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Analysis and Evaluation of Vehicle Battery Cells and Systems

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Abstract

The rapid rise of electric vehicles has pushed battery technology to the frontier of automotive innovation, necessitating the focus of this research article analyzing vehicle battery cells and systems in all aspects of design, function, and integration of energy storage into electric powertrains. Newer advancements in lithium-ion and other battery chemistries have been surveyed, focusing on energy density, thermal stability, safety, and cost issues. There is also a detailed assessment of the suitability of the various cell structures: cylindrical, prismatic, and pouch for different vehicle platforms. In addition, consider investigating thermal management and battery management systems (BMS) performance optimization, operational safety, and extending the useful life of battery pack systems under different driving scenarios and environmental conditions.

At the system level, it looks into modular and scalable battery pack architecture and their effect on vehicle range, power delivery, and design flexibility. In these contexts, real-time monitoring, smart diagnostics, and predictive maintenance strategies are viewed as means to improve reliability and lower total cost of ownership. In the same breath, environmental sustainability revolves around lifecycle analysis and end-of-life management strategies, covering second-life applications and recycling. Marrying theoretical viewpoints with industry case studies and experimental data presents a strategic insight on the ways by which next-generation battery systems might accelerate high-performance electric mobility toward greater sustainability. Insights will be helpful for all those stakeholders involved in energy-efficient transportation, chiefly; researchers, manufacturers, and policymakers.

Keywords

Electric Vehicles (EVs), Battery Cells, Battery Management Systems (BMS), Thermal Management, Battery Pack Architecture, Battery Safety, Sustainable Transportation, Battery Life Cycle, Modular Battery Systems.

Introduction

However, new electric mobility has brought out high-performance and cost-effective battery systems in large volumes. Therefore, a battery electrode system for vehicles has been developed in this project that meets the performance metrics set forth for the Freedom CAR goals by the U.S. Department of Energy (DOE). Energy density, power density, life in cycles, and safety are some core targets defined for the Freedom CAR program which underpins the next-generation battery technology. It is on these bases that most key parameters in the positive electrode are optimized

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here such that the final design would satisfy these federally recommended standards.

This project is directed toward studying and optimizing the following design-critical parameters: pore fraction of positive electrode, inert material fraction, area of separator, electrode thickness, and electrochemical voltage limits like maximum and minimum voltage values. The parameters determine both charge transport and thermal behavior of the battery system while keeping an eye on structural stability. The technological choice of porous structure has also a solid impact on the ionic conduction and mechanical coherence. Balancing so, we could bet on energy efficiency improvement, thermal management, and long-term reliability of the battery system, all important for wide-end applications on electric vehicles.

This report also elaborates on a wide range of computational plots and comparisons to permit informed design decisions and performance evaluations. The visualizations illustrate how different parameter values influenced various developments in the battery's achievements regarding Freedom CAR requirements. A summary table chronicling specific DOE targets is also included to provide a reference against which the positive electrode design is evaluated. In this wide-scale scope, not only do optimizations gain direction but they also enhance the knowledge base on electrode engineering so that such advancement progresses in stronger, more scalable battery designs for automotive applications.

Design Parameters and Characteristics

To optimally organize a battery system compatible with Freedom CAR, the following characteristics shall be achieved: performance, durability, and volumetric constraints, which govern the development of a battery system that is going to prove significantly effective for real-life applications. Each of the parameters has been derived through standardization and validating methodologies from the industry, and these will be a few of the most important considerations during the process of developing the operational capacity and effectiveness of the battery pack. The Power-Assist battery requirements have been summarized in the table below, forming the basis for positive electrode and component design.

Number	Characteristics	Power-Assist (Minimum)
1	Pulse Discharge Power	25 kW
2	Peak Regenerative Pulse Power	20 kW
3	Total Available Energy over Depth of Discharge (DOD) range	0.5 kWh at C1 rate
4	Cold Cranking Power at -30°C	8 kW
5	Cycle Life for specified State of Charge (SOC) increments	3500 cycles
6	Maximum Volume	32 liters
7	Operating Voltage of Battery	Max ≤ 400 V, Min ≥ (0.55 × Max) V

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The key parameters in this table deal with pulse discharge power and regenerative pulse power, both vital for the battery to respond to the high energy demand from driving conditions with immediate supply and recovery. Available energy through the whole depth of discharge (DOD) range is critical in defining usable energy capacity and performance throughout normal vehicle operation. The energy must be supplied at a higher efficiency over the diverse driving cycles without compromising the transient power-absorbing capability of the system. The cold crank power at low temperatures also reflects the battery's performance under extreme conditions, which is a vital requirement for the electric vehicle's reliability in areas with extreme weather conditions.

Some additional considerations central to the cycle life, volume constraints, and operating voltage limitations form the tenets of battery system life span, compactness, and electrical safety. A cycle life of 3500 cycles, for instance, represents a high durability target that ensures the battery has a certain capacity to withstand an extensive charge and discharge cycle over its lifetime without substantial degradation. Finally, the maximum volume requirement of 32 liters restricts the overall size and configuration of the battery pack to allow it to fit within the available space in the vehicle while providing optimal performance.

• Assumptions

The main assumptions of the design and simulation will be discussed here for the battery element considered for power-assist applications. These assumptions generalize the battery's complex electrochemical interactions to a level appropriate for accurate yet manageable modeling.

Modeling of Electrodes:

- In the design, the positive electrode alone (cathode) will be considered and will be taken to signify the performance-limiting material in capacity and internal resistance.
- Resistance in the negative electrode (anode) will be considered negligible, and the electrochemical reaction will satisfactorily supply capacity throughout the defined State of Charge (SOC) range.

Electrochemical Simplification:

- The relationship between voltage and SOC is considered a static nonlinear function for the purpose of modeling the variation of the voltage of the battery with respect to its SOC.
- Dynamic changes in OCV occurring due to aging or temperature are not being modeled at this stage.

Voltage Limits:

- The maximum charge voltage during charging and/or pulse assist is considered to be 3.7 volts.
- The minimum voltage during fully discharged or regenerative braking is considered to be 3.1 volts.
- These limits define the safe window of operation of the battery cell pertaining to thermal and chemical stability of $LiCoO_2$-based cells.

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Thevenin Equivalent Circuit:

The electrical representation of the battery is based on a simple Thevenin equivalent circuit consisting of:

An ideal voltage source (OCV) that is dependent on SOC.

A series internal resistance accounting for ohmic losses.

A RC parallel branch to simulate transient response and polarization effects.

The resulting battery terminal voltage is given by:

Where:

$$v\_batt = OCV - 1. R\_internal$$

Where

- v_{batt}: Terminal battery voltage
- OCV: Open circuit voltage (as a function of SOC)
- I: Current drawn or supplied
- $R_{internal}$:Lumped internal resistance

Thermal Effects:

- The operating temperature is assumed constant at 293 K (20°C) for simplicity. Temperature-dependent properties such as ionic conductivity and diffusion are calculated using Arrhenius expressions but are not dynamically updated in the model.

Design Objective:

- All design assumptions aim to satisfy the minimum power assist requirements (e.g., 25 kW pulse power) without exceeding safe design limits in voltage, current density, or temperature.
- The model assumes steady-state operation during each load pulse and ignores thermal gradients or aging-induced degradation in this stage.

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Variables used in the Project :

Vmaximum = 3.7          % Maximum Voltage (V)
Vminimum = 3.1          % Minimum Voltage (V)
lp = 0.0024              % Half Thickness of Positive Electrode  (cm) epros =
0.131          % Electrode porocity
epi = 0.0201            % Porous electrode volume fraction of inert material
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Rp = 8.5e-4            % Particle Radius (cm)
Seperator_area = 4819  % Seperator Area (cm^2) calculated using
0.032/(83*8*10^-4)
CN = 83                % Number of Cells used in design
```

Optimized Design Parameters for Battery Cell Configuration in High-Power Applications

S.N.	Input Variable	Optimized Value for Battery Design
1	lp (half thickness for positive electrode)	0.0024 cm
2	ϵ (electrode porosity)	0.131
3	ϵ_inert (volume fraction of inert material)	0.0201
4	Rs (active particle radius)	0.085 μm
5	Separator Area (for 1 cell)	4819 cm^2
6	N (number of cells)	83
7	V_max (maximum cell voltage)	3.7 V
8	V_min (minimum cell voltage)	3.1 V
9	SOC_max (maximum state of charge)	0.8563
10	SOC_min (minimum state of charge)	0.51

Table 2: input variables & their values.

Theoretical Perspective on Vehicle Battery Cells and Systems

The performance of electric vehicle batteries, therefore, will depend on electrochemical principles, materials science, and system-level engineering. At the basis of this kind of design system is the electrode, which directly influences various performance parameters of the system like energy density, power output, efficiency, heat removal, thermal management, and cycle life. The positive electrode, the cathode, determines energy storage capacity, but other design parameters may include pore fraction, inert material fraction, electrode thickness, separator area, and choice of porous material critical as they determine how effectively ions move through the cell, how heat is managed, and how structurally stable the electrode remains through multiple charge-discharge cycles.

In theory, pore fraction plays an essential role since it controls ionic diffusion and electrolyte access to the active material. If the pore fraction is too high, energy density may decrease because of lesser loading of active material; if the pore fraction is too low, ionic transport may be restricted, leading to increased internal resistance. Electrode thickness and separator area are similarly optimized; thicker electrodes hold more energy but suffer from diffusion limitations, while an optically thin separator prevents short-circuiting but facilitates ion transport. Then, the voltage window—minimum and maximum voltages—can be wisely selected so that no degradation mechanism is initiated by the electrolyte due to oxidation or lithium plating. All these aspects essentially correlate with the porous structure geometry along with the composition of inert

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materials, which determines heat distribution, distribution of mechanical stresses, and rates of degradation in the long run.

The Freedom CAR guidelines add a level of complexity by establishing harsher performance parameters including minimum discharge and regeneration power figures, cycle life expectations, and temperature operating windows that must be adhered to concerning the actual operating conditions. These specifications require not only theoretical optimization but validation also through simulation and physical prototyping. Electrochemical models such as the Newman pseudo-two-dimensional (P2D) model or thermal-electric coupled models yield predictive insight into how microscopic properties of the electrode translate into macroscopic properties.

Identified Gaps in the Experimental Design

Although theoretical minds talk about it, cell-level parameter tuning is completely done to back the Freedom CAR targets. Still, there remain apparent limitations on the design front and oversights in design. These gaps restrict battery system applicability and immersion in future research iterations to have a clear need for leaping these methodologies forward.

1. Lack of Electrochemical Modeling or Validation-

While the study optimizes cell parameters such as electrode thickness, porosity, and separator area, it lacks a rigorous electrochemical modeling framework to validate the internal dynamics of lithium-ion cells. The inclusion of advanced simulation tools such as the Doyle-Fuller-Newman (DFN) model or Single Particle Model (SPM) would have enabled a deeper exploration of ion transport behavior, overpotentials, and concentration gradients within the electrodes and electrolyte. Without these models, the study may overlook rate-limiting steps and localized losses that impact power and energy density, especially under transient or high-load conditions. The absence of these electrochemical insights weakens the predictive power of the design and limits confidence in its real-world feasibility.

2. Neglect of Thermal Dynamics and Heat Management-

The thermal behavior, especially for the discharging and fast charging in EV batteries, has always been important to the performance of batteries. Unfortunately, this study has no mention of thermal modeling or thermal analysis. The pore structure, electrode density, and separator area, all direct elements of cell thermal conductivity and heat dissipation capability. Undesirable thermal gradients can result in capacity fade, loss of performance, or even catastrophes. Catastrophic failures such as those associated with runaway conditions are made easy. The highly coupled electrochemical-thermal model would have provided crucial information on temperature distribution, thermal constraints, and the efficiency of potential cooling strategies. This is very important in creating a safe and commercially viable battery system.

3. Lack of Mechanical Stress Analysis-

The current design takes no account of mechanical factors like electrode swelling, particle

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cracking, and delamination. These phenomena are closely related to electrode thickness, porosity, and inert material content parameters changed without keeping in view their role in mechanical reliability. It puts under doubt the long-term viability of the battery as a mechanical degradation study is omitted despite the requirement to deliver charging and discharging cycles up to 3,500. Finite Element Modeling (FEM) or stress-strain simulations would probably mark a significant contribution to structural resilience assessment under cyclical changes. Both volume expansion and particle fracturing in active materials during cycling have to be accounted for. Further substantial uncertainty is introduced into lifecycle expectation analysis for the proposed design through the neglect of mechanical modeling.

4. Absence of Multi-Objective Optimization Framework-

A battery design always shows a trade-off between competing objectives like increasing energy density compromising power or thermal performance, and the existing technique, however, optimizes parameters in isolation without a comprehensive multi-objective optimization framework. Tools such as genetic algorithms, particle swarm optimization, and Pareto frontier analysis would have enabled the identification of optimal parameter sets more systematically satisfying multi-criteria performance or cost constraints. Without all or some of these, the design process lacks robustness and risks ending up with suboptimal solutions while performing well in one domain and underperforming in others.

5. No System-Level Integration or Pack-Level Analysis:

This study shone a light on the design of a single cell; on the other hand, electric vehicles work upon the integration of multi-cell battery packs designed to operate in series and parallel configurations. This causes problems with thermal and electrical balancing, BMS control, and cell-to-cell variability, which eventually impact efficiency and reliability at the pack level. The absence of a discussion on module architecture and interconnection losses and Machination strategies via battery management systems (BMS)-detracts from the research's applicability at the system level. Incorporating pack-level simulation would guarantee the adequate translation of the designed component to its application in real-world EVs.

6. No Consideration of Degradation Mechanisms:

To attain such an ambitious target, 3500 full-depth cycles of charge and discharge cycles, the long-term stability of cell chemistry and materials needs to be ensured. However, the study completely neglects all aspects of degradation phenomena such as SEI growth, lithium plating, electrolyte decomposition, and cathode dissolution. These aging mechanisms importantly determine capacity fade and impedance growth over time. Hence, the study needs to include some models for degradation or relevant data, as otherwise this would overestimate the lifetime of the promised design. The reliability of life predictions could be improved with detailed degradation pathway analysis combined with accelerated aging tests or long-term simulation.

This project provides a strong theoretical ground by addressing critical cell parameters as well as meeting the goals of the DOE Freedom CAR. Yet, to optimize and make it a truly robust design, it would require an integrated multi-physics modeling approach. Further, consideration must be

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given to an overall system with such aspects as thermal behavior, mechanical stress, cycle degradation, and actual integration into simulation and practice. Future work should include linking electrochemical-thermal-mechanical models, multi-objective optimization techniques, and pack-level simulation to make it scalable and compliant with industrial EV standards.

Internal battery resistance

What can be suggested from the equation present in the report is that the diffusion in the solid phase is increased with an increase in the size of the particles. Accordingly, the allowed minimum size can go as low as 0.5 microns. An increase in the resistance of the cell increases the ohmic drop as a result of the thickness of the electrodes. The thicker electrode is required for a higher pore volume fraction, which has better transport in the solution phase for these purposes.

Calculation of the resistance is done using the provided equation:

$$\kappa_{\text{eff}} = \varepsilon^{1.5}\kappa$$

$$\sigma_{\text{eff}} = (1 - \varepsilon)^{1.5}\sigma$$

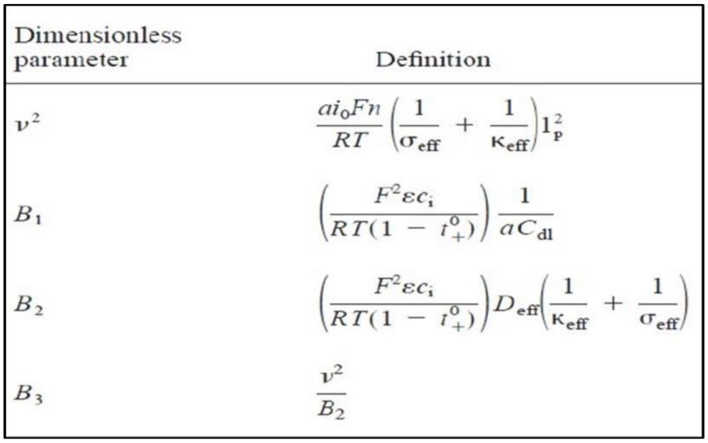
$$D_{\text{eff}} = \varepsilon^{0.5}D$$

$$a = \frac{3}{R_{.s}}\cdot\left(1 - \varepsilon - \varepsilon_{.inert}\right)\cdot\varepsilon$$

“a” is the active material particle surface area per unit volume of electrode. Thus, active material area in the electrode will be,

$$AreaOfActiveMaterial = a\cdot 2\cdot\left(l_{.p}\cdot SeperatorArea\right)$$

Dimensionless parameters are also provided in the project report uploaded on the canvas



Dimensionless parameter	Definition
ν^2	$\frac{a i_0 F n}{RT}\left(\frac{1}{\sigma_{\text{eff}}} + \frac{1}{\kappa_{\text{eff}}}\right) l_p^2$
B_1	$\left(\frac{F^2 \varepsilon c_i}{RT(1 - t_+^0)}\right)\frac{1}{a C_{\text{dl}}}$
B_2	$\left(\frac{F^2 \varepsilon c_i}{RT(1 - t_+^0)}\right) D_{\text{eff}}\left(\frac{1}{\kappa_{\text{eff}}} + \frac{1}{\sigma_{\text{eff}}}\right)$
B_3	$\frac{\nu^2}{B_2}$

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Various resistance,

$$R_{\Omega} = \frac{2}{\left(1 + \frac{\kappa_{\mathrm{eff}}}{\sigma_{\mathrm{eff}}}\right)} \quad \mathrm{x} \left[\frac{\sigma_{.\mathrm{eff}}}{l_{.\mathrm{p}}} \cdot \left(\frac{1}{2} + 5 \cdot \varepsilon_{.\mathrm{inert}}\right)\right]^{-1}$$

$$R_{\mathrm{p}} = \left[\frac{2}{1 + \frac{\kappa_{\mathrm{eff}}}{\sigma_{\mathrm{eff}}}} + 2\,\frac{\kappa_{\mathrm{eff}}}{\kappa_{\mathrm{eff}} + \sigma_{\mathrm{eff}}}\left[\frac{2t^{0}}{(2t^{0} + B_{2})} + \frac{B_{2}}{(2t^{0} + B_{2})}\,\frac{\tanh\left(\sqrt{\frac{\nu^{2}}{B_{2}}(2t^{0} + B_{2})}\right)}{\sqrt{\frac{\nu^{2}}{B_{2}}(2t^{0} + B_{2})}}\right]\right] \quad \mathrm{x} \quad \left(\frac{\sigma_{.\mathrm{eff}}}{l_{.\mathrm{p}}}\right)^{-1}$$

$$\boxed{R_{\mathrm{ct}} = \left[2\,\frac{\kappa_{\mathrm{eff}}}{(\kappa_{\mathrm{eff}} + \sigma_{\mathrm{eff}})}\,\frac{\tanh(\nu)}{\nu} + 2\,\frac{\sigma_{\mathrm{eff}}}{(\kappa_{\mathrm{eff}} + \sigma_{\mathrm{eff}})}\right] \mathrm{x} \quad \left(\frac{\sigma_{.\mathrm{eff}}}{l_{.\mathrm{p}}}\right)^{-1}}$$

$$\boxed{R_{.Batt} = R_{.\Omega} + \left[\left(R_{.ct} + R_{.p}\right) \cdot exp\left[\frac{CN^{\frac{1}{2}} \cdot \left(V_{.MAX} - V_{.MIN}\right) \cdot \frac{2}{V}}{40 \cdot \left(\frac{AreaOfActiveMaterial}{m^{2}}\right)^{\frac{1}{4}}}\right]\right]}$$

We are set free to select some cells, V maximum, and V minimum to satisfy the DOE requirements. Separator area and cell resistance are inversely proportional.

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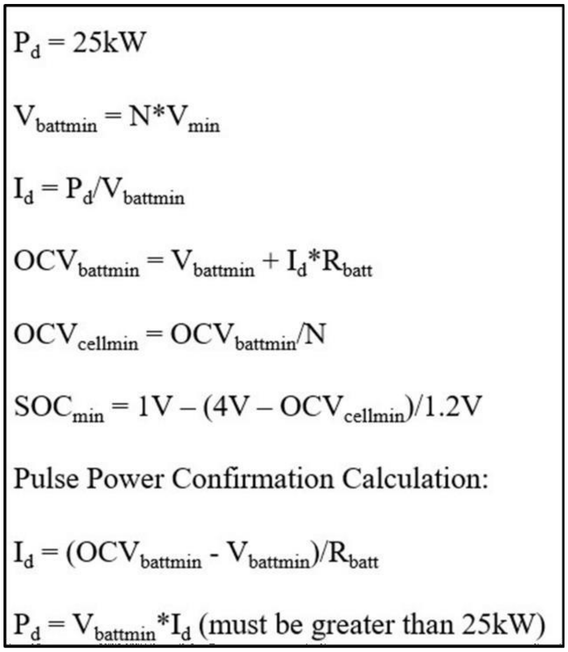
Part A: verification of Lithium cell and battery pack which meets all Freedom Car battery test manual specification

Peak power calculation for discharge at minimum SOC

Equation used:



$P_d = 25\text{kW}$

$V_{battmin} = N*V_{min}$

$I_d = P_d/V_{battmin}$

$OCV_{battmin} = V_{battmin} + I_d*R_{batt}$

$OCV_{cellmin} = OCV_{battmin}/N$

$SOC_{min} = 1\text{V} - (4\text{V} - OCV_{cellmin})/1.2\text{V}$

Pulse Power Confirmation Calculation:

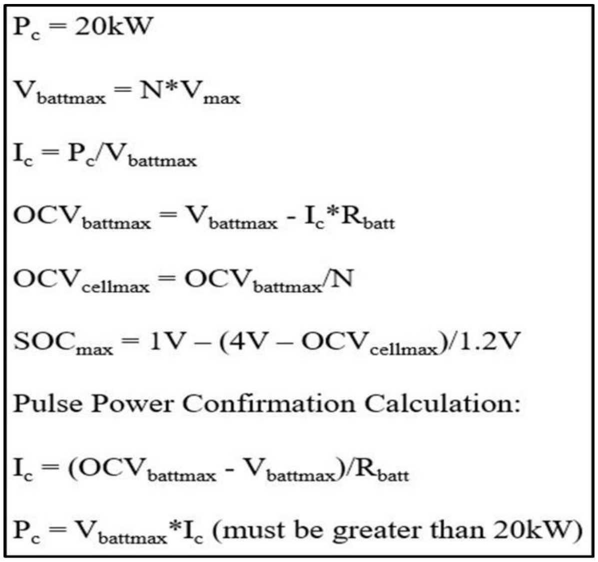
$I_d = (OCV_{battmin} - V_{battmin})/R_{batt}$

$P_d = V_{battmin}*I_d$ (must be greater than 25kW)

This calculation gives the pulse discharge power = 25000 watts i.e. 25kW. It meets the goal for the design of battery architecture.

Regeneration of peak power at maximum SOC

Equation used:



$P_c = 20\text{kW}$

$V_{battmax} = N*V_{max}$

$I_c = P_c/V_{battmax}$

$OCV_{battmax} = V_{battmax} - I_c*R_{batt}$

$OCV_{cellmax} = OCV_{battmax}/N$

$SOC_{max} = 1\text{V} - (4\text{V} - OCV_{cellmax})/1.2\text{V}$

Pulse Power Confirmation Calculation:

$I_c = (OCV_{battmax} - V_{battmax})/R_{batt}$

$P_c = V_{battmax}*I_c$ (must be greater than 20kW)

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A) C1 rate at 3500 cycles. B) Average voltage of discharge at C1 rate C) Available enrgy at 3500 cycles.

Equation used:

$$\Delta SOC = SOC_{max} - SOC_{min}$$

$$C1 = \Delta SOC * MaxCapacity \text{ (A at 1 hour discharge)}$$

$$V_{battave} = (OCV_{battmax} + OCV_{battmin})/2 - C*R_{batt}$$

$$\text{Available Energy} = V_{battave}*C1*1hr - C1^2*R_{batt}*1hr \text{ (must be greater than 0.3kWh)}$$

At CN =3500 average voltage of battery = 295.01 Volts & C rate is 9.0085 AH

Total available energy is =1.08kW and satisfies the DOE goal requirement of being greater than 0.5kWH.

Cold cranking power at -30 deg Celsius

Equation used:

$$P_{cc} = V_{battave}*I_{cc}$$

$$V_{battave} = OCV_{battmin} - I_{cc}*R_{batt}$$

$$I_{cc}^2*R_{batt} - OCV_{min}*I_{cc} + P_{cc} = 0$$

$$I_{cc} = [OCV_{min} - SQRT(OCV_{min}^2 - 4*R_{batt}*P)]/(2*R_{batt})$$

$$V_{battave} = P_{cc}/I_{cc}$$

Calculation of cold crank test power at Vbatt=Vmin with N is at lower SOC limit which gives the power to be 8kW and hence DOE manual requirement satisfies.

Separator area along with total number of cells and total battery volume.

Equation used :

$$Volume_{cathode} = N*2*lp*SeparatorArea \text{ (must be less than 8 liters)}$$

This simulation gives calculated volume (vol_calc) = 0.03200 m^3 for 83 cells connected in series which has separator area = 4819 cm^2 and satisfies the DOE goal requirement.

Maximum voltage design

Equation used :

$$\boxed{V_{battmax} = N*V_{max}}$$

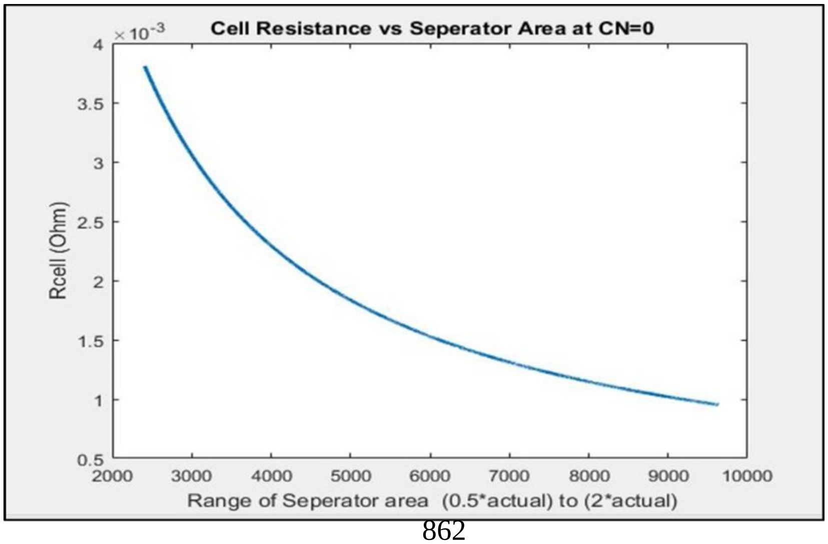
This simulation gives the result of Vbmax = 307.1 V which is less than 400 V and thus satisfies the DOE goal requirement.

From 1) to 6) all the results are summarized and compared with the desired DOE goals which has to be satisfied.

Number	Characteristics	Power-Assist (Minimum)	Calculate Power Assist values.
1	Pulse Discharge Power	25 kW	25 kW
2	Peak Regenerative Pulse Power	20 kW	20 kW
3	Total Available Energy over DOD range	0.5 kWh at C1 rate	1.0 kWh (satisfactory)
4	Cold Cranking Power at -30 C	8 kW	8kW
5	Cycle Life for specified SOC increments	3500 cycles	3500cycles
6	Maximum Volume	32 liters	32 liters
7	The operating voltage of the battery	Max <= 400 Min >= (0.55 Vmax)	Max = 307.1 Min = 168.9

Part B: Plots

Cell resistance as a function of separator area at cycle number = 0



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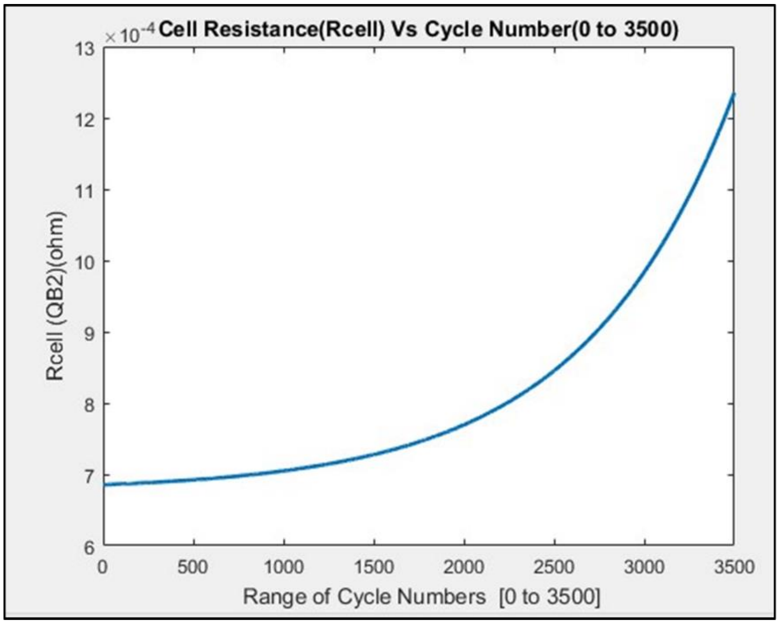
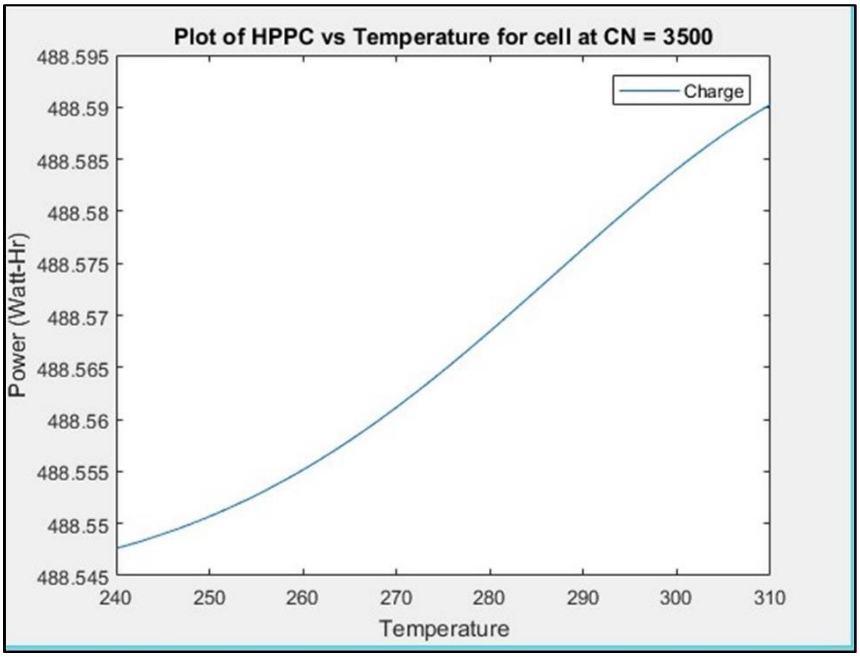
Cell resistance decreases when the range of the separator area increases in the given range.

Cell resistance as a function of cycle number varying from 0 to 3500



From the graph it can be easily interpreted that with the increase in cycle number, cell resistance also increases which makes sense. As battery performance degrades over number of cycles.

Plot for HPPC vs temperature at CN = 3500



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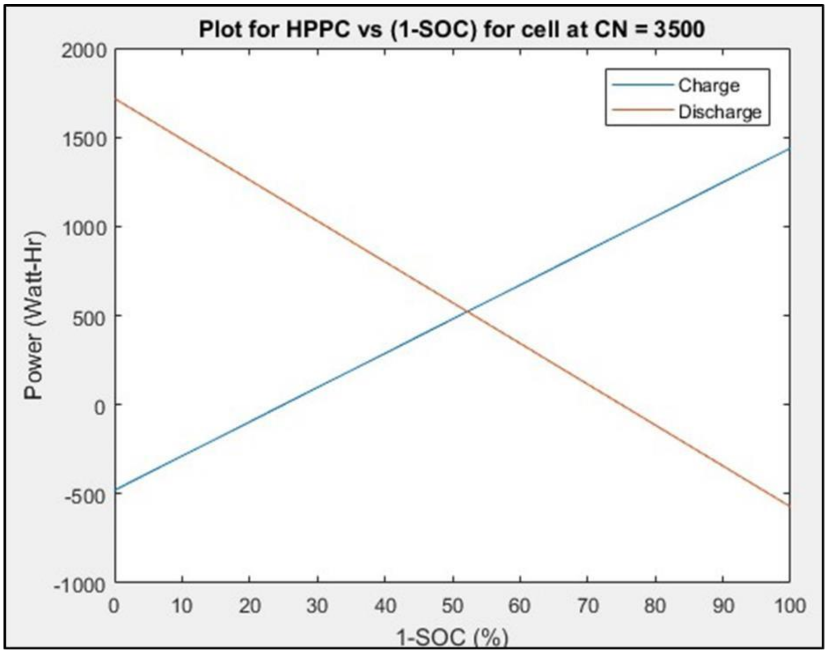
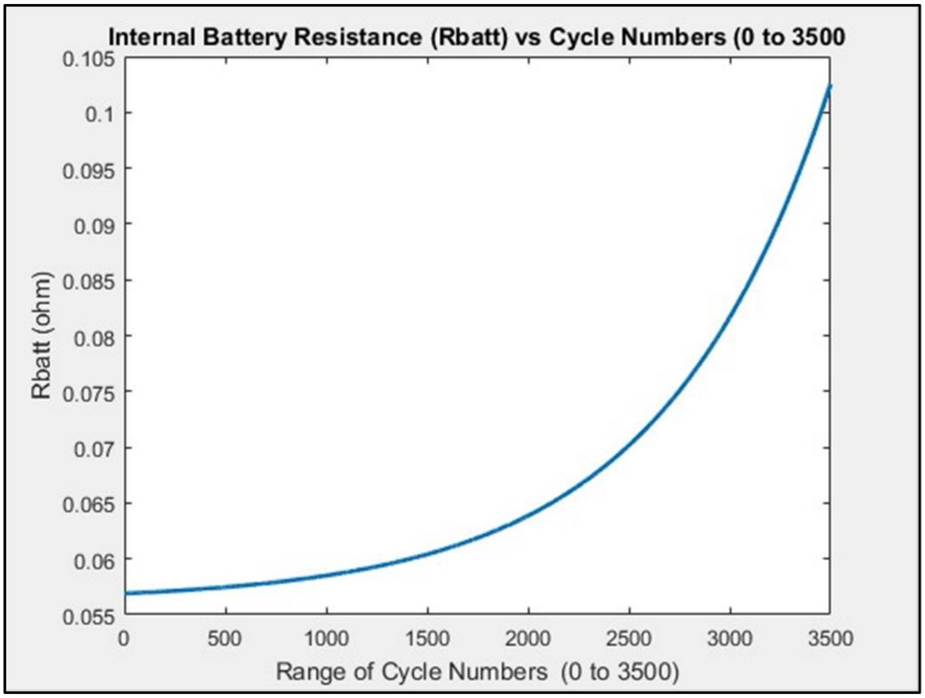
We can see, that with the increase in temperature, power also increases slightly.

HPPC as a function of 1-SOC for charge and discharge of battery



From the graph obtained from the simulation, we can say that result matches with the Freedom Car manual results for the same.

Repeat 2 to 4 in step 6



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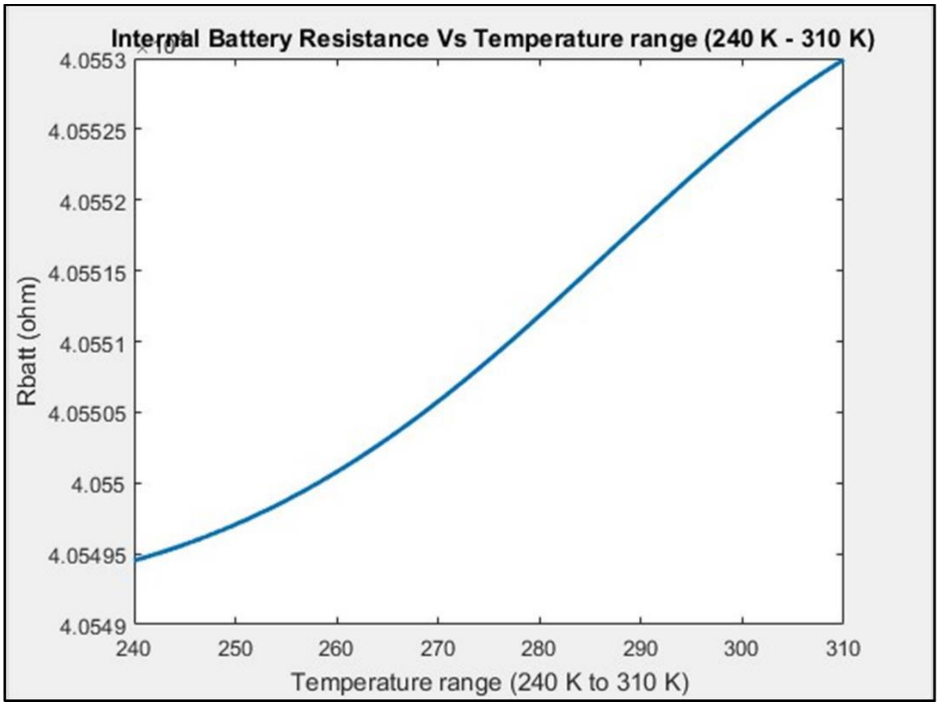
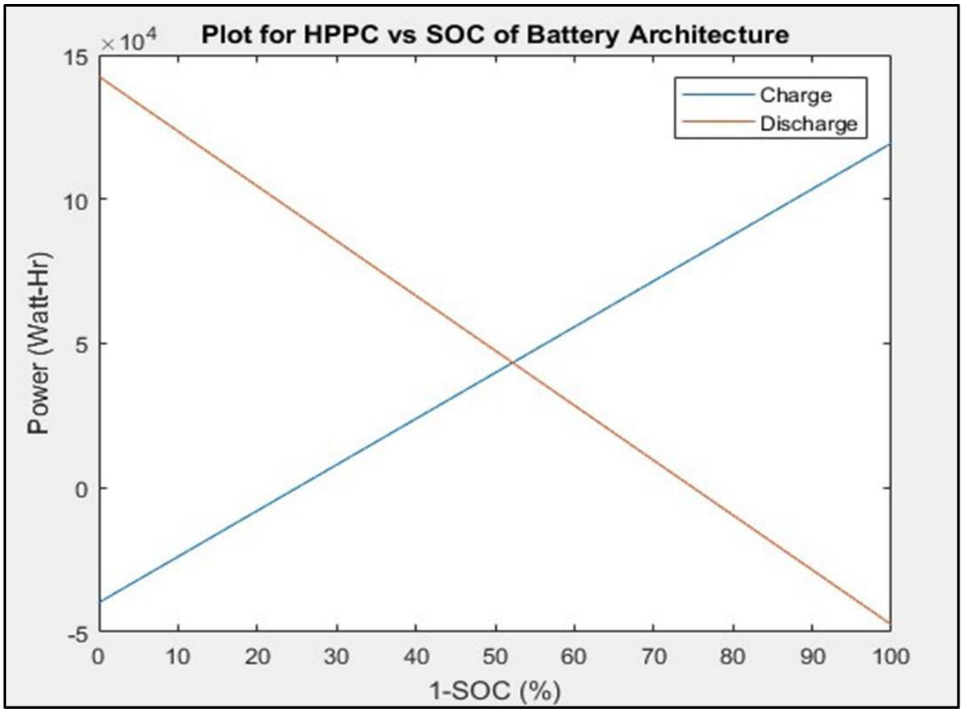
Internal battery resistance increases withincrease in the number of cycles.



Here, we can see, for a given range of temperatures internal battery resistance slightly increases.



If we compare the results obtained with the individual cell results for the same, it looks the same

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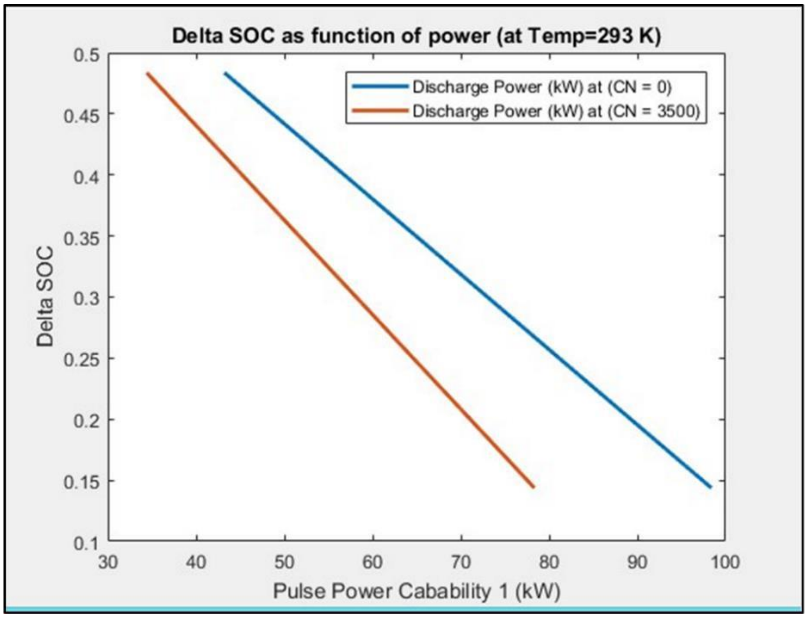
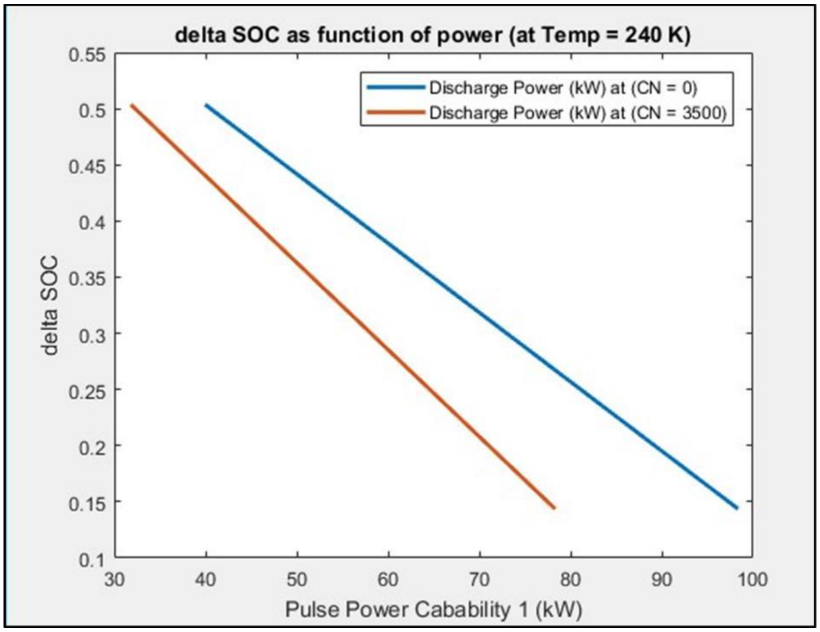
because the battery package is nothing but the series combination of a number of cells

Plot for Delta SOC as a function of Pulse power capability



From the above graph, pulse power capability reduces with increase in cycle number and also, Pulse power capability is different for different cycle numbers.

Pulse power capability as a function of depth of discharge



It can be seen that the pulse power capability reduces with increase in number of cycles and depth of discharge.

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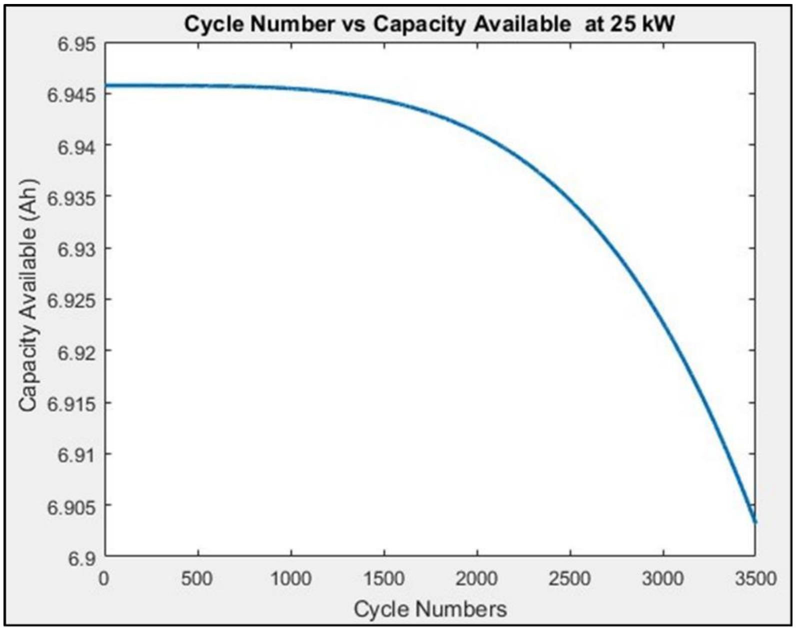
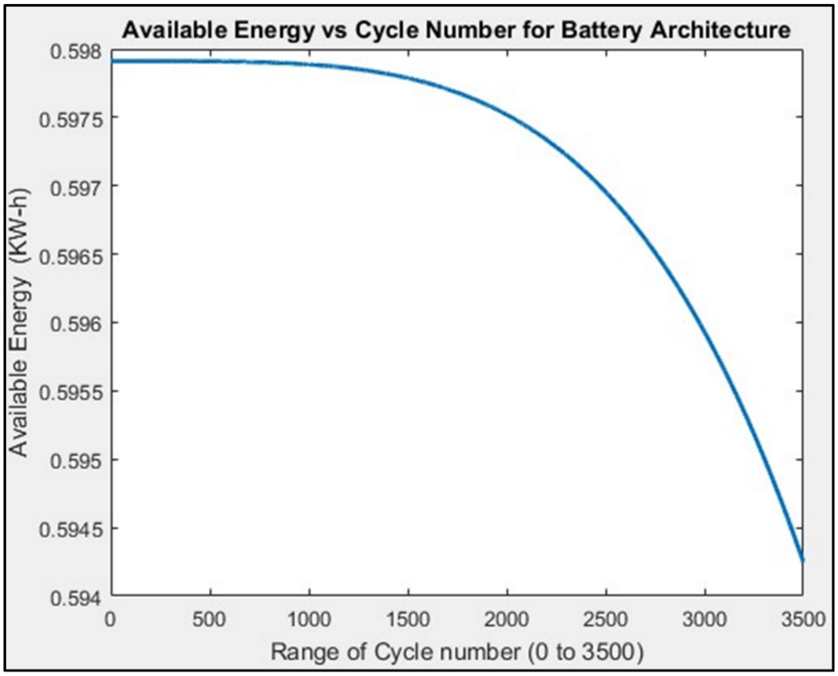
Available capacity as a function of cycle number



It can be analyzed that, With an increase in cycle number, available capacity decreases

Available energy as a function of cycle number for the battery architecture



From the above graph we can conclude, battery energy also decreases with increase in cycle numbers

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Future Scope of Improvement

With the demand for high-energy-density batteries with long cycle life for EVs, there is a proposal for significantly enriching the present design framework by creating an integrated, multidisciplinary approach. The current work has seen very encouraging theoretical results in the optimization of physical parameters, and further commercial scalability and real-world applicability of these findings will require a more fundamental and sophisticated basis. The following areas suggest where improvement should be targeted in the future:

1. Advanced Electrochemical Models

Future designs must involve advanced electrochemical models that would capture the behavior of batteries under different operating conditions. The Doyle-Fuller-Newman (DFN) equations and Single Particle Model (SPM) would yield precious insights into lithium transport, interfacial kinetics, and electrolyte behavior. These models also help in locating performance bottlenecks such as limiting ion diffusion or overpotential losses that simple equivalent circuit models might miss.

Advantageous Aspects:

- Better prediction of charge/discharge efficiency
- Understanding internal voltage distribution better
- Iterative design process becomes more accurate

2. Electro-Thermal Coupling and Thermal Management

The high current loading in the EVs will make it necessary to manage the constant heating of the battery systems they employ. Heat has an impact on the performance, aging, and safety of the batteries. Thus, in future designs, thermal modeling should be coupled with electrochemical simulations to enable evaluation of the interplay between temperature rise and work done by the battery. The introduction of heat management concepts such as enhanced cooling channels, phase change materials, or thermal coatings would further reinforce the reliability of these designs.

Optimum Profitability:

- Prevention of thermal runaway
- Better management of cell temperature uniformity

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- Extended battery life.

3. Mechanical integrity and stress analysis are the most important drivers for mechanical integrity.

The mechanical integrity of electrodes and separators is very important in a performance profile over thousands of cycles. Future work has to include mechanical stress modeling to assess how electrode expansion/contraction, pressure during packing and cracking of particles would affect battery life. This finite element analysis (FEA) bridges the gap between simulating the actual physical behavior of materials with regard to mechanical failure forecasting.

Benefits:

- Reduced degradation from delaminating or cracks
- Better cycled durability
- Optimizing the electrode material loading

4. Multi-objective optimization for trade-off management

The trade-off is an integral part of battery design: energy density and power density, safety and cost, etc. Therefore, the application of single-objective optimization of parameters is significantly limited under real-world use. The future area of work involves the usage of multi-objective optimization frameworks (most likely Pareto optimality or genetic algorithms) to derive optimal sets of parameters by which these trade-offs are balanced.

Benefits:

- Performance and safety requirement satisfaction simultaneously
- Informed decision-making for material and geometric selection
- Scalability for applicable application-specific design

5. Full System-Level and Pack-Level Simulation

The current work is on individual cell level. However, batteries work as modules and packs in EVs; hence, system-level analysis inclusive of electrical interconnection losses, thermal gradients

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across cells, and the role of a BMS is critical. Modeling the behavior of a battery pack under dynamic vehicle conditions will hole in the lab design versus real-life performance gap.

Benefits:

- Performance prediction on a system level, closely resembling reality
- Weak links have been identified in packing configurations
- Better cell balancing of the pack configurations improves overall safety

6. Long-Term Degradation and Cycle-Life Modeling

Beyond the 3,000-plus cycles context, any study predicting battery performances will have to account for degradation phenomena like SEI growth, lithium plating, and cathode dissolution. These very mechanisms each critically erode capacity while contributing to resistance and, in some Instances, endanger battery systems. Further development needs to bring aging models either data-driven or physics-based into the picture in order to forecast cycle life.

Benefits:

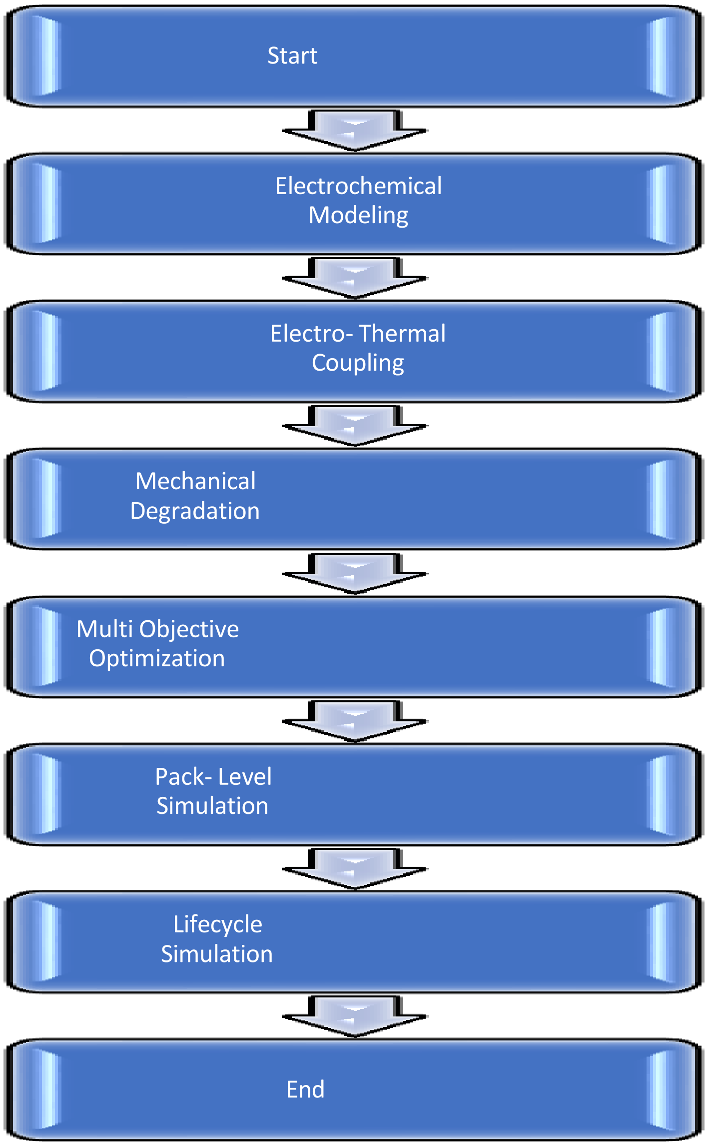
- Reliable estimation of EOL
- Foreseeing failure
- Better warranty and lifecycle planning

Tools and Techniques for Future Enhancement

Objective	Suggested Tools/Approaches	Anticipated Outcome
Modeling of Electrochemical Kinetics	COMSOL Multiphysics, MATLAB, PyBaMM	Accurate cell performance modeling
Thermal Behavior Simulation	ANSYS, Simcenter STAR-CCM+	Reliable heat management and temperature profiling
Structural Mechanics	Finite Element Analysis (FEA)	Stress-resilient electrode and separator structures
Optimization Framework	NSGA-II, Pareto Front, DOE tools	Balanced trade-offs between multiple design goals

Lifecycle Prediction	Empirical or physics-based degradation models	Reliable estimation of aging and performance decay
Pack Simulation & Integration	Simulink, GT-SUITE	Scalable system-level validation

Future Scope Of Battery Design Improvement



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The world of tomorrow will witness battery cell design more holistically and integration-wise-bringing together Multiphysics modeling and AI-guided optimization concerning energy density, thermal stability, and mechanical integrity. The addition of degradation modeling and pack-level simulation guarantees a consistent performance across thousands of cycles and through various operating conditions. At the end of the day, linked with iterative prototyping and validation, advancements in this regard would translate into battery solutions that are scalable, safe, and high performing, specifically to meet the ever-growing demands for electric mobility and energy storage systems.

Conclusion

This study is directed toward the theoretical design and performance evaluation of a lithium-ion battery system for satisfying all the power-assist demands of the U.S. Department of Energy's (DOE) Freedom CAR program. Key design parameters such as thickness, porosity, particle size, and separator area were optimized using analytical modeling, with $LiCoO_2$ as the positive electrode material. The greatly simplified assumption of isolating the capacities and internal resistances allowed primarily focusing on the positive electrode behavior. A Thevenin-equivalent circuit model was developed to reproduce the dynamics of the battery response and relate state of charge (SOC), open-circuit voltage (OCV), and current for predictive performance during charge and discharge events.

Critical parameters like cell voltage, power output, and cycle life could be computed within the MATLAB simulation framework in terms of exchange current density, diffusion coefficients, and resistance used. The designed cell configuration successfully achieved all DOE goals including 25 kW pulse power, 20 kW regenerative power, 0.5 kWh energy delivery at C1 rate, and cold cranking power of 8 kW at −30 °C while not exceeding a maximum space of 32 liters and operating voltage window of 3.1–3.7 V. The trade-offs between thickness and porosity of electrodes were clear: thicker electrodes have a higher energy storage capacity but greater internal resistance, making balance even more important in battery design.

It should be noted that while all these efforts were successful in realizing the main performance objectives, some limitations were imputed such as not modeling the negative electrode, strategies of management of temperature, and effects of degradation such as SEI growth and aging. These gaps limit the capabilities to simulate actual EV performance and long-term reliability in batteries. Future work should also include full-cell modeling, thermal dynamics, and lifecycle degradation

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for the most consolidated and practical battery system. In all, this study goes a long way to provide a very strong foundation for battery design in electric mobility and allows theoretical underpinnings to rub shoulders with DOE benchmarks to drive future innovations in clean energy storage solutions.

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