distribution between the battery and the engine under diverse driving conditions. The objectives are high fuel economy, low emissions, charge balance etc.

Engineering rule based methods are based on engineers' experience. Rule based control system uses a set of simple rules in order to split the power between the two sources. One modern approach of rule based control is fuzzy logic control.

In global optimization control approach the optimum operating path is found though dynamic programming. The optimal operating points can be found if the whole speed profile is known in advance. But the actual speed profile depends on the driver and traffic conditions.

To address this issue, the optimization problem can be reduced to a local optimization problem. The two approaches for this are point wise optimization and interval optimization. The point-wise optimization techniques compute equivalent energy consumption at several operation points and minimizing control variables are computes off-line.

2.3.3 Plug-in Hybrid Control

Plug-in hybrid electric vehicles are essentially combination of an electric vehicle and HEV, having the all electric capability of an EV in urban areas and an on-board internal combustion engine for extended range capability. This added layer of operation has made control strategies for PHEVs significantly more complex. Existing PHEV control strategies are tuned to achieve the best fuel economy for specific driving conditions and are therefore not ideal in real world application due difficulties in predicting driving behavior. Hence control designers are shifting their focus to real time control strategies.

Most of the controllers for PHEVs are expansions of the controllers that have been designed for HEVs and have been modified to incorporate the electric only drive capability and the additional discharge range due to the larger battery pack. The all electric range adds significant complexity to the control design creating challenges for design engineers in terms of optimizing a universal controller.

A PHEV may operate either in charge-sustaining mode, or charge depleting mode. Rule based control strategies are inherently rigid. This has made the designers turn their attention to optimization based controllers. The cost function to be minimized is derived based on the vehicle and component parameters and performance expectation of the vehicle.

2.3.4 Simulation Tools

In terms of technology development tools, various computer programs exist for the simulation of vehicle power-trains, in particular hybrid electric power-trains. Such software tools include SIMPLEV, CarSim, HVEC, CSM HEV, V-Elph, ADVISOR, Powertrain System Analysis Toolkit (PSAT). Each major automotive company has its own specialized, proprietary modeling software. In addition, there are several test rigs and labs that conduct testing and development.

2.3.5 ECU Development

In most cases HEV controls development is synchronized with existing gasoline/diesel ECU development. Most OEMs did not follow the standard V-cycle for ECU development for the first generation hybrids. Model based development was not fully leveraged, rapid controls prototyping techniques were not used as much, and hardware-in-loop validation was used sparingly.

The engine control module (ECM) for HEV applications consists of approximately 80 per cent base ECU code and 20 per cent hybrid related code (e.g. to handle features like start/ stop, regenerative braking, power modes etc.). The additional hybrid features are mostly hand-coded by a dedicated group of HEV specialist software engineers.

Similarly most of the software development for the hybrid control unit (HCU) and the battery and motor control units (BCU, MCU) in the first generation of hybrid vehicles has been done manually.

A flexible platform for HEV development is required. A modern development approach could be as follows:

- The HEV components and energy management control algorithms are modeled and validated in the environment of Matlab/ Simulink/ Stateflow, and the off-line simulation is done to confirm the control algorithms.
- The floating point ANSI-C codes are generated in the tool of Matlab/ RTW/ Build.
- The automatic generated codes are compiled and downloaded into the AutoBox and the simulation on HIL is done to validate the control algorithms.
- The tested code of control algorithms are downloaded into ECU to have a test and modification
- Calibration of the control system is carried out.
- Model based control along with rapid prototyping. Universal rapid prototyping controller which can be easily adopted for development of vehicles.

The small IC engine cars in Indian market have much less number of ECUs as compared vehicles abroad. Thus software architecture standards with less number of ECUs may be appropriate for Indian EV/ HEV. This means that there is opportunity to introduce Software Standards for Small Cars (S3C) for Indian xEVs.

Tata Elxsi developed an AUTOSAR 3.0 compliant gateway electronic control unit (ECU) for Subaru hybrid electric vehicle, the automobile manufacturing division of Fuji Heavy Industries.

2.3.6 Networks & Wiring Harness

The cables and connections are major hardware issues which do not receive much attention in India. At present automotive electrical suppliers are used to working with 12 V systems for passenger vehicle and 42 V for commercial vehicles. Now with xEV, the voltage level may go up significantly. Electrical safety is a prime concern for such systems. The specific needs of High Voltage Cables, specific connectors need to be addressed. The basic electrical safety technologies are already in place for industrial applications. The challenge lies in making these technologies suitable for automotive applications. Since the voltage and current involved is very high, issues related to automotive high voltage cables, relays, connectors are to be addressed.

Increasing demand for the exchange of data prompted use of in-vehicle networking, which was introduced in 1980s. Major in-vehicle network technologies in use include The Controller Area Network (CAN), Local Inter-connect Network (LIN), FlexRay and Media Oriented System Transport (MOST).

However, the bandwidth requirement of modern vehicles is reaching a point where existing network technologies may either be insufficient, or not cost-effective. There is a high communication demand in electric and hybrid electric vehicles, due to the increased electrical components. In such context, use of Ethernet in automobile applications is becoming progressively important. The next generation of electric vehicles represents the unique opportunity for the adoption of new network topologies, with Ethernet playing a significant role in it.

2.3.7 Sensors

The automotive industry has increasingly depended on sensors and microcontrollers. Apart from basic power train operation various sensors have been widely used in the other applications like vehicle dynamics, body electronics, environmental control, chassis, emission, telematics, etc. to meet strict government regulations on safety, emission, efficiency, comfort, and driver assistance.However, in case of xEVs, sensors play further important roles.

Current sensing is essential in on-board battery management, traction motor drive, charging equipment and auxiliary systems & accessories. Two most commonly used current sensors are open-loop Hall effect current transducer and shunt-based current sensors. The key requirements for the current sensors are high frequency response (>100kHz), galvanic isolation to avoid issues related to HF common mode voltages, compact size, 5V operation, stable performance over the automotive temperature range, immunity to stray magnetic fields and low quiescent current.

Temperature sensors are used in battery packs, to determine the temperature of the windings of the traction motor. The requirements are robustness, reliability, galvanic isolation, high speed, low-cost, ease of integration, and low power consumption. They should be able to work in hostile environment, subject to electrical noise, vibration, mechanical shock, fluctuating temperatures, moisture etc. GE is developing low-cost, thin-film sensors that enable real-time mapping of temperature and surface pressure for each cell within a battery pack, which could help predict how and when batteries begin to fail.

Speed and Position of the moving component like motor, wheel, crank shaft needs to sensed continuously. Commonly used motion sensor technologies are magnetic, Hall-effect, optical and potentiometric.

Pedal Angle sensors are used to integrate regenerative braking and activation of the wheel brakes. To accomplish this, the driver's braking intentions must be detected electronically at the brake pedal and a signal to that effect must be sent to the control unit.

Resolver is a type of sensors used for measuring the rotational angle and position of Traction motor rotor.

Present sensor development is focused on making tiny, lightweight sensors by using optical fibres or thin film materials which will significantly reduce the size and cost of the battery (mainly Lithium-ion). Such new sensors technology will allow precise monitoring of the battery's current, voltage, temperature and pressure relay the information to the BMS which ensure performance and reliability of the entire Battery Pack with enhanced lifecycle and vehicle range.

2.4 ELECTRIC MACHINES

For EV and HEV applications, the general demand on electric motors are – small mass and size, large torque, high speed, high power density, quick response, good dependability, and EMC. In EV/ HEV applications, the electrical machines alternate frequently between motor and generator mode of operation, with wide range of speed and torque. Thus normal electrical machine design method is not sufficient for EV/ HEV electrical machines. Cost, weight and volume reduction are the major R&D issues related to electric motor.

Poly phase machines (synchronous & asynchronous) are mainly used in xEVs today. **Permanent Magnet Synchronous Machine** that have a very good overall power density, degree of efficiency (90-95%) and a relatively small, compact design are often preferred. However, due to the high cost and limited access to rare earth materials which are available primarily in China, there is research and development of externally excited electric machines, besides asynchronous (induction) machines. Apart from induction motors, switched reluctance motors are also being explored.

Induction Motors have been used in small city EV like the Renault Twizy or Th!nk City for cost reasons, but it is also used in high-performance cars like the Tesla Roadster, the Model S or the Audi R8 e-tron concept vehicle. Over 80% of vehicles using an induction motor are Battery Electric (EV) or Range-Extended Electric Vehicles (REEV). Very few Hybrid Electric Vehicles (HEV) that are propelled by this type of machine (e.g. Chevrolet Silverado Hybrid, 2004),

As mentioned in the context of different possible xEV layouts and power-train configurations the traction machine can be installed as

- One single central motor, as front-, rear- or axle-split-motor. Use of one single electric motor is still by far the preferred solution, regardless of the installation place as central motor or axle motor. As the axle motor is gaining significance, from 2009 on, OEMs tend to use 2 electric machines in the car more often.
- Inside the wheel-hub (in-wheel motor) with usually 2 or 4 motors installed, allowing for superior driving dynamics in terms of e.g. torque vectoring and all-wheel drive. The in-wheel motor has been mainly used in high performance prototype cars like the Brabus Project Hybrid or the Infiniti Emerge as well as large luxury cars like the Citroen C-Métisse.

An analysis of the power density of all HEV and BEV from 2006 to 2012 shows an increasing trend, starting at about 0.5kW/kg in 2006 and arriving at over 1kW/kg in 2011/2012.

R&D programmes on electric motors attempt to increase the efficiency and power density, in order to reduce the size and weight of the traction motor. For example, U.S. Government aims to raise the power density up to 1.6kW/kg and 5.7kW /l in the midterm. Another challenge for current research is that in the past electric machines have mainly been developed for industrial applications. The specific requirements in the automotive environment concerning durability, temperature resistance and freedom of maintenance need to be incorporated into the development of electric motors for future vehicles.

In the early electric vehicles with dc motors, a simple variable-resistor-type controller controlled the acceleration and speed of the vehicle. With this type of controller, full current and power were drawn from the battery all the time. At slow speeds, when full power was not needed, a high resistance was used to reduce the current to the motor. With this type of system, a large percentage of the energy from the battery was wasted as an energy loss in the resistor. The only time that all of the available power was used was at high speeds. The most common type of DC Motor controller uses the 'pulse-width modulation' technique.

Subsequent to arrival of better and less expensive electronics, ac motors have become more popular.

In-wheel motor technology has several advantages in terms of saving space for chassis, passenger or cargo, and also in terms of reducing parts counts and offering better design freedom. Potential for regenerative braking is increased. Better traction control, anti-lock braking and anti-skid capability can be achieved as each of the wheels can be controlled separately. No gearbox is needed if in-wheel motors are designed to operate in direct-drive configuration. However, technical challenges of in-wheel motor technology are introduction of excess unsprung mass and mechanical brake integration.

2.5 HYBRID TRANSMISSION SYSTEM

The optimum transmission of the hybrid electric vehicle depends on the system architecture, along with other factors.

Series Hybrid Vehicle Transmission System can be simple, since the electric motor drives the wheel and there is no direct connection of the transmission with the engine. The motor speed can be controlled electronically, and in many cases a single reduction gear after the motor is enough.

Parallel Hybrid Vehicle Transmission System is more complex than in usual vehicles, since the driving torque to the wheels is provided by electric drive and/or internal combustion engine. Apart from this, when the engine produces more power than is required for propelling the vehicle, the electric drive can be used to act as a generator to recharge the battery. Since parallel hybrid vehicle involves load sharing between two independent driving sources, clutches are required to separate internal combustion engine and electric drive from the drive shaft.

In order to maintain certain peak power density for the battery, a multi-speed transmission is required between the electric drive and the differential. While different transmission solutions have been implemented for HEVs, most state-of-the-art parallel hybrid systems utilize **Continuously Variable Transmission.** Toyota (Prius & Lexus RX-400h) uses a CVT with a specially designed planetary gear configuration, which is discussed in detail in the next section. Nissan (Tino Hybrid) system is similar but instead of the planetary gears they have used CVT with clutch plate. Honda (Insight, Civic) uses belt and pulley type CVT,

In **Toyota Hybrid Synergy Drive** an electromechanical system replaces the usual geared transmission system. A Power Split Device split the power produced by the gas/petrol engine between the drive train and the generator. It uses a planetary gear consisting of a ring gear, pinion gears, a sun gear and a planetary carrier; by controlling the rotation rates of certain gears, the system is made to act as a CVT with a power splitting and sharing mechanism. Electric motor, output shaft & differential are connected to the ring gear. Generator is connected to the sun gear and engine-output-shaft is connected to planet carrier/gear.

Automated Manual Transmission may also have potential applications in parallel hybrid electric vehicles, specially in light and heavy duty commercial vehicles. By using the electronically controlled AMT, users can achieve the optimal gear shifting, with regard to the efficiency of the hybrid drive-train. Owing to the speed control of the induction machine and the diesel engine at gear shifting, the synchronization is always guaranteed and it reduces the shift shock and shortens the shift time. However, AMT use in commercial hybrid vehicles has started only recently (2017 Suzuki Swift Hybrid)

Quest for higher drive-train efficiency has led to the efforts to simplify transmission of hybrid vehicles too. In 2013 Honda Accord a single fixed gear is used only at highway speeds. At city speeds, the gasoline engine is disconnected from the wheels via a clutch and instead only spins an electric generator. At speeds of less than about 40 mph, the car is completely reliant on electric motors for acceleration.

2.6 ENGINES FOR HEVS

In Hybrids, the demands on the internal combustion engine will differ, depending on the hybridization architecture and control strategy. Achieving higher efficiency is the major thrust for the developmental efforts for engines for HEVs.

The **Atkinson Cycle Engine** is used in Toyota Prius, Ford Escape/ Mercury Mariner/ Mazda Tribute and Toyota Camry. A modified four stroke engine using Atkinson cycle provides good fuel economy, but at the expense of a lower power per displacement than a traditional four-stroke engine. A small amount of fuel air mixture is allowed to flow back from the cylinder into the induction system, without being burnt, thus reducing the effective displacement of the engine. The expansion ratio of Atkinson Cycle engine is greater than its compression ratio as it takes more heat from the exhaust gas instead of pumping them into the exhaust system, thereby achieving 10% higher efficiency as compared to Otto cycle engines.

A new engine concept, the **Wave Disc Engine,** has advantages of very high efficiency (60% obtained in lab-scale design), reduced number of parts, and 20% lightweight as compared to conventional engines. The engine has no piston, crankshaft or transmission. It does not require any cooling system. This technology is still at the R&D stage.

For range extended electric vehicles, the development of compact range extender engine is necessary, and these alternative engine types can be explored.

2.7 AIR-CONDITIONING

When the vehicle stops at traffic signal, the hybrid vehicle can switch off the engine to gain fuel economy. In traffic with frequent stop-and go also, the hybrid control system may switch off the engine frequently. However this presents a functional difficulty for the conventional air-conditioning system, since the compressor is driven by engine power, using a belt. The initial hybrid models (2002-2006) of Honda (Insight, Civic) and Toyota (Prius) had used conventional air conditioning, and showed significant drop in fuel economy with air conditioning running.

Two different approaches have been developed to address this issue.

In the second generation Toyota Prius & Lexus Hybrids, which are high voltage systems, the air conditioning compressor is integrated with a high voltage 3 phase AC motor and control inverter.

Honda Hybrid vehicles use parallel configuration and a lower voltage system. So an electric air compressor system with high current draw cannot be implemented. Instead, a hybrid dual scroll air compressor is used in 2006 Honda Civic Hybrid and 2005-2006 Honda Accord hybrid. It has a conventional 75 cc belt (ICE driven) compressor at the front. A three phase high voltage electric motor drives the rear 15 cc electric scroll compressor. The control system determines if the AC runs either 'belt only', 'electric only' or 'belt and electric' operation.

2.8 COMPONENTS INTEGRATION AND PACKAGING

In terms of integration of various components/ subsystems like battery, motor, inverter/converters, engine, transmission etc., the major considerations are safety, compactness, weight and thermal management.

2.8.1 Battery integration

Typically lithium-ion cells are connected in series and/or parallel to achieve the required capacity, voltage and energy ratings from the pack. It should meet requirements of the motor and auxiliary, as well as the desired electric range of the vehicle. The challenge is to get best performance of the battery pack in its operating environment. Issues that need to be considered include battery chemistry, cell packaging, electric connection and control, thermal management, assembly , service maintenance as well as recycling.

The battery housing should make optimum use of the available installation space. Safety of the passengers, vehicle as well as the battery pack itself need to be considered while designing the battery pack and its integration with the vehicle. Protection of the individual cells needs to be taken care of.

Lightweight design and functional integration of the battery pack have received significant focus. Some R&D projects pursue development of lightweight crash safe battery housing made of fibre composite materials, which is expected to weigh 25% less than the conventional steel housing. The housing provide protection from humidity, while allowing the battery to 'breathe'. Some other R&D progrmmes follow the approach of using innovative sandwich materials made of aluminium face sheets and a core of aluminium hybrid foam for the battery housing. Such a technology is expected to result in 10-15% weight reduction as compared to the state-of-the-art.

Optimized Storage Integration for the Electric Car (OSTLER), a consortium project under the European Commission's FP7 Green Car Initiative and Sustainable Surface Transport call, has adopted a storage-centric design approach. The project will also investigate the feasibility of removable storage elements that enable the customer to mount or dismount part of the energy storage bases on his daily needs for the range-speed balance. There are many scientific and technological challenges for development such a system meeting all homologation requirements for passenger cars, and remaining hazard-free over the lifetime of the vehicle.

Another important issue for design of battery pack and its integration with the vehicle is influence of the battery mass and its position on the driving dynamics.

The battery can be installed in different places within the vehicle. Majority of OEMs prefer to place the energy storage devices in the under-body of the car. From 2006 on, the number of vehicles with under-body batteries increased significantly. Other packaging solutions for batteries – like centre tunnel, trunk, rear and front of the vehicle – have significantly lower shares.

2.8.2 Motor & Inverter integration

The electric drive system mainly comprises motor and the inverter, and these two components occupy significant amount of space. Efforts have been directed towards integration of motor and inverter to save space and reduce weight and cost, allowing more space for battery. The cost of wiring the motor to the inverter is eliminated. Siemens has developed one such integrated drive unit Sivetec MSA 3300 on the basis of a series electric motor. It features electric car's motor and inverter in a single housing. A major challenge for such a system is to have a common cooling system for both the components.

Usually inverters in electric cars always have their own water cooling system. In an integrated system, it should be ensured that the proximity of the electric motor does not affect the output or service life of the inverter's power electronics. Some arrangements should be made to create a thermal isolation between the two units. Since contact between the chip and the bonding wire is the weak point of semiconductor components under the condition of fluctuating thermal loads. In case of Siemens integrated drive, the SkiN bonding technology has been used to connect the surface of the semiconductor chip, thereby eliminating need for bonding wire.

Under the European research project **"MotorBrain"**, a prototype featuring the integration of motor, gear drive and inverter has been developed by a consortium comprising Infineon Technologies, Siemens, the Institute of Lightweight Engineering and Polymer Technology at the Technische Universität (Technical University) Dresden and ZF Friedrichshafen. It has only three-quarters the size of models from 2011, when the project began. This resulted in the weight reduction of the powertrain by approximately 15 percent, from 90 kilograms to less than 77 kilograms. It is estimated that a medium-sized vehicle with MotorBrain electric motor rated at 60 kilowatts would be able to drive 30 to 40 kilometres farther than today's electric vehicles with their average range of approximately 150 kilometres per battery charge.

In another R&D effort, **integration of electric motor and compressor of air conditioning** system has been achieved by the scientists from Nanyang Technological University (NTU) and German Aerospace Centre (DLR). It is estimated that this technology can increase the range of electric vehicles by an additional 15 to 20 per cent. The compressor can also tap energy available from regenerative braking.

In India, the air-conditioning unit will have to be run with battery power. Hence the technologies that reduce weight of powertrain components and allow more space for battery are very relevant.

2.8.3 On-board Charger Integration

Typically electric vehicles are provided with an on-board charger so as to provide the flexibility of charging the vehicle anywhere. However, it contributes to the vehicle weight and also occupy space. Since the vehicle is not charged when it is on the move, the traction motor and inverter of the powertrain can be used as an integral part of the converter for the on-board charging. The motor windings serve as inductor. This can also support bidirectional flow of power, with the vehicle supplying power to the grid when not in use. The Chalmers University, Sweden has developed integrated charger at laboratory level and is conducting further investigations and experiments to achieve a more optimal system. Volvo is involved with further works on the system.

The research approaches are:

- Use of traction motor windings as inductors for converter to develop the charging system. No additional component is used.
- Traction motor windings used as filter components.
- Reconfiguration of stator windings of a special electric machine
- Interior permanent magnet traction motor used for charging with power factor correction
- Use of three phase machine windings and three inverter phase legs with an interleaved configuration to distribute the current and reduce the converter switching stresses.

2.9 THERMAL INTEGRATION

The vehicle thermal management system needs to balance the needs of multiple sub-systems. Some may require heat of operation, some require cooling for rejecting heat, and some may require operation within certain temperature ranges. Integration of thermal management systems for various components of xEVs can play an important role towards the success of these vehicles.

Hybrid and plug-in hybrid vehicles have more complex powertrain with increased component count. This complexity increases challenge for designing suitable thermal management system within affordable cost, weight and size.

The issue of integrated cooling system for motor and inverter has been discussed in the earlier section. Integrated cooling loop for HEV is one of the research goals under the US DOE Vehicle Technologies Program, which estimates a cost savings of approximately $188 for a hybrid such as the Toyota Prius.

For optimum design of xEV thermal management systems evaluation of the transient and continuous heat loads of the individual components is required. There are research efforts towards establishing a linkage between various thermal systems including heat-pump air-conditioner, waste-heat from the electric drivetrain, and a heat exchanger between the air-conditioner refrigerant and powertrain coolant water.

Use of phase-change materials have also been proposed and investigated. The heat generated during discharge of battery and stored as latent heat can be utilized during charge, and a smaller part of it is transferred to the surroundings.

The lifetime of the lithium ion battery is maximized at an operating condition of 25°C. Thus the battery pack needs to be cooled or heated depending on surrounding temperature.

2.10 REGENERATIVE BRAKING

Regenerative braking has been used in many modern electric and hybrid electric vehicles. They also require mechanical braking, since regenerative braking is not effective at low speed, and may fail to stop the vehicle in required time. There could also be electrical failure.

Several concepts of kinetic energy recovery systems for vehicles exist

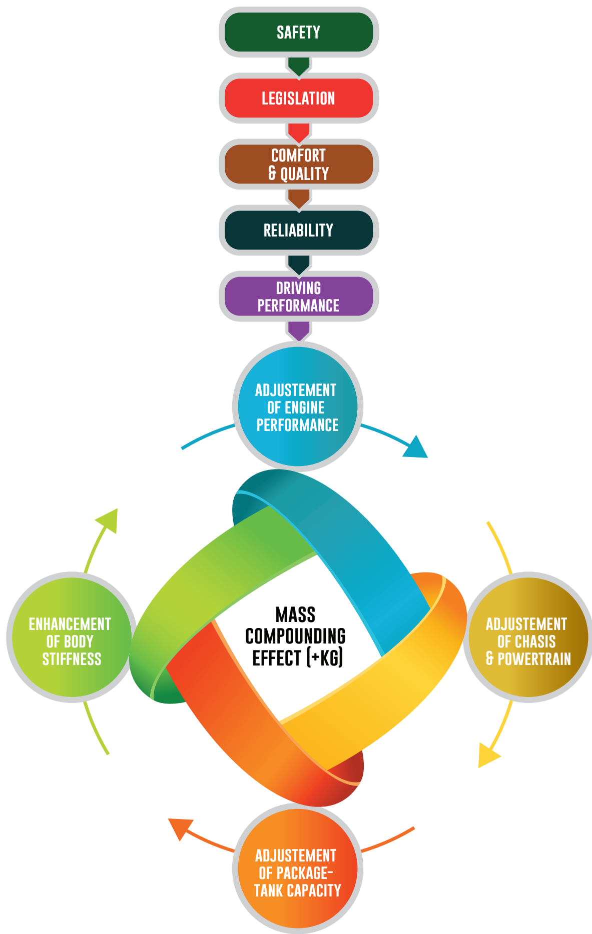
- Most systems use traction battery to store the energy recovered. These include General Motors EV1, Toyota Prius, Honda Insight, the Vectrix electric maxi-scooter, the Tesla Roadster, the Tesla Model S, the Nissan Leaf, the Mahindra Reva, the Chevrolet Volt, Fiat 500e, and Ford C-Max etc. Presently Bosch, Continental, Lightning Hybrids, Mazziotta Motors, TRW, XL Hybrids are manufacturing these regenerative braking systems.
- Use of flywheel for kinetic energy recovery is another option and is particularly suitable for heavy hybrid vehicles. With the advances of materials supporting high speed operation, the feasibility of use of flywheel in such vehicles has been enhanced.
- Other storage options include hydraulic storage and ultra-capacitor.

2.11 LIGHTWEIGHT VEHICLE DESIGN

2.11.1 Importance of Lightweighting of xEVs

A key challenge for electric vehicle manufacturers is to strike a balance between range and performance on one hand, and vehicle weight and cost on the other hand. Reduction of vehicle weight can play a very important role in this context. While light-weighting has been considered as an important technology option for fuel economy improvement of conventional vehicles, it assumes much greater significance in case of electric and hybrid electric vehicles. For a BEV, the contribution of the battery to the vehicle weight is about 15% to 35% of the total vehicle mass. The extra weight that a battery adds to a vehicle amounts to between 140 kg and 450 kg, depending on the model and concept. Since battery pack contributes major share of the overall vehicle cost, lightweighting measures could be more viable in case of xEVs. Secondary weight reduction through powertrain resizing can be of much higher magnitude in case of xEVs.

FIGURE 3.3



Achieving real mass reduction become increasingly challenging as new vehicle models tend to be heavier as compared to similar older models, due to addition of advanced features such as safety and entertainment systems etc., and its compounding effect. This is a phenomenon termed as "mass creep". Lightweight measures are necessary to compensate the additional vehicle mass and thus the extent of lightweighting efforts required to achieve net benefits in terms of fuel economy or performance improvement are often associated with significant incremental costs, which is the main reason for the limited usage of these measures in conventional vehicles. But in case of xEVs, lightweigting has an enhanced significance.

2.11.2 Lightweighting of xEVs

In case of xEVs, the on-board energy storage is the principal contributor to the vehicle weight as well as cost. Vehicle mass reduction helps significantly in either increasing electric driving range or reducing the level of energy storage. This would results in cost savings. The weight spiral and mass de-compounding effect of reducing the primary mass can be seen in Fig 3.3

Vehicle mass reduction often necessitates the application of alternative materials (aluminium, magnesium, carbon fiber composites etc.) resulting in significant incremental cost.But the studies shows that the additional cost incurred using lightweight materials can trade-off the reduction in cost of energy storage system.

Due to weight and volume of the batteries and substitution of mechanical drivetrain components through electric motor specific elements, the boundary conditions for lightweight architecture may change. Hence, material concepts and vehicle architecture of body-in-white and manufacturing processes have to be looked at together as they are closely related. Lightweight measures that can be applied on electric vehicles which include: integration of battery housing, x-by wire and new vehicle architectures using lightweight materials.

2.11.3 Conversion and Purpose Design

Traditionally, electric vehicles are designed based on existing conventional vehicle platforms to minimize investment, mainly by removing relevant components of the combustion drive, adding components required for an electric drive. Components not directly connected to the drive, like chassis, shell and interior remain same. Due to the overall heavier electric drive system (battery, electric motor. etc) this procedure causes a net increase in the vehicle's weight.

Purpose design of an electric vehicle adopts a fresh approach for energy and resource efficient vehicle design. The vehicle is designed, engineered and developed as a grounds up, dedicated xEV. Some of the modern electric cars are purpose designed so as to maximize the benefits. Purpose design employs a lightweight vehicle body and may employ novel strategies like integrating the battery system into the vehicle body's structure as a load-bearing element. BMW i3 is an example of purpose designed

Table 3.3 Case Studies/ Global Scenario

PROJECT/ PROGRAMME	OBJECTIVES/ HIGHLIGHTS
ULSAB Project	The Ultralight Steel Auto Body (ULSAB) car body demonstrated a 19% mass reduction in a body structure based on AHSS and associated advanced design and fabrication techniques, apart from superior strength and structural performance (including crash-worthiness), reduced parts count and net manufacturing cost savings compared to a conventional steel body.
Lightwighting project of US DoE	First phase target of 22% weight reduction compare to baseline vehicle, maintaining its architecture, and using commercially available materials and processes Second phase target: 50% weight reduction, without architectural constraints, while retaining basic size attributes and customer accommodations of the baseline vehicle In the first phase, 25% weight reduction of a 2013 Ford Fiesta has been achieved

Ford Fusion	25% weight reduction using high strength steel, magnesium, aluminium and carbon fibre in various structural and other components
HiLite Project, UK	Objective is to define a glide-path to achieve a 30% weight reduction on the existing steel component and a 40% reduction in costs from traditional composite materials and processing
Structural Analysis of Hybrid Materias Concepts for Lightweight Vehicles (SALVO)	Development of methodologies for the analysis of components and assemblies manufactured from hybrid materials so that these methodologies can be readily used by the automotive industry
SuperLIGHT-CAR	To develop a BIW for a mid-size car in multi-material design using for each part the best material and manufacturing processes in terms of weight and cost minimization, while fulfilling a wide range of automotive requirements in areas such as stiffness, crash performance, fatigue and corrosion resistance, etc. Target is 30% weight reduction in the C-class car models of the future generations.
Lightweight Automotive Materials Programme (LAMP)	High-strength materials technologies that could significantly reduce vehicle weight. Focus is on improved manufacturability, lowered costs for the deployment of new lightweight materials, and introducing sustainability considerations into the design process
Affordable COMPosites for LIghtweight Car Structures (ACCOMPLICE)	Aims to significantly reduce the cost of composite body-in-white vehicle structures through the development of pre-impregnated broad application materials suitable for robotic lamination and fast cure technologies
Development Efforts by OEMs	AHSS and HSS structure in Honda's 2009 Insight Hybrid Purpose design in BMW i3, with weight reduction of 250-350 kg Body panels of Volvo S80 is made as a battery
Light e-Body (ThyssenKrupp together with 13 cooperation partners)	The target is to achieve a multi-material construction that combines metallic and synthetic materials in an optimized way by using new super high strength steel and innovative deformation processes. With the new body, future electric cars could have a range of 150 km with a battery capacity of 25 kWH. Altogether, the lightweight measures aim at a reduction of the body weight by 25%.
Advanced Structural Light-Weight Architectures for Electric Vehicles (e-light)	Development of an innovative multi-material modular architecture specifically designed for electric vehicles, achieving optimal lightweight and crash worthy performances. The project would identify architectural requirements for future EV, focusing on lightweight for different battery and electric motor configurations.
Advanced Lightweight Design of Electric Vehicles (ALIVE)	Develop materials and design concepts to reduce the weight of the electric vehicle by 20% including body-in-white weight reduction of 45-50% and weight reduction target for the hang on parts, chassis, and main interior subsystems is 25-30%.
ECOMOVE	QBEAK Mini small electric vehicle from ECOmove uses several technologies developed by the company like an ultra-lightweight carbon-fibre-chassis (QStrung) and Qwheel wheel hub motor. The company has also developed modular powertrain. The company is working on BEHICLE project, an updated version of QBEAK.

electric vehicle. In future there may be more purpose designed electric vehicles, particularly because such a design has higher possibilities of extracting the maximum benefits of electric mobility.

2.11.4 Lightweight Materials Options

High Strength Steels

HSS offer potential for weight reduction but are difficult to form. Conventional HSS are hardened by solid solution, precipitation or grain refining, while advanced high strength steels (AHSS) are hardened by phase transformation, and the microstructure may include martensite, bainite and retained austenite.

AHSS, including dual phase steel, TRIP steel, complex phase steel and martensite steel, are superior in strength and ductility combination as compared with conventional HSS and thus facilitate the energy absorption during impact and ensure safety while reducing weight.

AHSS for automotive applications include hot-rolled, cold-rolled and hot dip galvanized steel, which are all strengthened by phase transformation hardening though the processing parameters are somewhat different. Nowadays, hot stamped and die-quenched ultra high strength steel also has wide application in automotive industry in Europe. High strength boron steels offers structural strength at a reduced weight to help improve fuel economy and meet safety and durability requirements.

These materials provide excellent mechanical strength and are lightweight. However, they exhibit low formability and higher cost of materials. Further, joining of high strength steels/ AHSS is also an issue to be addressed.

Therefore, the following are potential areas where R&D intervention is needed:

- Improving formability of HSS/AHSS
- Joining of HSS/ AHSS

TABLE 3.4: APPLICATIONS OF HIGH STRENGTH STEEL

COMPONENTS ALREADY IN USE	POTENTIAL APPLICATIONS
Hot stamped structural parts, tailor welded blanks, steering columns	Paneling, pillars, bumpers, Tailor welded tubes, semi-structural or structural components

- New generation of forging steels for cyclic loaded safety components with improved fatigue properties need to be explored.
- Tailor welded tubes

High strength steels cost as much as 50% more than traditional mild steels, but they allow use of lower thicknesses than milder steels for achieving needed part performance specifications. Also different grades of steels can be combined in tailored blanks, so that the more costly or thicker materials can be placed only where needed. The advantage of HSS is that it does not call for much change in the current vehicle manufacturing infrastructure. However, manufacturing challenges such as low formability, spring back, die material and tooling need to be addressed. Further, not all high tensile steels can be cold formed, so capital intensive hot forming technologies (for grades above 980 MPa) need to be opted.

AHSS allows to take up to 15% of the weight out of a steel body structure while optimizing the overall body architectures.

2009 Acura MDX/Honda Pilot, BMW X6, GM Lambda crossovers (Chevrolet Traverse/Buick Enclave/GMC Acadia/Saturn Outlook), Honda Civic, Nissan Altima, Toyota's new-generation Prius, and Chevrolet Volt, all use a high proportion of AHSS in their BIW.

Aluminium

While traditional applications of Aluminium are mostly in the form of castings, in the recent years, a wide variety of aluminium alloy products have been developed such as extrusions, stamped sheet parts, hydro-formed and forgings for automotive applications in chassis, suspension, body-in-white (BIW) and other structures. Use of aluminium to produce lightweight structures has many inherent advantages, as it is considerably lighter than steel and is highly recyclable. It can easily be adapted to existing automotive design and production processes. Indian automotive industry has been using aluminium mainly for engine, transmission, HVAC parts, wheel rims and also in a very limited way for suspension applications. This material is yet to make inroads for BIW and closure applications. While aluminium has good potential for automotive applications in near future, there are a few challenges that need to be addressed for its effective use. These include consistent quality and availability of raw materials and supply chain, expertise in design & simulation, which is evolving, and material joining issues. Regular spot welding is not possible to integrate multi-materials. Hence new joining technologies are to be investigated. Cycle time & cost reduction in non-conventional joinery methods such as friction stir welding and riveting pose a significant challenge. Repairability of aluminium structures is also another challenge that needs to be addressed.

Technology Interventions are needed at various stages in the production line i.e. primary production, semi-fabrication, component manufacturing and system and vehicle integration at OEM level.

The following are the key challenges associated with development of component/ subsystem using aluminium:

ALUMINIUM CLOSURE PANELS

- High formability, high strength, Class A sheets : alloy chemistry; rolling and heat treatment; surface coatings; formability, hemming and strength characterization
- Design, prototyping and testing of closure panels : adhesive bonding, riveting, hemming

HIGH STIFFNESS BIW

- Space Frame Design : high strength, high modulus extrusions (alloy chemistry and heat

treatments);high strength forging grade alloys
- Monocoque Design : ultra high strength, weldable aluminium alloys; similar and dissimilar metal joining

BRAKING
- Metal Matrix Composites: composite design; composite synthesis; characterization, machining and heat treatment
- Brake design, prototyping and testing: casting, dynamometer and vehicle testing
- Forged alloy wheel : Alloy selection and stock design; Forged die design; Wheel design, prototype and testing

BUMPERS
- Alloy Selection (high strain rate testing; forming study); Hydroforming Design, fabrication and testing

POWERTRAIN
- Battery pack design; Fabrication (adhesive bonding); welding

Apart from above, development of detailed material database is also crucial.

India has got 5th largest bauxite reserves in the world and there are 5 major primary producers of aluminium in the country. Downstream manufacturers and design houses are blooming up. Hence, there exists potential for automotive industry to have tie ups with aluminium sector to develop innovative solutions for automotive industry.

2013 Range rover has an all-aluminium construction. The vehicle body is 39% lighter than conventional steel body, which resulted in total weight savings of 420 kgs. Aluminium hoods and deck lids offer a 40 to 50% weight savings over the comparable steel counterpart- and being large panels they are logical targets for cutting weight. Ford is doing R&D on aluminium doors.

Niche and premium-market entries, such as Tesla's EV roadster and Fisker Automotive's plug-in hybrid sports sedan, are engineered with relatively high aluminium content.

Jaguar XE uses aluminium-intensive monocoque, with lightweight aluminium accounting for 75 % of the structure yet with high torsional stiffness. It uses bonded and riveted technology. A new grade of high strength aluminium called RC 5754 was developed specifically for the XE. This new alloy features a high level of recycled material.

As a percentage of average vehicle curb weight, aluminium reaches an all-time high at 8.7% in 2009-about 148 kg of all product forms per North American light vehicle. Steady growth is expected in suspension and driveline components, along with a final assault on the remaining 25% of engine cylinder blocks still in cast iron. Experts expect aluminium's percentage of average curb weight to exceed 10% in 2020.

Plastics & Composites

Weight reductions of up to 50 % per component are achievable by replacing components made of metals with plastics. In case of car seats, comfort, safety, weight and cost aspects are all involved, so that all the advantages of plastics as light-weight construction materials can be exploited. The new production-line seat in the Opel Insignia OPC as well as the prototype from Faurecia show that, with seats, it is possible to dispense almost entirely with metal and so save considerable weight without compromising safety. The plastics used are special polyamides characterized by high energy absorption capacity and high elongation at break and are part of innovative hybrid structures consisting of over molded continuous-filament composites.

TABLE 3.5:
APPLICATIONS OF PLASTICS & COMPOSITES

COMPONENTS ALREADY IN USE	POTENTIAL APPLICATIONS
Engine components : intake manifold, cylinder head covers, oil sumps, seats	Safety components: lower bumper stiffeners and crash absorbers High stressed structural parts: engine mountings, stabilizer links and transmission cross beam

Over the last two decades, the volume and number of applications of composite materials have grown steadily. Unlike conventional materials (e.g., steel), the anisotropic/orthotropic properties of composites can be tailored to specific applications that have various types of fibre reinforcements in the preferred directions. Such designs of composites, e.g. Carbon Fibre Reinforced Plastics (CFRP), can lead to superior crash safety compared to steel or aluminium. Composites also offer the ability to manufacture complex shapes as a single part and to reduce the number of joints and machining operations.

While fibre-reinforced composites have shown potential for automobile parts in the past several decades, the application is yet to be realized on a mass production scale due to several drawbacks including low production, automation rates, and significant costs.

Apart from reinforcing fibres and polymer matrices, additional processes such as textile manufacturing and prepreg preparation are often required in composite manufacturing prior to integration of fibres and polymer resins. These processes also need additional energy, although not as much as in the primary processing. In addition to energy, many materials use solvents and additives. In general during fabrication processes, a significant amount of energy is used to provide heat and pressure necessary for curing.

Due to their anisotropic/ orthotropic behavior, predictive modeling of composites is very difficult. It requires deeper understanding of prediction techniques and material as well as processing technologies. Thermoplastics

PP and Nylon, as well as PET, PBT, etc. can be very good candidates for weight reduction possibilities.

The majority of glass fibre composites are used in semi-structural applications such as outer door panels, hoods, etc. Although the weight reduction potential of GFRP composites is much lower than carbon fiber composites, the combination of low-cost and flexible manufacturing make them competitive in many applications. On the other hand, application of carbon fibre is growing phenomenally for body-in-white applications in vehicles.

Due to their ultra-light weight and superior strength, composites are ideal constituents for creating a car body especially Body-in-White (BIW) with more strength and less weight.

Carbon fibre can be a potential candidate for structural applications. However, Carbon fibre cost is higher compared to conventional metals and 50% of fibre cost is for precursors. Today the cost of a CFRP (Carbon Fibre Reinforced Plastic) component is at least ten times that of metal, even though carbon fibre costs have dropped ten-fold in the last decade. Development of low cost precursors is the key. There is also need to develop efficient manufacturing processes for composites fabrication.

So far PAN precursors have been widely used, which are very costly for their adoption in commercial applications. The industry has evaluated a few polymers as low cost precursor materials, such as rayon, lignin and polyolefin. Property translation is immature for carbon fiber in automotive resins. Designers are not comfortable with carbon fiber composites, especially in crash critical applications. Many composite processing methods are optimized for performance, not production rate efficiency.

But, more research is needed to optimize processing conditions for the required mechanical properties and carbon yield for these precursors:

RAYON PRECURSOR:

- The production of carbon
- fibres from rayon has reduced due to its low carbon yield (20-30 %), high processing cost, and limited physical properties. Research efforts have been focused on modifying the degradation mechanism to increase the carbon yield.

LIGNIN PRECURSOR:

- Lignin is a well known potential precursor for low cost and medium property carbon fibres. High-purity organosolv lignin can be spun into precursor fibres directly. Bio-renewable lignin is the most abundant phenolic compound in nature and is produced as the byproduct of the pulping process and cellulosic ethanol fuel production.

POLYOLEFIN PRECURSOR:

- Polyolefins have significantly higher carbon content than traditional PAN carbon fibre precursors. The carbon fibre made from PE has shown a high carbon yield of 75 % and an appropriate strength of 2.5 GPa. However, not enough work has been done on the process optimization.

Property translation is immature for carbon fiber in automotive resins. Designers are not comfortable with carbon fiber composites, especially in crash critical applications. Many composite processing methods are optimized for performance, not production rate efficiency.

TABLE 3.6: CARBON FIBRE APPLICATIONS

Resin Transfer Molding (RTM)	Glass, Carbon	Fenders, front & rear panels, bonnets, bumpers
Vacuum Assisted Resin infusion (VARI)	Glass, Carbon	Closure panels
Sheet Molding Compound (SMC)	Carbon	Closures
Dough Molding Compound (DMC)	Carbon	Head lamp reflectors
Direct Long Fiber Thermoplastics (D-LFT)	Carbon	Instrumentation Panel, under the hood components for cooling system
Filament Winding	Glass, Carbon	Tubular components, CNG cylinders, Fuel tanks
Polyurethane Resin Infusion Molding (PURIM)	Carbon	Instrumentation Panel
Pultrusion	Glass, Carbon	Structural components, sections

Automated processes such as the filament winding and pultrusion tend to spend lower energy. Other highly automated processes including the SMC molding and preform matched die employed in the auto industry have similar low values. There is need to develop indigenous expertise in processing technologies both for sheet and structural components.

At present the size of the carbon fibre industry and its supply chain is limited in the country. Only National Aeronautical Laboratory has carbon fibre manufacturing facility. It is also evident that test standards are not uniform. Further carbon fibre secures market position by guarding surface treatment & sizing. There is also a need to work on commercial aspects such as investment in plant & machineries /cost and so as to know how the material cost will move over the next seven to ten years.. The widespread use of carbon fibre in India would be possible only if there are strongly directed efforts to develop the low cost production capabilities and develop a strong market in the automotive sector.

The following are potential areas where R&D intervention is needed:

- Development of low cost precursor for carbon fiber production
- Composites material characterization/predictive modeling and simulation
- Thermoplastic Composites (PP, Nylon, PET, PBT)
- Long fibre thermoplastic (LFT) composites for structural applications
- Development of database of composite materials

Magnesium

Magnesium alloy is 30 % less dense than aluminium and 75 % lighter than steel. The two main alloys (Mg-Al-Zn and Mg-Al-Mn) have excellent strength-to-weight ratio. Advanced magnesium alloy also offers greater noise and vibration dampening compared to aluminium or steel. Magnesium thin-walled die-castings can be used to light-weight transmission components, engine cradle, seat frames, instrument panels and steering wheels. Magnesium shows great promise for vehicle body applications. Extrusions with magnesium-wrought alloys have potential for use in space frames. OEMs across the globe are gearing up to have collaborations to develop these components. The industry target is to use an average of 159 kg of magnesium components in vehicles by 2020. This would significantly lower the weight of the average car.

Magnesium is hard to deform under room temperature conditions, which makes it dent resistant in service. Magnesium prices are much higher than steel or aluminium, and are prone to fluctuations. It is worthwhile to note that per kg of Mg is expensive but per component it is cheaper than aluminium as it has higher volume and is flexible for redesign.

Magnesium front end research and development project was supported by Department of Energy, US under US AMP. The project aimed at demonstration of Mg casting, extrusion, sheet and joining techniques in automotive body structures. It also covers performance validation of Mg crashworthiness, corrosion and fatigue.

At present, the use of magnesium in Indian automotive industry is very low. Recently, M/s. Sundaram Clayton has set up manufacturing facility for production of Magnesium powertrain components. Apart from this, there are no major activities happening in the country in this area. High cost of extraction of raw material, lack of suitable processing technologies and inadequate infrastructure are key barriers for effective use of this material in automotive industry. However, considering vast resource availability and growing demand for this material in automotive industry, there is a need to develop low-cost technologies that may address these issues.

TABLE 3.7: MAGNESIUM USAGE

COMPONENTS ALREADY IN USE	POTENTIAL APPLICATIONS
Engine Components: Transmission case, engine block, cylinder head, air intake system, oil pump body/pan, intake manifold	Safety Components: frame, steering booster pump and generator, steering wheel frame, steering link bracing, automatic transmission, engine cradle Highly stressed structural parts: wheel rims, seat frame, instrument panel, clutch case, gear controls housing, lower crankcase, camshaft driven chain case, inner doors and steering column.

A few challenges are inhibiting wide spread applications of this material in automotive sector. These include: poor corrosion and creep resistance; low formability at room temperature; higher GHG emissions during production; inferior fatigue resistance; higher cost than aluminium and steel alloys, inflammable nature and fire hazards.

However, these barriers can be overcome with suitable technology interventions.

- Hot forming of Mg alloy sheet metal parts, joining of formed Mg parts, recycling of Mg scrap, low cost composite of Mg
- Mg alloys with high fatigue strength, enhanced creep and corrosion resistance
- Advanced material processing techniques Improving formability of Mg at room temperatures (warm forming)
- Development of wrought magnesium alloys for automotive applications
- Spot welding of Magnesium alloys Joining of dissimilar materials such as Mg-Al and Mg-Steel
- Development of less energy intensive production processes
- Development of newer coatings for Mg sheets

TABLE 3.8
CHALLENGES ASSOCIATED WITH LIGHTWEIGHT MATERIALS

LIGHTWEIGHT MATERIALS	Advanced high strength steels : Low formability, joining/welding, material cost Aluminium alloys: Joining, formability into complex shapes, cost Reinforced Plastic (composites) such as CFRP, GFRP, bio-composites (like Jute based composites): Consistency of properties, brittleness, high volume production, recyclability and cost Magnesium alloys: Joining, formability into complex shapes, impact safety performance and cost Metallic and non-metallic materials such as PU foam, aluminium foam: Manufacturing, integration with bulk material based structural components, judicious combination of mild steel, high strength steel and lightweight materials as mentioned above.
GEOMETRY	Cross sections of components, body architectures (such as space frame), robustness of joints
DESIGN OPTIMIZATION	NVH, Durability, vehicle dynamics, aerodynamics, crash safety, special considerations for xEVs.

2.11.6 Vehicle Design

The body-over-frame construction served the industry over sixty years. In this construction, separate body and chassis parts are bolted to the frame, which is usually a high strength structure used to support other parts of the vehicle. It holds the engine, transmission, suspension, body and other parts in position.

In the unibody construction, the body parts are bolted together to form an integral frame. In this design, heavy gauge, cold rolled steels have been replaced with lighter, thinner high strength steel alloys or aluminium alloy. New handling, straightening and welding techniques are required for unibody design. CAFE regulations prompted US vehicle manufacturers to launch bold vehicle downsizing programmes, with a massive shift from body-on-frame to unibody structure.

In case of space frame construction, structure is made of tubular members and the tubular structure is covered with an outer skin of metal sheet or plastic or fiberglass panels, attached with mechanical fasteners or adhesives. Audi has pushed ahead with its lightweight space frame technology, now used on the TT Roadster, A8, R8, and Lamborghini Gallardo. The ASF (Audi Space Frame) architecture introduced on the 2008 TT models is an aluminium/ steel hybrid that cuts weight by around 100 kg compared to the previous all-steel structure.

Multi-material design approach is also adopted by OEMs towards lightweighting. For example, Ford's efforts centered upon using increased percentages of advanced high-strength steels (AHSS) for the body-in-white. Aluminium and magnesium will be used for closures and, depending on the vehicle program, for various structural and chassis applications such as magnesium radiator supports and suspension systems.

One critical issue regarding lightweighting of conventional vehicle has been requirement of major up-front investment in manufacturing process.

However with a weight-optimized design using advanced analytical techniques, aluminium intensive vehicle is cost-effective and viable option. From life-cycle point of view, aluminium based vehicle construction offers unmatched advantages due to absence of rust, fuel economy, recyclability and re-use.

The following are potential areas where R&D intervention is needed:

- Innovative concepts of purpose design; Vehicle Design and Architectures
- Multi-material design concepts for xEVs
- Space frame designs for xEV passenger cars and buses
- Auto Car body using Magnesium based Technologies

2.11.7 Manufacturing

Efficient manufacturing processes are crucial for bringing down energy, cost and weight of the components. Development of energy efficient processing technologies for aluminium, magnesium and also precursor for carbon fiber production are crucial. Component manufacturing technologies such as porous free near net shaped castings, hydro forming, warm forming, super plastic forming can help significantly reduce component weight. Advances in manufacturing technologies such as laser welding, Tailor Welded Blanks (TWB), hot forming, and hydroforming (HF) have contributed significantly in manufacture of automotive components especially made out of steel. Both TWB and HF allow parts counts to be reduced, providing significant savings on tools and dies, simplifying further stages of assembly and improving the integrity of components, sub-assemblies and body structures. Castings with less porosity such as vacuum assist casting and near-net shaped technologies such as squeeze and semi-soild castings have contributed for lightweight transmission components.

Composites fabrication including resin transfer molding (RTM), compression molding technologies, filament winding and pultrusion need to be explored. Industrial infrastructure is another important issue to be addressed.

The following are potential areas where R&D intervention is needed in manufacturing:
Manufacturing: Potential Areas for R&D Intervention

- Tube hydroforming technology for BIW (AHSS and Aluminium)
- Warm/hot forming (Aluminium and Magnesium)
- Vacuum assisted thin wall castings
- Standardization of manufacturing processes for composite fabrication
- Semisolid thixo-formed extrusions of Aluminium and Magnesium
- Super plastic forming of high specific strength Aluminium Alloys (Long term)
- Development of plug and play vacuum assist equipment and control systems

Hydroforming
The hydroforming process is suitable for forming metals such as steel, stainless steel, copper, aluminium, and brass. Hydroforming technology can be used both for sheets for paneling and tubes for structural applications.

Tubular hydroforming is increasingly becoming an important element of automotive BIW assembly and more and more hydroformed parts are adopted in vehicle design.

Ford Motors had introduced the first tubular hydroformed engine cradle, followed by many OEMs developing various components and subsystems as given under :

- Body-in-white (Audi); Engine Cradle (Ford and Dodge); EU Project Hydrotube;
- Exhaust Systems (Daimler Chrysler); A pillar lower and upper with cowl (BMW); Chassis (Opel GM); B-pillar and A-pillar roof rail (Ford);
- Chassis Frame (Ford); Chassis (Mahindra & Mahindra); Engine Cradle (Opel); Dashboard cowl (Porsche); Hydroformed side members (USLAB) and Suspension Parts & Body Panels (GM)

Indian OEMs have not fully exploited this technology for automotive applications (only Mahindra & Mahindra used it for Chassis construction of Scorpio). However, there exists, some capability in the country in terms of machine building, component design and development. It was reported that one of the companies has built ingeniously hydroforming equipment and developed process for manufacture of automotive components.

TABLE 3.9: POTENTIAL APPLICATIONS OF HYDROFORMING

VEHICLE BODY SYSTEMS	CHASSIS SYSTEMS	ENGINE, DRIVE TRAIN AND OTHERS
Space frame, Side rails, roof rails A-Pillar, B-Pillar	Engine cradle	Exhaust manifold
Wide shield headers	Front & rear sub-frame	Engine bonnet
Seat frames	Lower rail frames	Camshafts rear axle
Radiator supports	Suspension frames	Control arms
Instrument panels	Cross members	Steering columns
Dash board cowl	Long members	
Roll over bars	Bumper beams	

Vacuum Assisted Die-Casting
The process can reduce rejection rate due to low porosity, lessens the force required on the plunger, increases tool life and mould life of the machine; allow producing thinner, stronger and more complex high quality castings with reduced scrap and provides excellent surface quality.

The only drawback is that this process is very costly. Applying vacuum in specified locations in casting line is a feasible and cost effective option. This would require development of plug and play vacuum assist equipment suitable for die casting process. This also involves development of control systems so as to automate the process.

Squeeze Casting
Generally, the SC-fabricated engineering components are fine grained with excellent surface finish, have almost no porosity, and have superior mechanical properties compared to conventional die casting. Squeeze casting has significant potential in producing high quality aluminium castings for lightweighting.

Semisolid Casting
"Semi-solid forming" is an effective near-net-shape forming process where the metal is formed in the semi-solid state. This property represents a great potential for further processing in a semi-solid state by various forming techniques such as pressure die casting and forging.

There are two basic variants of the SSF process, namely 'Rheo-casting' and 'Thixo-casting'. The rheocasting process is simpler and cost effective as no billet making is required. Rheocasting envisages preparing semisolid slurries directly beside a die-casting machine and casting the slurry into parts. In the thixocasting operation, billets having non-dendritic microstructure are first produced through a direct chilled (DC) casting operation along with mechanical or electro-magnetic stirring.

The Semi-Solid Forming process can be adopted for alloys such as aluminium, magnesium, copper, zinc, titanium alloys and MMC's, and the components made of these alloys are being used in strategic applications. SSF material can also be processed by forging or extrusion, besides casting. The components so produced are of superior dimensional integrity and better mechanical properties – both static and dynamic.

Warm forming
Formability of aluminium and magnesium sheet metal alloys is very low at room temperature. While aluminium alloys possess moderate formability at room temperature, magnesium alloys have very little formability. Warm forming of these alloys improves their formability.

Welding/ Joining Technologies
Joining of similar and dissimilar metals such as AHSS, Al and Mg may be developed with following advance joining methods:

- Laser welding (AHSS, Al) -CO_2, NdYAG
- Friction Stir Welding (Al, AHSS, Steel)
- Electromagnetic Pulse Welding (Al all grades, AZ 91 and AZ 31)
- Friction welding (for Titanium material)
- Mechanical Joining (Self-piercing, Clinching)
- Adhesive Bonding
- Hybrid Joining (Mechanical + Adhesive)

Reuse and Recycling
Recycling is often associted with lifecycle benefits in terms of energy, emissions and cost. Porduction of primary aluminium is energy intensive, whereas recycled aluminium requires only 5% of the this energy. Research efforts are on in developing ways to recycle/ dispose of composite materials in an effective way. Magnesium components can be recycled but the major barrier is the existence of substantial amount of inclusions and impurity elements in the scrap, which would cause lose of ductility and strength and the corrosion related issues.

03 TARGET AND GAPS

3.1 WHAT IS DESIRED

Indian automobile market is largely driven by low cost requirements. There is a large proportion of two wheelers and small cars. Public transport is a major concern. LCVs play important role in congested city traffic.

Vehicles developed abroad cannot be directly adopted in India. The travel pattern and conditions are different. Daily travel demand in India is comparatively less. Very high performance of the vehicle in terms of maximum speed and acceleration are also not required. Fuel economy is a major driver.

3.2 REFERENCE VEHICLES

A few Reference Vehicles will be specified under the Mission, as it will help to focus the R&D efforts, enhance the capability to work across several Technology Readiness Levels (TRL) during the short mission period of 5-6 years. They will offer template for "R&D targets" to achieve low cost components, know-how for systems integration, and to explore the potential for modular approach.

Systems Integration projects will be first started with the following platforms, for all xEV variants:

- Electric 2/3 wheeler
- Electric city car/ LCV (up to 1.5 Ton)
- Hybrid electric car
- Electric city bus
- Hybrid electric truck

For BEV cars range could be 70 km and 140 km. Voltage level would be 72-140V, and above 170V.

Based on the recommendations of the electric motor subgroup formed by the Inter-Ministerial Technoogy Advisory Group (IM-TAG), specifications of reference two and three wheelers for the initial phase of the programme could be suggested as mentioned in Tables 3.10, 3.11 and 3.12.

TABLE 3.10
ELECTRIC 2-WHEELERS TARGET SPECIFICATIONS

KERB WEIGHT (KG)	100-120	100-120	100-120	100-120
Passenger load (kg)	150	150	150	150
Motor rating (Watt) Cont / Peak	500 / 1000	1000 / 2000	1500 / 3000	2000 / 5000
Voltage (Volt DC)	48	48	48	48
Battery	Lead acid/ lithium	Lead acid/ lithium	Lead acid/ lithium	Lead acid/ ithium
Maximum vehicle speed (km/h)	45	60	60	80
Gradeability (degree @ 10 km/h)	7	7	7	7
Regenerative braking	Yes	Yes	Yes	Yes
Ambient temperature (°C)	-10 to 60	-10 to 60	-10 to 60	-10 to 60

TABLE 3.11
ELECTRIC 3-WHEELER TARGET SPECIFICATIONS

KERB WEIGHT (KG)	250-350
Passenger load (kg)	375
Motor rating (kW) cont/ peak	2000/3000
Voltage (Volt DC)	48
Maximum vehicle speed (km/h)	30
Gradeability (degree @ 10 km/h)	7
Regenerative braking	Yes
Ambient temperature (°C)	-10 to 60

TABLE 3.12
SUGGESTED TARGET SPECIFICATIONS FOR ELECTRIC 4-WHEELERS

PARAMETERS	PASSENGER CAR	LCV	BUS
Kerb weight	800-1100	1000	13000
GVW (kg)	1100-1400	1750	16200
Peak power (kW)	30	15	130
Voltage (Volt DC)	72 and above	72 and above	Above 300
Maximum vehicle speed (km/h)	120	60	60
Gradeability (degree @ 10 km/h)	7	7	7
Regenerative braking	Yes	Yes	Yes
Ambient temperature (°C)	-10 to 60	-10 to 60	-10 to 60
Range (km)	150	150	200

3.3 CHALLENGES

Major challenges for R&D in Vehicle Systems Integration are

- xEV systems integration requires a multi-disciplinary and multi-domain expertise.
- Indian Customer is value conscious, and would prefer small xEV cars
- The traffic and temperature conditions are unique and diverse. Real world usage data of xEVs has to be developed.
- Simulation & Testing infrastructure is virtually non-existent
- Capabilities to bring xEVs to the mass market are to be developed.

The domestic capabilities for developing xEV power train and components, and their manufacturing need to be expanded. While a few OEMs have initiated such efforts, they are critically dependent on imported technology and products. The new entrants and startup companies that are developing vehicles are also similarly dependent. All of them will have difficulty in achieving desired level of performance, at costs specific to Indian conditions.

Hence, in addressing the priority R&D areas, the immediate focus should be on the areas in which India has a higher chance of success, while pursuing critical long term technology priorities in parallel.

An evaluation of the current capabilities in the country, investments required and global competitive intensity was undertaken and it emerges that R&D in the following areas has greater potential for success in the short-term

- battery management systems & packaging,
- power electronics,
- xEV power-train system integration and
- electric motors for xEVs

Standardization is required to reduce unit price and spares. Standards that need to be decided include voltage systems, motor control unit, A/C, battery modules etc. Commonly accessible testing set-up suitable for R&D activities is another important issue.

04 R&D IN SYSTEMS INTEGRATION

4.1 APPROACH TO XEV DRIVETRAIN DEVELOPMENT

A set of reference vehicle specifications will be worked out. To strike a balance between the need for vehicle level developments and component/ subsystem level developments, a spiral methodology may be used for vehicle level integration projects.

Initial target (CAD, Mechanical, Electrical, Electronics, CAN matrix etc.) approved by TPEM will be released for all components i.e. motor, controller, DC-DC converter, Battery, BMS etc.

Motor/PE -CoE, Battery/BMS-CoE, and other partners will simulate, soft and hard design, develop, bench test and before bringing components for systems integration.

Systems integrator will develop vehicle prototypes (TRL 6) and perform initial calibration before the vehicle is tested and evaluated on road.

Based on testing feedback, approved modified targets may be released and similarly another fleet vehicle may be built (TRL 7) and tested for at least 10,000 km on road.

PHASE I: SYSTEMS INTEGRATION AND TESTING

Initially development of vehicles as mentioned in the section titled “Reference Vehicles” will be taken up with mostly available off-the shelf components and subsystems. Certain level of indigenousness will be targeted for some of the component/ subsystems. This will help achieving the cost targets, apart from development of know-how.

The objective is to test functionality, fuel economy, control algorithm and safety in integrated vehicle environment. The works will involve definition, simulation and building the prototype vehicles. The output of this phase will be fuel economy in dynamometer test, on-road fuel economy, and speed-time, temperature and vibration data. These data and insights will be input for the phase 2 as well as technology development efforts for components and subsystems. Parallel development efforts (low level) will continue on the development of component and subsystem technologies.

Apart from vehicle development efforts led by the vehicle manufacturers, there may also be development of prototype vehicles by consortia or centres set up under this Mission, e.g., for demonstration of lightweight materials, design and manufacturing technology for xEVs.

PHASE 2: BENCHMARKING AND COMPONENTS MATURITY

In Phase 2, integration of vehicle will be based on the insights obtained regarding vehicle and components characteristics from the activities under Phase 1. Testing and evaluation of vehicle and components as described for Phase 1 will be carried out for providing inputs to component design and development.

Purpose design vehicles may be designed and demonstrated during this phase. It will be a full-fledged vehicle to be designed, engineered and developed as a ground up, dedicated xEV.

PHASE 3: INCORPORATION OF COMPONENTS/ SUBSYSTEMS DEVELOPED

The vehicle development efforts will continue throughout the program duration, with the technologies developed at component/ subsystem levels being integrated into the identified vehicle platforms.

4.2 APPROACH TO LIGHTWEIGHTING

In the initial phase, weight reduction potential can be demonstrated for Body-in-White applications on existing ICE vehicle platform.

Other parts of the vehicle such as chassis, interior subsystems and hang on parts can also be targeted for lightweighting. During the course of implementation, many technologies can be expected to be developed in the areas of materials, design and manufacturing including joining/ welding. A fleet of operations may be carried out to test commercial viability of these technologies and information/data may be collected for further R&D intervention.

TABLE 3.13
PERCENTAGE OF WEIGHT REDUCTION POSSIBLE

VEHICLE BODY SYSTEMS	CHASSIS SYSTEMS	ENGINE, DRIVE TRAIN AND OTHERS
Body-in-White (BIW)	25%	35 %
Chassis	10%	25 %
Interior/closures etc.	2 %	5%
Battery Assembly	15%	30 %
Motor/ electronics	10%	25%

Research projects on materials developments, design and manufacturing aspects will go parallel and these will even feed the inputs wherever needed during Phase 1. However, based on actual field trial data, the technologies may be further refined to suit to the requirement in Phase II.

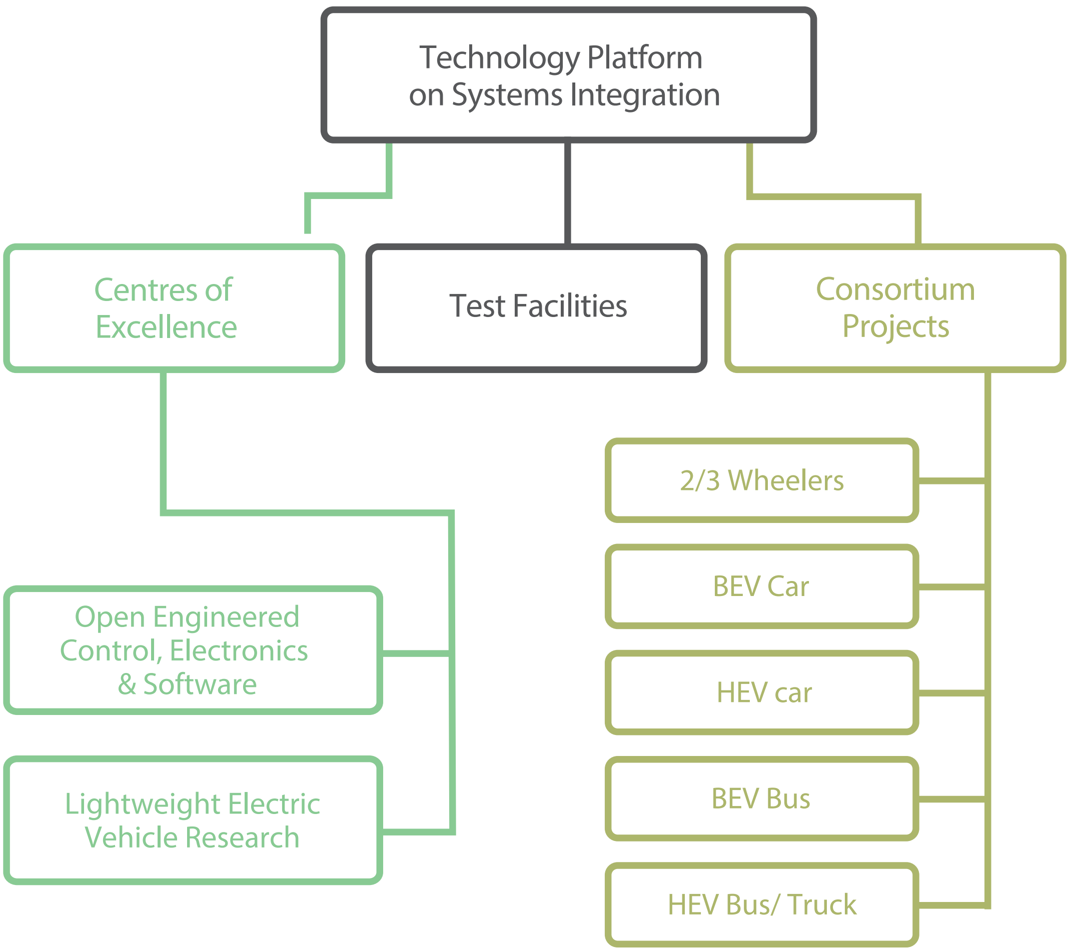
Lightweighting considerations for the purpose designed vehicle to be developed in the phase II will be taken up. The component technologies and joining methods developed in phase 1 can be further refined and utilized for application in new fleet of vehicles for demonstration. The weight reduction targets in this case will be much higher than phase 1.

05 ECOSYSTEM: TECHNOLOGY PLATFORM ON SYSTEMS INTEGRATION

5.1 OVERALL STRUCTURE OF THE TP SYSTEMS INTEGRATION

In accordance with the phased technology development strategy explained in section 4.1, the Technology Platform on Systems Integration will comprise consortia projects for vehicle prototypes development, test facilities as well as Centres of Excellence.

FIGURE 3.4



- TPEM Systems Integration will develop specifications for the critical subsystems based on desired vehicle level attributes.
- Studies will include simulation, soft and hard design, development of components and bench test before bringing components for systems integration.
- Systems integrator will develop vehicle prototypes and perform initial calibration before the vehicle is tested and evaluated on road. Objective is to generate requirements for components, control strategy integration, behavior of components in integrated fashion, road test in India and failure input to requirement, actual on road fuel economy benefit etc.
- Based on testing feedback, the subsystem targets would be modified and another fleet vehicle may be built and tested for 10,000 km on road.

5.2 CoEs ON VEHICLE SYSTEMS INTEGRATION

The Centres of Excellences will be virtual centres bringing together the strengths of various R&D institutions and participation of industry. Two Centres of Excellence on Systems Integration will be established as legal entities. Typically a CoE would be led by one of the premier R&D/ academic institutions having significant R&D activities in the relevant areas. The Systems Integration R&D efforts will also have linkage with R&D efforts on Energy Storage, Power Electronics and Lightweight Materials and Design.

These Centres will provide technical support to the consortia for development of identified vehicle platforms and also will undertake long term R&D activities on various issues of Systems Integration.

In addition to the financial support under the FAME Scheme, the CoEs are expected to generate funds from xEV industry including cash and kind contributions towards technology license fees and projects to mature the technologies from TRL 7-9.

Beyond this, the CoEs should largely become self-sustaining through attracting national and international research funding from industry, government and other sponsoring agencies.

• Light-weight Electric Vehicle Research	THE PROPOSED TWO CENTRES	• Open Engineered Controls, Electronics and Software (CES) for xEVs

Along with these two centres, the centres proposed in the areas of energy storage and motor and power electronics will also participate to support consortia for development of vehicle prototypes.

5.2.1 Centre of Excellence on Open Engineered Controls, Electronics and Software (CES) for xEVs

Development of xEV technologies is severely hindered by the fact that technologies for many of the critical subsystems like ECU, ABS, AMT etc are not available to Indian companies and are purchased by OEMs as proprietary subsystems at very high costs from Global Tier 1 suppliers. This dependence in the area of CES on global Tier 1 suppliers is nearly total today, hindering development and impacting cost of Indian vehicles. Technologically, it is perfectly possible to develop the complete vehicle control and management functionality on Open Engineered CES platforms not only because of the available computing capabilities but also because of the easy availability and upgradability of the technology that it is open. This is certain to drive the cost down significantly.

Moreover sensor based software technologies such as object/ signal recognition, Driver Assist, Real Time Energy Management, Integrated Vehicle Health Management (IVHM), smart navigation etc. are needed to improve passenger comfort, safety, fuel economy and pollution of the Indian roads at affordable costs. This is essential to ensure that xEVs offer a competitive value of the vehicle life-cycle compared to conventional vehicles based on hydrocarbons.

There is adequate R&D competence in India in areas like controls, vehicle dynamics, instrumentation and signal processing, embedded electronics and communication, software engineering etc. The OEMs on the other hand, have considerable expertise and infrastructure in IC engines, transmissions, vehicle integration and testing. It is therefore a golden opportunity for the Indian academia and industry to come together and develop this critical technology base for xEVs in India.

The Mission is to develop platforms, tools, IP and expertise related to Open Engineered Indigenous CES technology for xEVs leveraging commercially available embedded software and hardware components and associated tools and open standards.

This would enable the use of high volume, standard embedded hardware along with open standard embedded software and accessible models and tools using which suppliers can build competitive and cost effective products, which can be integrated into a custom architecture, configured or tuned by OEMs and Tier 1s for commercial xEV design and implementations.

There will be two streams of activities related to the two technology sub-domains:

A. System Controls, Monitoring and Autonomy
B. Embedded Hardware, Software and Networks

Target sub-systems for 2, 3 and 4 wheeler xEVs would be :

- Battery Management System (BMS),
- Motor Control Unit (MCU)
- Vehicle Control Unit (VCU)
- Engine Control Unit (ECU)
- Vehicle Energy and Health Management
- Driver Assist and Advisory

Objectives and Deliverables:

- To develop open engineered CES sub-systems and benchmark with global state of the art and standards on test beds and vehicle subsystem prototypes as required for maturing up to TRL 6.
- To develop tool chain for design and configuration, development, test and validation of CES subsystems for target custom vehicle specifications
- To establish resources, facilities and competencies to continue globally competitive R&D in the above areas
- To develop IP and disseminate, transfer the same following principles of Open Engineering.

The CoE will also develop & validate models and simulation tools for various xEV configurations/ architectures, components sizing, performance, fuel economy & emissions. Evaluation of various architectures and configurations with respect to Indian driving conditions will also be taken up to benchmark them in Indian conditions. It will help to outline the differences and trade-offs between the configurations/architectures and also provide insight into various control systems.

Potential Partners

A hub-and-spoke model is proposed. The hub would be a Centre of Excellence (CoE) on CES for xEVs. In view of the strong component of original R&D required, it is suggested that it be established at one of the premier academic institutions (such as IIT Kharagpur) with a strong research base both on CES technologies as well as others related to xEVs such batteries and motor drives and vehicle mechanics. It should also have strong interests and experience in xEV CES research.

The spokes can be realized through a technology consortium of industries and institutions (such as Tata Motors, BHEL, CMERI, CEERI, CDAC, other IITs and IISc etc.) which would form the rim of the overall R&D wheel. The CoE will coordinate the activities under the R&D Mission on xEV-CES including consortia projects, and smaller R&D centres at various R&D/ academic institutions/ industries. Additional technology partners may be inducted from national and international organizations.

5.2.2 Centre of Excellence in Lightweight Vehicle Research (CELVeR)

A vehicle is an integrated system in which all sub-systems should function in a harmonious manner to deliver customer satisfaction. Therefore development of new technologies needs to be backed with sound product design processes and design optimization. Although usage of lightweight materials such as aluminium, magnesium, plastics, fibre-reinforced composites, etc. is key to obtaining an advanced lightweight vehicle, it is equally important to design a compatible body architecture and modified geometries of other parts (such as control arms, engine block, transmission housing, wheel rim, etc.) through engineering design innovation. In other words, contrary to what may appear, merely replacing steel with lightweight materials such as aluminium in a conventional vehicle will not lead to a lightweight vehicle design. This is the basis for formation of CELVeR to carry out vehicle research.

Objectives

- Develop and test lightweight solutions encompassing vehicle body structure (comprising BIW, i.e. body-in-white, closures etc.) and all other subsystems such as powertrain (electric motor, controller and transmission), suspension and steering systems including wheels, brakes, battery and other miscellaneous hardware which can be integrated into an optimally designed xEV that will meet customer requirements in terms of aesthetics, functional performance (in attributes such as ergonomics, aerodynamics, vehicle dynamics, NVH, durability, crashworthiness etc.) and cost as well as government regulatory requirements
- Product design and innovation will play a significant role in the development of lightweight vehicle platforms with an aggressive design cycle of 3-4 years
- A measurable benchmark in terms of achieving lightweight vehicle can be a car of similar size as Tata Nano but of 20-30% lower weight.

Deliverable:

Amongst the tangible deliverables of the centre are 4 prototypes of lightweight electric vehicles as given below:

- Two prototypes will be made with lightweight body design and best available sub-systems including electric powertrain for initial development and testing (these may be a compact car and a quadricycle).
- Two additional prototypes will be made with technologies developed by the centre especially in the areas of electric powertrain and possibly with option for hybridization using IC engine-based range extenders.

The objective will be to complete the design details and first two prototypes at the end of 36 months. The completion of remaining prototypes will take another 24 months. The total duration of the project would be thus 60 months (i.e. 5 years). However, the centre will continue functioning after this initial project duration.

R&D efforts towards achieving the targets

Applied research will be carried out by identifying priority areas in which improvements to current state-of-the-art or enhancement of indigenous manufacturing capability are required such as:

MATERIALS

- Develop aluminium alloys and its processing route to achieve strength, formability and aesthetics requirements for closure applications. Aluminium Sheets need to be thin to medium thicknesses (typically 1.2 to 3.5 mm) to provide targeted weight saving up to 40% over corresponding steel sheets and these are to be amenable to stamping (deep draw) with standard presses & in required line speeds, be dent resistance at par with bake hardening grade steel sheets, be paintable with available machineries, etc. The challenge in manufacture of auto grade aluminium sheets is to obtain required radius and sharpness. Issues to be investigated include Alloy chemistry, heat treatment, deformation maps, texture, formability, surface treatment and corrosion.

- Development of technology for low-cost, high-volume production precursors for carbon fibre production: The biggest hurdle for wider implementation of carbon fibre composites is the high cost of carbon fibre as compared to other alternatives.

- Development of Long Fibre Thermoplastic Composites: Long fibre thermoplastic composites falls in between injection molded short fibre-reinforced thermoplastics (SFT) and compression molded glass mat reinforced thermoplastics (GMT). However, LFT show better mechanical properties than SFT and GMT and is close to those of advanced continuous fibre-reinforced plastics. Using LFT, more complex products that require higher strength can be manufactured. The conversion processes such as compression, extrusion-blowing or injection molding can effectively be used with low production cost and high production rates. Efforts have been more on development of fibre-matrix combinations (like natural, glass, aramid, and carbon fibres and matrix polymers such as polypropylene (PP), epoxies and various polyamides (PA)s). Focus will be on development of long-fibre thermoplastic composites components for semi-structural applications in automotive applications.

- Characterization and development of other lightweight materials, for example, fibre-reinforced composites, PU (polyurethane) foam, sandwiched constructions, etc.

DESIGN

- Develop lightweight structures for xEV platform. The key focus of this development is on a vehicle body structure which is lightweight, easily joined, easily recycled and easily repaired. This objective may be met by (a) choosing one or two alloys for entire BIW – this may help in recycling and reuse; (b) adopting joining methods such as friction based welding technologies and mechanical joining.

- Development of cost effective technology for forged underbody components having high strength, high stiffness, and corrosion resistant aluminium alloys. There is enormous potential for use of aluminium extrusions for structural applications of vehicles. Investigations should focus on alloy chemistry, die design, forging, heat treatment, stress corrosion cracking etc. The potential area of applications will be BIW and reinforcement. Since many of these extrusions are to be made in required shape, stretch bending becomes an important area which needs to be explored.

- Development of monocoque, space frame, mufti-material design concepts

MANUFACTURING

- Forged aluminium underbody components: The unsprung mass components such as wheels, knuckle, brake disc and control arms are currently manufactured using High Pressure Die Casting (HPDC) process. If we can replace these products with forged aluminium, we can obtain excellent mechanical properties. However, constraints which need to be overcome include achieving balance between strength and corrosion, low stiffness of aluminium alloys, understanding the relationship between processing parameters and properties. A study to understand the tradeoffs between cast and forged aluminium components will be useful.

- Joining Technologies: Steel/aluminium joining is possible though there are issues to be addressed such as obtaining required strength at inter-metallic zones and corrosion issues. Corrosion issue can be addressed with suitable coating on the surfaces of parent metals.

- Development of brazing/ welding and adhesive bonding is crucial. Range of joining technologies such as structural adhesives, self piercing riveting (SPR) technology, are crucial for both similar and dissimilar material joining. Adhesive bonding has equal strength compared to conventional welding.

- Welding of joints of extruded aluminium components in a spaceframe configuration meeting various requirements such as minimum consumption of energy during joining, impact strength, durability, etc.

- Bending of aluminium extrusions and press-forming aluminium sheets conforming to vehicle body styling for large-scale production

- Joining of dissimilar lightweight materials such as aluminium, fibre-reinforced composites, magnesium, etc. Development of processes such as mechanical Joining – Clinching, self-pierce riveting, hemming and adhesive joining, friction based welding processes – friction stir welding and linear friction welding are crucial.

- Develop technologies for hot forming of Mg alloy sheets. Examine technological alternatives for joining of formed Mg parts. There are limits to which auto body can be made lighter using steel as the work material. Hence magnesium shows great promise as a car body material. Mg and its alloys need to be formed warm or at superplastic forming temperatures. Aside from alloying and fine grain size as strengthening mechanisms, Mg lends itself to formation of a metal matrix composite, which can enhance further the advantages of using magnesium. Hot forming of Magnesium alloys need to be explored. Spot welding is not common. Hence it might be worthwhile if the spot welding technology which is so standard to the automotive industry can be made usable for magnesium and its alloys.

- Hydroforming and warm Hydroforming (Al and Mg): Materials such as Aluminium, Magnesium have low formability. At elevated temperatures their formability increases. Hence, dies are heated to desired temperature and insulated to maintain the temperature. Deformation principle is same as tube hydroforming/ sheet hydroforming at room temperatures.

DISSEMINATION OF KNOWLEDGE

- The envisaged center will be a forum for dissemination of knowledge and expertise in lightweight electric vehicle design as well as advanced design methodologies involving techniques such as finite element modeling and analysis to industry and academia through means such as training, workshops, seminars, certificate courses, conferences, etc.

- Creation of open access Centralized Aluminium Database: Creation of database for the complete range of Aluminium Alloys will be required for predictions on NVH, structural durability and crash behaviors with good accuracies. At present this kind of database is not presently available in the country and Indian companies rely upon sources from abroad. This effort on developing data base will help automotive industry in a big way.

Potential Partners:

This will be a virtual CoE with a hub-and-spoke model and led by a premier institution such as IISc, Bangalore. Other potential participants are ARAI, CSIR-CMERI, IITs, ARCI, JNRDDC-Nagpur etc. It will have strong linkage with the automobile manufacturers, componenet manufacturers such as Bharat Forge as well as industry associations such as Aluminium Association of India, ACMA, SIAM etc. It is expected that that the CoE, after being established with inital funds under the FAME progamme, will be able to generate the funds for its own operation in the long run.

TABLE 3.14
R&D COMPETENCY IN LIGHTWEIGHTING TECHNOLOGIES

TECHNOLOGY AREA	ORGANIZATIONS WHERE COMPETENCY EXISTS
Auto grade aluminium sheets	IIT Madras. IIT Bombay, ARCI, JNRDDC-Nagpur
Forged aluminium under body components	ARAI, HAL
Aluminium extrusion for structural applications	NML, JNRDDC-Nagpur
Aluminium joining technologies	ARAI, IIT Bombay, IISc Bangalore, IIT Guwahati
Lightweight structures for xEV platforms	ARAI, IIT Bombay, NIT-K, NITT
Lightweighitng of auto -body using magnesium based technology	IIT Bombay, IIT Guwahati
Low-cost precursor for carbon fiber production	NAL Bangalore
Long fibre thermoplastic composites	IISc Bangalore, IIT Bombay, IIT Delhi
Warm hydroforming	IIT Bombay, IIT Delhi, IIT Guwahati.
Friction Stir Welding	IISc, Bangalore, IIT Kharagpur

5.3 CONSORTIA FOR VEHICLE SYSTEMS

5.3.1 Study on xEV driving cycle and usage patterns

Segmented studies on the urban driving cycle & traffic pattern for different categories of vehicles have to be undertaken by both using telematics equipment and traffic surveys. The data collection exercise would be conducted over a period of 1 year, covering winter, summer & monsoon.

5.3.2 Electric three wheelers

The focus should be on development of compact and affordable drivetrain for three wheelers meeting the defined performance levels.

Activities may include design and development of major component/ subsystems like:

- Battery pack
- Battery Management System (BMS)
- Electric traction motor
- Battery charger

Drivetrain development with both BLDC and SRM motors will be taken up. Purpose designed protoypes of the vehicles will be developed and trial runs will be taken.

5.3.3 Development of Electric City Car/ LCV

The objective will be development of drivetrain and design and safety guidelines for electric city car. Development of purpose-built prototypes may be taken up in three phases. The project will help in assessment and validation of technology options and innovative vehicle architectures, packaging and integration concepts.

Other targets will be:

- Reduced weight through improved packaging, reduced wiring complexity and other lightweighting measures
- Increased efficiency of the battery management system
- Demonstration of these modules on a final system

There is a need for affordable electric vehicle for last mile connectivity with passenger capacity of 6-10, since they can play significant role in providing seamless transport in urban areas in conjunction with mass rapid transport systems. Even semi-urban and rural areas where there are not enough options for mobility, the demand for such vehicles are growing. Such platforms can also be used to develop low capacity goods transport vehicles both for captive and outdoor uses.

SMALL 1 TON EV : PHASE I

Phase I deliverable will be development of indigenous competence in integration of the xEV and design, test and evaluation of components such as battery, BMS, motor, motor controller etc. The possibility of common development in other associated components will also be explored.

Broad scope conceptual design study.

VEHICLE DEFINITION
It is expected that the vehicle manufacturers will converge in terms of components specifications. Common component developments will bet taken up including motor (20 kw-60 kW, IM/SRM/PMSM), motor controller with scalable common hardware

VIRTUAL ENGINEERING
Drivetrain Control/ Energy Management System Design
Determination of the safety requirements for the vehicle and its subsystems

Design of energy management system and the high-voltage components (IGBTs, high-voltage FETs) and the architectures and subsystems for the electronics of electrical vehicles

Achieve 35% energy saving, and increased integrability against the current state-of-the art EV power electronics systems

Prototype manufacturing and detailed realistic performance assessment

SMALL 1 TON EV : PHASE II

The second phase will target improved efficiency through
- .Innovation in drivetrain architecture/ configurations
- .Improved packaging
- .Improved regenerative braking

SMALL 1 TON EV : PHASE III

- Incorporation of materials and design concepts developed under lightweight technology
- Incorporation of components and subsystems developed under various projects e.g., battery modules, motors, inverters,
- Incorporation of battery modules/ packs

5.3.4 Hybrid Electric Car

Major Indian vehicle manufacturers are working on the development of hybrid passenger cars.

PHASE I

- Deciding target fuel economy and component sizing simulation
- Development of high voltage system architecture
- Indian Automotive component manufacturers will validate their components in the hybrid vehicle
- Build, test in test-bed & on road based on off-the-shelf components
- Control strategies development and optimization based on developed components
- Motor: design, manufacturing of motor, motor controller, battery pack, battery management systems
- Vehicle integration, dynamometer testing, certification & road run
- Generation of optimized specifications for components/ subsystems for improved performance

PHASE II

- Hybrid transmission development Optimization of powertrain configuration
- Lightweighting measures

PHASE III

- Incorporation of battery developed under the programme
- Better packaging of power electronics and other systems
- Integrated thermal management system
- Hybrid energy management system and improved regenerative braking

5.3.5 Electric City Bus

Electric buses should be seen as a part of smart city system. The realistic driving cycle for city commuter buses involves frequent starts and stops. Potential benefits of electric city buses are more in such conditions.

Objectives are to develop prototypes for lightweight electric city bus and conduct trial runs. The project should also target establishment of a world-class electric bus test platform and generation of experiences from electric bus technologies and their real life performances.

The bus to be developed may feature

- Regenerative braking – flywheel or ultra-capacitor.
- High voltage architecture
- Lightweight technologies: Aluminium super structure (conversion design)

The Department of Heavy Industry has supported a project on 'development of design guidelines for aluminium intensive urban electric city bus as per bus body code: AIS: 052'. Further developments in terms of fabricating bus prototype and demonstration of its environmental benefits need to be taken up. Efforts should be launched with the participation of ASRTU, who can place lightweight xEV buses with STUs.

TABLE 3.15
LIGHTWEIGHT URBAN EV BUS DEVELOPMENT

OBJECTIVES	DEVELOPMENT OF PROTOTYPE FOR LIGHTWEIGHT ELECTRIC CITY BUS AND CONDUCT TEST AND TRIAL RUNS
Deliverables	Electric city bus prototypes with aluminium superstructure; joining technology; performance validation – safety, durability, comfort, repairability & serviceability
Project Scope	Benchmarking and target setting; comparison of different electric buses and their subsystems; finalization of vehicle specifications; concept and packaging layout finalization; aggregate finalization (axles, suspensions, steering, brakes, electrical control systems); EV system configuration and specification finalization Detail design of superstructure and chassis; design of extrusion sections and material grade selection; design of joinery (mechanical/ thermal/chemical); Integration of chassis and superstructure DFMEA/PFMEA; Preparation of BOM; integration of other systems to prepare complete vehicle; design considerations for manufacturability, assembly, repairability and serviceability. Virtual validation using CAE tools – safety, durability, comfort meeting AIS 052 and MoUD requirements Detailing of assembly sequence, equipment, tooling and fixturing requirements; prototype manufacturing; procurement of aggregates; procurement of EV system; procurement of raw materials, extrusions; development of tools and assembly fixtures; assembly and integration of chassis, superstructure and other systems; component testing and setting references Battery pack and battery management systems Motors development: Large size motors development for xEV buses have been initiated by BHEL Experimental validation of mechanical and electrical systems – Lab testing and field trials for determining efficiencies, driving cycle dependence; refinement in design based on feedback from testing; finalization of design and generation of 2D drawings. Experiments with charging options like induction charing, conductive fast charging, pantograph based fast charging and battery swap options may be taken up.

5.3.6 Hybrid Electric Bus/Truck

As per an estimate of Petroleum Conservation Research Association (PCRA), annual diesel consumption by trucks and buses in India in the current fuel economy scenario would reach about 104.7 million tonne in 2024-25, 76% of it being contributed by trucks. Application of hybrid drivetrain technology to medium- and heavy-duty vehicles can improve fuel economy by 20-50%, and also reduce pollution. In fact the fuel saving and emission reduction potential per vehicle is even higher than that of passenger hybrid cars.

Basic targets of the project would be:

- Smaller and more efficient engine
- Study of the feasibility of regenerative braking technology with the options of mechanical regeneration with flywheel technology and electrical regeneration
- Vehicle weight reduction

The high amount of power available during braking the trucks may not be adequately utilized with a battery-only regenerative braking system. Use of flywheel or supercapacitor based systems. should be considered. Similarly during acceleration such trucks require high power, and development of suitable motor is required.

Light-weighting of the vehicle assumes even more significance in case of hybrid trucks than any other kind of vehicles.

As mentioned in case of electric city car, the project can be in three phases, with

- The first phase concentrating on development of prototype with available technologies. In the second phase further design optimization
- Use of outputs of component R&D activities in the third phase

Development of hybrid electric trucks for military applications should also be considered.

5.4 TECHNOLOGY ISSUES FOR VEHICLE DEVELOPMENT CONSORTIA

Certain common activities are essential for each of the vehicle prototype development activities. These are outlined in the following sections.

Study on xEV Usage Pattern

For successful development of electric vehicles appropriate for Indian conditions, it is required to study how the vehicles and its components/ subsystems function under Indian roads, driving conditions as well as ambient conditions. Such studies provides insight into thermal design, safety and expected fuel economy. Effect of factors like humidity, dust, temperature ranges, rain and water logging, road conditions etc need to be studied. Apart from vehicle and component design related insights, study on xEV usage patterns will also help in planning of charging infrastructure installations.

This may involve simulation studies as well as pilot run of test electric vehicles equipped with appropriate on-board diagnostic systems.

Development of Detailed Specifications
The detailed specification of generic reference vehicles to be worked out based on engineering analysis based on estimated use pattern, applicable standards and desired performance. Overall benefits from such vehicles should also be taken into consideration while working out the detailed specifications.

Powertrain calibration (with multiple ECUs) for optimum HEV application
Powertrain calibration is carried out to ensure that the vehicle meets emission limits and fuel consumption targets, drivability under all environmental conditions, specified performance targets, and OBD requirements.

Powertrain calibration through on-road testing under a wide range of environmental conditions is very expensive and time consuming. Requirement of extensive road testing can be reduced with the use of vehicle model in conjunction with dynamometer. However, traditional models replicate only vehicle inertia and road loads (aerodynamic and tire rolling resistance). Modern trend is to use vehicle model that replicates an extensive range of vehicle behaviour running in real time to create 'powertrain-in-the-loop' test systems.

Powertrain calibration for evolving powertrain architectures of xEVs is challenging as they unite technologies from various fields, such as energy control strategies, electronic power system, electric motors, and high-voltage batteries etc. Vehicle manufacturers need to deal with such increasingly complex systems, and at the same time, need to ensure that the development time-line remains same as before. Further, they need to adapt testing facilities and development tools. There should be test centres adapted for hybrid component evaluation including component, engine, powertrain, and complete vehicle test beds that can be used for defining control strategies, pre-calibration of modules, electric component simulation, and 4x4 chassis dyno emissions testing.

It is required to establish state of the xEV powertrain calibration facilities. Some of the facilities may be procured by vehicle manufacturers themselves. ARAI and other laboratories under NATRIP may be equipped with suitable facilities for xEVs that can be used by the vehicle manufacturers.

Simulation and test of battery in vehicle context.
Estimation of battery life degradation and battery performance during vehicle operation is very important for xEVs. Developing knowledge of the battery aging process is required for this purpose.

Traditionally, standardized tests for cell and battery are performed with constant current or square pulse current profiles, and are used to characterize battery capacity, calendar life, cycle life, and pulse power capability. These tests are important for benchmarking battery performance from a comparison perspective. Although these tests can be carried out on a cell, module, or pack but are generally conducted at a cell or module level. In such situation, the battery management system (BMS) does not interfere with the test(s) being conducted.

But when used in vehicle, battery is associated with additional constraints imposed by BMS, and standardized tests for cell and battery do not provide much insight into battery performance in a vehicle.

During vehicle benchmarking and testing on a chassis dynamometer, it is possible to evaluate the battery indirectly in a controlled environment. It enables study of the battery operation within the confines of battery utilization by the vehicle. For example, chassis dynamometer testing can be conducted at cold, normal and hot conditions to study the impact of ambient temperature on battery and vehicle performance.

The gap between standardized tests at cell level and battery evaluation on chassis dynamometer can be filled by Battery in Loop (BIL). It involves evaluation of a real hardware battery (pack/module/cell) in a virtual vehicle (or system simulation model) environment.

In this context, it is also important to develop a battery model which includes interactions of all its components (cells, joints, external inputs etc.). Such a model is not available at present, although studies on both individual battery cells and battery pack as a whole have received substantial amount of attention. Such a model would be able to simulate the performance of a battery during its usage, such as battery charge, discharge, and idle status, the impacts of internal and external temperature, the manufacturing quality on joints, the cell capacity and balance management etc.

Control systems - algorithms, ECU, sensors and HMI
Major constituents of the control system in xEV are the standard engine controller and standard motor controller. The auto industry as well as the automotive researchers are familiar with these. However, knowledge on the higher level controller is limited at present in India. Developmental activities has to be focused on this aspect.

HEV design problem involves mathematical complexity with a large number of variables and complex non-linear relationships between them. Advanced modeling capabilities and robust computational methods are required to solve these problems analytically.

Since the number and complexity of the functions distributed over many control units is very large and further increasing, functional safety is an important issue for both electric and hybrid electric vehicles. Even well established safety related functions of conventional IC engine vehicles may get affected when the vehicle is hybridized. Thus hybrid controls development should be as per ISO 26262 (functional safety) requirements.

Automotive controllers need to withstand harsh environment. Vibration and temperature in the engine compartment is a major challenge. The working environments are extreme and also there are size constraints and thermal management constraints. Hence not many venture into such products, although they might have necessary required technical expertise. There is a large number of small companies in the field of factory automation etc., but for them to venture into automotive controllers, competency development is a must.

The electric drives are placed in safety-critical vehicle functions which are highly dependent on electronic communications with other systems or sensors in the vehicle.

Because of the higher voltages and power consumption of motors involved in motion of the vehicle, the ability of the battery system to provide adequate power and state of charge is more critical than ever.

The ECUs responsible for these controls should be fast, accurate and robust. Hence focus is required on design, development, and testing of ECUs for xEVs.

The cost of ECU vary from Rs 1 lakh to 60 lakh. Therefore, development of ECU should be taken up. Use of open ECU should be considered. Apart from algorithms, it is important to develop competency in ECU hardware development.There is an urgent need for development of transmission hydraulic control as there is not even one manufacturer in India which produces it.

The ECU development process may involve:

- Model Based Design involving development of mathematical models of all systems to be controlled and also models of the control algorithms. Thus, the entire system can be simulated mathematically on a PC providing insights on the design aspects even before the components have been manufactured.
- Next, software that will reside on an actual production type microprocessor should be developed and used in simulations.
- Optimization of the design functions by connecting the prototype controller to a test bench, e.g., a dynamometer with the motor, or in an actual vehicle.
- HIL simulation with the ECU hardware. In the HIL, the vehicle dynamics and other vehicle systems that affect the ECU performance are simulated. Even some actual systems can be connected to the HIL to further improve correlation to the real world.

The basic challenge in controllers lies with algorithm development. The next challenge is integrating the same with targeted hardware. As volume picks up, it may become feasible for Indian industry to venture into hardware developments.

HV Electrical Architecture & Safety

Modern electric vehicles are increasingly adopting high voltage systems. Often electric vehicles have higher voltage than safety voltage. At the same time, the impedance of the electrical system is small. Normal operation current of such high voltage system can reach up to hundreds of amperes while the short circuit current can be several times higher than normal current. This underlines the need for careful consideration of the safety of passengers.

Issues that need to be addressed are:

- Studies on failure mode, self diagnosis, invalidation strategy and safety control strategy.
- Monitoring and analysis of main parameters in high voltage system including insulation condition,

connection condition of electrical system and high voltage connector condition
- Simulate and define the optimum distribution of High Voltage on-board nets on hybrid and full-electric vehicles
- To develop high fidelity models of the HV architecture including the battery, inverter, electric machine and its controller, cables, connectors and the complete system for improved robustness and safety
- Verify the HV model using a prototype drive with optimum control algorithm and using Hardware-in-the-loop (HIL)
- Decoupling high voltage energy storage system voltage level from the vehicle DC bus voltage level
- Identify the causes of noise and impact in a given Hybrid Electric Vehicle (HEV), leading to possible solutions including design and control algorithm enhancements.
- To quantify the impact of different control strategies on system voltage and current, hence component sizing and cost in PM machines.

xEV diagnostic system development and validation
As compared to a conventional vehicle, a hybrid electric vehicle comprise new components such as electric machines, battery, and power electronics.They should be monitored with the same accuracy as the components used in a conventional vehicle. Hybrid electric vehicles can work in various modes; thus designing diagnostic system for HEVs should take into account the new features such as mode switches. Design and implementation of diagnosis systems on vehicle level should be taken up to study the influence of this on the performance of the diagnosis system.

There will be an increasing demand for remote monitoring systems for xEV.

This will enable:
- An optimized energy management control strategy.
- Access to information on running parameters of the HEV.
- Integration with Intelligent transportation system services that can improve efficiency.
- Improvement in traffic safety by monitoring the running status and performance parameters of xEV in real time.

Hybrid Energy Storage System
Yet another component the vehicle development consortia may explore is experimentation with hybrid energy storage system comprising battery and super-capacitor which are connected to the same voltage bus through appropriate DC-DC power converters. While the main power source aims to supply mean power to the load, the super-capacitor would supply transient power and peak load demand.

Deliverable
- Power control strategy for hybrid power source by using DC-DC converter.
- Design and development of DC-DC converter
- Downsizing the battery considering the energy usage only
- Measurement of overall drivetrain performance by use of hybrid power sources
- Field testing of the electric vehicle employing hybrid power sources

High power density efficient on-board charger

- Calculation of rating of battery pack for the given vehicle specifications.
- Drawing up the specifications of the battery charger for the Lithium ion battery pack.
- Design and development of power converters and associated controllers comprising the battery charger.
- Lab level testing of the developed power converters and controllers.
- Field testing of the developed battery charger in the electric vehicle.

Thermal Management System

Electric currents and alternating electromagnetic fields cause power dissipation in all electronic parts, which results in increase in their temperatures. This in turn affects the reliability and life expectancy of these components. Thermal management system should ensure semiconductors, capacitors and wire insulation operate within their typical maximum operating temperatures (125-175^{0}C, 85-125^{0}C and 105-200^{0}C respectively at junctions).

Development of integrated thermal management system:

Major challenge that need to be addressed is the integration of thermal management systems for various components of xEVs. Particularly, in case of hybrid and plug-in hybrid vehicles, which have higher level of complexity. Designing suitable thermal management system within affordable cost, weight and size is an issue that requires special attention.

- Integrated cooling system for motor and inverter
- Integrated cooling loop for HEV
- Develop and validate waste heat recovery systems for xEV propulsion
- Exploratory studies on graphene coating on aluminium/copper plate to be used as heat dissipating element for possible replacement heat sink fins with graphene composite sheets.
- Exploratory studies on heat transfer performance of different textured surfaces would be attempted
- Design & development of experimental prototype heat sinks.

Energy efficiency improvement

Application of vehicle technologies such as light weighting, low resistance tyres, aerodynamic design etc. for xEVs to improve performance and reduce cost.

ICT for electric mobility

The objective will be to investigate how the lifespan of electric vehicles can be enhanced through the application of latest asset management tools and techniques utilizing the rich data available from telemetry and tracking systems.

This will include:

- Identification of the major components of battery electric vehicle drivetrain
- Identification of the frequently occurring failure modes and assess their impacts on vehicle operation
- Development of database of early adopters, component manufacturers, service/ maintenance providers etc.

The experience of electric mobility can also be enhanced through connection and information exchange between multiple infrastructure systems related to electric mobility.

EMI/EMC Shielding

Another important issue is Electromagnetic Induction (EMI). With xEV car or bus having high voltage and also high current, EMI is an area of concern. This issue is further complicated due to wide variation of technologies used in xEVs. Even for today's 12 V cars, EMI issues are very important; so when we have 200V, 300V systems, the level of concern will multiply. Apart from DC, xEVs will also feature AC, that too at high frequency. Safety isolation is a key issue.

xEV specific engine systems development

The Atkinson engine mainly works on Otto four stroke engines with a different type of linking the piston mechanism with the crankshaft. In an effort to minimize waste of energy, the intake valve is left open for a small portion of the compression stroke. Due to shorter power stroke, Atkinson engines typically have a narrower rpm range. However, in case of HEV applications, using the engine in conjunction with electric motor and suitable transmission, this issue can be addressed.

Efficient electrical auxiliary devices for xEV applications

Energy consumption in electrical auxiliary devices such as electrical compressor, superchargers, vacuum pumps etc need to be reduced.

- Testing and validation methodology
- Develop India specific test procedures for battery and motor performance evaluation
- Develop vehicle testing procedures to determine component duty cycles
- Development of a consistent approach for a systematic, detailed characterization of the real world driving cycle data for engineering analysis leading to determination of component duty cycles

Electric Differential and 2/4 Wheel Drive

Development of control schemes based on active differential drives for implementing different vehicle stability and control functions like Anti Slip Regulation (ASR) and Electronic Stability Program (ESP).

- Studies on the applicability of different options like FWD, RWD and 4WD for the developed vehicles
- Calculation of rating of requisite individual motors
- Development of intelligent control schemes for traction control of individual wheel motors
- Development of active torque distribution schemes for ensuring lateral stability of electric vehicle
- HIL testing of the developed schemes

5.5 TEST INFRASTRUCTURE FACILITIES

5.5.1 Vehicle Test facilities

Regulator test facilities are proposed to be set up at ARAI Pune. The proposed test facilities at ARAI Pune are as follows:

Electric Motor Test Bed
Motor Test Bed is required to facilitate complete development, testing, verification and validation environments for electric drives and also for determining and analyzing electrical, mechanical and thermal characteristics. Functionality, reliability, endurance test as well as cold start performance measurements are implemented under real operation conditions.

To cater to all vehicle types, 2 motor test bed facilities for motor performance testing as per AIS041 and as per following brief specifications are recommended:

- 100 kW, 1000 rpm (2/3 wheelers, passenger cars)
- 250 kW, 1500 rpm (LCV/HCV)

Some test facilities related to R&D on Systems Integration will be available in respective R&D Centres.

Battery simulator
The most important development tasks for energy storage systems are optimization of life-time, safety, power, energy and costs. Battery simulator facilitates development tasks of performance evaluation and life-time investigations of electrochemical energy storage systems for hybrid and pure electric vehicles.

For type approval testing, battery simulator will facilitate providing DC supply to the motor under performance test.

Following systems are required for type approval testing of xEVs:

- DC Power Supply 450V/200A with power meter (0.2 accuracy class) - passenger cars
- DC Power Supply 800V/600A with power meter (0.2 accuracy class) - LCV/HCV

Battery Test System
The present type approval requirements for xEV batteries as per AIS 048 call for safety. The battery performance requirements are not mandatory for approval. However for development / durability testing of battery packs it is recommended to establish battery test system (800 V / 1000 A) capable of programmed charge / discharge cycles under different environmental and duty cycle conditions.

The modular battery test system is used in a wide range of applications:

- Examination of cells, modules and packs
- Characterization of various energy storage systems for different applications (for e.g. scooter, passenger car, light and heavy duty)
- Testing and verification of supercapacitors, nickel-metal hydride and lithium-ion batteries

Chassis Dynamometer, Dilute Emission Measurement System for 2-3 W & Passenger Cars
This equipment is required for running the vehicle in the laboratory for range, electrical energy consumption and emission measurement (Hybrid Electric vehicles) under different driving cycles. Presently these equipment are available/

planned at NATRIP centres and the same can be utilized for type approval of xEVs provided these facilities are enhanced with suitable power meter and DC power supply.

Power Meter Class 0.2
Along with accessories such as Current Clamps, Voltage Monitors, etc.

DC Power Supply
100 kW, 450V DC, 200 AMP to emulate the battery during vehicle running condition.

These equipment are required for enhancement of present emission measurement test facilities at test agencies for testing of xEVs.

Hydrogen Analysis System
Present Indian standards do not call for measurement of hydrogen emissions during charging of open type batteries. Relevant ECE regulation stipulates this requirement. Accordingly, Indian standard is under active consideration for revision. For hydrogen emission measurement, hydrogen analysis system is required to be integrated with VTVV Shed System available/planned at NATRiP centres.

HCV Chassis Dynamometer (up to 20000 kg) & Dilute Emission Measurement System
Along with Power Meter Class 0.2. accessories such as Current Clamps, Voltage Monitors, etc. and DC Power Supply 250 kW, 800V DC, 600 AMP to emulate the battery during vehicle running condition.

Utilities

- Vehicle Test Cell (25 m x15 m) - 1 No.
- HVAC System for Controlling Vehicle Test Cell Temperature and Humidity
- Electricity Supply Requirements (3 Phase, 415V AC /50 Hz, 1000 kW)
- Air Compressor
- UPS Power Supply (50 KVA)
- Centralised Calibration Gas Handling System
- Exhaust Handling System
- E-Motor Test Cell - 2 Nos. (30 m x 20 m)
- HVAC System for Controlling E-Motor Test Cell Temperature
- Electricity Supply Requirements (3 Phase, 415V AC /50 Hz, 750 kW)
- Air Compressor
- UPS Power Supply (30 KVA)

For emission measurement of xEV heavy commercial vehicles, HCV chassis dynamometer with suitable dilute emission measurement system is required. For conventional HCVs, emission measurement is done on engine and not on the vehicle. For hybrid electric vehicles, emission test will be required to be carried out at vehicle level since it involves two power trains, i.e. engine and motor. AIS:102-Part 2 for approval of hybrid vehicles having GVW >3.5 ton does not specify emission test procedure and driving cycle to be deployed during the testing on chassis dynamometer, due to non-availability of such facility. Hence, AIS:102-Part 2 is an interim standard and needs to be updated in line with worldwide developments. However, considering the future requirements, facility is required in the country for carrying out emission development / type approval testing of HCV xEVs.

INDIAN COMPETENCY IN SYSTEMS INTEGRATION

POTENTIAL PARTNERS: Potential partners in the lightweighting efforts include ARAI, Hindalco-Novellis, Alcoa, apart from IISc Bangalore. ARAI, Association of State Road Transport Undertakings (ASRTU), IISc Bangalore, IIT Bombay, HAL, Aluminium Association of India.

DETAILED SPECIFICATIONS OF xEVs: IIT Kharagpur, ARAI, CDAC, OEMs

POWERTRAIN CALIBRATIONS: ARAI, NATRIP

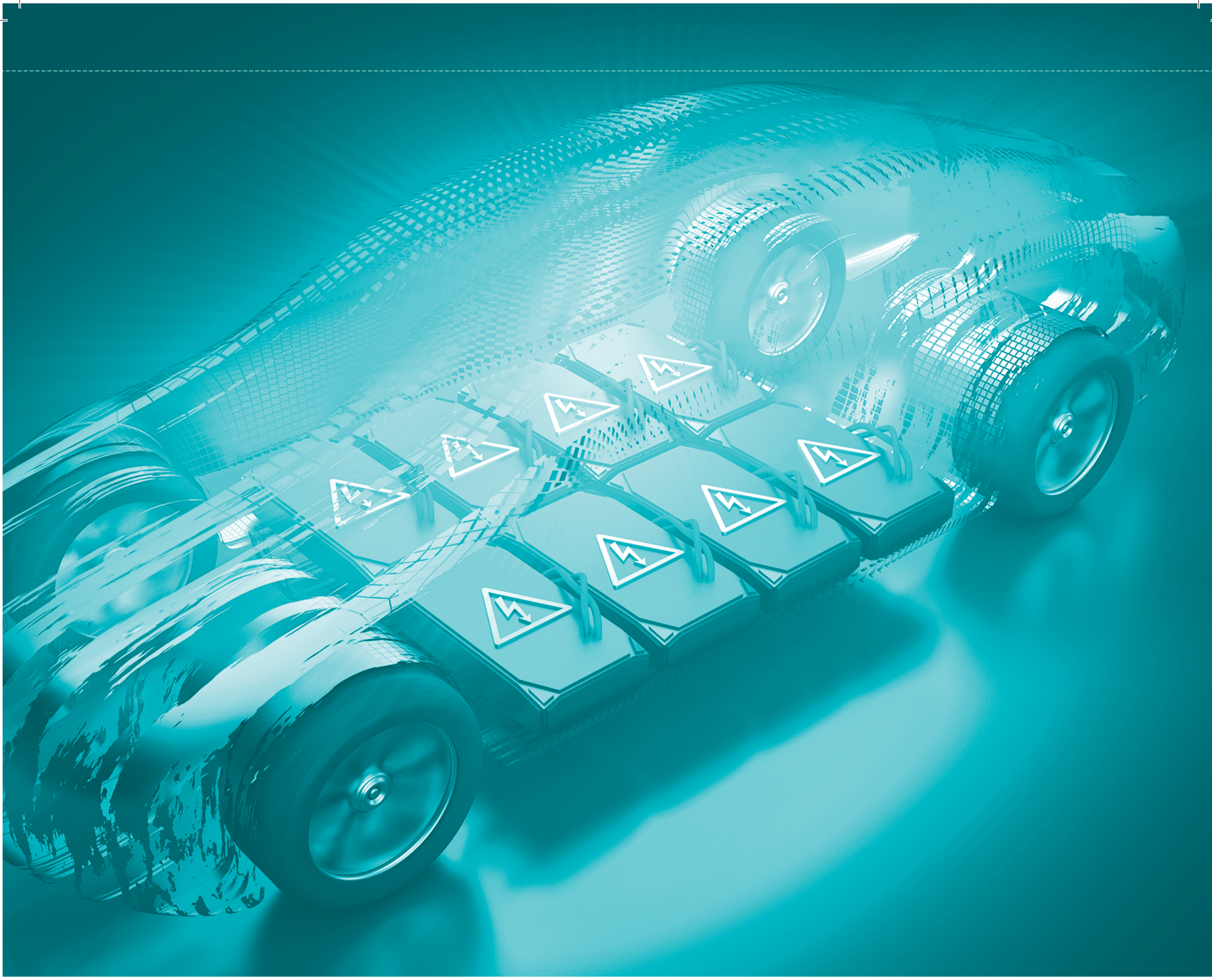
SIMULATION OF BATTERY IN VEHICLE CONTEXT: CDAC-T, IIT Kharagpur, IIT Gandhinagar, ARAI, IIT-Kanpur

04
RECHARGEABLE ENERGY STORAGE SYSTEM

01 INTRODUCTION

Currently, rechargeable batteries are used on board xEVs for the electrical energy storage. Fuel Cells and Ultra-capacitors are not ready for widespread commercial use. The xEV batteries must have high specific energy (energy stored per kg) and high specific power (power output per kg). The high cost of the electric drive vehicles is mainly due to the battery pack.

‘Specific energy’ (energy stored per kg) of battery is at least 50 times less than that of gasoline. Thus the battery may weigh 15-35% of the total weight of the BEV; In a HEV, there are two powertrains, and some weight has to be taken away from the vehicle structure to gain good fuel economy. Hence reduction of weight battery pack while increasing its energy content is desirable.



Battery performance deteriorates with time. The End of Life (EoL) of Lithium Ion Battery in HEV is decided by power fade (impedance growth), or State of Function (SOF), and in EV & PHEV, it is based on energy loss (capacity fade). Even after EOL, there can be 2nd or 3rd use in other applications such as telecom tower backup supply, home inverters etc.

Batteries have to be optimized for the specific energy, energy density, specific power and power density, charge acceptance, cycle life, cost, safety and environment impacts. Trade-offs between specific energy and specific power is important for vehicle applications.

Battery Electric Vehicle (BEV)
Battery Electric Vehicle (BEV) requires battery with large energy storage capacity, since it is solely dependent on battery for its driving range.

Range Extended Electric Vehicle (REEV)
REEV is similar to BEV, with provision for battery getting charged by onboard engine.

Hybrid Electric Vehicle (HEV)

Hybrid Electric Vehicle (HEV) load profiles have narrow state-of-charge (SOC) bandwidth variation, usually around 50-60%. So the battery works mainly under partially discharged conditions. The battery must have capability of providing and absorbing relatively high current pulses in an irregular frequency. High specific power is more important for HEVs than for PHEVs and EVs. Hybrid electric vehicles require cells with high power densities. Thinner electrodes generally provide high power densities. Such cells are expensive to manufacture.

Plug-in Hybrid Electric Vehicle (PHEV)

PHEV has both BEV and HEV characteristics and has a complex demand on the battery. Similar to BEV, the PHEV need high energy cells, which demand for thicker electrodes.

COMMON FEATURES

- The system must perform well over a wide temperature range, and give stable output over life-time (aging and calendar life). xEVs operate at high voltage and EMC is also an important issue.
- The charge acceptance characteristic is important for regenerative braking.
- The Battery Management System (BMS) is required mainly for Lithium ion battery. BMS continuously estimate the state-of-charge (SOC), state-of-health (SOH) and available power. The BMS monitors individual cells and protect them from reaching the threshold condition. BMS for lead acid or NiMH battery could be much simpler.
- An energy management strategy requires the BMS to communicate the status to other systems within the vehicle or through remote networking to the systems of Vehicle Manufacturer or Battery Supplier. In short, the BMS works in real time for battery monitoring, maintenance, regeneration, battery optimizing, failure prediction and/or prevention, battery data collection/analysis and planning.

02 TRENDS IN ON-BOARD ENERGY STORAGE

The right batteries and design greatly influence how electric vehicle functions on the open road, in terms of speed, range, reliability and consistent performance under varying conditions. Battery pack design should meet these requirements, within the physical and financial constraints.

Since early days, various types of batteries that have been used in electric vehicles include lead acid, nickel-cadmium, NaNiCl2, nickel-metal hydride etc. Zinc air fuel cells have also been used in some demonstration vehicles. Starting from 2009, the trend has shifted significantly towards lithium ion battery.

2.1 LEAD ACID BATTERY

Lead Acid Battery has been in use since 1860 and is a safe and reliable option. It was used in electric vehicles as early as 1899 by Lohner Porsche .

Commercially available lead-acid batteries have specific energies of 25–40 Wh/kg and energy density 60–75 Wh/l. Their discharge-charge watt-hour efficiencies lie between 80 and 85%. At present they find limited application in EVs. Low specific energy and energy density, short calendar life and cycle life of a few hundreds of cycles are big drawbacks for lead acid battery in electric vehicle applications. Even after 150 years since its invention, improvements are still being made to the lead acid battery and despite its shortcomings and the competition from newer cell chemistries the lead acid battery still retains the lion's share of the automotive battery market. In the short term, the lead acid battery is expected to have a considerable market share in electric two wheeler applications. Lead acid battery is expected to remain a choice for the micro-hybrid vehicles that are being introduced.

Some basic problems of the lead acid battery chemistry are

- Sulphation/ string imbalance created under partial state of charge conditions. This is a major issue in case of HEV battery, because it may lead to early decline of battery capacity
- Continuous charge/ discharge rate capability needs to be improved to enhance regenerative braking and acceleration performance, and
- Grid corrosion affecting the cycle life / longevity of the battery

Research needs to be directed towards solving these problems to enable development of high performance and longer lasting lead acid batteries for xEVs

Approaches to enhance specific energy and energy density of lead acid batteries:

- Designing more active elements in the materials of the batteries to change the behavior of positive and negative performance.
- To enhance performance by overlapping its structure of wall building style
- Energy Power System working on these and claims to have enhanced the working capacity from 300-400 W/kg to 2000 W/kg.

2.2 ADVANCED LEAD ACID BATTERY

In carbon enhanced lead acid, or "Lead Carbon" batteries, attempt is made to improve the partial state of charge operations by adding certain types and amount of carbon to the negative plate, which inhibits the sulfation.

Firefly International Energy, USA carried out R&D of a new concept of using Carbon Foam in Lead Acid Batteries to deliver better efficiency and 2-3 times life cycles. In India, Advanced Microcell Carbon Foam Batteries are being manufactured by Firefly Batteries Pvt. Ltd., Ahmedabad for Electric 3 wheelers. Firefly International Energy, USA has granted license to Firefly Batteries Pvt. Ltd., Ahmedabad to manufacture and sell batteries using Firefly's patented Microcell Carbon Foam Technology in Indian market. These batteries have improved performance, cycle life and fast charging capability as compared to lead acid battery used in electric vehicles.

2.3 ZEBRA (Na- $NiCl_2$)

Zebra battery was invented in 1980s under the “Zero Emission Battery Research Activity” project at CSIR, South Africa. It was an improvement over the sodium–sulfur (NaS) molten battery and replaced the sulfur cathode with metal/metal halide impregnated with molten $NaAlCl_4$, and increasing the safety. Molten Sodium is used as negative electrode (anode). The electrolyte in Zebra battery is molten sodium aluminum-chloride which has a melting point of approximately 160°C.

The ZEBRA battery has a specific energy of 90 Wh/kg and a specific power of 150 W/kg, which is nearly that of some Li-ion batteries, while being considerably cheaper. The battery materials can be recycled. It was used for some experimental electric vehicles like 2007 Modec and 2007 Smart EV.

Zebra batteries are not practical for vehicle applications since it has to be held at high temperature (270°C-350°C) even when the vehicle is not in use. So it needs heat insulation. The specific power is also low. There have been some research activities exploring the combination of zebra battery and ultra-capacitor to solve the problem of specific power.

2.4 NICKEL METAL HYDRIDE NiMH

The NiMH batteries have nickel oxide anode and metal hydride cathode. The cell reactions involve a cyclic transfer of protons between the metal hydride (MH) anode and the NiOOH cathode. The first generation hybrid vehicles used NiMH batteries and they lasted for the entire life of the vehicle. However NiMH battery is not suitable for battery electric vehicles as they need higher specific energy. In HEVs also, the NiMH has been supplanted by lithium ion battery.

Limitations: NiMH battery discharge-charge watt-hour efficiency is only about 80%, and they have high rate of self-discharge, typically 30% per month. This battery requires costly raw materials - about 7-8 kg of nickel per kWh and they also utilize rare earth metals. The cycle life is drastically reduced at high operating temperatures.

Currently nickel-metal-hydride battery packs are only found in a handful of hybrid vehicles like Toyota’s Prius hybrids. Even Toyota offers lithium ion option in new generation of Prius.

However some efforts of developing NiMH battery with higher specific energy and reduced cost are still in progress.Scientists of BASF research centre have changed the microstructure of the electrodes used in nickel-metal battery packs, making it far more energy dense and durable. BASF have produced NiMH cells in a laboratory environment with an energy density of 140 watt-hours per kilogram. NiMH is inherently more stable as a battery chemistry, requiring less safety measures than lithium-ion.

2.5 LITHIUM ION BATTERY

Lithium ion includes a family of battery chemistry with wide variety of anode, cathode and electrolyte combinations. They have energy densities of 150–200 Wh/kg (at cell level), low self-discharge rates and nearly 100% charge (Coulombic) efficiency.

Currently it is an expensive solution, but with more xEVs coming to the market, the costs of lithium-ion batteries are expected to fall rapidly. For Nissan Leaf, the battery pack costs about $470/ kWh, which is estimated to come down to $370 per watt-hour. Tesla Motors hopes to reach a price of less than $200/kWh in the near future for battery packs of Model S.

Electrodes are constituted of thin metal foils coated with active material. In terms of geometry, lithium-ion cells could be cylindrical, elliptic cylindrical, pouch or prismatic.

2.5.1 Cathode materials

The cathode is a metal oxide, in which lithium ions are inserted into the crystal structure, or intercalated. The materials must be able to accept and release lithium ions repeatedly (for recharging) and quickly (for high current). The energy stored in the cathode depends on the material's charge-storage capacity and the voltage it needs to absorb and release lithium ions. Any new cathode material has to be stable, and has to work well with other components.

One stability problem is the collapse of the cathode material crystal structure when the lithium ions flow out of it, causing reduction in the electrode's lithium storage capacity over time; or even its break down.

If the cathode works at too high voltage, it can oxidize or decompose the liquid electrolyte. Other unwanted reactions between the cathode and electrolyte can lead to corrosion of the cathode or deposition of current reducing layers on its surface.

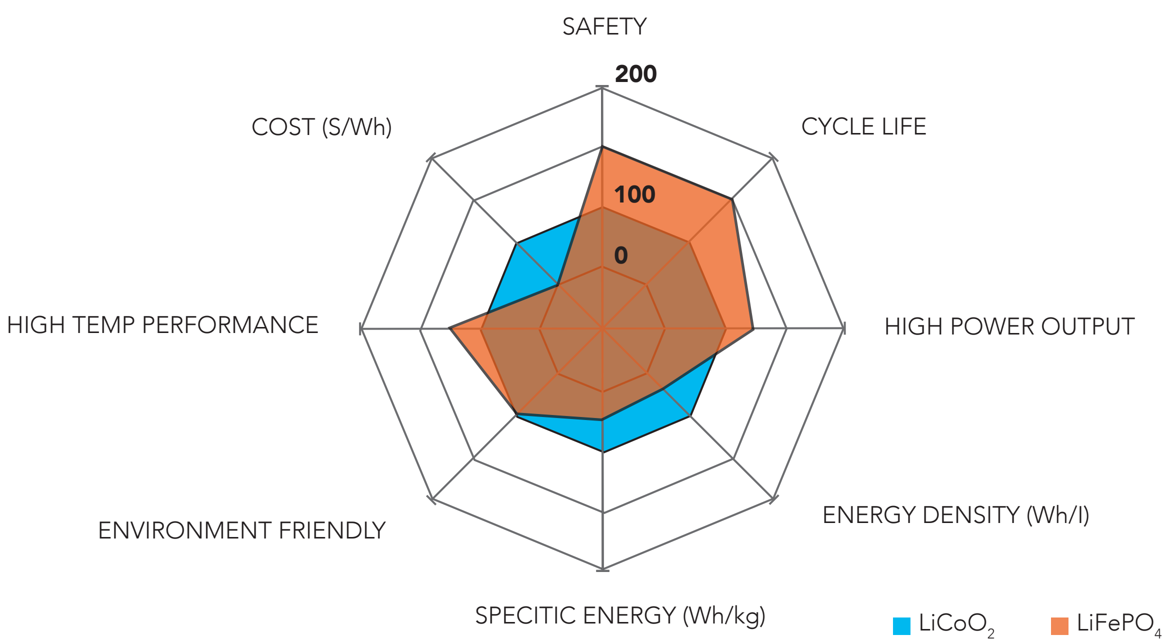
The commercially important variants rely on three important materials – $LiCoO_2$ (Cobalt), Li-$FePO_4$ (Iron) and $LiMn_2O_4$ (Manganese).

TABLE 4.1
CATHODE ACTIVE MATERIALS

MATERIAL	STRUCTURE	AVWG V	SP CAPACITY mAh/g	SP ENERGY Wh/kg
$LiCoO_2$	Layered	3.9	140	546
NCA	Layered	3.8	180-200	680-760
NMC	Layered	3.8	160-170	610-650
LMO	Spinel	4.1	100-120	410-492
LFP	Olivine	3.85	150-170	518-587

FIGURE 4.1

COMPARISON OF $LiCoO_2$ AND $LiFePO_4$ BATTERY



These are layered, olivine and spinel type of pristine materials. Since no single pristine cathode material meets all the requirements of the lithium ion cell/ battery for EV application, EV cell manufacturers after years of research and development have started using composite cathode materials.

Electric vehicle Lithium ion cell manufacturers blend one or more of the cobalt, Nickel, Manganese and Iron phosphate material to have their own recipe for the composite cathode material as a best compromise (optimum performance) with regard to energy, power, safety and cost.

$LiCoO_2$ is used in portable electronic gadgets and it has high charge capacity. But the disadvantage is that cobalt is quite expensive and toxic. Their thermal stability is inadequate for xEV applications, and has structural instability under overcharge. So $LiCoO_2$ is not used for electric propulsion. In their efforts towards developing a more stable cathode material, researchers have replaced some of the cobalts by nickel and manganese.

Lithium nickel oxide is characterized by a good specific capacity and a good cycle life, but it shows lower thermal stability. Lithium nickel cobalt aluminium oxide (NCA) offers high specific energy. It is however relatively expensive. The Tesla Model S runs on lithium nickel cobalt aluminium oxide (NCA) battery, with liquid cooling.

Lihtium nickel manganese cobalt (NMC) has a charge-discharge cycle life of twice as much that of $LiCoO_2$. Nissan Leaf and BMW-i3 use NMC battery. Since nickel allows the cathode to operate at high voltage, efforts towards developing next generation NMC focus on increasing its nickel content. A lithium and manganese rich NMC cathode being developed at Argonne National Laboratory and Oak Ridge National Laboratory promises specific energy of 280 Wh/kg. However, the challenge that needs to be overcome is the voltage drop over time.

For lithium iron phosphate, the strength is safety, but it compromises in terms of specific energy. Two major advantages of the $LiFePO_4$ based batteries are high thermal stability and less cost as compared to other lithium ion chemistries. Fe is used in this cathode material, which is abundant and low cost.

2.5.2 Anode materials

Carbon-based materials are typically used in the anode (negative electrode), including simple graphite or petroleum coke. Lithium titanate has also been used as anode in commercial lithium ion battery for electric vehicle. Although the energy density is reduced, but a broader operating temperature range and safer voltage range can be obtained. Lithium titanate battery uses additional lithium titanate nanocrystals on the surface of the anode, offering it enhanced surface area. It has enhanced lifetime and is suitable for fast charging and low temperature operation.

Lithium battery with silicon anodes is still under development, and promise to have very high energy density. Silicon has a charge storage capacity 10 times that of graphite. The difficulty is, silicon swells drastically when it absorbs lithium ions. As a result the anode degrades after a few hundred recharge cycles. Approaches being explored to address this difficulty include combining silicon with graphite or graphene, embedding it in protective coatings, or using silicon nano-structures.

Sekisui Chemical of Japan is developing lithium ion battery that uses silicon in place of carbon in the negative electrode and high performance gel-type electrolyte. The company claims that it will be able to triple the specific energy. The company also expects to reduce the cost by one-third.

A few research groups are working on anode made of pure lithium metal, and graphene also.

2.5.3 Electrolytes

The electrolytes are LiPF6 dissolved in organic carbonates or esters. Ethylene carbonate (EC) is required since it helps in the formation of the anode solid electrolyte inter-phase (SEI).

Such electrolyte has 10 to 1000 time's lower electric conductivity, compared to the aqueous electrolytes used in nickel-metal hydride and lead-acid batteries. But water is electrochemically stable within 0 V to 1.25 V; and outside this voltage range electrolysis of water occurs. Non-aqueous electrolytes will give higher energy density. Recent research efforts have focused on overcoming the voltage stability issues of aqueous electrolytes.

Lithium ion battery using inorganic electrolyte is available for stationary energy storage applications.

Lithium polymer battery
uses a conductive solid polymer or plasticized or gel polymer electrolyte. With such electrolytes, the possibility of electrolyte leakage is reduced, and the cell becomes much more abuse-tolerant. Shape versatility and flexibility are the other advantages. The gel polymer type lithium ion battery has been commercialized. Typical weakness of lithium polymer batteries is its low temperature characteristics. Low ionic conductivity at low temperature is the issue. High ion conductivity at low temperatures is the issue. Apart from this, use of flammable organic solvents in gel polymer electrolyte may cause battery "flashing". R&D on solid polymer electrolyte is required. Low ionic conductivity of solid polymer electrolyte at lower temperature is a major challenge.

2.5.4 Solid State lithium ion

In solid state lithium ion battery, a solid state ionic conductor is used as electrolyte. Since the need for liquid container and separator can be avoided, this type of battery offer design flexibility as well as potential improvement in specific energy.

Conventional Li-ion batteries use organic solvents in electrolyte which are flammable, cause safety concerns and cannot be used with high capacity active materials such as sulfur cathode and lithium metal anode due to dissolution or dendrite formation. Solid electrolytes can overcome this barrier for enhancement of the specific energy, and are safer.

There are generally two types of solid electrolytes – oxides and sulfides.

High internal resistance has been a major challenge for development of solid state battery.

Approaches to overcome this include:

- Reduction in the interfacial resistance by forming a buffer layer between the solid electrolyte and cathode material
- Using nanostructured form of solid electrolyte

2.5.5 Separator

A microporous separator is used between anode and cathode. It maintains an even spacing between anode and cathode and prevents direct contact between the electrodes, while allowing the ions to move. Although normally electronic devices are used for thermal management, the separator acts as a safety device in case of failure of such system. In case of overheating, the porous film melts and seals the electrodes from each other.

Overcharging of lithium ion cells causes plating of the electrode surface by metallic lithium. A lithium ion battery needs to carry some charge always, as otherwise irreversible changes in the electrodes may result into loss of charge capacity. To take care of these aspects, lithium ion cells are equipped with built in electronic circuit.

A metal casing made of nickel plated mildsteel or aluminium is used to house the functional parts of the cell. The electronic circuit is contained in a shell, usually made of plastic, but for vehicle use the casing could also be metallic for improved safety.

2.5.6 Safety of lithium ion batteries

Internal Factors

- thermal runaway due to breakdown of the cathode crystal structure, caused by overcharging
- abnormal heat up due to internal short caused by dendrite growth, current collector short, and infiltration of foreign matter.

External Factors

- Crushing, collisions causing internal short resulting in abnormal heat up
- Heating, fire etc causing forced heat up

Since abnormal heat up is the direct cause of the damage of the battery in both these cases, it is necessary to consider methods which can suppress abnormal heat up.

Design of safe lithium ion battery must consider:

- Use of materials that are thermally stable
- Structure with no local heat up
- Possibility of use of carbon fibre composites for battery case
- Optimization of each components
- Control of manufacturing quality

Lithium-ion battery designs inherently have poor heat dissipation, and since it is used for high power applications, the heat dissipation is a major engineering challenge. The heat generation is non-linear with current and steeply increases with it. The main factors for heat generation are entropy (reversible heat) and resistance & polarization.

Lithium ion cells may ignite if overcharged. If there is abnormal rise in cell temperature and it goes above 130-150°C, then exothermic chemical reactions will begin between the electrodes and electrolyte, leading to thermal runaway.

The following may happen.

- thermal decomposition of the electrolyte;
- reduction of the electrolyte by the anode;
- oxidation of the electrolyte by the cathode;
- thermal decomposition of the anode and cathode; and
- melting of the separator and the consequent internal short.

2.5.7 Fast charging of lithium ion battery

It is widely believed that fast charging significantly reduces the battery life cycle as it can lead to overcharge of individual cells. The cell-internal resistance will cause cells to heat up and break down.

In a cell designed to stand fast charge, the path length and resistance for the transport of ions and electrons have to be reduced. Li+ ion diffusion path length can be shortened by changing the morphology of active material or changing the material's chemical structure, or by doing both.

The approaches are

- reduce particle size of materials to nano-scale,
- use thin electrodes to lower resistance of cells,
- increase the amount of current collectors and electrolyte concentration and
- reduce viscosity with solvents.

Lithium iron phosphate couple has the inherent ability to accept charge at high rate. Potentially the Li-polymer cells, which can be very thin, can be used in designing for fast charge batteries. A recent study by Stanford University has questioned whether rapid charging the battery is as damaging as researchers had thought. The study also concludes that the benefits of slow charging may have been overestimated.

2.6 EMERGING BATTERY TECHNOLOGIES

2.6.1 Lithium Sulfur

This type of battery was invented in 1960. A basic Li/S cell consists of a lithium metal anode, a carbon-sulfur cathode, and an electrolyte that permits lithium ions to pass. Although LiS battery promises high specific energy, cycle life is a major concern. Depletion of sulfur in the cathode has been attributed to be the main cause of short cycle life. However, a recent study has shown that sulfur in cathode remain largely intact during discharge.

The Li_2S deposited on the cathode has nearly double the volume of the original sulfur. This mechanical stress causes mechanical deterioration of the cathode, reduces the electrical contact between the carbon and the sulfur. It also prevents the flow of lithium ions to the sulfur surface.

The EC, PC, DMC, DEC solvents commonly used in lithium ion cells cannot be used in Li-S cells. These cells use different type of organic solvents tetraethylene glycol dimethyl ether (TEGDME),1,3 dioxolane (DIOX) etc.

Cycle life has remained the major challenge for lithium sulfur batteries. Researchers at the Lawrence Berkeley National Laboratory, USA have cycled LiS cells 1500 times, losing half the capacity. This performance is comparable to commercial lithium ion cells.

Oxis Emerg, UK, claims to have run large Li-S cells for 900 cycles. Cell level specific energy of 400 Wh/kg has been achieved.

2.6.2 Metal Air

In a metal air electrochemical cell, anode is a pure metal, and cathode is air. The metals that can be used as anode include zinc, aluminium, iron and lithium. Possible recharging options are either by replacing the metal cathode (cathode material is used as a 'fuel' – it is basically a fuel cell), or electrically. Electrical recharge has been a stiffer challenge.

Zinc Air Batteries can potentially be manufactured at low cost. According to a projection by ARPA-E, it may be possible to achieve cost of $100/kWh. Zinc air primary cells with 300 Wh/kg specific energy have been developed. Some demonstration electric vehicles have used Zinc Air Fuel Cells. Theoretical specific energy of 1350 Wh/kg excluding oxygen is technically feasible. Supply of carbon dioxide free air is necessary to achieve acceptable life and durability. Available energy of Zinc Air battery drops significantly when high power is required. These batteries are sensitive to extreme temperature and humid conditions, and also have high self discharge (after seal is broken). After activation, chemicals tend to dry out and the batteries have to be used quickly. Zinc Air Batteries have flooding potential. High external relative humidity causes moisture absorption. Volume expansion when Zn is converted to ZnO. Zn deposits as dendrites when recharged electrically. Zinc electrodes typically exhibit short lifetimes, because of problems with zinc material redistribution and undesirable zinc morphologies that form during recharge. Recently ReVolt has developed electrically rechargeable zinc air button cells.

Lithium Air cells potentially can have 10 times higher specific energy as compared to existing lithium ion batteries, hence a real alternative to liquid hydrocarbon fuels. Globally research efforts are intense. Companies like IBM Research, PolyPlus etc are pursuing development of lithium air battery. The cells cannot use alkaline electrolyte, since lithium reacts violently with water. A catalyst is required to facilitate reaction between oxygen and lithium ion to form Li_2O_2. A protective membrane also needs to be used to exclude water and let in only oxygen. Commercial development is not expected before 2025.

CHALLENGES

- There are four types of electrolytes which can be used. Each one of them has their distinct advantages and disadvantages.
- In the cathode, the effect of pore size and distribution is poorly understood.
- There is a significant loss due to over-potential, as a result of which the electrical efficiency is around only 65 %. To improve the performance catalysts such as MnO_2, Co, Pt, and Au are being tested.
- With increasing discharge rates there is a significant drop in cell capacity. This is due to kinetic charge transfer limitations. Since the anodic reactions occur very quickly, the charge transfer limitation is due to cathode.
- Air compressor and blower are needed to pump in oxygen in to the battery. This increases the weight and volume of components, and negates the weight advantage of using oxygen from air as the cathode material.
- Water tight design is needed as Lithium is flammable and ignites in presence of water, and water vapor must be removed from air that is pumped in.
- Making lithium air batteries rechargeable.
- Charging lithium air batteries is a relatively slow process.
- Li-O battery is also faced with difficulties such as formation of lithium carbonate as a result of reaction between carbon in electrolyte materials oxygen, and lithium. This causes capacity loss of about 5-10%.
- Na-air battery has been found to recharge more efficiently than lithium-air battery. It is also claimed to have worked reversibly for more than 100 cycles at laboratory.

Toyota and BMW have announced a joint research program to develop Lithium air batteries. They aim to develop batteries offering a range of 500 miles on a single charge.

In order to optimize the performance of the aqueous electrolyte based lithium air cells, researchers in the Mie University in Japan developed a new approach. They sandwiched a layer of polymer electrolyte with high conductivity and a solid electrolyte between the lithium electrode and the watery solution. This resulted in a unit which had energy storage capacity (Wh/kg) almost double that of lithium-ion battery.

Theoretically, Al-based batteries could offer cost-effectiveness, high capacity and safety, since Al has low cost, low flammability and three-electron redox properties. However, development of Al air battery has been faced with problem such as cathode material disintegration, low cell discharge voltage, capacitive behavior without discharge voltage plateau, and insufficient cycle life. However, recently researchers at Sanford University unveiled an Al-air battery with an operating voltage sufficient for common applications, and charge and discharge cycle more than few 7500 cycles. Theoretical specific energy of Al-air battery is 8000 Wh/kg, but development of electrically rechargeable Ai-air cell has not been possible.

Apart from metal-air, recently the concept of silicon-air battery has also been introduced. Although these batteries have much higher specific energy than current lithium ion batteries, short lifecycle is the major barrier that needs to be overcome.

2.6.3 Na-ion and Mg-ion

These batteries are still at R&D stage. Sodium ion batteries are similar to lithium ion battery, but use sodium as the charge carrier. Potentially they can have specific energy higher than 150 Wh/kg at the cell level. As a raw material, sodium sources are much more geographically uniformly distributed, and significantly less costly. However since redox potential of sodium is 0.3V above that of lithium, there is a small energy penalty. Since Na-ion is 30% larger than lithium and 3 times heavier (Atomic Mass=22.989769), gravimetric capacity is lower than lithium ion battery. Na metal is also more active than lithium.

Na-S battery is commercially available for grid energy storage applications. But it operates at high temperature, and not suitable for transportation applications. $NaNiCl_2$ (discussed in earlier section) battery had been tried in electric vehicles.

In recent years, development of room temperature sodium ion batteries have received attention. Research works on Na-ion batteries are underway at Pacific Northwest National Laboratory, USA. FaradVion, UK claims to have developed sodium ion battery that costs 30% less than lithium ion battery.

- Anode :hard carbon
- Electrolyte: $Na\text{-}ClO_4$-EC/DXC/PC) or $NaPF_6$-EC
- Cathodes: Polyanions (phosphate); $Na_3M_2XO_6$ and Na_2M_2XO; or layered oxides (O_3 and P_2 structural type)

The typical cell (pouch type) capacity is 10-12 mAh (4cm^2), and 250-300 mAh (100cm^2). Typical bi-cell capacity is 500-600 mAh (100cm^2).

In Mg-ion battery the concept is similar to lithium ion, in which Mg is used as insertion material. Toyota is reported to work on the development of Mg-ion batteries. Magnesium ion has the advantage of carrying two positive charges. R&D efforts on Mg-ion battery are also on at the University of Illinois Chicago. Since Mg is an abundant material, it may be possible to have cost-effective manufacture of Mg-ion battery. However, R&D is still at the stage of basic electro-chemistry of the cell, and much will depend on further development of the technology and manufacturing process. For Mg-ion battery, enhancing the movement of magnesium ions is the major research challenge.

2.6.4 Supercapacitor/Ultra-capacitor

Supercapacitor family includes both double-layer capacitors that store charges electrostatically, and pseudoccapacitors that involve electrochemical charge transfer. Batteries and supercapacitors complement each other. Supercapacitors have lower specific energy (<10 Wh/kg) than batteries (30-200 Wh/kg). They are 'power devices' with high power densities of 100-2,000 W/kg, and quick discharge ability (between 1 sec to 1 min). When used together in xEVs, the batteries can provide power for continuous drive while electrochemical capacitors can provide sudden bursts of power for acceleration, hill-climbing and for storing energy from regenerative braking.

The key differences are
Supercapacitor: Supercapacitors use two layers of the same substrate with a very small distance between layers. Charge and discharge processes is physical phenomena with no chemical changes, so they can sustain several thousand cycles for decades and do not change shape during use. Other advantages are good reversibility, high efficiency, safety and maintenance-free operation.

Weaknesses: They are currently costly and unaffordable for general use in xEVs. Energy efficiency depends on use and is lower than measured in labs. The loss in energy efficiency is due to high dielectric absorption (losses or dissipation), high self discharge and high increase in ESR with cycling.

Maxwell (US) and Epcos (Europe) use carbon and cloth for electrodes. Panasonic (Japan), Ness (Korea) & Montena (Europe) use carbon particulate with a binder to form the electrodes. These devices use an organic electrolyte, usually acetronitrile with salts added. The cells are rated 2.3-2.5 V for continuous operation, and at 2.5-3.0 V for short pulses. The target is to increase the voltage to 3 V in near future.

Examples of supercapacitors usage include stop-start idle elimination systems in PSA Peugeot Citroen, Mazda and Volkswagen and hybrid transit buses from MAN, Gillig, New Flyer, BAE Bus.

In China, forty-one seat fully ultra-capacitor powered buses made by Sinautec have been plying in the Greater Shanghai area since 2006. These buses get recharged at frequent intervals in the bus stops. The 6 kWh supercapacitor bank used in these buses weigh 1450 kg.

The Mazda6 i-ELOOP system uses supercapacitor. The system, weighs just 9.3 kg, out of which weight of the supercapacitor bank is 6 kg.

2.6.5 The promise of Graphene

Graphene is a single layer of graphite consisting of carbon atoms arranged hexagonally and 2 dimensionally in infinite length. While single layer graphene is highly expensive, multi-layer graphene can be made by low cost chemical processes.

Graphene can be used to replace activated carbon in ultra-capacitors and as an auxiliary support to the electrodes in lithium ion and lithium air battery. It may also be used in lead-acid battery to reduce the weight and volume. Carbon is abundantly available, and has high chemical and thermal stability. It is environmentally benign and can be recycled.

Multi-layer graphene is sufficient for ultra-capacitor. Capacity of 900 F/g has been achieved at laboratory scale with simple electrolyte like alkali, or acid. 1200 F/g was demonstrated in the laboratory but it had some stability problem.

Due to the physical bonding between graphene layers, it offers good intercalation space for lithium ion or lithium metal, increasing the storage capacity of lithium based battery significantly. The chemical and thermal stability are reasonably good, and its use in electrodes as a composite with metal oxides is expected.

CHALLENGES

The manufacturing of Multi-layer Graphene is based on pyrolysis of hydrocarbons using transition metals (Ni, Fe, Cu, Co) as catalysts, and also in presence of chemically inactive cheap nano-fillers. Various inexpensive raw materials like natural gas & CNG, petroleum tar and carbohydrates of natural origins have been tried. The process is inexpensive and does not pollute. It is scalable to large scale manufacturing, with simple quality controls. However, the method of optimization is still held in-house by the various research groups and is not yet available in open domain. Research is underway for obtaining efficient molecular configuration of multi-layer graphene and for insertion of right electrolyte with high chemical stability and compatibility with the system. The choice of electrolyte is important.

2.7 LITHIUM ION BATTERY MANUFACTURING

2.7.1 Industry Trends

Vehicle manufacturers work closely with the battery manufacturers or choose to make the battery packs themselves. GM is making the final battery pack assembly at its Brownstown, MI plant, giving it more control over how the battery pack interacts with the vehicle's overall power system. Phase I of Tesla Motors Giga Factory to make the batteries 30% cheaper is already in operation.

The following trends are noticeable:

- VERTICAL INTEGRATION: Manufacturers are moving further upstream into components/materials
- MARGIN COMPRESSION: Component EBIT margins expected to be cut in half from today's 20-40%
- PRODUCTION OUTSOURCING: Relocating to countries with low labour cost
- REDUCED VC APPETITE: History of failed battery start-ups (A123, Ener 1, Imaraa etc)
- CONSOLIDATION: A continuous shake-out can be expected with only the low cost producers surviving

Lithium Resources

Currently, three companies that produce lithium at brine lakes in South America have a combined share of about 70% of the global lithium market. Simbol Materials (SIM), based in California, has independently developed innovative, breakthrough technology to recover and commercialize lithium from spent geothermal brine used in geothermal power generation facilities. SIM's exclusive production method, which is not influenced by the weather, makes it easy to expand facilities in comparison with the method used in South America, which requires solar evaporation. Accordingly, SIM's method facilitates further gains in cost competitiveness through increased production capacity.

ITOCHU, which invested in SIM in June 2010, is now working to provide lithium compounds for various applications. These applications include cathode materials and the electrolytes in electrolytic solution, which are core components of LiBs, as well as other commercial applications.

Investment

Worldwide investment in lithium ion battery manufacturing during 2009-2015 has been $10-12 billion, with capacity more than 50 GWh. Average investment cost for lithium ion battery manufacturing has been $250/kwh. Average cost of lithium ion cells for EV in 2015 is estimated to be around $275/kwh. However the pack level cost is about $420/kwh.

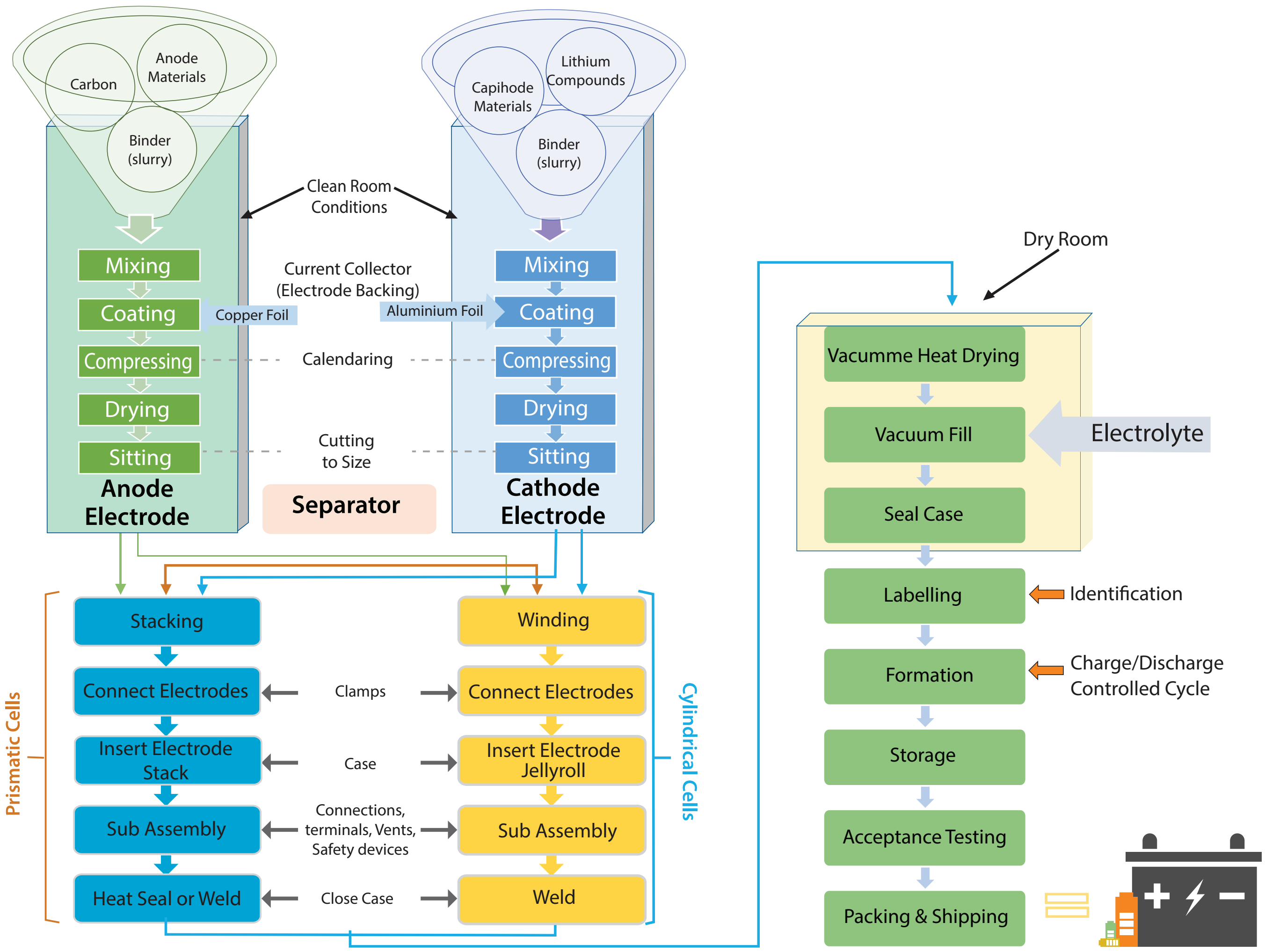
2.7.2 Design

LiB BASIC COMPONENTS

Lithium ion cells consist of three different type of foils – anode, cathode and separator. Electrodes are made by a coating process in which an active layer is applied on a copper (anode) or aluminium (cathode) foil. The active material is mixed up with coal and binder. State of the art coating methods are slit coating, die coating, tape casting, and blade scraping. After coating, the electrodes are dried and finally compressed.

Separators usually consist of porous or punctuated polymer film that is extruded out of polymer granulates.

FIGURE 4.2



Module & Pack Design

Battery pack design for xEVs may vary by manufacturer and specific applications, but the basic design is similar. Many discrete cells are connected in series and parallel to achieve the total voltage and current requirements of the pack. In lithium ion batteries, about 70% of the value-addition is in the development and manufacture of the cell itself. And about 15% value is added in the assembly of the battery, and 10% in electrical and mechanical components.

Battery Management System

Li-ion Battery for xEVs needs to have Battery Management System for ensuring efficient operations and long cycle life. Typically many cells are connected in series (for getting the required voltage) and parallel (to increase the overall capacity). When cells/battery are connected in series, the usable capacity of the entire pack will be equal to the capacity of the lowest cell. On the other hand, due to different internal impedance of the cells connected in parallel, there may be circulating currents.

Li-Ion battery also has some safety concerns. It has highly oxidizing and reducing materials and is not designed for good heat dissipation. So unless it is constantly managed, there is potential for accidental, uncontrolled release of energy that can result in dangerous situations such as release of toxic materials (i.e. smoke), fire and high pressure events (i.e. explosions). Some physical safety methodologies utilize shutdown separators and electrical/pressure interrupts (limited to 18650 cells). However, for xEV purposes, elaborate electronic safety circuitry is also necessary for ensuring safety of the batteries.

2.7.3 Electrodes

The anode material is usually graphite with binder. It is the design and characteristics of cathode materials that determine the performance and lifespan of LiBs. In addition to lithium, cathode materials also contain manganese, cobalt, nickel, and other components. The production process involves dissolution, reaction, drying, mixing, firing, and pulverization.

Electrode Materials Manufacturing has to be done at high level of cleanliness to avoid contamination, to ensure good lifespan and safety of the cell. Low humidity environment is a must to prevent atmospheric moisture from reacting with lithium ions in the electrolyte. High water content of electrodes also leads to gas-liberating electrolysis during operation.

Coating Process: The cathode material is deposited as slurry on a metal substrate. Properties to consider include the electric sheet resistivity, adhesion of the coating to the metal collector, and volume porosity of the electrode.

The important slurry properties include rheological characteristics, density, porosity, adhesion, coating ability, stability and manufacturability. The slurry recipe as well as the slurry preparation technology has to be individually adapted to the raw material powder. The powder properties are variable based on their morphology, electrical conductivity and particle sizes.

The slurry is prepared with mixing equipment like dissolver, planetary mixer and kneader, and the particle stability and degree of dispersion is defined by process parameters like the energy input and mixing time. Drying of electrode slurries is a high cost operation for lithium ion batteries. Some research efforts thus focus on use of Variable Frequency Microwave (VFM) oven, which is used in production of semiconductor electronics. Microwave penetrate the electrode slurry and interact with polar water or solvent molecules and rapidly drive them out of thick coatings.

N-methyl pyrrolidone is used in the production of electrode, which is expensive, flammable and toxic. This is required only during the manufacturing process, but not present in the final product. However, because of presence of this flammable substance, all electrode processing equipment need to be explosion proof, increasing the cost of the capital equipment considerably. Moreover, necessity to recapture of this toxic solvent from the exhaust, distill the product and recycle it, further add to the manufacturing cost. Use of water based aqueous binders can potentially reduce the cost of manufacturing of lithium ion cells. One challenge for use of aqueous binders is the agglomeration of active materials. Plasma treatment is considered as a possible solution to address this issue.

The electrode slurry is coated at 50 to 200 micron thickness (wet thickness on one side) on aluminium or copper foils using doctor blade, comma bar and slot die. In order to get defect free and adhesive electrode layers, the coating process has to be optimized for homogeneous and reproducible layer thickness and high casting speeds.

Electrode Foil morphology (porosity & mechanical integration of coating) determines its electrical properties, which in turn decide the operating characteristics and long term stability of the battery. So, suitable coating, drying, and calendaring conditions, the slurry recipe and coating weight are the important determinants of the battery cell power or energy.

Characterization Tools are used to assess material behavior in battery R&D, manufacture and operation. Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) is used to measure the composition of major elements. Instrumental Gas Analysis (IGA) is used to measure H, C, N, O and S. Glow Discharge Mass Spectroscopy (GDMS) is used to monitor impurity levels, at ppm level.

Researchers at MIT and a spin-off company 24M are working on a new process for electrode manufacturing. The new process uses electrode material which is semisolid, colloidal suspension of particles. It is not required to wait for the drying of the material before going to next stage, as in case of conventional process. It is claimed to result into simpler manufacturing process, reduction in the amount of non-functional material in the structure, reduction in the path length for the charged particles. The researchers expect that it would reduce the battery cost by half, and will produce flexible and damage-resistant batteries.

2.7.4 Cell Manufacturing

LiB Cell fabrication involves three steps: tailoring, stacking and cell finish.

Tailoring: The rolled (coated) electrode foils are spread out, prepared and cut for stacking. A cycled punching process can be used to cut the electrodes out of the continuously fed materials. Alternatively, they can be steplessly trimmed by a cutting blade.

Stacking of prismatic or pouch cells has three different processes – flat winding, single sheet stacking, and z-folding.

Cell Finish process includes

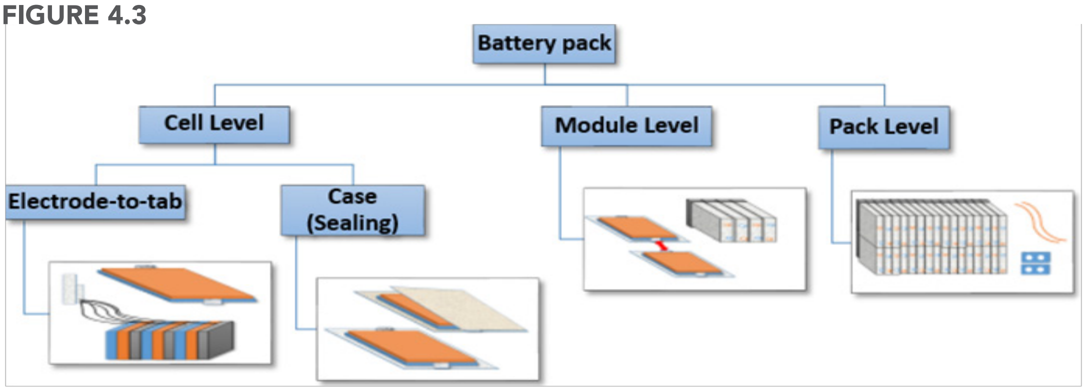
- Joining of copper and aluminium conductors.
- packaging the stack into a thermoformed aluminium barrier film or a rigid metal case
- Filling in the electrolytes
- Sealing the package under vacuum
- Formatting and testing the cells

Joining of the conductor lugs is obtained by ultrasonic welding process. By using laser welding process, the electrical resistance and durability may be obtained.

The electrolyte has to wet the separator, soak in, and wet the electrodes. The wetting and soaking process is the slowest step and therefore is the determining factor in the speed of the line.

Recently, efforts have been made in combined and hybrid processing, such as direct deposition of separators onto electrodes and rapid heat treatments.

FIGURE 4.3



2.7.5 Modules & Battery Packs

Within a cell there are welded joints. When cells are connected together to form modules of a battery, smaller capacity cells are joined by welding and large capacity cells are generally bolted together to form the battery module. The hierarchical assembly of many cells into modules, and a stack of modules into the battery makes it easy to scale up assembly of battery packs and simplifies the control of battery functions. The type of cell supervision circuit (CSC) used is one important consideration for deciding on the number of cells and modules. With the current technology, the maximum number of cells that a CSC can monitor ranges from 12 to 16 cells[1].

The capacity of cells used in battery pack vary from OEM to OEM. Nissan uses cells with capacity 30 Ah or greater in Leaf.

Battery packs design goals

- Lowest electrical resistance between each cell to minimize energy losses and permit higher peak currents for more torque
- Mechanical connection between the cells should withstand multiple drops, tool vibration, impact and temperature cycling
- Use minimum weld energy to minimize overheating the cell's internal separator materials
- Cost of interconnection material should be kept low.

Each module have a few safety features like a main fuse to limit the current of the pack under short-circuit conditions, and a "service plug" /"service disconnect", which when removed can split the module into two electrically isolated halves. Each cell-module-pack also contains sensors to measure temperature, voltage, and current as well as cooling mechanisms.

1. John T Warner; The Handbook of Lithium-ion Pack Design -Chemistry, Components, Types and Terminology

Typically there are at least two main relays that connect the battery cell stack to the main positive and negative output terminals. Some pack designs will include alternate current paths for pre-charging the drive system through a pre-charge resistor or for powering auxiliary buses which will also have their own associated control relays.

The Battery Management System (BMS) collects data from the pack sensor, activates the pack relays, communicates information to systems outside the battery and carries out several key functions.

Joining Techniques
The three most common metal-to-metal joints in an EV battery pack are Electrode Foil to Tab, Tab to Tab, and Tab to Busbar.

Ultrasonic Welding is used for joining of electrode (foil) layers, foil-to-tab joining and tab-to-tab/ tab-to-busbar joining. It is a solid state welding and works well for dissimilar materials and multiple sheets. It results in good weld for highly conductive materials (Cu, Al). However there is a limitation in joint thickness. It is also sensitive to product/ process variation.

TABLE 4.2
JOINING TECHNOLOGIES IN BATTERY MANUFACTURING

CELL TYPE	JOINING
Cylindrical	Flat tabs and bolted tabs. Resistance, laser weilding or mechanical joining
Prismatic (Container)	Mostly mechanical type (sometimes joining)
Prismatic (Pouch)	Resistance, laser, ultrasonic weilding or mechanical joining

Nickel 200, Nickel 201 and Nickel 205 are used for the tabs. These materials are electrically and thermally resistive and are relatively easy for Parallel Gap Resistance Welding. Brass or Copper tabs are difficult for parallel gap resistance weld technique, due to the high electrical and thermal conductivity and the poor metallurgical characteristics of brass.

Most challenging is the welding multiple layers of Foil to Tab. The joint is often made up of dissimilar metals, the metal thickness is mismatched, and one side (the tab) is relatively thick (e.g., 0.2 mm) while the other is made up of multiple, extremely thin, layers. The foil to tab weld is needed to gather all the current collector plates (foils) inside the cell and join them to a tab that exits the cell casing and allows the cell's energy to be transferred to an external source. There are two foil to tab welds in each cell, and hundreds of cells in a typical EV battery pack. Because of the series and parallel connections, one failure in a foil to tab joint will compromise the output of the entire pack, therefore, a robust joining process is required.

The battery pack level energy density depends to a large extent on the packaging. Various components of battery packaging may include the following: Tray, Retention of modules, Interconnections, Interface to vehicle

The Chevrolet Volt battery pack consists of 288 cells grouped by connecting three cells in parallel to create 96 individual sub modules.

2.7.6 Testing & Quality Control

Thermal Performance Tests: show the effects of the ambient temperature environment on device performance. It uses the static capacity test, lower-current HPPC test and/or cold cranking tests at various temperatures ranging from -30°C to +52°C to characterize the performance of the technology and to see if a thermal management system is needed.

Cold Cranking Test: Intended to measure power capability at low temperature (-30°C).

- Operating Set Point Stability test
- Cycle Life test
- Calendar Life test
- Reference Performance test
- Impedance Spectrum Measurement Test
- Thermal Management Load Test
- System Level Combine Life Verification Test
- Vibration Endurance Test

Static Capacity Test: Measure device capacity at a constant current discharge rate determined by the manufacturer's rated capacity.

Hybrid Pulse Power Characterization Test: determines dynamic power capability over the device's usable charge and voltage range using a test profile that incorporates both discharge and regenerative pulses in order to find available power and available energy.

Self-Discharge Test: demonstrates the temporary capacity loss resulting from a cell or battery standing without use for a predetermined period of time. Lithium-ion batteries have a shelf life of 10 years or more, with self-discharge rates of 2-3% per month.

Energy Efficiency Test: involve separate efficiency test profiles for minimum (25 Wh) and maximum (50 Wh) power-assist modes in order to see how efficient the battery can be.

2.7.7 Battery Management System (BMS)

Even when the batteries manufactured with well matched cells, the imbalances develop over time. Since xEV battery is frequently charged and discharged, the imbalances among the cells may develop faster. So, the accurate measurement of the voltage of each lithium ion cell, in every charge-discharge cycle, is essential. Since the various Li batteries have unique characteristics (discharge profile, self discharge rate etc), their charge algorithms are different.

So the Battery Management System (BMS) should be able to measure the voltages of individual segments, and use equalization process to re-balance the voltages, to ensure the full battery pack has maximum capacity possible. In passive balancing the heat dissipation will be large and cannot be handled without mass, volume and cost penalty. Active balancing (in continuous mode) electronics has to be designed for large currents. This has cost implication. Desired characteristics of battery management system include reduced board space, low power dissipation, and increased overall efficiency.

Functions of BMS

- Supervise charge/ discharge of cells;
- Control heating & cooling of cells
- Balancing of cells
- Identification of degree of charging
- Estimation of available range
- Documentation of cell history

VEHICLE INTEGRATION OF BATTERY PACK

Integration of the bttery pack with the electric vehicle has to meet several challenges. It should ensure optimum utilization of the available space, lightweight design and function integration. Apart from safety of the individual cells, the integraiton should also ensure that the pack is crash proof. Several issues need to be considered including battery chemistry, cell packaging, electrical connection and control, thermal management, assembly and service and maintenance.

Vehicle manufacturers have adopted various cell chemistry/ formats and various approaches for battery pack integration. In Chevrolet Volt, the T shaped battery pack is loaded under the car along the tunnel between the passenger and driver seat. The Tesla Model S, has a flat battery pack comprising cylindrical cells and it is integrated into the chassis of the car. Nissan battery packs are placed under the seat and under the floor. Nissan chose not to build an active thermal-conditioning system (otherwise known as cooling) into its battery pack. Instead, it relies on ambient air to shed heat—which got the maker into trouble with owners in very hot climates like that of Phoenix, Arizona, where asphalt temperatures can reach 140 degrees F or more in the summer. Nissan later switched to a more heat-resistant battery chemistry, informally known as "lizard cells," but many earlier Leafs have experienced significant battery capacity declines.

Several research efforts are directed towards developing innovative solutions for integration of lithium ion battery to electric vehicle. European Commission's FP7 project Optimised Storage Integration for the Electric Car (OSTLER) proposes a novel modular concept to enable a storage-centric design approach. It will also investigate the feasibility of removable storage elements. One of the subproject under the Fraunhofer project "System Research for Electromobility" is "Integration of durable and crash-proof battery and energy storage systems in lightweight structures for electric vehicle".

03 PROGRAM FOR ENERGY STORAGE

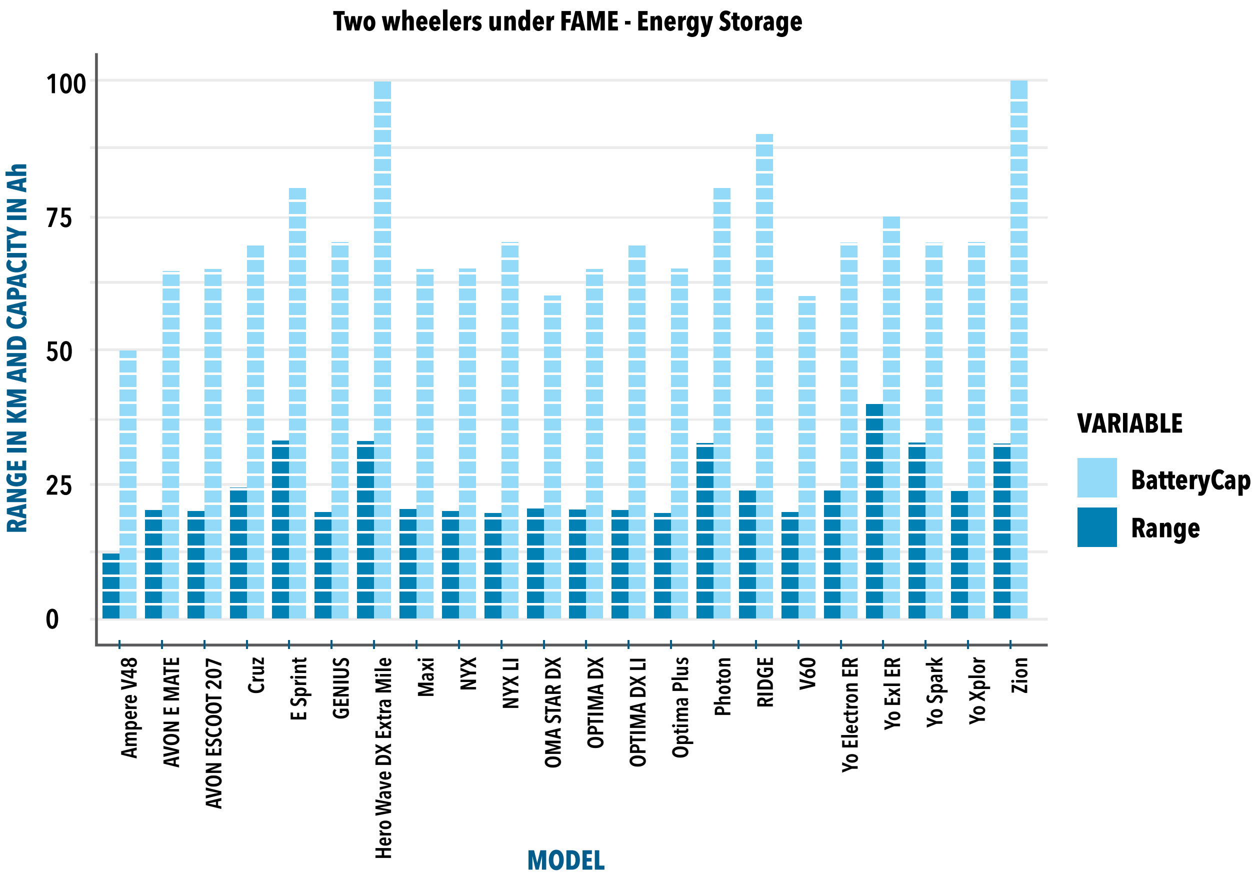
3.1 ECOSYSTEM FOR TPEM ENERGY STORAGE

TABLE 4.3:
SINCE 2009, USE OF LITHIUM ION BATTERY HAS BEEN PREFERRED

Battery Electric Vehicles (BEV)	Renault ZOE, Mitsubishi iMiEV, Renault Kangoo rapid z.e.
Plug-in hybrid and range extender	Suzuki Swift PHEV, Volvo XC60, Toyota Prius
Hybrid Electric Vehicle	Volvo A6 Hybrid, Audi A3 eTron, B-Klasse-F-Cell, Ford Fusion Energy

Although a few R&D efforts on lithium ion cells manufacture have been initiated in the country, it is unlikely that very near term needs of the industry can be met with indigenous manufacturing based on indigenous technologies, since lithium ion cell for automobile is a safety critical application and requires high level of manufacturing precision and reliability.

FIGURE 4.4



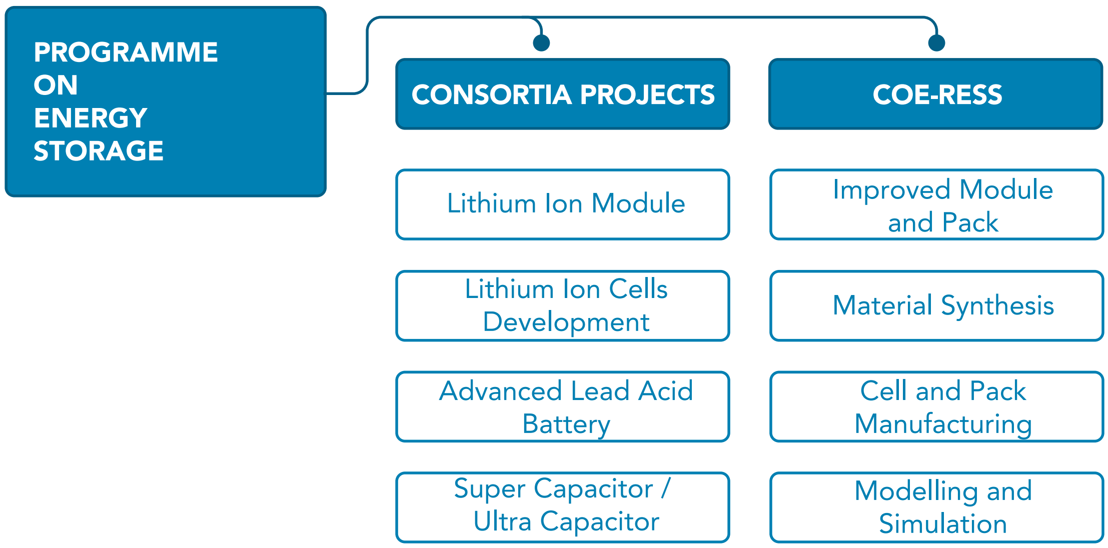
It is our assessment that LiB will remain the main choice for electric traction applications in near future, but it is also likely that the intense research on emerging battery technology may find a breakthrough in a decade. So the Mission needs to pursue both Short & Long Term options to secure battery production in India.

In India, two wheeler manufacturers are mainly dependent on lead acid battery, although use if lithium ion has started. Battery packs of Indian electric two wheelers typically have capacity or 20-33 Ah, and range per charge varies between 60 and 100 km.

The programme on energy storage is proposed to include

- Centre of Excellence on Energy Storage
- Short term consortia project on lithium ion battery pack/ module
- Simulation and modeling activities

FIGURE 4.5: PROPOSED PROGRAMME ON ENERGY STORAGE



Consortia projects in the field of rechargeable energy storage will be:

- Design and development of lithium-ion modules
- Lithium ion and other battery cells development
- Ultracapacitor/ Supercapacitor
- Emerging chemistry battery development

3.2 CONSORTIA PROJECTS IN RECHARGEABLE ENERGY STORAGE

3.2.1 Lithium ion Battery manufacturing

Challenges

Lithium ion Battery (LiB) is the costliest item in xEV, but a make-in-India approach for LiB cell production for automotive application require very high levels of competency.

Electrodes, electrolyte and separators determine the performance of the cell, and even the minimum disturbances have severe impact on life of batteries. Electrodes manufacturing start from preparing slurry and then coating, drying and treatment of electrode sheets, before cutting it to size to ship to a Li battery cell manufacturing unit. It involves expensive monitoring and quality control mechanisms. Ceramic Separator also involves a very similar process of slurry preparation, coating on a sheet and drying.

Complex manufacturing process control is necessary for the various steps involved in making of cells, and the smallest error impacts the performance significantly. The cell capacity depends on the number of layers of electrodes and separator and some cells may even have 250 or more layers. They are packaged into prismatic or cylindrical casing and electrolyte injected in it; just enough electrolytes to keep electrodes wet but not more. Electrode tabs should preferably be laser welded to the terminals to have external contacts. This part of the process needs careful monitoring and control and testing.

Driving Forces

LiB packs are assembled from "modules" (eg., Nissan Leaf Module of 4 cells). The recent trend has been for vehicle manufacturers to use common LiB module, for several vehicle models. The BMW and Nissan have already started implementing it. Others like Volkswagen and Honda are planning to do so. Further, the cell sizes have also been standardized to a limited extent due to the five specific cell size adopted as standard by the German automotive industry.

Thus Make-in-India objectives can be pursued in the initial stage of the Mission itself by adopting the LiB module as the entry point. The manufacturing of LiB modules could begin with commercially available cells along with Battery Management System. It would later graduate to the production of "standard size" LiB cells and modules.

LiB Module

Development of lithium ion modules with available cells and for use in 2/3 wheelers should be achieved within two years, for use in the Mission Program itself. So module to pack level work and small production facility need to be established in 2 years. The facility should run continuously to produce small volumes of battery modules to supply to OEMs; such a facility will provide the opportunity for innovations in LiB manufacturing and introduction of new materials.

Optimization of LiB Module under Indian Conditions

Optimum design of lithium ion battery module and packs under Indian driving conditions based on simulations models should be taken up. A major focus should be on design of effective thermal management system to enhance the battery life under Indian driving conditions, while also minimizing the mass, volume and battery cost taking into consideration multiple safety and performance constraints.

Design & Develop LiB Module, as a common building block

The aim is to define, design and develop the standard building blocks (or components) for the Energy Storage Systems. The proposed LiB-Module is envisaged as a commonly acceptable module size/ geometry that can

TABLE 4.4: SUGGESTED SPECIFICATIONS OF BATTERY

BATTERY CHEMISTRY	LEAD ACID				Li-ION			
Battery T echnology	SLA							
Vehicle Category	2W BEV	3W BEV	4W BEV	4W HEV	2W BEV	3W BEV	4W BEV	4W HEV
Nominal Voltage (Module)	12V	12V	24V	24V	12V	12V	24V	24V
Nominal Capacity @ C2 (Ah)	20Ah, 33Ah & 40Ah	80Ah, 100Ah	200Ah	75Ah - 150Ah	20Ah, 40Ah	80Ah	80Ah to 100Ah	75Ah - 150Ah
Weight (kgs)	Vehicle manufacturers to specify manufacturers to specify							
Maximum Dimensions of module (LxWxH)								
Pack level energy requirement	2 kWh to 5kWh	5kWh to 8kWh	12kWh to 15kWh	1kWh to 2.5kWh	2 kWh to 5kWh	5kWh to 8kWh	20kWh to 32kWh	1kWh to 2.5kWh
Minimum Life cycles	1000 cycles				2500 cycles			
Normal Operating Temperature Range	-40oC to 60oC				-40oC to 60oC			
Minimum Safety test Certifications	AIS-048				AIS-048			
Minimum Warranty (Years)	3 Years				7 Years			
Normal Charging time	4 to 5 hr				<1 hr	<1 hr	<2 hr	<2 hr
Fast Charging time	<60 mins	<60 mins	<60 mins	<60 mins	< 15 mins	< 15 mins	<60 mins	< 15 mins

TABLE 4.5: PRELIMINARY SPECIFICATIONS FOR THE THREE MODULES

PARAMETERS	CELL	MODULE 2W	MODULE 3-4 W	VALUE
Voltage		12-48	12-48	v
Capacity	20-60			Ah
DOD	87			%
Peak Power		4C	4C	W @ 30s
Heat Rise w/o cooling		<2	<2	degC/100%DOD@1C
Temp. Range		-10/+60	-10/+60	deg C on system level
Dimensions		20-25	50-120	l, packing space
Cycle life time	2500			Cycle@100% DOD@1C/1C@30degC
Safety		AIS 38/ 48	AIS 38/ 48	
Charge	1C			
Discharge	1.5C			
Weight				
Energy density	>150			Wh/kg
Impedance	<0.5			mOhm@20Ah
Format	Pouch/ prismatic			
Calendar life time	10	10	10	Y

accommodate different LiB types. Three candidate LiB chemistries are: Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Iron Phosphate, or Lithium Titanate.

The “modularity” will also extend to the electronic controls and safety-designs like thermal management systems also. Three types of modules can be defined for the 2W/ 3W, the Cars/ SUVs/ LCVs and the Buses/ Trucks. This effort could start with the two wheeler EV.

The technology competence for LiB is at nascent stage in India. The Design Phase for Cell Development is long, and requires establishment of large R&D Infrastructure and teams of expert technologists. So while efforts for development of cells continues, it is better to purchase a ready design of cell with proven prototype from a foreign technology vendor, with prior experience in developing LiB Modules. The common LiB modules defined under NMEM could then be developed with their assistance.

Module Development

WP-1 Design of LiB Module

The deliverable from this work-package will be complete design for LiB Module, which will be owned by the CoE, for selling/ distributing the design to potential manufacturers. The tasks involve selecting the chemistry/ electrode combinations and establishing design groups for the three module types, with automotive companies leading each of the groups; Provide or procure the BMS; Coordinate the team efforts and be responsible till module design validation.

International collaboration may be required. CoE must select and engage companies with experience in designing LiB cell based on their capabilities and willingness for technology licensing/ transfer.

In the initial stages the cells can be imported, provided they are aligned to the common design arrived at in the NMEM, and suited to the type of modules envisaged in the program.

WP-2 Fabrication & Testing of LiB Prototypes

This program will develop prototypes, and establish the essential equipment & facilities for prototype work in India. Collaboration with established R&D labs or technology companies abroad is envisaged (like ThyssenKrupp R&D facility in Germany / Fraunhofer Labs/ others). Initial Prototype of cell for primary electrical testing (preparation of electrode combination and pouch format cell) - can be done at a facility abroad.

The activities will include:

- Safety system design and component selection/ pack design, thermal management
- Benchmarking existing BMS & develop BMS design
- Architecture, topology/ power handling and management/ thermal management/ component selection/ communication/ authentication/ SoC, SoH/ cell balancing/ diagnostics/ isolation (in high voltage application)
- Testing; stack level test rigs, integrated testing with motor test rig

WP-3 Pilot Production for Vehicular Testing

Pilot production of modules may be taken up initially with cells procured from collaborators/manufacturers abroad. Typically the manufacturers only build cells as per their own defined formats.

Any new cell type/format/size need to be proven and built by the collaborators having appropriate facilities and expertize (such as ThyssenKrupp system Engineering R&D facility, Germany).

WP-4 Detailed Project Report for LiB Module Manufacturing

PSUs like BHEL or BEL, or existing Battery Manufacturers can take up pilot level production of LiB modules, under the NMEM scheme, provided the industry gives firm agreement on utilizing the LiB Modules for producing their battery packs in EV and HEV. System Engineering firms (like ThyssenKrupp) can help to define the complete process of manufacture, and assist with equipment for pilot production.

3.2.2 Lithium ion cell development

Objectives

Fabrication of cells for lithium ion and other emerging chemistry will be taken up under this program. Pilot facilities will be put up so as to be able to develop and manufacture cells as per requirement of the xEV energy storage systems under Indian conditions.

For lithium ion, a few institutions in the country have started pilot level facilities. This programme will build further on the existing capabilities and investigate into the process of manufacturing of cells of lithium ion and emerging battery technologies. The materials and components for the cells will be either imported or developed under the programme on materials synthesis mentioned in the following section.

STUDY TOPICS

Develop manufacturing processes & incorporate components to increase performance and safety.

Scale up & optimize process steps for manufacture of cells e.g., slurry preparation/ characterization, electrode coating, calendaring, cutting of coated electrode foils, cell assembly, electrolyte filling etc.

Design the production environment

Benchmark traction batteries, cells, ultra-capacitors

Fabricate cells, modules & battery pack for xEVs

3.2.3 Supercapacitor/ Ultracapacitor

Objectives

Development of cost-effective technology for ultracapacitor/supercapacitor, and fabrication of cells that can be used in conjunction with battery for supporting regenerative braking, and also in the long run, for pure ultracapacitor/supercapacitor based energy storage systems for vehicle fleets having provision for fast charging at frequent intervals.

There have been a few initial efforts towards development of ultracapacitor in the country. In a consortium project under Collaborative Automotive R&D (CAR), IISc Bangalore, NCL Pune, IIT Kharagpur developed various electrode materials for ultracapacitors. Prototype ultracapacitors were developed. CMET has developed prototype ultracapcitors. Companies like Chheda Electrical and Aartech Solonics have offered various ultracapacitor based applications such as two wheeler engine starter, cranking of IC engine etc. Some companies in India have also decided to venture into ultracapacitor/supercapacitor manufacturing (e.g. SPEL Technologies).

STUDY TOPICS

Definition of target specifications

Development of electrode, electrolyte materials and other components

Manufacturing of the materials in quantity sufficient to support cell fabrication

Characterization of mechanical, electrochemical, and electrical and electronic properties;

Fabrication of cells; mechanical, electrical and lifecycle tests of fabricates cells.

3.2.4 Advanced Lead Acid Battery

Objective

To develop a high performance, long life advanced lead acid battery for electric 2/3 wheeler or similar small vehicles and micro/ mild hybrid vehicles. Improvement in the partial state of charge performance will be a major focus.

Scope

- Design a baseline cell/pack with targeted parameters such as specific energy, cycle life etc.
- Studies on materials and additives for improved performance, durability and Dynamic Charge Acceptance characteristics (DCA)
- Battery design and development
- Study on high and low temperature performance
- Study to minimize gassing and water losses
- Test on charging/ discharging efficiency
- Development of the battery management system, battery pack integration with vehicles and test/ trial runs

3.3 CENTRE OF EXCELLENCE IN RECHARGEABLE ENERGY STORAGE SYSTEMS (CoERESS)

3.3.1 Overview

Technology development for energy storage for automotive traction will require concentration of a multitude of expertise, so the CoE may need a hub-and-spoke structure. The core establishment under the NMEM will have adequate prototyping, pilot production and testing/ validation facilities. For the more basic technology work, the existing research centers must be strengthened and mandated to work for Automotive Traction Battery Systems. A confluence of expertise from multiple technology fields such as automotive, electronics and chemical is required for the CoE in Energy Storage.

The CoE should be a registered legal entity, and companies will take subscription/membership in the CoE. A Governing Body comprising R&D institutions & industry, supported by a Core Management Team, with representations from each of the program streams is also envisaged.

They would:

- Facilitate integration among the members of the CoE, in a strong collaborative institution framework
- Track progress in the programs, compile progress reports, coordinate evaluation and benchmarking of the R&D achievements, and setting up of new R&D targets
- Disseminate results to private sector and research communities.

The CoE will have a network of multiple laboratory set ups/ pilot facilities covering the entire value chain including simulations. material sysnthesis, cell fabrication, pack assembly and testing . Existing facilities of the members will be utilized and the balance equipment necessary would be supported, along with other necessary resources as applicable. The CoE will focus on basing the battery development process on clear understanding of the scientific and engineering principle that affect the performance and service life, in place of the trial-and-error development cycle.

- Materials Sysntheris: Development of low cost, high capacity and long cycle life materials for lithium ion, advanced lithium ion, other emerging battery chemistry and supercapacitors
- To develop a fundamental understanding of battery electrical and thermal performance, damage and aging mechanisms
- Development of reliable, high speed processes for joining substrates in battery cell, and pack assemblies
- Improved processes for electrical, mechanical and electronic integration in advanced battery cells and packs. (e.g., making metal to metal joints etc.)
- Investigating the reasons for manufacturing variability and ways to reduce such variability to reduce rejection rate, premature aging and performance degradation
- Simulation and modeling on various aspects including investigations on materials, cell design, module and pack design. It will span issues related to thermal management, safety, reliability, Materials characteristics, new materials, Best chemistry for Indian conditions, Thermal management – pack, module, pack level, appropriate design for pack and modules

The CoE will set quantitative targets in terms of battery parameters like specific energy, specific power, energy density, power density, temperature tolerance, cost, lifecycle, manufacturing qulity etc. and the progress with respects to these targets will be monitored by an advisory group.

Technology issues to be investigated by the Centre of Excellence are described in the follow-ing sections.

3.3.2 Improved Battery Modules and Pack

The long term activity on battery modules will involve development of technologies towards effective integration of battery modules and packs, to enhance pack level specific energy, safety, thermal and mechanical stability, battery management system development etc. In India Bharat Electronics Limited has been involved with Lithium ion pack integration, and this existing expertise can be utilized.

Development of battery management system is also important as it ensures more efficient use of the energy inside a battery. In electric vehicle battery pack, there could be thousand of cells connected in series and parallel connections. The probability of problem occurrence is increased, as well as the repair cost. The battery management task is difficult in these systems due to the low ratio of the cell voltage to the string voltage, and the particularity of each battery string.

STUDY TOPICS

Safety system design & component selection

Component testing & specification – fuse, wire, connectors

Pack design, thermal management

Modeling & simulation. Develop simulation model for various battery chemistry

Domain knowledge for battery management systems

Integration with BMS

Testing; Stack level Test rigs, Integrated testing with motor test rig

Develop energy storage systems for xEV applications

3.3.3 New Materials Synthesis & Manufacturing Innovations

Objectives

Objective is to develop materials for various components of lithium ion and other emerging cells and manufacture them in sufficient quantities so as to enable further development activities in lithium ion cell. Study of the complex correlation between raw material selection, process technology and resulting battery properties will be taken up as well as upscaling of the materials production process. Materials and components of emerging battery chemistry and ultracapacitor will also be taken up.

Investigation Methodology:

Investigation on the compatibility of different components of lithium ion cells with each other prior to the recommendation of better performing cell assembly.

Some of the issues that R&D activities may focus on to reduce the cell manufacturing cost are:

- New UV-curable binders to permit much faster and less expensive slurry drying
- Use of aqueous or dry binding technologies to eliminate expensive organic solvents
- Fast cell formation techniques
- Very thick electrodes (1 mm vs. 100 μm) with aligned pores
- Spray pyrolysis techniques for active material production
- Diagnostic technologies to investigate manufacturing in-situ

MATERIAL SYNTHESIS

- Develop new materials: synthesis & characterization
- Fabricate & test cells. Test new materials for electrolytes, electrodes and electrolytes.
- Benchmark performance of new materials in commercial cell constructions
- Investigate for performance, cycle life & cost
- Process modeling to study cost estimates & process economics
- Investigate process technology for manufacture of cells
- Process scale-up 1-10 kg

MANUFACTURING PROCESS

- Anode, cathode, electrode and electrolyte materials for LiB, new battery & ultracapacitor

Technology development at pilot scale is an important link between basic research on laboratory scale and industrial process development. In such a facility scientists will have the opportunity to study all relevant process steps (slurry preparation/ characterization, electrode coating, calendaring, cutting of coated electrode foils, assembly of battery, filling of electrolyte). Such facilities have been established in Germany, under the LiFab project. Argonne National Laboratory USA also has Advanced Battery Materials Synthesis and Manufacturing R&D Program.

To address the challenges related to solid state lithium ion cells. R&D focus will be on improving the total ionic conductivities via achieving near-theoretical densification, with controlled stoichiometry and 'clean' interfaces and also exploring different combinations of solid electrolytes and electrode-active materials. Advanced processing techniques,such as spark plasma sintering (SPS), seem to have the potential to address some of these issues, bestowing solid electrolytes with improved ionic conductivities and mechanical integrity, electrodes with improved rate capability and also offer a facile route towards otherwise stringent fabrication of the all-solid-state 'full' batteries, with improved energy density, power density and cycle life. However, this is still at its preliminary stage and considerable R&D efforts need to be put.

3.3.4 Cell Manufacturing Process Innovation

The major cost in a battery comes from the Li ion cells. Thus indigenous manufacturing of cells can bring down significantly the cost due to battery, and improve viability of electric mobility in India. Moreover self-reliance in production of lithium ion cells will be advantageous for electric mobility ecosystem in India. Although a few efforts for pilot manufacturing of lithium ion cells have started in the country, development of competence for manufacture of high current cells for xEV applicaitons with desired quality and development of equipment for them requires concerted efforts bringing together all stakeholders.

Cell manufacturing process innovation can play a significant role in reducing the lithium ion battery cost and its overall performance. For emerging battery chemistries also development of appropriate manufacturing technology is essential. Apart from cost and performance, environmental aspects and recycling need to be addressed in cell manufacturing process.

Pilot facilities for manufacturing will be installed/upgraded suitably to study and introduce innovations in the manufacturing process steps.

Focus will be to

- Develop continuous processes
- Optimize manufacturing steps and components such as coating, slurry making , calendering, welding and joining methods
- Appropriate processes for new materials/ components that can contribute towards cost saving, performance enhancement or higher degree of recyclability
- Application of additive manufacturing technologies
- Design of the production environment
- Process control and monitoring
- Design and development of suitable equipment indigenously

Cells of different formats, capacities and power-to-weight ratios

3.3.5 Simulation & Modelling

Objectives

Design of Batteries for E-Vehicle using Multi-scale Modeling coupled with Optimization. This programme will undertake development of simulation models for evaluation of batteries for electric vehicles, predicting structure and behavior of different materials in order to accelerate development of low cost materials and next generation of batteries. It will explore low cost, safe and environment friendly electrode materials through simulations. It will also study reliability aspects at cell and pack levels.

STUDY TOPICS

To predict the battery performance under different circumstances, investigate the impacts of manufacturing process, and obtain feedback for improvement in battery design, control, and manufacturing processes.

Predicting the performance of a battery during its usage, such as battery charge, discharge, and idle status, the impacts of internal and external temperature, the manufacturing quality on joints, the cell capacity and balance management, etc.

Cell capacity, temperature, driving profile, the joint (manufacturing) quality etc. Such a framework can help battery design and manufacturing engineers to evaluate battery performance, investigate the impacts of manufacturing practices, and provide feedback for improvement

Cell level reliability modeling, Defining cell level performance requirements, identification of factors affecting cell reliability, identification of potential failure mechanisms leading to safe and unsafe failures of cells, developing a mathematical model for predicting cell reliability based on simulation results

Battery pack reliability modeling, defining battery pack level performance, requirements; identification of pack level reliability influencing factors; develop a model relating cell and interface reliabilities features to predict reliability of battery pack; using the model to predict reliability using the design and reliability simulation results;

Case study using model to predict reliability of prominent cell and battery pack technologies developed and compare it with existing technologies; Documentation and presentation of results.

Investigation Methodology
Simulation models to be developed based on the fundamental principles governing the electrochemical behaviors. Understanding of underlying mechanisms by which battery work, and internal information that is difficult to obtain even from experiments to get insights into design and optimization of battery packs.

Design of battery includes (a) design of battery materials (b) geometrical aspects of the battery and (c) battery management system. Thus, designing battery for a specific application will involve specifying (a) materials, namely, for anode, cathode, electrolyte and casing, (b) geometric parameters of the battery and (c) battery management system. The performance of a battery is evaluated in terms of (i) electrochemical characteristics (voltage, power, cycle ability, energy storage etc.), (ii) thermal behavior (should not get over heated) and safety, and (iii) mechanical strength (should withstand vibration and impact).

Optimization of all the variables (material, geometry, battery management system) will be carried out using optimization tools. Often materials engineering problems are multiphysics, i.e., multitude of physical and chemical phenomenon happen together. Thus the possibility of optimization on the basis of comprehensive models is often ruled out. So many a time simpler models, which are computationally fast, are used for real life conditions and optimization. The parameters in these simple models are evaluated using comprehensive models as well as experimental data.

Coupled comprehensive cell model as described above will be supported by atomistic and quantum ab-initio models for exploring new materials and will be experimentally validated. Based on the results of the continuum comprehensive model of cell, (i) computationally fast model for predicting thermal, concentration and potential fields within the cell and (ii) equivalent circuit cell model that can be integrated with battery management system will be developed. This will enable the modeling of real-time performance of battery pack integrated with vehicle.

The comprehensive models on the basis of which the simple and computationally fast model will be developed are as follows.

a) Electrochemical model, which will take the design variables associated with cell (materials, geometry of cell) as well as thermal field predicted by thermal model as inputs and will predict the electrochemical characteristics.
b) Thermal model that predicts the thermal field within the battery, using the results of the electrochemical model (mentioned above).
c) Stress model that predicts the stress-strain distribution within the battery under different conditions.

Coupling of all these models will enable simulation of current flow, potential difference, concentration profile, thermal profile and stress distribution under different electrical loading and mechanical loading conditions.

3.3.6 Potential Partners of CoE Energy Storage

The Centre of of Excellence on Rechargeable Energy Storage is envisaged to be a virtual centre with participation of multiple institutions and having a hub-and-spoke structure. The hub could be a leading R&D institution such as the Central Electrochemical Research Institute (CECRI) and International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI). Apart from this, the CoE may also be considered as a combination of three virtual centres, each with focus of one broad area of energy storage R&D, and led by one of the premier research/ academic institutions having strength in the specific broad area.

It is envisaged that the CoE-RESS will be a registered legal entity. Existing facilities of such institutes should be utilized, and additional facilities as required may be supported. R&D competency existing in various institutions/ organizations in India is discussed in brief in the following section.

Central Electrochemical Research Institute is a premier institute in the country focusing on electrochemistry. An independent battery-testing center with

TECHNOLOGY AREA	POTENTIAL PARTNERS
Materials Development	CECRI, ARCI, ISO, CGCRI, IISc, IITs, CMET, IICT
Modules Development, thermal management, BMS integration, failure analysis, reliability	Bharat Electronics Limited (BEL), BHEL, IIT Kanpur, IIT Gandhinagar, ARCI Hyderabad, Bharat Heavy Electrical Ltd.
Simulation - materials, cells and modules	IIT Kharagpur, CDAC-T, CSTEP

state-of-the-art-test facility catering to the needs of Indian battery industry and also global industry was established under CSIR 11th five year plan. Subsequently, during the 12th Five Year Plan, an R&D Program was initiated on Li-ion battery for Solar Photovoltaic applications. The institute has separate groups working on various aspects of lithium ion battery – cathode, anode, separator, integration, and failure mode analysis. The institute is also working on computational material science, Finite Element Model, predictive model etc. CECRI activities also include development of lightweight lead acid battery for solar photovoltaic applications.

The International Centre for Powder Metallurgy and New Materials (ARCI), has established a semi-automatic pilot plant for fabrication of lithium ion cells at its Centre for Automotive Energy Materials, Chennai. The initial target is to make 2032 coin cells, followed by 18-650 cells and later on prismatic cells. The main purpose of the facility is to develop and test new materials for battery that are available indigenously.

Research on batteries and supercapacitors have been carried out in IISc Bangalore. The Department of Inorganic and Physical Chemistry, and the Solid State and Structural Chemistry Unit of the institute are active in this field.
IIT Kharagpur has 10 years' experience of fabrication of lithium ion cells – coin cells, 18650 and prismatic cells. IIT Kharagpur has also carried out fundamental studies on alternate electrode and electrolyte materials. Present focus includes thin film batteries, Na-ion batteries, battery management system, cathode composite, silicates, phosphates, oxides and composites. A team of about 15 faculty members work on various aspects of battery technologies. Modeling is a core strength of IIT Kharagpur, and the institute can play lead role in the simulation and modeling activities of the CoE. The institute also has a Reliability Engineering Centre which can contribute to reliability modeling of battery cells and packs. IIT Kharagpur can contribute to NMEM on fundamental research on new materials development, thermal safety and battery management systems, modeling and simulation, fabrication of prototype Li-ion/ Na-ion batteries for xEVs, generation of scientific manpower, and providing hands on training on fabrication of lithium ion cells.

CSIR-CGCRI took up the development of high energy density Li-ion battery technology under a DRDO sponsored progrmame coordinated by IIT Kharagpur during 2004-2009. The deliverable of the CGCRI component of the project was indigenous cathode and anode materials ($LiCoO_2$, $LiMn_2O_4$, $Li_4Ti_5O_{12}$) for 18650 cells. Another project exectures is "Investigation on Si-C based anode materials for Li-ion battery "(DRO sponsored, 2006-09). CSIR-CGCRI is involved with the CSIR TAPSUN Programme, 2011-17 for development of innovative solutions for solar enegry storage. CGCRI is also engaged in developing a ceramic coated separator for Li-air battery under this project for application in actual cells (pouch) to be fabricated by CSIR-CECRI.

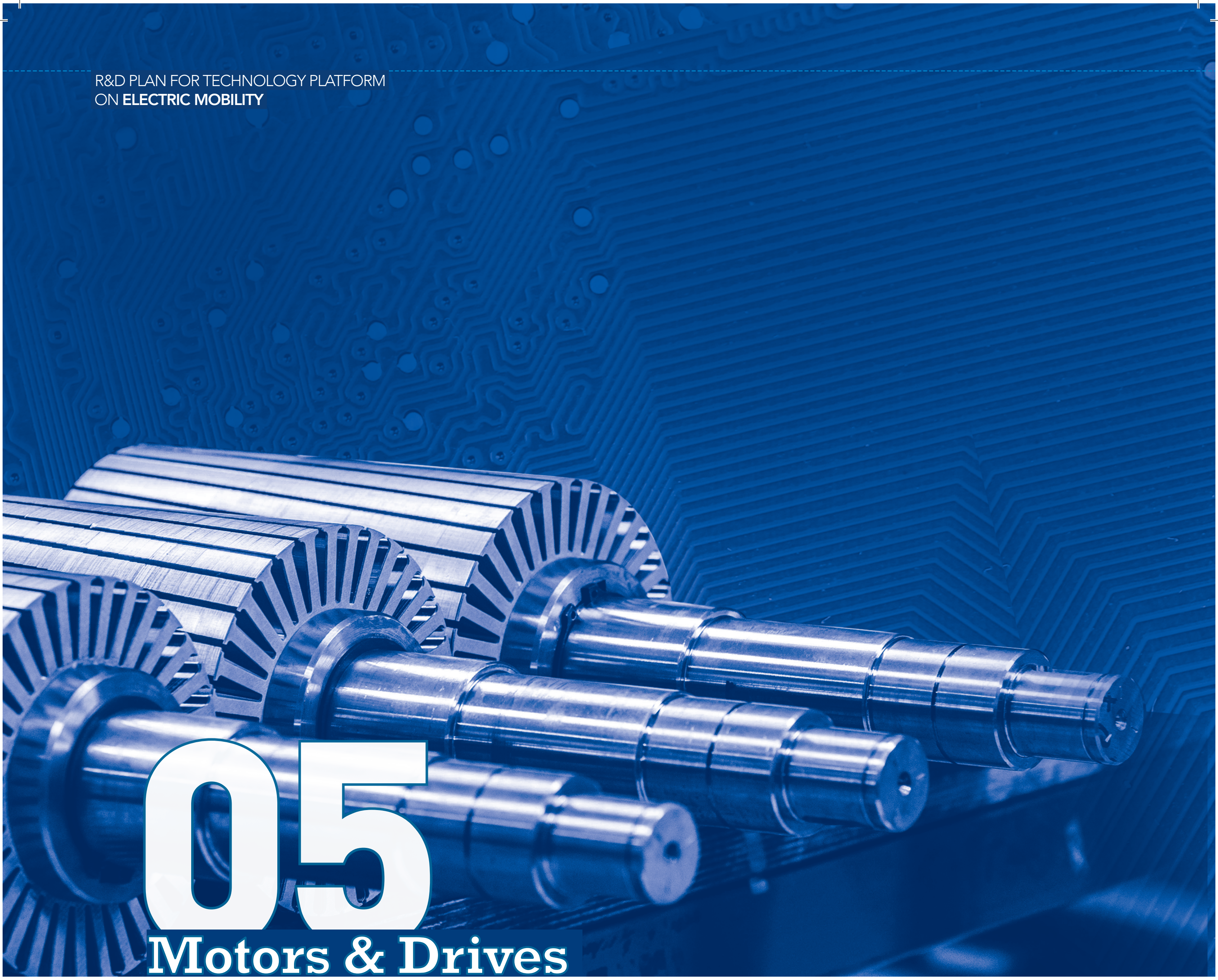
The Non-Ferrous Technology Development Centre (NFTDC), Hyderabad has initiated R&D activities on lithium ion manufacturing process equipments.

At CMET, Pune works have been carried out on energy storage applications of Ionic Liquids. CMET Pune has already completed two such projects and are in the process of product demonstration of hybrid battery. Prototype ultracapacitors using carbon aerogel have been developed.

Indian Space Research Organization (ISRO) has taken up development of lithium ion cells as well as packs. ISRO, along with ARAI, spearheads an effort towards development of automotive lihtium ion batteries. Public Sector companies Bharat Electronics Ltd. (BEL) and Bharat Heavy Electricals Ltd. (BHEL) are also involved with R&D in lihtium ion battery. BEL has the experience of manufacturing lithium ion packs for defence applications.

Naval Science and Technological Laboratory (NSTL), Visakhapatnam has taken up development of lithium ion cells for underwater applications.

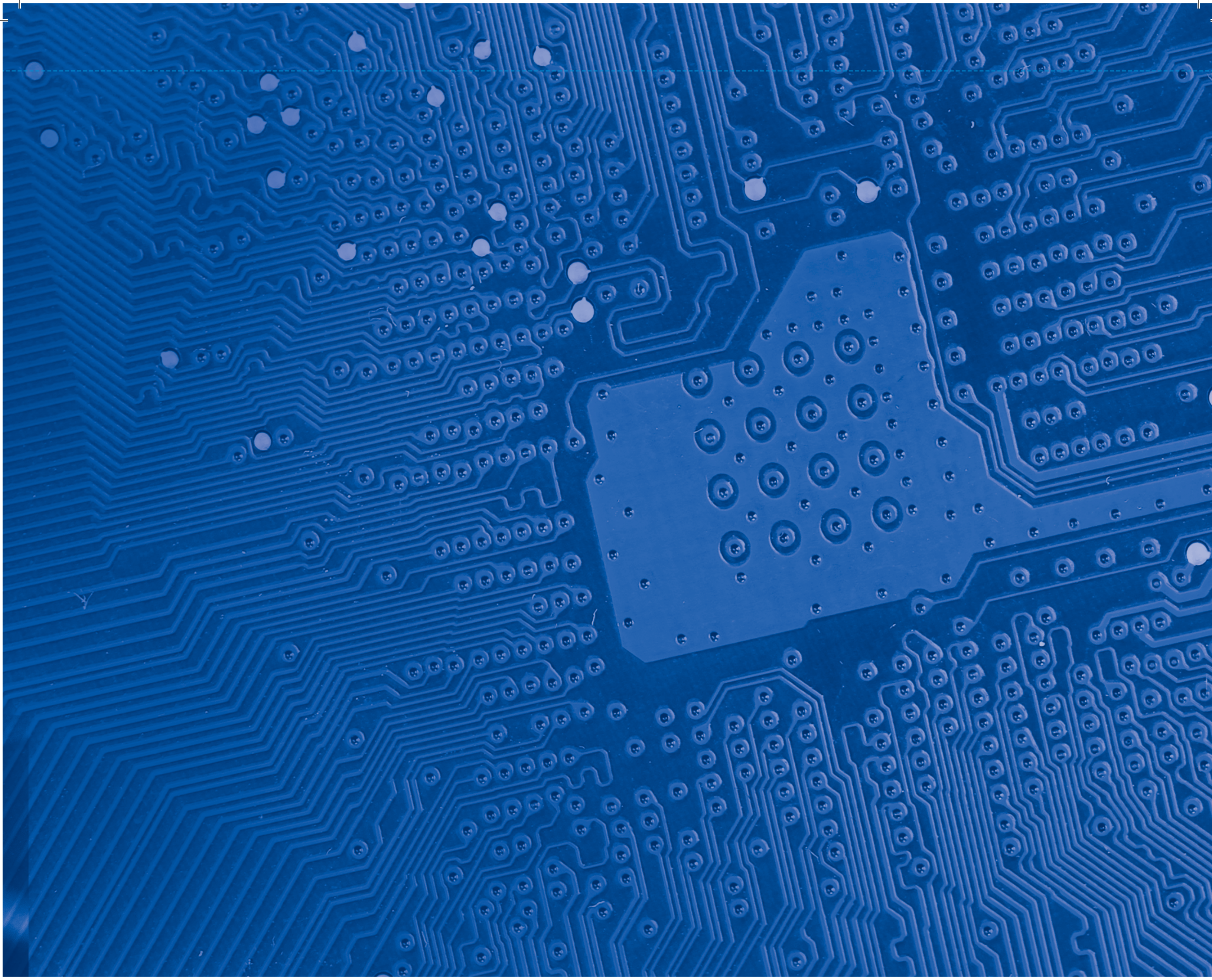
Apart from these, various other institutions may contribute through specific R&D activities on various materials for lithium ion and other emerging batteries. These include IIT Bombay, IIT Madras, IIT Roorkee, Central Salt and Marine Chemicals Research Institute, National Metallurgical Laboratory, IACS Kolkata etc.



05 Motors & Drives

01 INTRODUCTION

Electric motor is the heart of the electric propulsion. The comparative advantages of electric vehicles over conventional vehicles is largely due to higher efficiency of electric motors over a wider speed range. Operation of the electric drives has direct impact on the overall performance of the electric vehicle. Electric motors make it possible to implement features such as start-stop and regenerative braking. However, motors used in electric vehicles are different from motors used in industrial application in terms of operating conditions and required characteristics. Current technology for electric vehicle motors needs further improvements to achieve the desired level of size, efficiency and cost. This



has driven R&D efforts for advanced electric machine topologies and drive systems, as well as manufacturing process development to reduce the unit cost of the electric motors. R&D efforts are seeking innovations in terms of materials, design, thermal management, control and power electronics.

Apart from motors and drive systems, power electronic devices for charging systems for electric vehicles are also discussed in this chapter.

1.1 DESIRED CHARACTERISTICS

Electric motors are highly suitable for traction applications. Motors can be switched off even at temporary halt like at a traffic junction, while IC engines require idling. A wide range of speed variation is possible with electric motors, and they produce large torque at low speed. Lighter, more compact & efficient vehicle systems can be developed by taking advantages of the electric motors characteristics. Depending on the xEV architecture, there could be one or several motor drives, and it is also possible to have traction motors on each wheel of an electric vehicle.

Performance of motor drives is assessed based on Starting-Acceleration (time used to accelerate the vehicle from zero to given speed), Gradeability (the maximum road grade that the vehicle can overcome at a given speed), and the Maximum Speed that the vehicle can reach. Since size of an electric machine is almost proportional to the torque, and power output at any instant is a product of torque and speed, it is required to have high speed machines for electric vehicle applications.

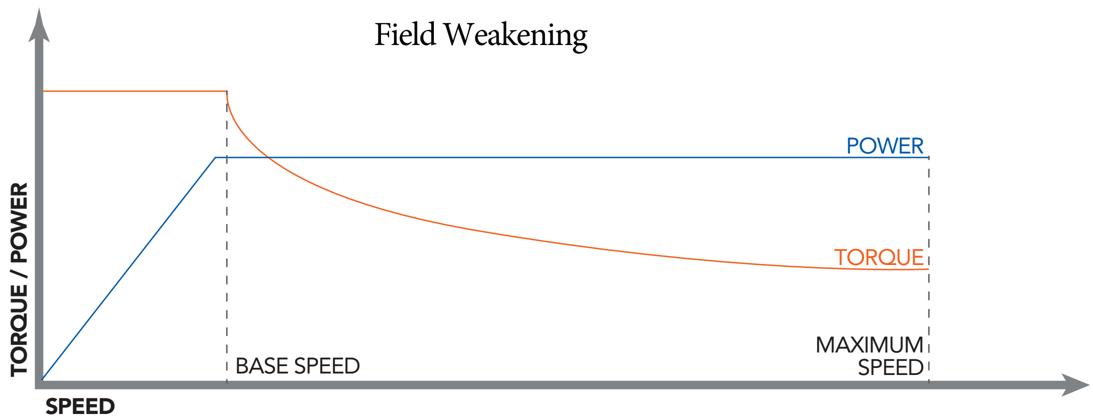
Key criteria:

- Start-Up Phase: High & constant torque for fast and smooth acceleration.
- On reaching the maximum rated power the machine should deliver constant power until the maximum continuous speed of the vehicle is reached (without interruptive gear shifts)
- High Speed Region: with reduced power requirements for safety in highway driving.

Other considerations

- Four quadrant operation
- Fast torque response for use in braking (ABS).
- Low cogging torque and torque harmonics for refined drivability.
- High efficiency over wide speed torque ranges, including regenerative braking.
- High reliability and fault tolerance
- Good overload capability for uphill climbing.
- Low Cost, low weight and volume,
- Wide field-weakening range
- High power factor
- Adequate inertia of rotating parts for improved driveability
- Minimum cooling requirement
- High controllability, steady-state accuracy and good transient performance

FIGURE 5.1: DESIRED CHARACTERISTICS OF EV MOTOR



**THE PERFORMANCE OF THE EV IS DETERMINED BY TORQUE-SPEED OR POWER-SPEED CHARACTER-ISTICS OF THE MOTOR.
IDEALLY IT SHOULD FEATURE:**

- A high torque at low speed for starting and acceleration
- High power and high speed for cruising, along with the wide speed range

The maximum torque at the low speed is maintained only up to a Base Speed. Above that speed, the maximum torque is gradually reduced to reach a Constant Power Region or the Field Weakening Region of speed. At low operating speeds the voltage requirement is low, and the torque is mainly dependent on the current. So a maximum constant torque can be achieved by varying the current.

The back EMF generated during the motor rotation depends on the flux and motor speed, and it acts opposite to the applied voltage. Thus for achieving a higher range of speed, either increases of the supply voltage or reduction of the flux (field-weakening) is necessary. Due to practical constraints in applying higher voltages, field weakening is a better option.

An over speed region with reduced speed is also desirable.

1.2 SIGNIFICANCE OF POWER ELECTRONICS

Power Electronic devices control the flow of electrical energy within the xEVs power systems.

Electric motor drive and control: Modern xEVs use ac motors for higher efficiency and maintainability. Power electronics is an integral part of ac motor control mechanism.

Advanced Engine Control: Engine controls need precise timing and dynamic control of actuators, and advanced fuel injectors control involve power electronics devices.

Regenerative braking: The AC (generated by the electric machine during braking) is changed into DC for on board charging of Rechargeable batteries.

Charging of Batteries: Batteries are charged from various sources having different specification like household supply (240 V) or DC fast charging station (420V).

Voltage Conversion on Demand: Accessories like power windows, entertainment systems, dashboard instruments and air conditioning, seat-heaters need a voltage level different from the xEV battery voltage. Converter is used to step-down the power to match the requirement.

Thermal Management Systems: Thermal management systems for various components and devices are required to be controlled by ECU (Electronic Control Unit) for the optimum operation.

02 MOTORS FOR xEVs

Various types of electric motors used in xEVs include DC, induction, permanent magnet and switched reluctance machines. Out of this induction machine and permanent magnet synchronous machines are the main choice at present. Hybrid excited and non-magnet or less rare-earth magnet topologies such as synchronous reluctance machine (SynRM) and PM assisted SynRM have good future prospects.

2.1 DC MOTOR

All electric vehicle models till 1989 used DC motors. A host of advantages went in favour of use of dc series motors in electric vehicles. These include: high torque at low speed, technological maturity, robust and simple controllability, linear torque-speed characteristics low torque ripple, a wide constant power speed range, and reasonable efficiency while cruising at high speeds. However due to presence of commutator, dc motors are not suitable for maintenance free operation. Maximum achievable motor speed is limited due to friction between brushes and the commutator. Requirement of commutating poles and compensation windings make them bulky and expensive. Due to these reasons, dc motors are not favored in electric vehicle applications anymore. Currently they are used only in some e-bikes, golf caddy cars, and wheelchairs, and is not preferred for higher vehicle categories.

2.2 INDUCTION MOTORS

Induction motors have simple and rugged construction and can work in harsh conditions. They offer high reliability and good dynamic performance. It does not have brushes and slip rings, or permanent magnets; it does not require any maintenance. The highest efficiency of induction motors are obtained at higher speeds, since the copper and core losses are reduced at higher speeds. But at low speed rotor losses increase. The efficiency and power factor in general are lower than the PM machines due to the inherent rotor loss. As a result, the issue of rotor heating is more prominent in case of induction motor than in PM motors. But since rotor position sensor is not required, induction motors have simpler speed control than PM motors.

Due to the brushless operation, a higher limit of maximum speed can be achieved, which enables high output power. Control on speed is achieved by changing the frequency. Induction motor can achieve control like separately excited dc motor by using Field oriented control (FOC) to separate its torque control from field control. Extended speed range operation beyond base speed is obtained by flux weakening, once the motor has reached its rated power capabilities.

Inverter-fed induction motor fulfills the requirement of high Constant Power Speed Range (CPSR) for electric vehicles, which can be achieved by flux weakening controlled by reduction of magnetizing current. It also offers the advantage that one inverter can feed several motors. Adjustment of motor excitation in accordance with load and speed can improve part-load efficiency and power factor.

Most induction motors available today contain rotors made of die cast aluminum which is not expensive to manufacture. But poor electrical conductivity of aluminum, the larger size and lower efficiency than their copper motor counterparts are the drawbacks.

On the other hand, copper rotors were expensive and hand fabricated. Die casting of copper rotor was difficult as the high melting temperature of copper (compared to aluminum) led to rapid deterioration of the dies. In the last decade, a solution in the form of nickel-base alloy die inserts has been developed to extend the tool life.

The copper die cast rotor motor is about 25% lighter and about 30% smaller than the aluminum rotor machine. Due to high conductivity of copper (30% more heat transfer capability than the aluminum rotor motor), motor cooling from the outside of the stator core is adequate.

2.3 PERMANENT MAGNET MOTORS

In xEVs, the Brushless Direct Current Motor (BLDC), and Permanent Magnet Synchronous Motor (PMSM) are used – and these two terminologies represent the same motor topology. Some researchers though, used to distinguish them in terms of shape of flux density, current and back EMF. Whereas for PMBLDC it is trapezoidal, for PMSM it is sinusoidal. However, nowadays both are fed with sinusoidal currents.

The rotor is built with rare-earth (Neodymium-Iron-Boron - NdFeB) magnets which are used to generate the main machine flux. Since the rotor doesn’t need magnetizing current and copper loss is avoided, it is more efficient than induction machines. The high-performance, small-diameter magnetic rotors reduce the inertia of the armature, allowing high acceleration rates, a reduction in rotational losses, and smoother servo characteristics. This optimal motor response also allows for more constant speeds, instant speed regulation and a quieter drive system.

The stator is manufactured of stamped metal sheets and copper-coil which gets magnetized through dc supply, to generate the magnetic field that interacts with PM-rotor’s magnetic field and makes the rotor to move. Due to back emf generated in the stator coil as the speed increases the current in the coil is reduced and hence the torque gets reduced. This is a desired property in electric-drives, as high torque is needed at low speed to overcome inertia and the lower torque at high speed enables better control of the vehicle.

The speed range may be extended three to four times over the base speed if conduction angle control is used. PM Motors have a narrow constant power speed range (CPSR), widening of which requires a special technique or construction. They can be used effectively in transmission-less electric passenger vehicles (CPSR >4:1), and larger electric vehicles (trucks, tanks & heavy equipment can require a CPSR of 10:1).

PMSMs may be classified into three major families -

- Surface Mounted PMSM- magnets are glued to the cylindrical rotor outer surfaces and magnetized in the radial direction
- Inset PMSMs- magnets are placed in radial slots or grooves cut at the rotor surfaces
- Interior PMSMs (IPM)- magnets are located with the rotor core. This has led to many rotor topologies

Both surface mounted PMSM and Interrior PMSM are used in EV applications. IPM offers good overload capability, mechanical robustness, field weakening capability and high speed operation. They are particularly suitable for hybrid electric vehicles.

SPM motors are more efficient at low speed and much less at high speed. They are not in general preferred for high speed applications because of the limited mechanical strength od the assembly between rotor yoke and the permanent magnet.

In terms of magnetic flux distribution, PMSM can be divided into axial flux, radial flux and transverse flux machines. *Axial Flux PM Machines (AFM)* have certain advantages over radial flux machines. They can be designed to have higher power to weight ratio with less core material. Since they have a larger diameter to length ratio, required stack length of stator is less for a particular amount of torque production. Hence AFM can be easily integrated with transmission mechanism enabling design of a compact powertrain in light electric vehicle applications. Other advantages of AFM include planar and easily adjustable air-gaps, good efficiency, balanced rotor-stator attractive forces and better heat removal. Due to these properties AFM are more suitable than RFM for direct drive or in-wheel motors. Excellent low speed performance and high torque generating capacity make them good candidate for buses and shuttles also. They can be used for both low speed direct drive and high speed flywheel applications.

TFM are relatively recent development, and they are particularly suited for direct drive (high torque and relatively low speed). Both AFM and TFM have three dimensional flux path, and hence, a more complex structure.

Radial Flux PM Machines (RFM) have lowest cogging torque (It is generated due to the interaction of the magnet flux and stator teeth and may cause additional vibrations, acoustic noise and complicated starting conditions), as the rotor is segmented. It has higher torque capability & efficiency than induction machines. RFM have been also been used in HEVs. The RFM, topology has long end windings with small diameter /axial length (D/L) ratio. This can result in high copper loss and lower flux density due to air gap (in the winding). But this structure dissipates the heat from stator frame and can take higher electrical loading.

Because of its wide torque-speed range **Distributed-Winding Interior Permanent Magnet (IPM)** motor is used in HEVs . However, the big winding-overhang produces copper losses and extends the stator axial length. This reduces torque density & increases costs. Using concentrated windings about 50% reduction of winding overhang can be achieved. Another issue is permanent magnet demagnetization at high current operation, which limits increase of torque density. To solve this problem, high coercive magnet is necessary, preventing the motor from demagnetizing.

Doubly-Salient Permanent Magnet (DSPM) motor drive has the advantages of both PMBLDC and Switched Reluctance motor drives. But it still suffers from the uncontrollable PM flux and high PM material cost. Stator-Doubly-Fed Doubly-Salient (SDFDS) motor solves the fundamental problems of the DSPM machine, and offers possibility of optimizing the efficiency on-line.

PMSM/BLDC: STRENGHTS AND WEAKNESSES

STRENGTHS

The PM-BLDC motors have simple construction. They are compact, smaller in size and heat is efficiently dissipated to the surroundings. Further they do not have any commutator and compensation winding.

WEAKNESSES

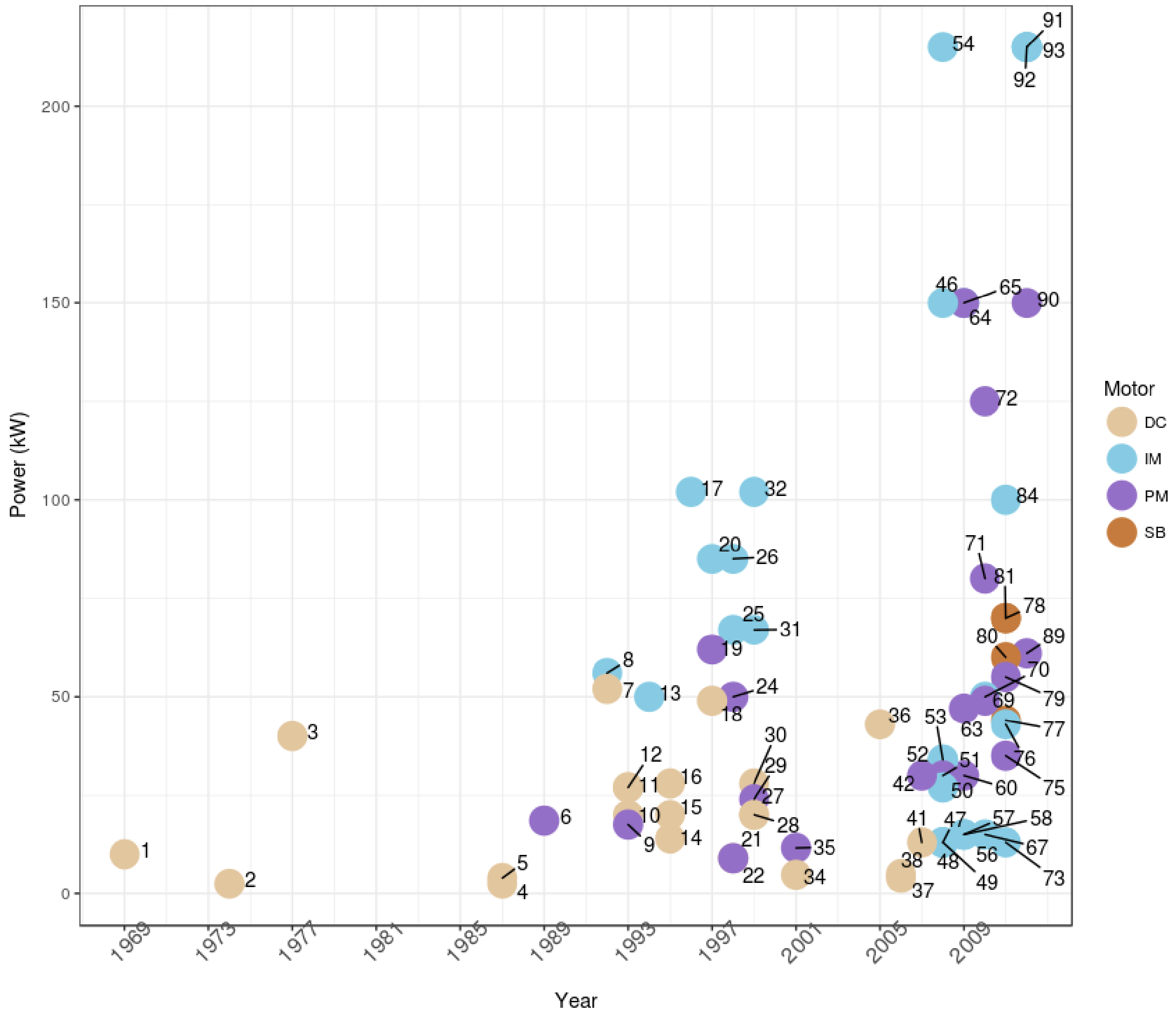
High cost due to the cost of permanent magnets, and small constant power region are the main drawbacks of the BLDC/ PMSM.

The torque density is limited by the maximum temperature allowed for winding insulation and permanent magnets. The motor winding can withstand upto 165°C on the average, and 180°C in a hot spot. NdFeB permanent magnets can operate up to 180°C, and can get demagnetized by severe demagnetizing fields produced by stator currents (e.g., a short-circuit at high temperature).

These motors use expensive magnets and the limited mechanical strength of the magnets also present difficulty in building of a large torque in the motor. It has limited field weakening capability due to presence of PM field which can only be weakened through production of a stator field component which opposes the rotor magnetic field. However, it is possible to extended constant power operation by advancing of the commutation angle. High Quality Magnets are from Japan & rest of permanent magnets come from China.

Rare-Earth Supply is a source of uncertainty; & more than 90% comes from China. India is 2nd largest producer of rare earth ore (1.2%), but lacks supply chain capacity to produce magnets.

FIGURE 5.2: MOTORS USED IN BEVs



Enfierld 8000	1
Chloride Citicar	2
Oka NEV ZEV Lucas	3
CityEl	4
CityEl	5
FVW Golf CityStormer	6
Bertone Blitz	7
Ford Ecostar	8
VW Golf CityStromer	9
Citreon AX	10
Chrysler TEVan	11
Chrysler TEVan	12
Solectria Sunrise	13
Subaru Minivan 200	14
Citreon Saxo	15
Citroen Berlingo	16
General Motors EV1	17
Honda EV Plus	18
Nissan Ultra	19
GM S-10	20
CityCom Mini-El	21
GEM car	22
RenaultExpress Electric	23
Toyota RAV4 EV	24
Ford Ranger EV	25
GM S-10	26
Peugeot 106	27
Myers Motor NmG	28
Hypermini	29
Peugeot Partner	30
Ford Ranger EV	31
General Motors EV1	32
Dynasty IT	33
G-Wlz	34
Cree SAM	35
Commuter Cars Tango	36
NICE Mega City	37
ZAP Xebra	38
CityCar	39
The Kurrent	40
Kewet Buddy	41
Smart ED	42
Phoenix sut	43
Phoenix sut	44
ZAPI OBVIO 828E	45
AC Propulsion eBox	46
ZENIN	47
REVAi	48
REVAi	49
Stevens Zecar	50
Lumeneo SMERA	51
Think City	52
Think City	53
Tesla	54
Chana Benni	55
Tazzari Zero	56
Micro-Velt Fiat 500	57
Micro-Velt Fiat Panda	58
Zytel Gorilla Electric	59
Citroen Ci ev'ie	60
Smart ED	61
Subaru Stella EV	62
Mitsubishi iMiEV	63
BYD e6	64
Mini E	65
Venturi Fetish	66
Wheego Whip LiFe	67
Gordon Murray T-27	68
Ciroen C Zero	69
Ford Transit Connect EV	70
Nissan Leaf	71
BYD F3M	72
REVA NXR	73
Renault Twizy	74
Peugeot iOn	75
Fiat Doblo	76
Kangoo Express Z.E.	77
Ford Tourneo Connect EV	78
Tata Indica Vista EV	79
Renault ZOE	80
Renault Fluence ZE	81
Volvo C30 Drive Electric	82
Skoda Octavia Green E Line	83
Ford Focus Electric	84
CODA Sedan	85
Saab 9-3 ePower	86
Toyota RAV4 EV	87
Honda Fit EV	88
Hyundai BlueOn	89
Lightning GT	90
Tesla Model S	91
Tesla Model S	92
Tesla Model S	93

2.4 SWITCHED RELUCTANCE MOTOR (SRM)

SRM is a doubly salient machine with a passive rotor that runs by reluctance torque. Both the stator and the rotor have salient poles. The torque is developed by the tendency of its rotor to reach a position where the inductance and the flux produced by the energized stator winding are maximized and the magnetic field is symmetrical. The number of salient poles is always two less than the number of coils. Also, when using a core of high magnetic permeability the torque that can be produced within given volume exceeds that produced in induction motor and BLDC motors. Combining this with possibility of higher speed means that a higher power density is possible.

ADVANTAGES

The Switched reluctance motor has structural simplicity, high efficiency, low cost and control flexibility. The torque speed characteristics of SRM matches very well with EV load characteristics. The SRM has high speed operation capability with a wide constant power region. The motor has high starting torque and high torque-inertia ratio. The rotor structure is extremely simple without any windings, magnets, commutators or brushes. The fault tolerance of the motor is also extremely good. Because of its simple construction and low rotor inertia, SRM has very rapid acceleration and extremely high speed operation. Due to its wide speed range operation, SRM is particularly suitable for gearless operation in EV propulsion. In addition, the absence of magnetic sources (windings or permanent magnets) makes SRM relatively easy to cool and insensitive to high temperatures which is very much suitable for automotive applications.

CHALLENGES

SRMs are difficult to analyse, therefore we need a design process and methods that will accurately model their performance. Advanced control techniques are being researched for the following issues:

- Variation of the phase induction with rotor position
- High torque ripples
- Need of accurate rotor position detection
- Special converter topology
- Electromagnetic interference
- Acoustic noise produced by stator vibrations of SRM

A stator with a high stiffness can help reduce vibration deformation. Low vibration and noise can be achieved by mismatching the waveforms and frequencies of the excitation force with the stator mode shapes and resonant frequencies of the SRM. Electronic techniques for noise reduction include Random Pulse-Width Modulation (RPWM) and active noise cancellation techniques. Because the resonant frequencies of the stator have to be known or measured before implementing electronic techniques, an accurate determination of the natural frequencies and their corresponding mode shapes is essential in vibration control of the SRM drive.

In Japan SRM with torque density of 45 Nm/l was developed with optimum combination of a carefully selected motor structure and related materials.

2.5 SYNCHREL MOTOR

The Synchronous Reluctance motor has many advantages of the Switched Reluctance Motor, yet it uses standard components in common with brushless dc or induction motor, including the stator and power electronics circuits. The torque ripple is also less than that of the SR motor. Synchronous reluctance motors become popular in EVs and HEVs for their simple and rugged construction and for hazard-free operations.

ADVANTAGES

- It can be driven by a conventional six-switch inverter, as would be used to drive a PM AC or induction machine, primarily as a result of the sinusoidal excitation and distributed winding construction. This enables the use of commercially available and established hardware. The cost and risk of drive development is reduced to just that of implementing a new current control strategy, which is typically done entirely in software.
- Freedom from permanent magnets.
- A wide speed range at constant power.
- Synchronous operation, leading to high efficiency and the ability to maintain full torque at zero speed

CHALLENGES

- In small motors the torque/ampere and the torque/volume are lower than the permanent magnet motors. SynchRel motor is preferred for larger motors (over 5-10 kW in rating), because of high cost of magnets in large motors, and since the performance of reluctance motor improves with increasing size.
- A sine wave drive is required, with continuous shaft position feedback for the orientation of stator MMF. A small air gap is required, comparable to that of induction motor

2.6 IN-WHEEL MOTORS

Putting a direct drive electric motor inside motor wheel eliminates many of the conventional modules in the vehicle like ; gear box, differential box, drive shaft. The motor must have a high torque density and efficiency, and survive the rigors of in-wheel stress, and failures should not lead to loss of control of the vehicle. By making concentrated, single tooth windings and fractional numbers of slots/pole/phase, the torque density can be maximized, with high slot fill factors and short end windings.

ADVANTAGES

- Wheel-slip based control gives shorter braking distance & improves vehicle response.
- Torque at each wheel can be independently controlled, provides true 4 wheel drive.
- Elimination of drivetrain components leads to simpler and reliable mechanical vehicle design, and more space for battery and accessories.

CHALLENGES

- Precise control technique is required for ride and handling.
- Increase in the vehicle unsprung mass.
- Safety methods are required in case of a motor fault occurrence.
- Development of uneven torque distribution.

TABLE 5.1: SOME EXAMPLES OF MOTORS USED IN BEVs

CATEGORY	MODEL	MOTOR	MOTOR SIZE (KW)
2-Seater	Smart ForTwo	DCPM	55
Mini Compact	Fiat 500e	ACIPM	82
Subcompact	Coda	DCPM	100
Subcompact	Mitsubishi i-MiEV	DCPM	49
Compact Car	Ford Focus Electric	PMSM	107
Midsize	Nissan Leaf	DCPM	80
Large	Tesla Model S	AC Induction	225
Large	Tesla Model S	AC Induction	270
Small STATION WAGON	Honda Fit EV	DCPM	92
Small SUV	BYD e6	PMSM	75
Small SUV	Toyota RAV4 EV	AC Induction	115
Bus	BYD e-Bus 12 M	PMSM In wheel	90*2

TABLE 5.2: SOME EXAMPLES OF MOTORS USED IN HEVs

CATEGORY	MODEL	MOTOR	MOTOR SIZE (KW)
Two Seater	Honda CR-Z	BLDC	10
Midsize Car	Acura RLX Hybrid	PMSM	35 (front)/ 27X2 (back)
Compact Car	BMW Active Hybrid 3 PHEV	PMSM	40
Compact Car	Honda Civic Hybrid	PMSM	17
Compact Car	Honda Insight	BLDC	10
Compact Car	Toyota Prius C	PMSM	45
Mid Size CAR	Ford Fusion Hybrid	PMSM	88
Mid Size Car	Honda Accord Hybrid	PMSM	124
Compact Hatchback	Ford C-Max Hybrid	PMSM	88
Sedan	Hyundai Sonata Hybrid	PMSM	35
Bus	Volvo 7900 Hybrid	PM	120

2.6 COMPARISON OF MOTORS

Cooling/Heat Dissipation:

In an SRM, the phase windings on the stator set up a magnetic dipole between stator and rotor poles. This gives rise to tendency to reduce the air-gap reluctance and the rotor pole moves toward an aligned position with an excited stator pole. SRM drives are easily cooled, since heat generated due to both copper loss and iron loss in the core are mainly in the stator.

TABLE 5.3: COMPARISON OF VARIOUS TYPES OF MOTORS: HIGHER VALUES INDICATE ADVANTAGE/ BETTER PERFORMANCE (SOURCE: YILMAZ 2015)

INDEX	DCM	IM	BLDC	PMSM	SRM	SYNRM	P-M ASYNRM	PM HYBRID
Cost	0	2	-1	-1	1	2	1	0
Torque/ power density	-1	0	2	2	0	0	1	1
Efficiency	-1	1	2	2	1	1	2	1
Simplicity/ manufacturability	2	2	1	0	2	2	1	-1
Controllability	2	2	1	0	2	2	1	-1
Reliability	-1	2	1	1	2	2	1	1
Size/ weight/ volume	-1	1	2	2	1	1	1	1
Overload capability	-1	1	1	1	1	2	2	2
Robustness	0	2	1	1	2	2	1	1
Field weakening	2	2	-1	1	2	2	2	0
Fault tolerance	1	2	-1	-1	2	1	1	0
Thermal limitations	0	1	-1	-1	2	2	1	-1
Noise/ vibration/ torque ripple	-1	2	0	2	-1	-1	0	1
Lifetime	-1	2	1	1	2	2	1	1
Maturity	2	2	1	1	1	1	-1	-1
Future expectations/ potential	-1	2	0	2	2	1	2	2

- **Selection criteria:** Weight, Efficiency, Cost, Reliability, Power Density & Controllability. Typically, it is a trade-off among design factors like as iron saturation, thermal capabilities, constant power speed range (CPSR), geometry constraints etc.

Other motors (DC motors, Induction Motor or PM BLDC motors) depend on rotor windings or magnets on the rotor in order to establish proper magnetomotive force (mmf) in the air-gap. These flux sources on the rotor have either winding resistance (induction motor) or permanent magnets, which are strongly affected by temperature. There may be thermal coupling and heat transfer into the rotor, which is a potential problem since their performance are determined by temperature and rotor structures.

High Speed Operations

SRMs rotors have a low-cost construction with no windings and permanent magnets. Ratio of 5-6 for maximum speed to base speed can be reached; and acceleration performance & regenerative braking needs minimum power. SRM drives are capable of high-speed operation over a wide constant power region, and meet the criteria >10,000 rpm.

PM BLDC and IM drives are limited to lower ranges. PM BLDC motor drives, inversely, must have rotor modifications that result in degraded performance/cost in order to operate in this range of speed. IM drives maximum speed is generally smaller than 10,000 rpm.

Fault Tolerance:

For IM and PM BLDC motor drives, their electromechanical energy conversion is interdependent upon proper excitation. SRM drives are naturally fault tolerant, since they have discrete phase windings and thus phase windings are independent of each other. So, if one phase fails in the SRM drive, it can still operate at a somewhat degraded performance until repairs can be conducted. The converter topology used for an SRM protects it from serious electrical fault of shoot-through, which is not eliminated fully in IM and PM BLDC motor drives.

03 NEW MOTOR TECHNOLOGIES

Significant investments are being made by OEMs, Tier 1's and new startups in developing advanced electric drivetrains. General Motors Co. and Renault amongst OEMs, Continental and Bosch amongst Tier-1's and startups like Mission Motors, Via Motors, etc. have made significant investments into drivetrain technology development in recent years. At present permanent magnet machines dominate the electric and hybrid electric vehicle applications. It is used in the most popular commercial hybrid electric vehicles. Battery electric vehicles Tesla Roadster and Think use induction motors. This type of machine was also used in the obsolete GM EV1 and Ford Electric Ranger pickup. The drive system in all available applications in xEVs consists of a voltage source inverter (VSI). A mixture of ethylene glycol and water (60:40) is used for power electronics cooling in most cases. The inlet temperature is around 70°C and typical ambient temperatures in the electronics are between 70-80°C.

Following are some of the potential electric machine candidates for future vehicle powertrains, which have not yet been commerciallized:

Flux-Switching Permanent Magnet Machines
The flux-switching permanent magnet machine is proposed as a new potential machine candidate for aerospace applications, due to its inherent fault tolerance capability. The permanent magnets are located on the stator side for easy cooling arrangement and the coils are non-overlapping with small mutual inductance and influence in case of phase failure.

Synchronous Reluctance Machines with Permanent Magnet Assist
The synchronous reluctance machine with permanent magnet assist using ferrite is proposed as a cost effective machine alternative with high efficiency and power factor. Ferrites are relatively weak magnets that cost only one tenth of the cost of NdFeB magnets per weight unit. The ferrites are mainly used for reducing the required inverter rating and for increasing the constant power region.

Under the SyrNemo project funded by the European Union, the Austrian Institute of Technology took up the development of SyRM. The project aimed at increase in specific power and power density by 5%, elemination of the dependency on rare earth PM (either using no PM or optional ferrites). Overall driving cycle efficiency improvement in the range 5-15% was targeted. As per the test results, drive system efficiency achieved was 92% on the NEDC and 89% on the WLTC.

Memory Motors

Memory motors have Aluminium-Nickel-Cobalt (AlNiCo) [low power] permanent magnets in the rotor. AlNiCo magnets are easily demagnetized. So the stator currents can continuously alter magnetic flux in the rotor – from high-flux-level-at-low-speed to a low-flux-level-at-high-speed in the constant power region. This minimizes the required current amplitude and corresponding losses. AlNiCo magnets also have high thermal stability (>500°C) compared to NdFeB magnets.

04 ELECTRIC VEHICLE MOTOR CONTROL

Past generation of electric vehicles used the DC motor/ controller systems, and it did not require complex electronics. A simple variable resistance was used to control the speed of the vehicle. Thus this system involved high energy loss in the resistor.

Before the invention of variable frequency voltage and current source inverters the Induction motor was never considered as continuously variable speed drive. Only some adaptation of the load characteristics was feasible by manipulation of the rotors resistance. In 1960s, the silicon controlled rectifiers (SCRs) became available. Variable speed induction motor drives can be traced back to that period. In that time the principle of speed control was based on the steady state considerations of the induction machine. Induction motor speed control by varying supply frequency (v/f control) became popular in industry. The slip frequency control method also became well known for better dynamics. Subsequently, field oriented control (FOC) became the industry's standard for AC drives. Modern controllers are based on pulse width modulation technique, and rotor position sensing.

Electronic commutation is used in Brushless DC motors. A 3 phase PWM inverter is used with a rotor position sensor to perform phase commutation and/or current control. In the trapezoidal wave PM Brushless motor, only the knowledge of six phase commutation instants per electrical cycle is needed; hence cheap Hall Effect sensors are used to control commutation. However, production of torque ripple due to the interaction between the fed trapezoidal wave current and magnetic field is a major issue.

On the other hand in the PM Brushless motors with sinusoidal back EMF, a continuous rotor position sensor is essential. In addition to commutation purposes, this measurement is used to eliminate the problems associated with the trapezoidal wave version.

However, emerging trend is to have sensorless motor drives that do not require a rotor position feedback sensor. A number of position measurement elimination techniques have been reported to operate such motors with sensorless strategies. Sensorless control is advantageous in many aspects like reduced cost, reduced number of electrical connections, elimination problems with mechanical alignment and reduced size and weight of the motor.

However, in all sensorless control algorithms, extensive computational power and accurate measurement of the voltages and currents, as well as accurate knowledge of the motor parameters are required. Moreover, the methods proposed so far ultimately at low and zero speed in wheel motor tests, due to the absence of measurable signals. Application of sensorless control to wheel motors is still at R&D phase.

Integration of the motor and the drive electronics into a single package is another major trend. This helps to simplify the system, minimize interconnection cooling, reduce noise and solve motor drive compatibility issues.

05 SCOPE FOR HIGHER EFFICIENCY

Increase motor diameter or overall size
Making a motor larger in order to improve its efficiency is an obvious approach since every motor has a peak efficiency operating point which is normally well less than the motor's maximum output power point. Therefore, specifying a larger than normal motor can align the motor's typical operation to coincide with the motor's peak operating efficiency point. This, of course, only works when the motor load is known and relatively constant. Also, specifying a larger motor increases the motor's cost. However, in case of electric and hybrid electric vehicles, the target is to ensure that the weight as well as the volume of the motor is reduced.

Increase materials used to make the motor
This also may not be in line with the objective of having motors with higher specific power/ energy and higher energy/ power density of the motor in electric/ hybrid electric vehicles.

Make the Air Gap Smaller
Making the air gap smaller is a good approach for all types of motors, except for the fact that modern motors usually are already designed with the smallest practical air gap. Reducing the air gap further would increase manufacturing costs, due to the need to keep better mechanical tolerances, and could result in lower motor reliability.

Use Better Grade Steel Laminations
Using better grades of steel for the lamination material would reduce core losses in the motor and improve efficiency. Currently, the better grades of lamination steel cost more due to enhanced control and precision in their manufacturing. With the progress in the supply chain, in future high performance soft magnetic materials will come at attractive costs.

Reduction of Machine Losses can be achieved with proper selection of machine topology, for instance slip losses in the rotor present in induction machines is avoided in synchronous machines. Better Steel Grades and Thinner Laminations will reduce hysteresis and eddy-current iron losses. Copper losses from ohmic resistance and eddy currents. Ohmic resistance losses depend on the current in the coils, while eddy current copper losses depend on motor rpm. Iron losses from eddy current and hysteresis depend on the rpm.

The maximum continuous temperature with the normally highest industrial class H winding insulation is 180°C in the hot spot and 165°C on winding average. The winding temperature can transiently pass 200°C, without insulation failure. However, rules of thumb states that the insulation lifetime is doubled for every 10°C temperature reduction in continuous operation.

Traction motors have very high power density. In case of AC induction motors, rotor has to be cooled as well. Improved cooling of the winding system will reduce the temperature and the resistance and therefore also the joule losses. Direct-water cooling of the copper conductors is complicated and expensive, but Oil Spray Cooling as in Toyota Prius is a practical and good solution. In HEVs the oil pump system is available. Water Cooling & Forced Air Cooling of the housing, and Heat Pipes to extract heat from a high temperature area to a cooler area, can be utilized.

Others
Use thinner lamination/Add more windings; Improve thermal resistance (e.g. potting); Use better bearings and low friction lubrication/ Reduce winding losses in rotor; Substitute copper for aluminum in induction rotor.

06 POWER ELECTRONICS SUBSYSTEMS

The major Power Electronics Subsystems are: Inverter to drive the motor and DC-DC Converter to link battery to high voltage DC bus.

6.1 INVERTER

The speed, torque and power output of the electric motor has to be controlled, depending on the driving conditions. The Inverter converts the dc power from the batteries into alternating current at appropriate frequency to enable the traction motor to match these requirements.

Current-Fed Inverters are not used for EV propulsion.

Voltage-Fed Inverters are used as they are simple and can have power flow in either direction. The switches are usually IGBT for high- voltage high power hybrid configurations, or MOSFET for low-voltage designs. The output of the VSI is controlled by means of a pulse-width-modulated (PWM) signal to produce sinusoidal waveforms. Certain harmonics exist in such a switching scheme hence high switching frequency is used to move the harmonics away from the fundamental frequency.

Current Source Inverter operates using the same principle as VSI, with the input as a current source. Three small commutating /filtering capacitors may be needed on the ac side.
In hybrid vehicles, the inverter and the motor are usually oversized to meet the wide speed range for constant power operation. A Z-source inverter can potentially provide cost effective and reliable solutions.

Multilevel Converters have been used in electric power systems and large motor drives, with high power demands (>250 kW). The two-level VSI or CSI are not useful at high frequency, due to switching losses and constraints of device ratings. Multilevel converters can reduce device stress, achieve high voltages with low harmonics, and produce minimum electromagnetic interference or common-mode voltage.

Soft-Switching Inverters for ac motors (like induction motors, PM brushless & PM hybrid motors) is an active research area. The three phase voltage-fed resonant dc link (RDCL) inverter developed in 1989 was a milestone.

Recent developments are:

- Quasi–resonant dc link (QRDCL)
- Series resonant dc link (SRDCL),
- Parallel resonant dc link (PRDCL)
- Synchronized resonant dc link
- Resonant transition, auxiliary resonant commutated pole (ARCP), and auxiliary resonant snubber (ARS) inverters.

6.2 DC-DC CONVERTER

DC-DC converters are used to convert direct current from one voltage level to another. In xEVs, a high voltage operation of the motor is desirable, for better efficiency. On the other hand, ECUs for body control or instrumentation cluster operate typically at 12 V, as in case of conventional vehicles.

Accordingly, two categories of DC-DC converters are required in xEVs:

- High-Power Converter links HEV battery at a lower voltage with the high voltage DC bus.
- Low-Power DC/DC Converter links the HEV battery with low voltage auxiliary battery.

When the voltage ratio is low, non-isolated power converters can be used. Non-isolated dc-dc converters feature no transformer or other kind of isolation between the low voltage or high voltage side. Five types of non-isolated converters are available - boost converter, buck converter, buck-boost converter, Cuk converter and charge-pump converter. The buck-boost and Cuk converters can be used either for voltage step up or step down. The Cuk converter can be used for either voltage step-up or voltage inversion, but only in relatively low power applications.

Isolated dc-dc converters need to be used in case the low voltage and high voltage side negatives can not be grounded together, or when the voltage ratio between both the sides is very high such that it is no longer economical to use one single component that handles both high current and high voltages. Usually a high frequency transformer is used in non-isolated converters. There are many types of nonisolated converters, including Half-Bridge, Full-Bridge, Fly-Back and Push-Pull DC-DC converters. All of these can be used as bidirectional converters.

Interleaved operation of dc-dc converters is used in case of high power applications. Such an operation can be achieved by parallel connection of multiple phase legs. The shift between the phases reduces the current fluctuation at the input as the input (battery) and the interleaved currents of the phases minimize each oter fluctuation.

DC-DC converters for future xEVs will require high power density and scalability. The current DC-DC converters need to be improved in terms of size, weight, efficiency and cost. Some of

- Zero-Voltage Switching DC-DC converters (95% efficiency, 1 kW/m^3 power density)
- ZVS Buck-Boost regulators (>97% efficiency, 1 kW/m^3)
- Sine Amplitude Converter High Voltage (SAC HV) bus converters with 97% efficiency at 1 kW/m^3).

Soft-Switching Converters for EV propulsion are receiving wide attention. The key of soft switching is to employ a resonant circuit to shape the current or voltage waveform such that the power device switches at zero current or zero voltage condition, and the switching loss is practically zero. Converter size and weight are reduced, due to low heat sinking requirement and snubber–less operation. Due to minimum switching stress during soft switching, the EMI problem is less severe and the machine insulation is less stressed because of lower dv/dt resonant voltage pulses. The acoustic noise is very small because of high frequency operation.

However, major challenges of the soft-switching converters are:
- Additional cost of the resonant circuit and increased complexity.
- Although soft-switching dc-dc converters have been widely accepted by switched-mode power supplies, the corresponding development for EV propulsion is much slower.

Functional integration of dc-dc converters and minimization of magnetics can potentially reduce size, weight and cost and enhance efficiency.

6.3 CAPACITORS

In EV, the capacitors prevent ripple currents from reaching back to the power source, and to smooth out DC bus voltage variations. Capacitors are used to protect semiconductors –originally thyristors, but now IGBT. Metalized film has become the capacitor technology of choice for electric vehicle and other medium and high power applications;

One major advantage is the ability of film capacitors to overcome internal defects. The latest dielectric films used for DC filter capacitors are coated with a very thin metallic layer. In the case of any defect, the metal evaporates and therefore isolates or fuses the defect, effectively self-healing the capacitor. The total capacitance is divided into elementary cells (sometimes several million) protected by fuse gate. If there is a weak point, the particular cell where the weak point is located will be insulated by fuses blowing up.

Capacitance decreases as a function of the ratio between elementary cell surface and total surface of capacitor, so there is no complete failure and no short circuit, only a minimal capacitance decrease which can be useful as a measure of aging.

Metalized film capacitors also offer significant space savings when compared to devices manufactured using other technologies - such as aluminium electrolytic capacitors - if high RMS current handling is a requirement.

Various types of capacitors are used in power electronics circuits.
- **DC bus capacitors:** responsible for energy storage and voltage smoothing. They require large capacitance (100-2000 μF) and energy density.

- **Snubber capacitors:** Used to reduced power dissipation in a solid-state inverter, and has a capacitance of 10-1000 nF.
- **Filter capacitors:** Remove unwanted frequencies and harmonics from the output ac signal. Their capacitance depends on the output frequency.

Currently DC bus and Snubber capacitors are made from electrolytic and polymer technologies, which are volumetrically inefficient. DC bus and snubber capacitors currently occupy over half of the total volume of power electronic circuits. The dielectric performance of stronger glass will make it the material of choice for next-generation high energy capacitors, and drive miniaturization and extended lifetime of the power converter in EV and HEVs.

6.4 POWER SEMICONDUCTOR DEVICES

Power semiconductor devices are a key factor in determining the efficiency, performance, and cost of hybrid, electric, and fuel cell vehicle systems. Power semiconductor devices are the main electronic components used in power electronic systems for modulating the energy flow to suit the demands of the application.

Different types of solid state power semiconductor devices have been developed to control the output parameters, such as voltage, current or frequency. At present, IGBT and Power MOSFET represent modern switching devices. Power integrated circuits (PIC) have been developed for the use of power converters for portable, automotive and aerospace applications. In Electric vehicles the voltage level of electrical power system drive is increasing so we need advancement in silicon technology to support this.

High-voltage power devices such as Insulated Gate Bipolar Transistors (IGBT) and freewheeling diodes play a critical role in hybrid electric traction inverters, voltage boost dc/dc converters, fuel cell air compressor motor drives, and other on-board power management converters. The electrical power conversion system typically uses an IGBT module as its main switching device. IGBT modules have been used mainly in industrial facilities. But automotive applications require IGBT modules having higher reliability and higher performance.

In addition, low-voltage power MOSFET and power integrated circuits are widely used in engine control, vehicle dynamic control, vehicle safety and body electronics subsystems in both electric and conventional internal combustion engine (ICE) vehicles.

Cost reduction has provided an important motivation for developing better switching devices in power converters. Power semiconductor devices count for roughly one-third of the total cost of vehicle power electronics. Advances in power semiconductor technology have improved the efficiency, size, reliability and reduced the weight and cost of power electronic systems and therefore of Electric Vehicles.

TABLE 5.4
MODERN POWER SEMICONDUCTORS – KEY CHARACTERISTICS

APPLICATION	PEAK POWER RATINGS	SEMI-CONDUCTOR DEVICES	CURRENT RATINGS	VOLTAGE RATINGS	SWITCHING FREQUENCY
Inverters for Propulsion Motor / Generator	20-100 kW	IGBTs, Power Diodes	100-600 A	600-1200 V	5-30 kHz
DC/DC Voltage Boost Convertor for battery or fuel cell stack	20-100 kW	IGBTs, Power Diodes	100-600 A	600-1200 V	5-30 kHz
Inverters for Air Compressors in Fuel cell stacks	10-15 kW	IGBTs, Power Diodes	20-50 A	600-900 V	5-30 kHz
Inverters for Air Conditioners	2-4 kW	IGBTs, Power Diodes	10-20 A	600-900 V	5-30 kHz
DC/DC Converters for 14V Power needs	1-2 kW	Power MOSFETs, Power Diodes	20-40 A	400-600 V	50-200 kH
14 or 42V Power Converters or load switches	<1 kW	Power MOSFETs, Power Diodes	1-20 A	40-100 V	0.1-100 kHz

6.4.1 Power Diodes

Diodes are the simplest semiconductor device, yet have a major impact on the overall efficiency of HEV inverters and converters. They are mainly used as the anti-parallel freewheeling diodes to conduct the load current during IGBT turn-off. In addition to the voltage rating, current rating, and forward voltage drop, the recovery characteristics of freewheeling diodes dictate the selection of rectifiers for fast switching power circuits. A power diode requires a finite time to switch from off state (reverse bias) to on state (forward bias) and vice versa.

The freewheeling diodes used in HEV inverters/converters should have the following features

- Low forward voltage and positive temperature coefficient for safe parallel diode operation;
- Low reverse recovery losses, soft recovery, and ruggedness against dynamic avalanching;
- Stable reverse blocking capability with low leakage current at high temperatures; and
- Surge current capability, avalanche withstand capability, and a low forward recovery overshoot voltage during the diode turn-on transient period.

6.4.2 Power MOSFET

At present, **Power MOS Field-Effect Transistors** (power MOSFET) are the most commonly used devices in power electronics applications up to tens kW range. Different types of MOS transistor have been developed that are able to switch relatively high currents and voltages, and can therefore be used in power electronic circuits.

Power MOS brings the following benefits to power electronic applications:

- High input impedance
- High power gain
- Voltage control
- Thermal stability

Since there is no excess carrier injection in the on-state, the turn-off losses are low, and devices can be operated at relatively high frequencies.

6.4.3 IGBT

Insulated Gate Bipolar Transistors (IGBT) are the active switching device of choice in nearly all HEV inverters and converters due to their superior current conduction capability over high-voltage power MOSFET. The IGBT is a switching transistor controlled by a voltage applied to its gate terminal. IGBT reduces on-state conduction losses by conductivity modulation.

The IGBT has high input impedance and fast turn-on speed like a MOSFET but exhibits an on state voltage drop and current-carrying capability comparable to that of a bipolar transistor while switching much faster. IGBTs have a clear advantage over MOSFET in high-voltage applications where conduction losses must be minimized.

It will be possible to operate an IGBT at a current density as high as 300 A/cm^2 in the future by further optimizing device design and developing an ultra-low thermal resistance package. This will result in a significant reduction in the size and cost of IGBT chips and those of the HEV inverters and converters where these IGBT are used.

IGBT modules that can withstand the automotive harsh environmental operation stresses, with switching ratings up to 400-600 volt and up to 400-600 Amp are used for EV and HEV automotive application. For these applications the OEMs require that the IGBT modules pass around 500000 thermal cycles with a ΔT of 40˚C and 1000 extreme thermal cycles from -40˚C to 150˚C.

6.4.4 Wide-bandgap semiconductor

Wide-band gap semiconductors permit power electronics devices to operate at much higher temperatures, voltages, and frequencies- making the power electronics modules using these materials significantly more powerful and energy efficient than those made from conventional semiconductor materials. SiC & GaN are good material with respect to band-gap, break down, and thermal conductivity characteristics. The on state and switching losses of SiC are half and one-fourth that of Si, respectively, and the temperature limit of SiC is 250 ˚C.

For xEV applications wide band-gap materials like SiC and GaN offer the potential to overcome both the temperature limitations and the power management limitations of Si.

- The cooling system can be simplified due to high-temperature operating capability
- Their high-speed switching characteristics enable to make the boost converter reactor more compact, also raise expectations for making the entire system more compact and less costly.

Recently Toyota Motor Corporation, in collaboration with Denso Corporation and Toyota Central R&D Labs., Inc. has developed a silicon carbide (SiC) power semiconductor for use in automotive power control units (PCU). Based on the test runs of prototype HEV, Toyota announced a fuel economy improvement of 5%. The benefit is expected to increase to 10% with optimization of motor control.

TABLE 5.5
OPTIONS IN SEMICONDUCTOR MATERIALS

MATERIAL	CHEMICAL SYMBOL	BANDGAP ENERGY (eV)
Germenium	Ge	0.7
Silicon	Si	1.1
Gallium Arsenide	GaAs	1.4
Silicon Carbide	SiC	3.3
Zinc Oxide	ZnO	3.4
Gallium Nitride	GaN	3.4
Diamond	C	5.5

TABLE 5.6
PROPERTIES OF SI, GAAS, 6H-SIC, 4H-SIC, GAN, DIAMOND

PROPERTY	Si	GaAs	6H-SiC	4H-SiC	GaN	Diamond
Bandgap (eV)	1.12	1.43	3.03	3.26	3.45	5.45
Dielectric constant	11.9	13.1	9.66	10.1	9	5.5
Electric breakdown field (kV/cm)	300	455	2500	2200	2000	10000
Electron mobility ($Cm^2/V.s$)	1500	8500	500	1000	1250	2200
Hole mobility ($Cm^2/V.s$)	500	400	101	115	850	850
Thermal conductivity (W/cm.K)	1.5	0.46	4.9	4.9	1.3	22
Saturated electron drift velocity (107m/s)	1	1	2	2	2.2	2.7

6.5 PACKAGING

Power module packaging plays an important role towards achieving higher power densities, improving reliability and reducing cost. Higher currents and voltages in power electronics systems mean higher thermal output and need of larger interconnections. Automotive power electronics also require properties such as mechanical support, electrical interconnection, heat dissipation path and protection from the outside environment. It has to meet high reliability standards in harsh operating environments, which include high ambient temperature range, high operation temperature, temperature excursion and thermal shock, mechanical vibration and shock, and frequent power surging.

As power semiconductors have moved from bipolar to MOSFET to IGBT, their switching frequency increased. But the limiting factor has been the packaging technology, which has significant impact on the electrical performance. A major challenge for the packaging technology is to reduce the parasitic inductance and capacitance. Stray inductances cause ringing and switching losses. Parasitic capacitance causes common mode current.

The two major factors that determine the size of the modern power electronics module are the size of the passive components and thermal management systems. Packaging is an area in which there is significant potential for cost saving.

Packaging of power electronics is interdisciplinary in nature. It should take into consideration thermal management, electrical insulation, interconnects and mechanical/chemical protection.

Typically packaging involves:

- Mounting the individual power devices on the heat sink
- Implementing the drivers, sensors and protection circuits on a printed circuit board and mounted near the power devices
- Packaging the power devices with wire bonding technology

The backbone in a Power Electronic module is the insulation substrate. As compared to microelectronics, the power electronics substrates need to carry higher current and voltage isolation, and need to operate at wide temperature ranges.

Substrates used in power electronics include

1. Thick film on ceramic
2. Insulated metal substrates
3. Direct bond copper on ceramic
4. Active Metal Brazed

The major limitations of traditional packaging technology are large parasitics of the wire bond, and inability to accommodate three-dimensional packaging.

TABLE 5.7

MANUFACTURERS/ MODEL	FEATURES OF POWER ELECTRONICS PACKAGING
Toyota Prius Hybrid III	Integrated cooler structure with an estimated improvement of 30% in the thermal performance. Direct cooling of the power module by brazing the DBA (Direct Bond Aluminium) substrates onto a specially fabricated cold plate. Elimination of separate thermal interface material (TIM) layer
Infineon Hybridpack 2	Integration of base plate with a heat sink or cold plate. Employs a Cu base plate with pin fins that can be dipped directly into the coolant flow when another Al cap with coolant inlet and outlet is mounted . Elimination of the TIM layer
Transfer-molded Power Module (TPM) from Mitsubishi	Mainly designed for hybrid vehicle applications. Lifespan 30 times longer than industrial power modules Directly water cooled module base plate, and uses a Direct Lead Bonding (DLB) structure that provides increased chip surface contact area
Nissan Leaf	The power semiconductor dies are attached onto a Cu bar which is an electrode and have wire bond connection to other electrodes to form a single-phase inverter. Then the whole module, with transfer molded encapsulation and exposed Cu electrodes, is mounted onto a cold plate with a separated electrical insulator sheet that has high thermal conductivity. This arrangement also eliminates the base plate compared to the baseline assembly.
SkiP technology from Semikron SkiM modules developed with SkiP technology (targeted for xEV applications)	No base plate. The substrate with the silicon chips is pressed onto the heat sink using a mechanical pressure contact system, allowing the substrate to expand or contract under temperature change. All semiconductor dies are attached to the modules using low temperature sinter technology. Silver paste is used as the connecting layer.

Initially the automotive power module packaging followed the standard of industrial drive module packaging, using the well established wire bond technology. For example, Toyota Prius Hybrid 2004 used direct bond aluminium on AIN ceramic. However, power electronics packaging structure in xEVs has gone through significant improvements in the pursuit of better electrical and thermal performance, reliability and cost-effectiveness.

Conventional package structure is asymmetric, in which the bottom electrode of the semiconductor device is specially tailored (e.g., made solderable). This has drawbacks like parasitic electric parameters, die bend under thermo-mechanical stress, less thermal conduction path etc. These can be overcome by changing the top interconnection configuration to a planar or symmetric package.

Researchers of International Rectifiers presented samples of power IGBT packages with a Cu clip directly soldered onto top emitter electrodes. Mitsubishi also developed a Cu lead bonded TPM automotive power module in which Cu leads are soldered directly on top of all switch dies (direct lead). All these new interconnection components reduce the package parasitic resistance dramatically.

Techniques/Design process to improve packaging include

- Reduction of number of packaging levels
- Functional elements integration
- Sharing packaging elements
- Multifunctional packaging elements
- Packaging elements and functional elements duality/ geometrical packaging

07 TESTING METHODOLOGY, STANDARDS & FACILITY

Reliability Demonstration testing

Reliability demonstration testing has been used by the automotive vehicle manufacturers for years to develop high quality parts, components and materials. By investing in strategic Design Verification/ Product Validation (DV/PV) solutions, one can eliminate failure modes and ensure the reliability of product.

Environmental/ Durability Requirements

The tests ensure reliability of power electronics performance over a life time of customer usage and exposure to various environmental conditions such as vibration, shock, temperature, humidity, electrical stresses and other forces that may occur during manufacturing, shipping and actual usage on field.

TABLE 5.8
LIST OF BASIC ENVIRONMENTAL & DURABILITY SPECIFICATIONS

ENVIRONMENTAL AND DURABILITY CRITERIA	BASE SPECIFICATION
Road Vehicles – Environmental Conditions and Electrical Testing	ISO16750
Road Vehicles – Test Dust for Filter Evaluation	ISO12103-1
Road Vehicles – Fuse-links	ISO8820-1
Environmental Testing – Test Cab : Damp Heat, Steady State	IEC 60068-2-78
Environmental Testing – Vibration, Broadband Random and Guidance	IEC60068-2-64
Environmental Testing – Salt Mist, Cyclic	IEC60068-2-52
Environmental testing – Composite Temperature/Humidity Cyclic Test	IEC60068-2-38
Environmental Testing – Damp Heat, Cyclic	IEC60068-2-30
Environmental Testing – Shock Test	IEC60068-2-27
Basic Environmental Testing Procedure – Change of Temperature	IEC60068-2-14
Environmental Testing – Cold Test	IEC60068-2-1
Standard Test Method for Random Vibration Testing of Shipping Containers	ASTM D4728

Electrical Safety Requirement

Electrical safety test is the most important requirement for electric powertrain vehicles to ensure requisite electrical quality for vehicle occupant. The application of electrical safety covers the power system, charging system, power wiring, charging line, charging connector and charging station etc.

TABLE 5.9
BASIC STANDARDS FOR ELECTRICAL SAFETY

ELECTRICAL SAFETY	CHARACTERISTICS
Road Vehicles – Environmental Conditions & Electrical Testing	ISO16750
Isolation Resistance Test	ISO 6469-1
Withstand Voltage Test	ISO 6469-3
Continuity Test for Potential Equalization	ISO 6469-3

EMC Requirement

Issues of electromagnetic interference (EMI) and electromagnetic susceptibility/immunity (EMS) are getting more and more attention with increasing functionality of electronic systems and complexity of key IC circuit design. Some alteration is required in setup & methodology for testing of power electronics (High Voltage Circuit) as compared to conventional automotive electronics.

TABLE 5.10: LIST OF BASIC EMC SPECIFICATIONS

EMC CRITERIA	BASE SPECIFICATION
Radiated Emissions	CISPR 25
Bulk Current Injection	ISO11452-4
Radiated Immunity Anechoic	ISO11452-2
Transient Immunity	ISO10605-2, ISO7637-2 and ISO7637-3
Electrostatic Discharge	ISO10605:2001

Accelerated Life Testing

An accelerated life test models product performance at elevated stress levels so that one can extrapolate the results back to normal conditions. The basic objective of an accelerated life test is to speed up the failure process to obtain timely information about products with a long life.

Because electronic components often take a long time to fail, accelerated life tests are common in the electronics industry. Accelerated life tests are also used to predict the performance of materials such as metals, plastics, motors, insulations, ceramics, adhesives, and protective coatings. Common performance variables include fatigue life, cycle time, wear and corrosion. Common stress variables include mechanical stress, temperature, vibration, humidity and voltage.

Highly Accelerated Life Testing

Highly Accelerated Life Test (HALT) is a stress testing methodology for electronic equipment during the design phase of product to make sure the design is reliable. During HALT testing, incremental step stresses (temperature, vibration and combined temperature and vibration) are applied until the product fails and thereby determining product's weaknesses, operational design margins and destruct limits. HALT Chamber features rapid thermal transitions with liquid nitrogen cooling and banks of multiphase heaters for heating; as well as pneumatic vibration system with six degrees of freedom.

08 TARGETS AND GAPS

Globally, cost reduction, weight reduction and volume reduction are the main focus for R&D on electric motor and power electronics. Power density has to be increased for the major power electronic modules like inverters, DC/DC converters and chargers, while lowering the costs. Effective thermal management is important as the efficiency, reliability, and life spans of all electronic devices drop with rising temperature. In present xEV applications, inverters are usually cooled by a liquid that is pumped through a dedicated portion of the vehicle's radiator, releasing its heat to the surrounding air. The insulated-gate bipolar transistors (IGBTs), used in inverters are fast-switching solid-state devices that must stay below 175°C to function properly.

TABLE 5.11: US DoE TARGET FOR 2022

	UNIT	CURRENT STATUS*	PHEV 40**	AEV 100**	AEV 300+
System cost	$/kW	20 ($1100)	5($600)	14($1680)	4 ($600)
Motor Specific Power	kW/kg	1.3	1.9	1.5	2
PE Specific Power	kW/kg	10.5	16	12	16.7
System Peak Efficiency	%	90	97	91	98

TABLE 5.12: ARPA-E TARGETS

Motor active materials (Stator and rotor cores, winding, magnets)	kg/kW	0.36 (20 kg)
Active materials cost	$/kW	3.2 ($175)
Input Voltage	V	200-400
Maximum Motor Phase Current	A	400
Efficiency	%	>93*

The basis for targets under the Advanced Power Electronics and Electric Machine (APEEM) R&D of the US DoE is the requirement of 55 kW peak power for 18s, 30 kW continuous powers, and a life of 15 years. The power electronics roadmap of the Automotive Council, UK, targets to achieve €10-16/kW for the traction system by 2020; whereas this value is 1.5 kW/kg for specific power and 3.5 kW/l in terms of power density. For 2025, these values are €8-15/kW, 1.6 kW/kg and 5 kW/l respectively.

Preliminary set of targets under the NMEM are given in Table 5.13 and 5.14. These will be further modified suitably based on studies led by the respective CoEs and stakeholder consultations.

TABLE 5.13 : MOTOR COST TARGETS

SIZE (KW)	MOTOR/ CONTROLLER	COST TARGET (RS.)
Two Wheelers (BLDC)		
0.5	Motor	4000
	Controller	1500
2	Motor	8000
	Controller	4000
FOUR WHEELERS		
5	Motor	12000
	Controller	15000

TABLE 5.14 : NMEM REQUIREMENT OF MOTORS FOR 2-WHEELERS

VEHICLE KERB WEIGHT (kg)	100-120	100-120	100-120	120-140
MOTOR RATING (Watt)	500	1000	1500	3000
CONT/ PEAK VOLTAGE (Volt dc)	48 - 72			
MOUNTING	WHEEL HUB/ FRAME			
MAX RPM	555	750	750	8000
CONT TORQUE (Nm)	13	18	21	5
REGENERATIVE BRAKING	YES			
AMBIENT TEMPERATURE (°C)	-10°C to 60°C			

09 TPEM ELECTRIC MOTOR AND POWER ELECTRONICS

9.1 R&D ECOSYSTEM

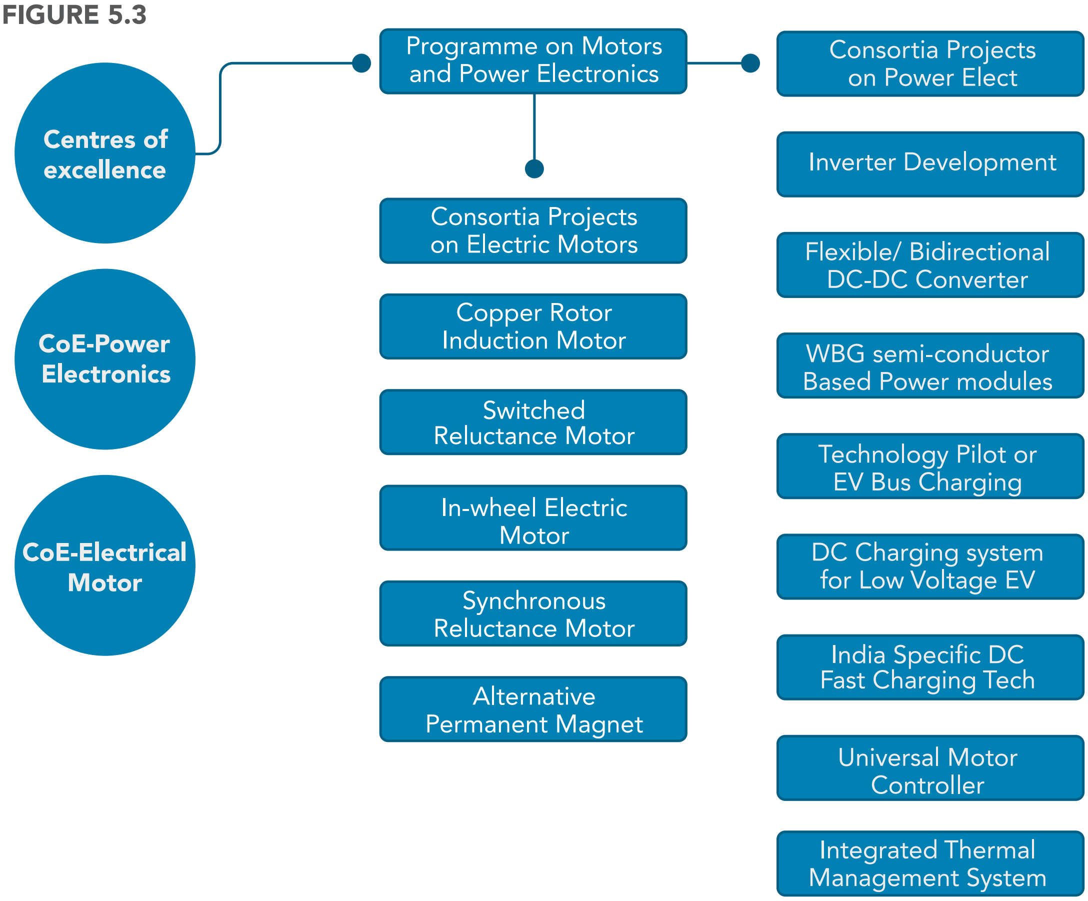
Immediate focus will be on achieving manufacturing capabilities for traction motors, while R&D efforts to develop supply side technologies are taken up as long term priorities. Industrial motors are manufactured in India, but traction motors for xEV is challenging. The equipment/ machinery is mostly imported, and a variety of advancements are required in casting, machining, welding, soldering, stamping etc.

The permanent magnet used in xEV motors need large quantities of Rare Earth Elements (REE), ~1kg high grade magnet for an HEV car to 400 g lower grade magnet for bicycles. Currently only Nd_2FeB magnets are used. It requires both "light REE" Nd as the mainstay and "heavy REE" Dyprosium as addition for the required temperature tolerance. While both are in limited supply, Dysprosium is expensive. India currently mines 2,500 tons of REE (mostly light REE), but there is a lack of technology and supply chain to convert them into magnets. Globally leading research programmers are attempting to either reduce dysprosium usage, or to develop anisotropic nano-composite permanent magnets with low rare earth content and to discover new permanent magnets.

For power electronics, efficiency improvement, packaging, thermal management are the major priorities. Development of lighter, smaller, more efficient and rugged components are desirable. Indigenous development of common drive power electronics platform suitable for all kinds of motors is also important. It is necessary to consider newer semiconductor switches, capacitors, magnetics, packaging, and new topologies.

Similarly, the power electronics industry also has grown primarily based on the power processing need in the electric power sector. Today more than 80% of all power generated is processed through some form of Power Electronics equipment for increased efficiency. Another important market for the PE manufacturers in India is the inverter/UPS segment. Regulatory standards that promote energy efficient devices have further encouraged the proliferation of products embedded with intelligent power electronics. At present semiconductor devices are imported but setting up of wafer fab units has been proposed under NPE.

FIGURE 5.3



The R&D Ecosystem on Electric Motor and Power Electronics will comprise of

1. Consortia Projects on Electric Motors
2. Consortia Projects on Power Electronics
3. Centre of Excellence on Electrical Motor
4. Centre of Excellence on Power Electronics

9.2 CONSORTIA PROJECTS ON ELECTRICAL MOTORS

9.2.1 Copper rotor induction motor

Copper Die-Cast Rotor Motor can be 20% lighter & 30% smaller than aluminum rotor machine. Rapid, cost effective die casting of Copper is required. Challenge is to reduce the cost and to control the melting process of copper. Since copper is a denser material, rotor mass would increase.

The project may focus on:

- Copper die cast simulation model; Optimize process to minimize porosity
- Prolonging the die life – study high temperature die materials; Mould construction and optimization
- Copper rotor manufacturing, prototype development and test on dynamometer

9.2.2 PMBLDC/ PMSM development

Focus will be low cost, high efficiency, high power/weight ratio and reliability from low rotor speed to high rotor speed.

The consortium will target development of

- PMBLDC hub motor for two and three wheelers
- Interior magnet PMSM for HEV application
- Surface mounted PMSM for EV applications

The project activities may include

- Study of the motor design parameters with respect to Indian conditions and determination of the optimal torque speed profile to meet the operational constraints with minimum power requirement.
- Modeling of electromagnetic, mechanical, vibro-acoustic and thermal parameters of the motor. Development of algorithm for design optimization for xEV applications both for surface mounted and interior permanent magnet motors. Verification of the optimum geometric parameters through Finite Element Analysis. Component level design and simulation.
- Analysis of the thermal issues will be an important criterion for the design of the motor and choosing the adequate cooling system. Thermal management system.
- Design of the control topology; Sensorless operation of PMSM (sinusoidal wave form). Design of power electronics and control board and software including the vector control algorithm, CAN input/output and user interface for calibration. In the Phase I trapezoidal wave permanent magnet motor with hall sensors based control; Sinusoidal wave permanent magnet motor development. In Phase II design of motor with sensorless control; Use of indigenously developed permanent magnet (based on samarium cobalt); Use of alternative magnets.
- Detailed component design
- Fabrication of prototypes and test/ trials.

Expanding the constant power range and field weakening capability should be a major focus in the design of the PMSM for electric vehicles.

9.2.3 Switched Reluctance Motor

Objective is the development of Switched Reluctance Motor with similar power density, efficiency and NVH of a comparable permanent magnet synchronous motor. The targeted cost should be lower as compared to similar PMSM.

Certain challenges related to SRM need to be addressed, which include high torque demand at the wheel, adverse effects derived from the increase of the unsprung mass, and wheel operating with high vibration levels.

Project activities could include:

- Target specification of the motor
- Use of design tools and simulators to evaluate the electromagnetic, thermal, vibro-acoustic and system level behaviours
- Evaluation of the options for control techniques and power electronics architectures
- Selection of appropriate mechanical, electrical and thermal design suitable for production of the motor, and definition of the dismantling process
- Integration of the motor and power electronics
- Determination of efficiency at different driving cycles

9.2.4 In-wheel Electric Motor

High torque, low speed motors are required for wheel hub applications. Reducing the motor weight is desirable to reduce the unsprung mass. Since the motor weight needs to be reduced, the motor should have large starting torque, overload capability, wide speed range and high power density. Hence high efficiency to wight ratio is required. Permanent Magnet Brushless motor is the most likely choice.

The project objectives would be

- Demonstration of in-wheel motor in electric three wheeler and passenger car applications.
- Development of a fully functional and integrated module into an existing car. Using air cooling.

Issues: High torque demand at the wheel, adverse effects derived from the increase of the unsprung mass, and wheel operating with high vibration levels. Vehicle dynamics, module management in in-wheel condition are the challenges that need to be addressed.

Project could include:

- Deriving the requirements of the in-wheel system based on the target reference vehicle specification. Both geared and direct drive configurations may be considered.
- Wheel motors design and fabrication - geared and direct drive
- Design and development of functional components for suspension, electric motor, power electronics, gear boxes, bespoke wheels
- Dynamometer testing & vehicle integration. It is expected that participating OEMs will provide vehicles which which integration of the motor can be done.

9.2.5 Synchronous Reluctance (SynChrel) Motor for EV

Synchronous reluctance motors are one of the potential options for high performing, compact, lightweight and rare earth free motors for electric drive vehicles. Use of low loss material and low cost manufacturing process will be targeted.

Project activities

- Define the required specifications
- Development of software design tools.
- Electromagnetic design and optimization of motor configuration & Manufactuirng process optimization
- Electrical model of the motor
- Fabrication of short stack prototypes
- Evaluation of performance efficiency against test and realistic drive cycles

9.2.6 Permanent magnets with no or low rare earth magnets

Development of alternatives for rare earth magnets, or at least reducing rare earth contents is important due to its high cost and limited or uncertain supply.

Project scope:

- Development of technology to reduce dysprosium used in rare earth magnets
- Development of high performance anisotropic nano-composite permanent magnets with low rare-earth content

- Review and benchmarking of technologies for non-rare earth magnets; identification of candidate materials
- Development of suitable technologies for processing, chemical manipulations, thermal treatment etc
- Techno-economic feasibility analysis of motors with magnets from the selected materials

9.3 CONSORTIA PROJECTS ON POWER ELECTRONICS

9.3.1 DC charging system for low voltage electric vehicles

Projects may be taken up for development of systems for home-charging as well as fast public charging.

These will include

- Development of charging plugs and sockets as per agreed specifications
- Charging control circuit and communication system
- Converter design
- Balance of system

9.3.2 Technology pilot for EV bus charging stations

One promising short term application of electric vehicles is the city buses. The project will include development of electric bus charging system, instillation of a few demonstration units and trial runs with a pilot fleet of electric buses.

Two categories of charging systems are to be developed:

- Opportunity charging at route terminals: Charge the battery at the terminals so that the buses have enough energy to travel to the next charging station.
- Flash charging system in which the electric bus can be charged within 15 s. The bus can be charged at every bus stop. Power transfer in the range of 400 kW. A longer a full recharge at the bus terminus.

The trial runs will be aimed at getting an insight into the optimum charging infrastructure for electric buses with either of these two types of charging stations, or a suitable combination of them. It is expected that relevant Indian standards will be developed in near future, and the development under this project will follow such standards.

The desirable features of the charging systems are:

- Automatic charging system, wireless communication, accuracy of parking, laser guidance system to align with the overhead receptacles.
- Low cost and lightweight system
- One option is overhead pantograph. Inverted pantograph is another option, in which the pantograph is mounted on the existing infrastructure
- Current collector design
- Communication between the charging station and the bus
- Provision for utilization of solar power

To determine whether such electric bus fleet can meet the service requirements, and to establish the feasibility of such systems.

Comprehensive unbiased evaluation of the in-service performance of electric buses as compared to that of similar conventional buses. On board logging devices will be used to collect data on relevant parameters.

9.3.3 India specific dc fast charging technology

For wide penetration of electric vehicles, availability of DC fast chargers is essential. DC fast chargers are directly connected to the battery, bypassing the on-board charger. The objective of this project would be to develop and demonstrate conductive type DC fast chargers suitable for Indian conditions. It is expected that Indian standard for DC fast chargers would be defined in near future and the development under this project will follow such standards.

Some of the essential features of the charger are

- Communication with the BMS
- Combination of controlled voltage charging and controlled current charging
- Isolation and other required safety features; Safety: Over-voltage protection, under-voltage protection, over-current protection, short-circuit protection, earth-fault protection
- User interface and display
- Billing and payment systems

Project activities are expected to include

- Development of dc-dc converter, transformers and other components
- Design of communication interface
- Design optimization for higher efficiency, low harmonics distortion

9.3.4 Universal motor controller

Due to similarities between PMBLDC/ PMSM and SRM, it is possible to develop controllers that can drive both machines. Objectives will be indigenous development of common drive power electronics platform suitable for all kinds of motors.

Project activities may include

- Simulations and experimental correlations between drives for different types of machines
- Controller algorithm development
- Development of the ECU
- SIL/HIL simulations
- Testing of the controller

9.3.5 Integrated thermal management system for power electronics

Objective is to reduce cost and size, and increase reliability. Integration of component thermal management technologies may be effective towards achieving these goals. Thermal management systems are required for the energy storage, power electronics and electric machines.

The project activities may include:

- Development of the thermal models for the motor and power electronics, energy storage system etc.
- Study and benchmarking the performance of commercially available, state-of-the-art power

electronics and electric motor thermal management systems; identification of the opportunities for integrating individual systems
- Integration of the electric drive thermal management systems with other vehicle thermal management systems.
- New technologies, cooling systems and materials for vehicle thermal management.

9.3.6 Wide band-gap semiconductors based integrated system design process with (SiC/ GaN based semiconductors)

Project objectives are development of packaging techniques and circuit designs needed for optimum properties of wide bandgap semiconductor devices to minimize the size and cost of cooling. New materials and packaging methods that can withstand the higher temperature operation are required to benefit from the use of wide band gap semiconductors.

The project activities may include:
- Integration of the WBG semiconductor devices into high order components.
- Demonstration of a GaN or SiC based device
- Packaging and system level integration, reliability testing
- Optimization of device operating models and packaging

Development of WBG materials based semiconductor devices is another important area, although that will not be a part of this project. It is expected that such important initiatives will be taken up separately. Apart from electric mobility WBG semiconductor devices will have applications in many other sectors, such as renewable energy, electric power etc.

9.3.7 Flexible, bidirectional DC-DC converter

The objective of this project will be to develop flexible DC-DC converters with reduced cost, weight and package space. Flexibility will be in input and output levels. In future there will be further voltage steps for supercapacitors and fuel cells, and it will not be viable to add extra converters for every additional voltage.

Some other targeted features are:
- Ability to operate at high inlet and outlet temperature
- Ability to handle multiple voltages simultaneously both at the input and output sides. Flexible conversion ratio leads to establishment of bidirectional power management for automotive applications
- Digital control
- Reduced volume and weight of the passive components

The project activities may include:
- System level modeling to determine the optimum operating voltages
- Defining system dynamics requirements for bi-directional dc-dc converter
- Define the architecture
- Design of the power module
- Construction of the module
- Design of a proof of concept unit
- Demonstration of the DC-DC converter

Under phase 1 silicon based semiconductors may be used, whereas WBG semiconductors should be used in phase 2.

9.3.8 Inverter development: Higher efficiency Inverter topologies for various power brackets

The project will aim at development of higher efficiency Inverter topologies for various power brackets (<2kW for 2W, 5-15 kW for 3W and smaller EVs, 20-50 kW for A-category EV, 60-100 kW for higher power EV).

Development of a scalable solution and reduction in power module losses, weight and size are the major objectives.

Phase I: Capacitor development and testing. DC link capacitor development to enhance the inverter's high temperature capability; Power devices packaging; System modeling; Thermal management; Control system for controlling the switching frequency so as to minimize heat generation; Interface characterization; Inverter system testing

Phase II: Use of WBG semiconductor devices; Improve power density

9.4 CoE ELECTRIC MOTORS

9.4.1 Objectives

The Centre of Excellence on Electric Machines will have facilities for simulation, design, high precision manufacturing methods and testing for electric motors. The technology issues to be addressed include

Development of efficient, compact and lightweight motors

Specific quantitative targets for motor power density, torque density and efficiency will be set. Activities to achieve this would involve simulation and design of motors of identified topologies; Improved thermal management; packaging; advanced materials and fabrication techniques that allow multi-material designs; joining methods like Friction Stir Welding; Solid state joining of Copper in rotor; Dissimilar material joining of copper to aluminum;; Laboratory testing of electric motors/ machines.

Design Optimization for Traction Motors

The design optimization of electrical machine is a non-linear multi-objective problem. Typical objectives include highest efficiency, lowest cost and minimum weight of active materials. Mechanical, thermal and materials aspects need to be considered during the optimization process. Traditional electric machine design methods mainly focus on single point performance optimization, and are based on empirical design formulations and rules gathered from standard designs.

- Understanding machine parameter for various topologies; & Models to capture the relationship with design objectives and inputs
- Modeling and simulation to understand all aspects of dynamics; & Optimization with respect to actual Indian driving conditions
- Precise model of the magnetic field to enable accurate prediction of electromagnetic

performance, such as torque capability and back-efm. Development of magnetic equivalent circuit based models.

Low or Non-rare earth magnet motors
Reduce or eliminate the use of rare earth matetrials while maintaining high power density, specific power and efficiency. Induction Motor, Switched Reluctance Motor & Synchronous Reluctance Motors do not require rare earth magnets. Another pathway for avoiding dependence on rare earth materials is development and manufacture alternative magnetic materials.

Permanent magnets from Indian Rare Earth Elements
Use of Indian Rare Earth Element (REE) sources for permanent magnet motors need to be a critical component in the R&D activities. xEV motors need large quantities of REE, ~1kg high grade magnet for an HEV car to 400 g lower grade magnet for bicycles.

Motor Thermal Management
Effective Thermal Management is essential to achieve high torque and power density of traction motors. Overheating will degrade insulation materials, demagnetization, and decrease motor life.

- Study of thermally conductive electrically insulating materials, heat transfer techniques, enhancement of heat transfer area, and alternative coolants
- Thermal analysis of the machine using FEA (Finite Element Analysis) and CFD (computational fluid dynamics) modeling – for simulation view of temperature distribution, and effectiveness of cooling system.
- Improve electromagnetic design to reduce the losses in the machine; & develop Integrated cooling systems.
- Designs to improve efficiency in thermal management

Manufacturing process and equipment
Notching equipment. High precision high press models on which round blanks and/ or segments can be produced. Fabrication techniques that allow multi-material designs; Joining methods like Friction Stir Welding; Solid state joining of copper in rotor; Dissimilar material joining of copper to aluminum

Integrated Traction Drive Systems
Develop integrated subsystems, including power electronics, motor and cooling. The motor, single stage gear, differential and inverter can be integrated in many ways to reduce weight, complexity and save space. Design of common cooling system can be attempted. The facilities will include equipment for power module, circuit board and mechanical part prototyping and testing by HIL/SIL.

Material for higher efficiency
Development of advanced low loss core materials and their processing. Improved thermal materials. Develop & manufacture soft magnetic materials to improve the efficiency/ reduce cost of stack laminates in the rotor/stator assembly.

Magnetic geared in-wheel drive system: high torque density and less cogging torque

9.4.2 Potential Partners for CoE Electric Motors

The CoE Electric Motor will be a virtual centre with a hub-and spoke model. An R&D Centre on Traction Motors has been established at Non-Ferrous Technology Development Centre (NFTDC), Hyderabad. Major activities of NFTDC in the field of electric motors include design and development of traction motors as per the target specifications; develop high precision manufacturing methods for electric motors; and laboratory testing of electric motors/ machines.

Bharat Heavy Electricals Limited (BHEL) had introduced electric minibuses several decades back. EML, BHEL has revived its electric vehicles activities. Manufacturing of large motors for heavy vehicles is one of the major focus of BHEL/EML.

Bhabha Atomic Research Centre (BARC) has developed PMBLDC motors for solar pump applications.

The CoE on Electric Motors will leverage the expertise available in the academic institutions like IITs, IISc and IIEST etc. IIEST and IIT Bombay have been involved with development of Switched Reluctance Motor. Under the NAMPET project, IIT Patna has developed 3 squirrel cage induction motor for propulsion applications, with design optimization based on genetic algorithm. Significant activities on design and development of electric motors exist in IIT Delhi. IIT Gandhinagar is working on design of Induction motors that can substitute PM-BLDC motors for similar power rating requirements.

TVS, Aditay Auto, Kirloskar are some of the private sector companies who can contribute to the activities of the CoE Electric Motors.

9.5 CoE POWER ELECTRONICS SYSTEMS

9.5.1 Overview

The objective of the Centre for Excellence on Drives, Power Electronics and Charging Systems would be to improve and support the technology for chargers, motor controllers, inverters, DC-DC converters, user interface control, etc. The CoE will also have testing centre for enabling investigation of the interaction of electric vehicles with assets in the distribution grid. This will make it possible to carry out a realistic assessment of the grid impact of the new technologies and components.

The basic objective is reduction of cost, volume and weight while improving efficiency of power electronics for xEVs including inverter, DC-DC converter etc. Among its participating organizations the CoE will have facilities for analysis, modeling and simulation of power electronics systems, test and benchmarking, as well as pilot manufacturing/assembly.

Apart from design of the module, focus will also be on improvements in processes like soldering, joining, cooling, EMI shielding etc, to enhance efficiency, thermal performance as well as reduction of cost. Control electronics will be developed.

The program will also take up development of power electronics based on wide band-gap semiconductors so as to reduce the size, cost and improve thermal tolerance of power electronics circuits for electric vehicles.

Based on common specifications for xEVs in Indian conditions, common range of key parameters like voltage, power etc will be worked out. Development of modules/ devices will be taken up as per the set targets.

Research Directions

- Improved switches - higher blocking voltage, higher on-state current density, higher switching frequency, easy to drive
- Power integration - integration of logic and power circuits in a single chip with increasing applications in the area of power management, automotive, telecommunication, power supply, etc.
- Improvements in reliability – solutions in device construction and technology, thermal management and packaging, better knowledge of how to use power semiconductors safely.
- Reducing cost and size.

As tangible deliverable, the CoE should target demonstration of a few power electronics components with improvements in terms of cost, efficiency. reliability, size and weight. Several technological issues will be addressed, such as the ones described in the following section, to achieve this.

9.5.2 Technology issues to be addressed

Power electronics systems manufacturers are, in general, not vertically integrated. With a core competence in systems design, they buy components & technologies from a critical group of suppliers. This is because some basic parts- standard power semiconductor devices – are supplied to everyone by a few multinational companies or by technology intensive small companies that offer custom solutions, with proprietary technology. Power Electronic Packaging that involves electrical interconnections, thermal management and mechanical support, is the area in which improvement in efficiency & reliability and reduction in cost can be achieved.

Drives Control: Software for special motors (SRM etc)

Design Issues:

Electrical design including main switching circuit design; controller circuitry design, switching frequency; Control Algorithm: Desired voltage, current and frequency at the output, and to realize bidirectional power flow as needed. Magnetics: Inductors, transformers, and capacitors, needed for filtering, switching, and gate driver units.

Power Electronics Components
These include chargers for electric vehicles, Inverters, DC-DC converters, on-board chargers etc. Focus will be to make them lightweight and compact, and increase their efficiency and ruggedness. Reduction of cost of these components is also another major target.

Additive Manufacturing of Power Electronics
Use of 3-D printing technology to explore complex geometries, increase power density and reduce weight and waste. This can be useful in optimizing the heat sinks, allowing for better heat transfer throughout the unit.

Thermal Management
Modeling of the loss in power devices and magnetic components; cooling system, heat sink, enclosure design; and integration.

Application of Wide Band Gap Semiconductor Devices
Benchmarking, evaluation and characterization of wide bandgap semiconductor devices. Innovative thermal management and packaging technologies to maximize the benefits of wide band gap semiconductor devices.

DC-link capacitors
DC-link capacitors are bulky, heavy, expensive and susceptible to degradation from self-heating, as the polypropylene capacitors are limited to 125°C temperature operation. Focus should be on development of DC-link capacitors with long lifetime, high reliability, low cost, high power density, and ability to handle the ripple current under all operating conditions for EV applications.

- Alternative Materials: metalized film capacitors, polyetherimide (PEI) film as the dielectric, Lead Lanthanum Zirconium Titanate (PLZT) ceramic capacitor, and glass materials
- Analytical tools and computer simulations to discover the minimum boundary of the DC link capacitor size for xEV reaction inverters.
- Fabrication of the capacitors; Testing under high frequency and high temperature

Packaging and Functional Integration
Development of a scalable solution and reduction in power module losses, weight and size are the major objectives. Inverters with 3-D printed parts, higher level of integration and use of Wide Band Gap semiconductors and innovative cooling concepts (e.g., double sided cooling) are expected to achieve higher power density and efficiency. Consolidated design and vertically integrated manufacturing process.

Develop integrated subsystems, including power electronics, motor and cooling.

For the power electronics, it is necessary to consider newer semiconductor switches, capacitors, magnetics, new topologies.

Wireless Charging for Electric Vehicles
To achieve the speed and efficiency as standard conductive charging systems.

9.5.3 Potential Partners of CoE Power Electronics

The CoE on Power Electronics will be a virtual centre with a hub and spoke structure. The hub could be one of the organization having extensive experience of dealing with power electronics for xEVs.

The Centre for Development of Advanced Telematics (CDAC), Thiruvananthapuram has been involved with development of xEVs, and also coordinates the National Mission of Power Electronics Technologies (NaMPET). C- DAC(T) has developed a 15 T series hybrid bus in association with Ashok Leyland Ltd and an EV three wheeler with Kerala Automobiles Ltd. CDAC is contributing in the development of power electronics technology in various applications including transportation. The institute has developed strength in liquid cooled power electronics converters, CAN networks, regenerative braking. Apart from this, CDAC Thiruvananthapuram has worked on power electronics for fuel cells and ultra-capacitor also. The expertise includes bidirectional converters (buck/boost) and boost converter for HV battery charging, bidirectional converters for ultra-capacitor and, poly phase boost converters for fuel cells. Available facilities include low power control electronics lab, high power prototype test lab.

The National Mission for Power Electronics Technologies (NaMPET) under the aegis of Ministry of Electronics and Information Technology (MeITy) and coordinated by CDAC Thiruvananthapuram is an important programme. NaMPET network involves many institutions of the country. The second phase of NaMPET has identified power electronics for electric and hybrid electric vehicles as one of the thrust areas. NaMPET phase-II started in 2012 and has taken up a number of projects in development and deployment in the area of Power Electronics system simulation, Renewable energy integration, High voltage Power Electronics, Devices for Smart grid. New technology area using Wide Band Gap (WBG) devices (SiC, GaN) are also taken up. In order to proliferate NaMPET activities a Simulation Centre for power electronics is setup at IITB and a number of short term courses and work-shops in specialized area in power electronics are periodically organized at academic institutes across the country.

Along with fabrication of motors, the Non-Ferrous Technology Develoment Centre (NFTDC) also pursues developments of motor controllers.

The Drives & Control Systems Technology Group of CSIR-CMERI, Durgapur has as its mandate the design and development of electrical drive and control systems, electrical machines and power electronic products for different R&D and industrial requirements and is currently concentrating on such issues as the application of Non-linear Sliding mode control for the speed control of BLDC motor, development of intelligent power electronics interface for energy sharing between battery and ultracapacitor for electric drives, development of zero-voltage switching-based phase-modulated converter for optimal extraction of energy from the PV panels in microinverter applications, etc. CSIR-CMERI has participated in several projects such as Smart Power Electronics for Solar Photovoltaics (CSIR TAPSUN); Study on and development of advanced converters for next generation electric cars (CSIR NMITLI); Selection of appropriate propulsion motor and development of dedicated controller for Soleckshaw Lite (CSIR NMITLI).

At C-MET Hyderabad, 4H and 6H SiC single crystals (diameter ~ 50 mm; thickness ~ 18 mm) have been successfully grown by Physical Vapor Transport (PVT) /sublimation technique in collaboration with DMRL and SSPL. These grown SiC (4H/6H) single crystal can be used further for high power device fabrication, characterization and packaging.

Electrical Research and Development Association (ERDA) specializes in providing solutions to industry in the field of electric power based on its R&D activities. ERDA is also a major test and certification authority in the electric power sector. ERDA can contribute in the NMEM R&D in the battery management system, electric vehicle charging interface/infrastructure etc.

Central Power Research Institute and Central Electrical Engineering Research Institute are also potential partners in the CoE Power Electronics.

IIT Bombay has carried out study and analysis and development of technologies for high speed low power synchronous motors and their sensorless controllers; Development of SEQUEL for real-time and off-line simulation of power systems and power electronic system. Other activities include: Remote-triggered Virtual Laboratory on Electronic Devices and Circuits; Off-line and real-time simulator for electric vehi-cle/hybrid electric vehicle systems; Simulation Centre for Power Electronics and Power Systems; Development of an Ultracapacitor based Bi-Directional Power Electronic System; High speed DSP-FPGA based Hardware and Software for closed loop digital control systems for power Electronic Converters; and Modular Power Electronic Converters for High Power Applications.

R&D activities at the Advanced Power Electronics and Motor Research Laboratory of the IIEST include design and fabrication of permanent magnet synchronous machine, PWM converter, surface mounted PM BLDC, PMSM as well as double sided axial flux SRM and its application in direct wheel drive.

The Centre for Nano Science and Engineering (CeNSE) at IISc Bangalore has relevant expertise to carry out works related to power electronics packaging. CMERI Durgapur also has a group of researchers who are interested to contribute to such efforts.

APPENDX: PROPOSED R&D INVESTMENTS

1 SUMMARY OF OVERALL BUDGET ESTIMATES

R&D Thrust Area	Programs	CoEs (Rs.Cr)	Consortia Projects (Rs.Cr)	Total (Rs.Cr)
Systems Integration and Lightweighting	2 Centres of Excellence, 6 consortia projects	150	420	570
Drives, Power Electronics, and Charging Systems	2 Centres of Excellence , 15 consortia projects	150	290	440
Rechargeable Energy Storage Systems	1 Centres of Excellence, 4 consortia projects	200	180	380
	TOTAL	500	870	1390
	INDUSTRY CO-FUNDING		900	900

2 VEHICLE SYSTEMS INTEGRATION AND LIGHTWEIGHTING

Centre of Excellence

Centre Name	Estimated Budget (Rs. Crore)
Open Engineered Controls, Electronics and Software (CES) for xEVs	75
Centre for Lightweight Electric Vehicle Research	75
TOTAL	150

Consortia projects

Project	Estimated budget (Rs. Crore)	Industry (Rs. Crore)
Study on xEV Usage Patterns	10	10
Electric City Car/ LCV	100	100
Electric Three Wheeler	10	10
Hybrid Electric Car	100	100
Lightweight Electric City Bus	100	100
Hybrid Electric Truck	100	100
Total for consortia projects on Systems Integration	420	420

3 DRIVES, POWER-ELECTRONICS AND CHARGING SYSTEMS

Centre of Excellence

Centre Name	Estimate (Rs. Crores)
Centre of Excellence on Electric Machines	75
Centre of Excellence on Power Electronics	75
Total for CoEs on Drives, Power-Electronics and Charging Systems	150

Consortia projects on electric motors

Project	Estimated budget (Rs.Crore)	Industry
Copper rotor induction motor	20	20
PMBLDC/ PMSM development	20	20
Switched Reluctance Motor	20	20
Synchronous Reluctance Motor	20	20
Permanent magnets with no or low rare earth magnets	20	20
In-wheel Electric Motor	20	20
Total for consortia projects on electric motors	120	120

Consortia projects in Power Electronics and Charging Infrastructure

Project	Estimated Budget (Rs. Crore)
DC charging system for low voltage electric vehicles	20
Technology pilot for EV bus charging stations	20
India specific dc fast charging technology	20
Universal motor controller	20
Integrated thermal management system for power electronics	20
Wide band-gap electronics based : integrated system design process with SiC/ GaN based semiconductors	20
Flexible DC-DC converter for electric vehicles; Bidirectional dc-dc converters	20
Inverter development: Higher efficiency Inverter topologies for various power brackets .	20
AC charging with net metering facilities	10
Total for consortia projects on Drives, Power Electronics and Charging Systems	170

4 RECHARGEABLE ENERGY STORAGE SYSTEMS

Centre of Excellence

CoE Name	Estimated Budget (Rs. Crore)
Centre of Excellence in Energy Storage (Materials Synthesis, Cell Fabrication, Module/Pack Assembly, Simulation)	200

Consortia projects

Project	Estimated Budget (Rs.Crore)
Design and development of lithium-ion modules	50
Lithium ion and other battery cells development	50
Ultracapacitor	40
Emerging chemistry battery development	40
Total for consortia projects on Rechargeable Energy Storage	180

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