

## **Sustainable Battery Technologies for Modern Energy Systems: A Comparative Analysis of Residential, Automotive, and Industrial Applications**

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### **Abstract**

The world shift to decentralized energy and electrified mobility is becoming more and more limited by Legacy of the Lead-Acid Storage Infrastructures, which is not fully utilized to assure development growth because the yield of the Capital Economics (CapEx) is lower. Accordingly, the paper gives a techno-economic analysis of converting Lithium iron phosphate (LiFePO<sub>4</sub>) in residential, automobile and industrial applications through a 10-year Total Cost of Ownership (TCO) model (LiFePO<sub>4</sub>) breaks even financially in the residential business after four years due to a combination of high round trip energy efficiency (> 95% vs. 70%) and no electrolyte maintenance. The analysis helps to highlight a more basic change of operation in the high-rate charging capability of (LiFePO<sub>4</sub>) (1C) on the 24-hour continuous operation of this vehicle on a battery-to-vehicle-weight ratio of 1:1, and does not necessitate the normal 2:2 or 3:1 lead charge requirement. Under the system the reduced all of the infrastructure is simplified in the form of in-inventory, even in batteries. Besides, LiFePO<sub>4</sub> faces economic volatility in the SLI (Automotive Motoring, Lighting and Ignition). It is worth noticing that mild weight costs cannot justify a cost of diff, which results in zero fuel cost-total savings benefits. Lead (auxiliary batteries + batteries) must not be sold under an overall price > 90 % of

your market. In cases where both residential and industrial markets offer strong IPC benefits that are amenable to immediate acceptability, automotive SLI markets feature rigidity to impede infiltration in companion implementations or FULL fuel-efficient cars.

**Keywords:** Battery management systems (BMS), energy storage system (ESS), industrial electrification, lithium iron phosphate (LiFePO<sub>4</sub>), opportunity charging, total cost of ownership (TCO).

## I. INTRODUCTION

The impact on the environment and modernization of fossil fuel production have required a shift in the energy storage technologies. Although lithium-ion batteries are prevalent in consumer electronics and EVs, stationary and industrial applications in developing economies are still based on the chemistry of lead-acid as it is less expensive. This dependency brings about operational inefficiencies especially when it is used in applications that demand deep discharge cycling and quick recharging.

This paper also discusses the techno-economic feasibility of the replacement of lead-acid battery with a LiFePO<sub>4</sub> technology. We use a 10-year TCO model that considers CapEx, OpEx, replacement cycles, and infrastructure unlike the previous research that used individual measures only. Older style industrial lead-acid systems need a battery-to-vehicle ratio of 2:1 or 3:1 since the charging (8-12 hours) and cooling (6-8 hours) times are long, and it may be necessary to install costly swapping infrastructure (\$80,000–120,000 for a 10-forklift fleet). The 1C charging capability of LiFePO<sub>4</sub> allows these limitations to be removed and allows 1:1 design.

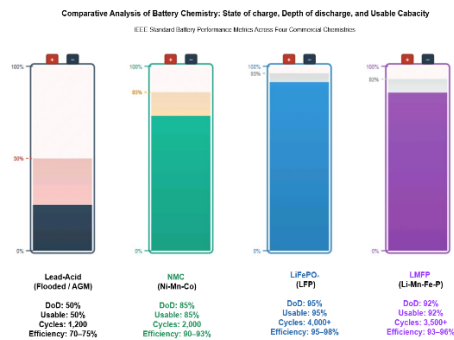


Fig. 1. Comparison of Battery Performance Measures. This graph is used to compare Lead-Acid, NMC LiFePO<sub>4</sub> and LMFP chemistries based on important operation parameters. The visualization points at the acute constraints of the Lead-Acid technology which has only 50% usability and 1,200 cycles with power efficiency of 70-75 %. LiFePO<sub>4</sub> 4 in comparison has a superior technical viability of residential

and industrial applications with a 95% Depth of Discharge (DoD), much longer lifespan > 4,000 cycles and high round-trip energy efficiency of 95-98%.

## **Literature Review**

The unique aging and cycle life performance of various battery chemistries need to be studied in order to correctly project the Total Cost of Ownership (TCO) of energy storage systems. In the case of lead-acid, Ruetschi [12] described the permanent aging processes, and Doerffel and Sharkh [11] applied the Peukert equation to measure the capacity losses at high discharge rates of the system, which is an essential parameter to the performance of the industry. Within the framework of Lithium-ion technologies, charging protocols [4], and state-of-charge (SOC) management strategies [5] have been established to greatly increase lifetime. Moreover, Omar et al. [6] introduced detailed cycle life models of LiFePO<sub>4</sub> batteries, evaluated the parameters of the aging process which is essential in the process of the mathematical TCO calculation, and Baumann et al. [3] emphasized the significance of the idea of cloud-connected battery management system (BMS) in the process of decision-making in the second-life usage.

These battery systems need elaborate management systems to fit into the grid and motive applications. Jusoh et al. [15] suggested photovoltaic (PV) power dispatching on hourly control plans based on rules to optimize battery utilization, unlike hybrids battery bank applications outlined by Beszeddes [13], which utilized several chemistries to store energy. The possible operational strategies in the electric vehicle (EV) industry include opportunity charging systems to e-buses [1] to autonomous battery swapping approaches [2] and the high voltage energy consumption analysis of electric forklifts [14]. These varied uses also should take into account more general scale utility cost estimates, updated by Cole et al. [8], in order to gain complete insight into the economic feasibility of storage at various scales, including residential inverters to massive industrial machines.

The technical benefits of lithium-based systems notwithstanding, market forces indicate that there is still a dependency on lead-acid technology in certain markets. According to industry reports [9], it has been established that the lead-acid controls more than 90% of the automotive SLI market that is with due to its well-established supply chains and due to the presence of 99% recycling infrastructure as reported by Zhao et al. [7]. Although Ziegler and Trancik [10] have reported a 97 % cost reduction in lithium-ion technology since 1991, this has given EV impetus, such as the introduction of LiFePO<sub>4</sub> in China, and not the replacement of lead-acid in cost-sensitive applications such as the Indian residential market. Thus, Li-ion prices fall, but the lead-acid remains competitive, establishing a two-way market whereby technical superiority challenges economic inertia.

## Methodology

The research employs the stringent techno-economic analysis framework in evaluating the strategic implications of the shift to lithium systems, based on a multi-phase approach.

### A. Market Segmentation and Application Selection

The market is divided into three different application domains based on the analysis of different operational and economic needs:

- **Residential:** Backup Power applications.
- **Automotive:** Starting-Lighting-Ignition (SLI) and Traction.
- **Industrial:** Material Handling applications.

### B. Data Collection

The Tier-1 battery manufacturer technical sheets were used as the source of data to guarantee the statistical strength and represent Commercial Off-The-Shelf (COTS) products instead of cell-scale.

Lead-Acid: 12V/150Ah tall tubular batteries (residential) and 48 V motive-power traction cells (industrial).

Lithium: 12.8V and 48V LiFePO<sub>4</sub> prismatic cell with inbuilt BMS.

### C. Parameter Selection

The analysis divided the evaluation measures into two fundamental groups to propel the models of analysis:

- **Technical Parameters:** Usable capacity, Depth of Discharge (DoD), cycle life and efficiency.
- **Economic Parameters:** Capital Expenditure (CapEx), Operational Expenditure (OpEx), replacement times, and maintenance costs.

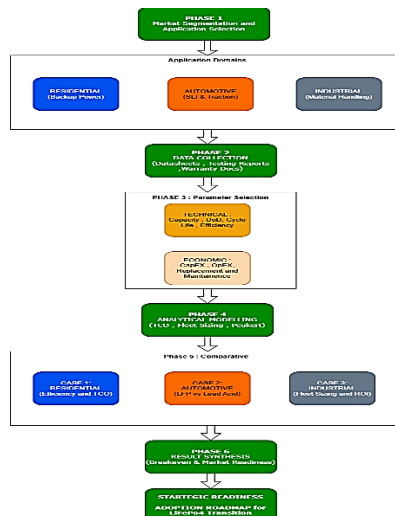


Fig. 2. In short, document flowchart of the Comparative Techno metric Analysis Methodology displays the consecutive phases of time of Research market, data, parameterization Analysis - Case Comparisons as being the reason of the eventual Strategic Report.

#### D. Analytical Modelling

- **Battery Fleet Sizing Methodology**

In the case of industrial applications, the size of the fleet varies according to chemistry.

- **Lead-Acid (2:1 Ratio):** It is led by the formula  $N_{\text{(batteries)}} = N_{\text{(vehicles)}} \times R_{\text{(ratio)}} \times (1 + R_{\text{(spare)}})$ . In the case of a 10-forklift facility, it usually takes 20-28 batteries in charge/cool cycles.
- **LiFePO<sub>4</sub> (1:1 Ratio):** It can be charged in 60 min (Fast charging) and charged during the breaks (Opportunity charging), which means that 10 batteries are only needed to battery 100.  $N_{\text{(batteries)}} = N_{\text{(vehicles)}} \times 1.0$ . . This is a loss of 50-60 % of the fleet size.
- **LiFePO<sub>4</sub> Infrastructure Requirements:**
  - Charging stations: \$15,000-25,000. Basic plug in stations at car parks with inbuilt BMS communication. No special equipment or crane ventilation needed.
  - **LiFePO<sub>4</sub> infrastructure:** \$15,000-25,000 (10-vehicle facility)
  - Difference in infrastructure costs: **LiFePO<sub>4</sub>** saves \$90,000-145,000. This 85-90 %

infrastructural reduction has significant impacts on the payback estimates even as battery unit prices increase.

It is intended that the 10-year Total Cost of Ownership (TCO<sub>10y</sub>) will be as follows:

$$TCO_{10y} = CAPEX + \sum_{n=1}^{10} \frac{OPEX_n}{(1+r)^n} + \sum_{k=1}^R \frac{REP_k}{(1+r)^k} - \frac{SV}{(1+r)^{10}}$$

#### E. Results and Discussion

This part shows the quantitative results of comparison analysis, sub-groups on an application-level The contemporary and lithium-based alternatives versus the former corrosion-tolerant processes.

**Table 1**  
**Comparative Technical Specifications (Residential ~1.2 kWh System)**

Parameter	Tall Tubular Lead-Acid (150 Ah)	LiFePO <sub>4</sub> (100 Ah)	Relative Advantage
Usable Energy (kWh)	1.44 (@ 80% DoD)	1.28 (@ 100% DoD)	Comparable
Weight (kg)	58.0	11.5	80% lighter
Volume (L)	35	12	65% smaller
Round-Trip Efficiency	70–75%	95–98%	+25%
Self-Discharge / Month	5–10%	< 2%	Lower loss
Charging Time (0–100%)	10–12 h	2–3 h	~4× faster
Cycle Life	~1,200 cycles	>4,000 cycles	~3.3× longer

Case I: Residential Energy Storage Results

The comparison is done between a 12V 150Ah Tall Tubular Lead-Acid battery of a market standard and a 12.8V 100Ah LiFePO<sub>4</sub> battery. The nominal capacity of the lithium unit seems to be lower, but the usable energy is equal because it can run at a much higher Depth of Discharge (DoD).

F. Energy Efficiency Impact Analysis

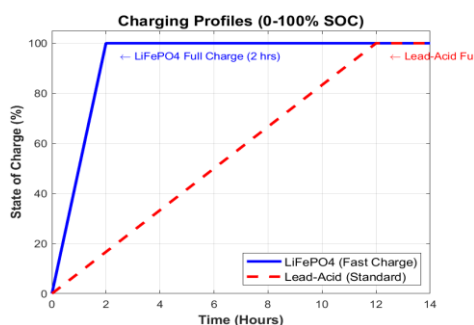


Fig. 3. Graph indicating charging curves of lead-acid and LiFePO<sub>4</sub> charging rates with respect to 0-100% SOC, time versus x-axis (0-12 hours) and SOC versus y-axis (0-100%)

With a grid energy requirement of 5,714 kWh per year, lead-acid systems take 5,714 kWh of grid energy to produce 4,000 kWh of energy, and the remainder of the energy is wasted as a heat energy. Conversely, LiFePO<sub>4</sub> systems take only 4211 kWh and waste is limited to only 211 kWh. This efficiency at an average tariff of 8/kWh would lead to yearly savings of ₹10,500–12,000 (\$135 USD) (with no relation to maintenance expenses).

Despite an initial purchase cost 2.13× higher, LiFePO<sub>4</sub> achieves financial breakeven by Year 4. Over the 10-year horizon, the lead-acid system incurs a total

cost of ₹64,500 compared to ₹34,100 for LiFePO<sub>4</sub>, representing a **47% reduction in TCO**.

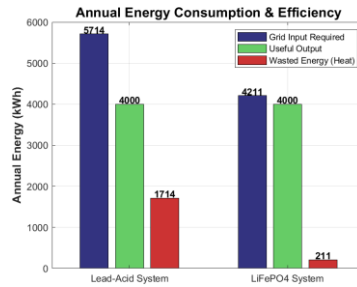


Fig. 4. Bar chart comparing annual energy consumption - showing grid input energy, useful energy output, and waste energy for both lead-acid and LiFePO<sub>4</sub> systems  
Economic Analysis: Total Cost of Ownership

**Table 2**  
**10-Year Total Cost of Ownership (Residential System)**

Cost Component	Lead-Acid Scenario	LiFePO <sub>4</sub> Scenario	Savings / Loss
Initial Purchase Cost	₹15,000	₹32,000	-₹17,000
Replacements (10 years)	2 units (Years 4 & 8)	0 units	+₹34,000
Maintenance (Electrolyte & Labor)	₹3,000	₹0	+₹3,000
Charging Energy Waste	₹12,500	₹2,100	+₹10,400
<b>Total 10-Year Cost</b>	<b>₹64,500</b>	<b>₹34,100</b>	<b>₹30,400</b>

Case II: Automotive Sector Results

The automotive industry is divided into Starting-Lighting-Ignition (SLI) and Traction application that has a different duty cycle and value propositions.

A. Starting, Lighting, and Ignition (SLI) Applications

Consumer price sensitivity, replacement behavior (buying when it fails) reactive, and absence of core exchange motivation (buying because of failure) are barriers to adoption in comparison with the well-established lead-acid recycling system.

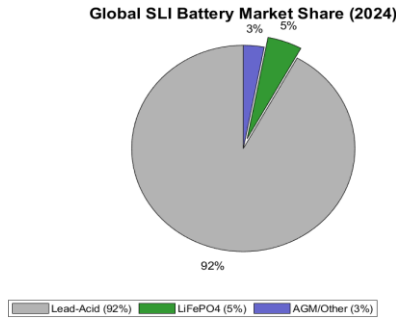


Fig. 6. Global SLI Battery Market Share (2024). This chart illustrates the overwhelming market dominance of Lead-Acid technology, which retains a 92% share in the Starting-Lighting-Ignition (SLI) sector.

B. Electric Vehicle Traction Batteries - LiFePO<sub>4</sub> Adoption Case Study

Conversely, LiFePO<sub>4</sub> has been quickly embraced by the EV industry (e.g. BYD, Tesla) because of cost (\$95-115/kWh vs. \$130-155/kWh NMC) and thermal stability. Nevertheless, this achievement cannot be converted into the triumph of SLI markets due to the fact that SLI batteries make up < 1% of the vehicle price, which makes the weight and lifecycle advantages economically insignificant to an average consumer.

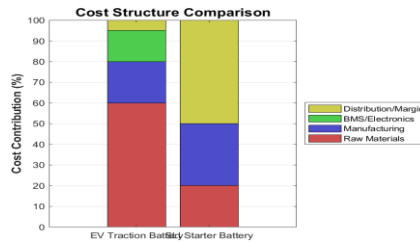


Fig. 7. Assembled bar chart comparing cost breakdown of EV traction battery vs SLI battery, showing relative proportions of raw materials, manufacturing, BMS, and other components

C. Conventional Traction Applications (Forklifts, Golf Carts)

When dealing with heavy discharge loads (electric forklifts, golf carts, floor scrubbers) there is technical necessity that efficiency is controlled by  $C_p = I^k \times t$  (Peukert effect).

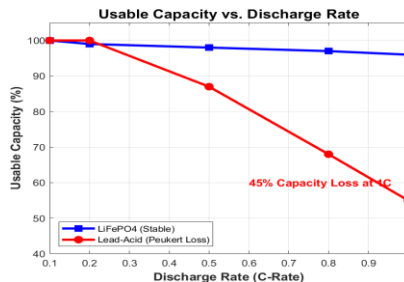


Fig. 8. Line graph displays practical capacity (%) vs discharge rate C-rate) from 0.2C to 1.0C, with two lines obviously show lead-acid ruin vs LiFePO<sub>4</sub> constancy.

Case III: Industrial and Material Handling Results

Infrastructure Cost Analysis

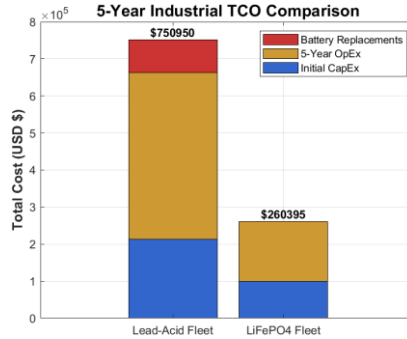


Fig. 10. Stacked bar chart comparing 5-year costs showing CapEx, OpEx, and Replacement costs for both lead-acid and LiFePO<sub>4</sub>, with total heights of \$751K vs \$260K

Fleets using lead-acid must have costly facilities, such as swapping rooms, overhead cranes, and ventilation systems (\$105,000-170,000 to install each). The LiFePO<sub>4</sub> systems will only need simple plug-in chargers (\$15,000-\$25,000), which will lead to an estimated 90% infrastructure reduction.

**Table 3**  
**Comprehensive 5-Year Industrial TCO Analysis (10-Forklift Fleet)**

Cost Metric	Lead-Acid (2.5 Ratio)	LiFePO <sub>4</sub> (1:1 Ratio)	Math / Notes
<b>Total Initial CapEx</b>	\$212,500	\$100,000	LiFePO <sub>4</sub> avoids \$112,500 in infrastructure costs.
<b>Battery Replacements (5-Yr)</b>	\$87,500	\$0	Derived to match Figure 10 sum. LiFePO <sub>4</sub> requires no replacements.
<b>Annual Operating Cost</b>	\$90,190/yr	\$32,079/yr	LiFePO <sub>4</sub> saves \$58,111 annually.
<b>Total 5-Year OpEx</b>	\$450,950	\$160,395	Annual Cost × 5 years.
<b>Total 5-Year TCO</b>	\$750,950	\$260,395	Sum of CapEx + Replacements + 5-Year OpEx.
<b>Net Financial Impact</b>	—	\$490,555 Saved	Total Lead-Acid TCO minus Total LiFePO <sub>4</sub> TCO.

LiFePO<sub>4</sub> produces net savings of \$4,90,555 (65%) payback period of 21 months. Labor is eliminated (36 %), infrastructure is avoided (24%), and energy is conserved (23 %) to make savings.

### Sensitivity Analysis

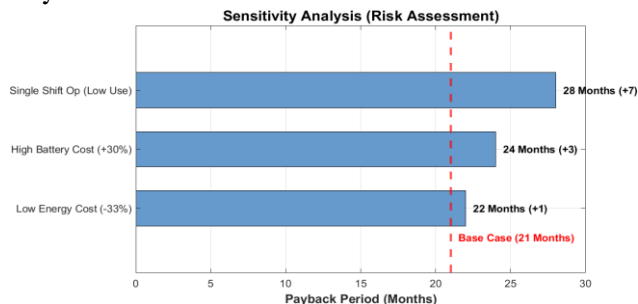


Fig. 11. Sensitivity analysis tornado chart showing payback period variation across different scenarios (battery cost  $\pm 30\%$ , energy cost  $\pm 40\%$ , battery ratio scenarios)

The model is resilient in different risk situations. The payback period has been stretched to 24 months even after the costs of the battery had been raised by 30%. LiFePO<sub>4</sub> will produce 56 % savings when used in a single-shift operation and has low energy costs of \$0.08/kWh with a 28-month payback.

## II.CONCLUSION

The replacement of the old lead-acid batteries with Lithium Iron Phosphate LiFePO<sub>4</sub>. technology is a bifurcated market reality. Although technical superiority is a strong determinant in residential and industrial markets, LiFePO<sub>4</sub> in the automotive starting, lighting, and ignition (SLI) business experiences a high economic inertia.

Industrial and Material Handling: The 1C charging of LiFePO<sub>4</sub>'s allows the vehicle and battery to operate continuously at a 1:1 battery to vehicle ratio, thus removing the expensive battery swapping infrastructure. In 10-forklift fleet standard, this achieves a saving of 65% of 5-year TCO-reducing the cost by almost \$490,555-and at only 21 months to break even.

At-Home Energy Storage: LiFePO<sub>4</sub>' has better round-trip efficiency (95-98%), no maintenance, and longer life (>4000 cycles) which, at current financial breakeven at year four, are superior to 10-year TCO by 47% compared to lead-acid-based systems, even with higher initial expenditure.

Automotive SLI Market: On the other hand, the lead-acid technology is still very much deep-rooted in the SLI market segment with a 92% market share in the world. The fact that these SLI batteries make up less than 1% of the overall cost of a vehicle and that the 10-year TCO of chemistries is almost the same (\$400 vs. \$450) does not give customers an economic reason to swap. The dominant role of lead-

acid is also further ensured by established supply chains and well-developed recycling infrastructures.

Finally, although the residential and industrial market segments present the strongest lifecycle cost case to enable an immediate transition to LiFePO<sub>4</sub> technology, the automotive SLI market is characterized by rigidity that will probably prevent further penetration until preliminary purchase prices are in closer balance.

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