Enhancing Lithium-Ion Battery Manufacturing Efficiency

Subjects: Engineering, Manufacturing

Contributor: Chia-Nan Wang , Fu-Chiang Yang , Nhut T. M. Vo , Van Thanh Tien Nguyen

Innovative carbon reduction and sustainability solutions are needed to combat climate change. One promising approach towards cleaner air involves the utilization of lithium-ion batteries (LIB) and electric power vehicles, showcasing their potential as innovative tools for cleaner air.

EBM lithium-ion batteries DEA Malmquist manufacturing efficiency

1. Introduction

1.1. Overview of the Lithium-Ion Batteries Industry

Lithium-ion batteries have emerged as a dominant technology for portable electronics, electric vehicles, and renewable energy storage due to their high energy density, long life cycle, and environmentally friendly characteristics [1]. As the demand for lithium-ion batteries continues to grow, it becomes imperative to assess the efficiency of lithium-ion battery manufacturers to optimize their performance and ensure sustainable production practices. The global lithium-ion battery industry has experienced remarkable growth, with a market value of USD 42.30 billion in 2020 [2][3][4][5]. It is projected to reach approximately USD 160.21 billion by 2026, growing at a CAGR of around 26.04% [6][7]. This growth can be attributed to several key factors driving the expansion of lithium-ion battery technology.

Firstly, increasing environmental concerns and the need to mitigate carbon emissions from conventional automobiles have spurred the adoption of electric vehicles worldwide [8]. Strict emission standards imposed by the highest authorities in many countries have accelerated the shift towards electric cars, which has fueled the demand for lithium-ion batteries as a preferred choice for powering electric vehicles [7].

Furthermore, the decreasing lithium-ion battery prices and rising investment by market players in research and development to launch batteries with an advanced capacity have contributed to the market growth. Introducing new market participants and model variations for electric vehicles has intensified competition and led to innovations to reduce production costs, further propelling the demand for lithium-ion batteries [9].

Governments of several developing countries are also promoting the adoption of electric vehicles through assistance and incentives for production, consumption, and the development of public charging infrastructure [4]. This encouragement has created a favorable environment for the expanding demand for lithium-ion batteries.

Besides that, lithium-ion batteries' small size, excellent energy efficiency, and low price make them an attractive choice for various applications, including manufacturing, automobile, electronic devices, healthcare gadgets, telecommunication buildings, and other sectors [3][10][11]. The expanding applications of lithium-ion batteries in diverse industries such as military, aviation, smart grid, and passenger cars are expected to boost the market growth further [4][12][13]. The global LIB industry is segmented based on category, structure, employment, market competition, and geographic distribution. A flourishing industry propels the strong demand for lithium-ion battery technology in the thriving automotive sector, an amplified allocation of electric vehicles, and a growing presence of market players in this domain [7].

The global LIB industry is witnessing robust growth driven by increasing environmental concerns, declining prices, investments in research and development, government incentives, and expanding applications [14]. The projected growth in the automotive and traction segment and the overall market presents significant opportunities for manufacturers, investors, and other stakeholders in the lithium-ion battery industry.

1.2. Research Gap and Research Motive

Despite the increasing demand and widespread use of lithium-ion batteries in various applications, there is still a research gap in evaluating the efficiency of lithium-ion battery manufacturers. The current research mainly focuses on assessing the performance of lithium-ion batteries in terms of energy storage capacity, durability, and safety features. However, limited research addresses the efficiency of manufacturers producing these types of batteries. An efficiency evaluation is crucial for manufacturers because it provides detailed information about their operational performance and identifies areas that need improvement. Traditional efficiency evaluation methods, such as Data Envelopment Analysis (DEA) and its variations, have been widely used in various industries to measure efficiency. However, there is still a lack of research applying DEA and other advanced methods to evaluate the efficiency of lithium-ion battery manufacturers.

The primary motive of this study is to bridge the research gap by assessing the efficiency of lithium-ion battery manufacturers using a DEA approach, especially the Malmquist and the Epsilon-Based Measure (EBM) model. The DEA Malmquist model is a widely used method for evaluating the efficiency of a Decision-Making Unit (DMU) over time. The EBM model is a relatively new approach incorporating undesirable outputs in the efficiency assessment process.

By employing these advanced methods, this research aims to provide a comprehensive and accurate assessment of the efficiency of lithium-ion battery manufacturers. This assessment can help identify best practices, benchmarking targets, and areas for improvement in the manufacturing processes of lithium-ion batteries.

2. Study Process

This research presents an innovative and incorporated approach for assessing the efficiency of the top twelve lithium-ion battery companies from 2018 to 2021. The proposed model combines Data Envelopment Analysis

(DEA) Malmquist and Efficiency-Based Measure (EBM) techniques, offering a comprehensive and sophisticated framework for evaluating efficiency in this context [15][16]. The research process for assessing the efficiency of lithium-ion battery manufacturers using the DEA Malmquist and EBM model can be outlined in three main phases, as demonstrated in **Figure 1**.

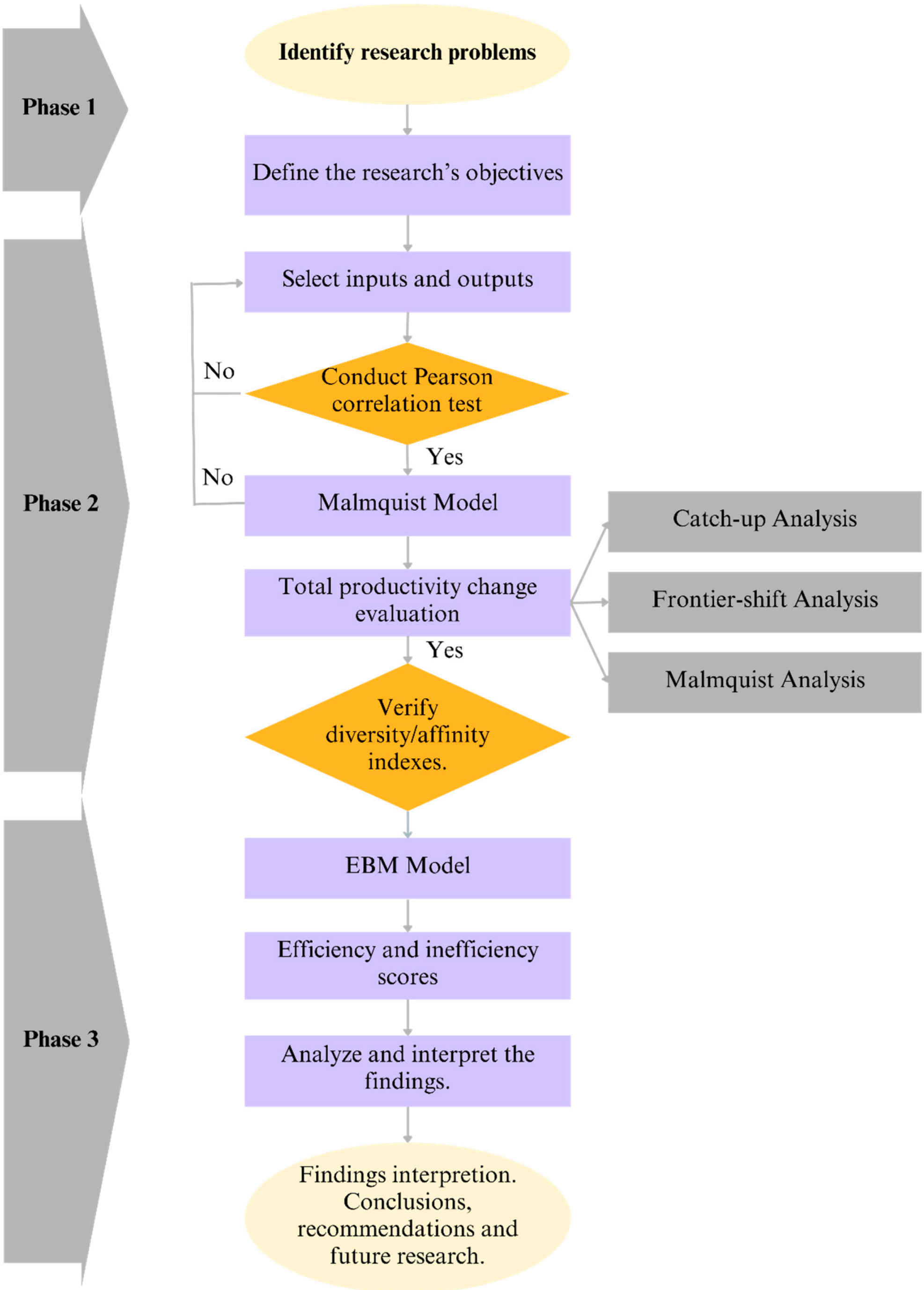

Figure 1. The research framework for a lithium-ion industry assessment.

Phase 1: Problem Analysis and Objective Definition

Researchers expect to find and examine the challenges connected to analyzing the efficiency of lithium-ion producers throughout this phase of the research. Researchers established a precise research objective with specified targets and measurable outcomes.

Phase 2: Data Collection and Analysis

This phase involves selecting the appropriate inputs and outputs for the DEA Malmquist model based on the study objectives and available data. Total assets, liabilities, and SG&A expenses are determined for entry. Based on the study objectives and open data, revenue and gross income are chosen as the outputs for the DEA Malmquist model at this step. A Pearson correlation test assesses data homogeneity and isotonicity, which ensures the study's validity. As part of this total productivity evaluation, the DEA Malmquist model measures lithium-ion producers' "technical efficiency change (catch-up)" and "technological investment (frontier shift)" [17][18][19][20]. Before proceeding to the next stage, a diversity affinity test is run to double-check the diversity and affinity coefficient indices [16].

Phase 3: EBM Model and Results Analysis

In this phase, researchers utilized the Epsilon-Based Measure (EBM) model to determine scores for the efficiency and inefficiency of the Decision-Making Units (DMUs), also known as lithium-ion battery producers, based on the DEA Malmquist model outputs. These scores rank DMUs based on their ability to manufacture lithium-ion batteries. The efficiency and inefficiency scores are evaluated, and the findings are interpreted considering the research objectives. The implications of the results are discussed, as well as the research's limitations and potential paths for additional exploration. The study draws several conclusions and makes recommendations to various stakeholders, including practitioners and policymakers in the lithium-ion manufacturing industry.

Combining the DEA Malmquist and EBM models, this three-phase research process offers a comprehensive approach for evaluating lithium-ion manufacturers' efficiency, considering total productivity change and efficiency scores while ensuring data integrity through a correlation analysis and diversity affinity testing.

The integrated DEA Malmquist and EBM models proposed in this manuscript offer a cutting-edge approach for assessing efficiency in the lithium-ion battery industry, accounting for technical efficiency change and technological investment. Using a Pearson correlation analysis and diversity and affinity coefficient index verification further strengthens the findings' robustness. The results of this study are expected to provide valuable insights for stakeholders, including policymakers and researchers, in the lithium-ion battery industry and contribute to the existing literature on efficiency assessments in the field of battery technology.

3. Efficiency-Based Measure

Some noteworthy studies implemented the efficiency evaluation problems for businesses and manufacturers by combining the Malmquist and EBM models in diverse approaches. Mykhalovskiy et al., 2004 give thoughts, reviews, and evaluations to assist in developing more comprehensive social scientific research of EBM [21]. Li et al., 2020 utilized a modified meta-two-stage EBM Malmquist approach to investigate regional disparities in thirty-one Chinese cities' economies, energies, environments, health, and media during 2014–2016 [22]. A quantitative method was used by Rusli et al. to evaluate the logistics sector in Malaysia before and after the COVID-19 pandemic by comparing the sector's effectiveness and efficacy using the EBM and Malmquist index approaches. [23]. Data envelopment analysis is used to analyze the energy efficiency of China's coastal regions in terms of air emissions between 2000 and 2012 (Qin et al., 2017) [24]. Carbon dioxide, sulfur dioxide, and nitrogen oxide emissions are all negative consequences of energy consumption.

Under the new regulation, the process by which banks develop appropriate internal judgments for absorbing international strategic capital becomes crucial for managing banks. Constant productivity improvements will lead to long-term growth; thus, the goals are as follows: (1) to figure out the connection between international strategic ventures and improvements in the output of China's banks and to validate the effectiveness of implementing overseas strategic investing; (2) to determine the best overseas ownership percentage; and (3) to illustrate the impact of overseas strategic expenditures on China's financial institution efficiency, i.e., the way it transmits between institutions [25].

Cheng et al., 2019 discover that the Malmquist trend of total factor productivity indicators corresponds with the findings from the best practice gap change (BPC) and pure technological catch-up indexes (PTCU), indicating that the BPC and PTCU indexes' innovation effects are the primary factors responsible for productivity improvement [26]. Lu et al. 2020 use a three-stage DEA model and a period neural network framework to assess and forecast total factor productivity in Chinese petroleum enterprises [27]. From 2009 to 2018, the panel data from 50 publicly traded Chinese petroleum companies were used. A three-stage Data Envelopment Analysis (DEA) model was used to exclude environmental and random effects. As a result, the radial basis function neural network prediction model was employed to forecast the total factor productivity of publicly traded petroleum businesses over the following two years.

A two-phase DEA methodology based on EBM and Malmquist is used to investigate the effectiveness of maritime transportation in European countries. The results identify the most prosperous nations across multiple economic sectors from 2016 to 2019 and demonstrate that the research gap in applying the EBM method to marine transport has been successfully filled [28].

References

1. Bridge, G.; Faigen, E. Towards the lithium-ion battery production network: Thinking beyond mineral supply chains. Energy Res. Soc. Sci. 2022, 89, 102659.
2. Lithium-Ion Battery Market Size, Share & COVID-19 Impact Analysis. Available online: https://www.fortunebusinessinsights.com/industry-reports/lithium-ion-battery-market-100123

(accessed on 20 March 2023).

3. Chordia, M.; Nordelöf, A.; Ellingsen, L.A.-W. Environmental life cycle implications of upscaling lithium-ion battery production. Int. J. Life Cycle Assess. 2021, 26, 2024–2039.
4. Duan, J.; Tang, X.; Dai, H.; Yang, Y.; Wu, W.; Wei, X.; Huang, Y. Building safe lithium-ion batteries for electric vehicles: A review. Electrochem. Energy Rev. 2020, 3, 1–42.
5. Kurland, S.D. Energy use for GWh-scale lithium-ion battery production. Environ. Res. Commun. 2019, 2, 012001.
6. Chapman, A.; Arendorf, J.; Castella, T.; Thompson, P.; Willis, P.; Espinoza, L.T.; Klug, S.; Wichmann, E. Study on Critical Raw Materials at EU Level; Oakdene Hollins: Buckinghamshire, UK, 2013.
7. Zhang, X.; Li, Z.; Luo, L.; Fan, Y.; Du, Z. A review on thermal management of lithium-ion batteries for electric vehicles. Energy 2022, 238, 121652.
8. Cairns, E.J.; Albertus, P. Batteries for electric and hybrid-electric vehicles. Annu. Rev. Chem. Biomol. Eng. 2010, 1, 299–320.
9. Velázquez-Martínez, O.; Valio, J.; Santasalo-Aarnio, A.; Reuter, M.; Serna-Guerrero, R. A critical review of lithium-ion battery recycling processes from a circular economy perspective. Batteries 2019, 5, 68.
10. Ding, Y.; Chen, X.; Wang, J. Deep Reinforcement Learning-Based Method for Joint Optimization of Mobile Energy Storage Systems and Power Grid with High Renewable Energy Sources. Batteries 2023, 9, 219.
11. Mohanty, D.; Chen, S.-Y.; Hung, I.-M. Effect of Lithium Salt Concentration on Materials Characteristics and Electrochemical Performance of Hybrid Inorganic/Polymer Solid Electrolyte for Solid-State Lithium-Ion Batteries. Batteries 2022, 8, 173.
12. Dunn, J.B.; Gaines, L.; Sullivan, J.; Wang, M.Q. Impact of recycling on cradle-to-gate energy consumption and greenhouse gas emissions of automotive lithium-ion batteries. Environ. Sci. Technol. 2012, 46, 12704–12710.
13. Emilsson, E.; Dahllöf, L. Lithium-Ion Vehicle Battery Production-Status 2019 on Energy Use, CO2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling; IVL Svenska Miljöinstitutet: Stockholm, Sweden, 2019.
14. Yu, M.L.; Jin, H.; Zhang, H.J.; Chong, A.Y.L. ICT, Financial Development and Renewable Energy Consumption. J. Comput. Inf. Syst. 2023, 63, 190–203.
15. Saranga, H. The Indian auto component industry–Estimation of operational efficiency and its determinants using DEA. Eur. J. Oper. Res. 2009, 196, 707–718.

16. Tone, K.; Tsutsui, M. An epsilon-based measure of efficiency in DEA—A third pole of technical efficiency. Eur. J. Oper. Res. 2010, 207, 1554–1563.
17. Charnes, A.; Cooper, W.W.; Rhodes, E. Measuring the efficiency of decision making units. Eur. J. Oper. Res. 1978, 2, 429–444.
18. Chen, K.; Ren, X.T.; Yang, G.L.; Qin, H.B. The other side of the coin: The declining of Chinese social science. Scientometrics 2022, 127, 127–143.
19. Chen, X.; Liu, Z.; Saydaliev, H.B.; Abu Hatab, A.; Fang, W. Measuring Energy Efficiency Performance in China: Do Technological and Environmental Concerns Matter for Energy Efficiency? Front. Energy Res. 2021, 9, 779032.
20. Chen, Y.W.; Yang, R.; Wong, C.W.Y.; Ji, J.W.; Miao, X. Efficiency and productivity of air pollution control in Chinese cities. Sustain. Cities Soc. 2022, 76, 103423.
21. Mykhalovskiy, E.; Weir, L. The problem of evidence-based medicine: Directions for social science. Soc. Sci. Med. 2004, 59, 1059–1069.
22. Li, Y.; Chiu, Y.-h.; Liu, Y.; Lin, T.-Y.; Chang, T.-H. The impact of the media and environmental pollution on the economy and health using a modified meta 2-stage EBM Malmquist model. Inq. J. Heal. Care Organ. Provis. Financ. 2020, 57, 0046958020921070.
23. Rusli, N.A.E.; Ramli, N.A.; Shariff, S.S.R.; Zahid, Z.; Hussin, S.A.S. Evaluating the efficiency and productivity of Malaysian logistics companies using epsilon-based measure and Malmquist index during the Covid-19 pandemic. J. Ind. Eng. Manag. 2022, 15, 521–537.
24. Qin, Q.D.; Li, X.; Li, L.; Zhen, W.; Wei, Y.M. Air emissions perspective on energy efficiency: An empirical analysis of China’s coastal areas. Appl. Energy 2017, 185, 604–614.
25. Yang, W.P.; Zhao, B.Y.; Zhao, J.K.; Li, Z.D. An Empirical Study on the Impact of Foreign Strategic Investment on Banking Sustainability in China. Sustainability 2019, 11, 181.
26. Cheng, S.X.; Xie, J.H.; Xiao, D.; Zhang, Y. Measuring the Environmental Efficiency and Technology Gap of PM2.5 in China’s Ten City Groups: An Empirical Analysis Using the EBM Meta-Frontier Model. Int. J. Environ. Res. Public Health 2019, 16, 675.
27. Lu, L.; Zhang, J.J.; Yang, F.; Zhang, Y.J. Evaluation and prediction on total factor productivity of Chinese petroleum companies via three-stage DEA model and time series neural network model. Sustain. Comput. Inform. Syst. 2020, 27, 100397.
28. Nguyen, P.H.; Nguyen, T.L.; Nguyen, T.G.; Nguyen, D.T.; Tran, T.H.; Le, H.C.; Phung, H.T. A Cross-Country European Efficiency Measurement of Maritime Transport: A Data Envelopment Analysis Approach. Axioms 2022, 11, 206.