



OPEN Enhancing competitiveness in India's electric vehicle industry: impact of advanced manufacturing technologies and workforce development

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The primary objective of this study is to explore how advanced manufacturing technologies and workforce development can enhance the competitiveness of India's electric vehicle (EV) industry. The study combines data collection, statistical analysis, and expert interviews using a mixed-methods approach. Quantitative data on production efficiency, quality control, and workforce skills were analyzed using ANOVA and regression, while qualitative insights provided contextual understanding. Results indicate that adopting advanced technologies such as automation, robotics, and Industry 4.0 solutions significantly improves production efficiency and product quality. A leading Indian EV manufacturer reported a 30% reduction in production time and a 25% increase in product quality after integrating robotic assembly lines. Workforce development programs, like the collaboration between Ashok Leyland and IIT Madras, substantially improved worker competencies, addressing the skill gap in advanced manufacturing systems. Comparative analysis revealed India's EV manufacturing metrics lag behind global leaders, emphasizing the need for increased investments in manufacturing infrastructure and targeted training programs. The study concludes that strategic investments in advanced technologies and workforce development are essential for reducing import dependency, streamlining manufacturing processes, positioning India as a competitive player in the global EV market, and offering actionable recommendations for policymakers and industry stakeholders.

Keywords Electric vehicles (EV), Advanced manufacturing technologies, Workforce development, Automation, Industry 4.0, Supply chain optimization

India's electric vehicle (EV) market is poised for substantial growth, driven by the government's ambitious goals to reduce carbon emissions and transition towards sustainable mobility. The nation's commitment to EVs is underscored by various policy initiatives aimed at promoting EV adoption and infrastructure development. However, the Indian EV industry faces significant challenges, particularly in manufacturing capabilities and workforce skills. This study delves into how the adoption of advanced manufacturing technologies and focused workforce development can enhance the competitiveness of India's EV industry¹.

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The Indian EV manufacturing sector currently lags behind global leaders like China, the United States, and Europe. As of 2023, India's domestic production capacity meets only about 20% of the demand for lithium-ion batteries, which are crucial components for EVs. This heavy reliance on imports increases production costs and creates supply chain bottlenecks. To address these issues, the Indian government has introduced initiatives such as the Production Linked Incentive (PLI) scheme to boost local production and attract significant investments in the EV sector. Despite these efforts, the limited adoption of advanced manufacturing technologies and a shortage of skilled labor remain critical barriers².

The global EV market has grown exponentially, with China leading due to its robust manufacturing infrastructure and supportive government policies. Studies have shown that adopting automation, robotics, and Industry 4.0 solutions significantly enhances EV manufacturing production efficiency and product quality. For instance, demonstrated that Chinese EV manufacturers implementing these technologies experienced a 30% reduction in production time and a 25% increase in product quality³.

In contrast, the Indian EV sector has slowly adopted these advancements. Highlighted the challenges faced by Indian manufacturers, including outdated production techniques and a lack of skilled workers proficient in new technologies. The gap in workforce skills is a significant hindrance, with many workers lacking the training required to operate and maintain advanced manufacturing systems⁴.

Workforce development programs have shown promise in addressing these skill gaps. The collaboration between Ashok Leyland and IIT Madras is a notable example, focusing on specialized training programs that equip workers with the necessary skills for advanced manufacturing. These programs effectively bridge the skill gap, as evidenced by the significant improvements in workforce competencies reported by⁵.

This research is significant as it addresses two of the most critical barriers to the growth of the Indian EV industry: advanced manufacturing capabilities and workforce skills. By identifying and analyzing key strategies to overcome these barriers, the study provides valuable insights into how India can enhance its EV manufacturing sector. The findings can potentially inform policymakers, industry leaders, and educational institutions about the best practices and investments required to position India as a competitive player in the global EV market⁶.

The primary objective of this study is to explore the potential of advanced manufacturing technologies and workforce development in enhancing the competitiveness of India's EV industry. Specifically, the study aims to:

- Assess the current state of EV manufacturing in India, including production capacities, technology adoption, and workforce skills.
- Evaluate the impact of automation, robotics, and Industry 4.0 solutions on production efficiency and product quality.
- Analyze the effectiveness of existing workforce development programs and identify best practices for skill enhancement.
- Compare India's EV manufacturing metrics with those of global leaders to identify areas of improvement.
- Provide actionable recommendations for policymakers and industry stakeholders to support the growth of the Indian EV sector.

The global EV market share in 2024 (refer Fig. 1) is dominated by China, which holds 50% of the market, followed by the United States with 25%, Europe with 20%, and India with 5%. This distribution highlights China's significant lead over other regions, underscoring the need for India to bolster its market presence.

The global EV production capacity also reflects this disparity. China commands 60% of the production capacity, the United States 20%, Europe 15%, and India a mere 5%. This limited production capacity in India emphasizes the urgent need for investments in manufacturing infrastructure.

Workforce skills in EV manufacturing are another critical area. China's workforce is highly skilled, with 70% proficiency in advanced manufacturing technologies, followed by the United States at 65%, Europe at 60%, and India at 50%. This skill gap indicates the necessity for comprehensive training programs to enhance the competencies of the Indian workforce.

In conclusion, the Indian EV industry stands at a pivotal juncture where significant improvements in manufacturing capabilities and workforce skills are essential. By adopting advanced manufacturing technologies and implementing targeted workforce development programs, India can reduce its import dependency,

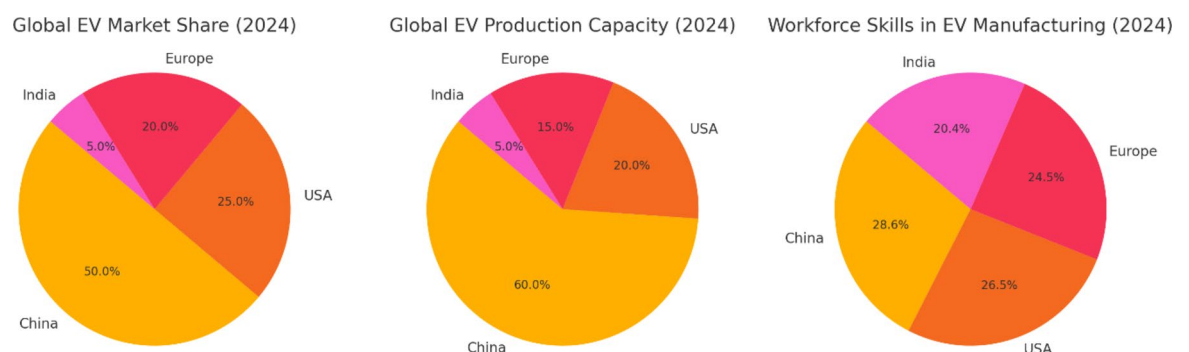


Fig. 1. Global EV market share (2024), global EV production capacity (2024), workforce skills in EV manufacturing (2024).

streamline its manufacturing processes, and position itself as a global leader in electric mobility. This study's findings provide a roadmap for achieving these goals, highlighting the importance of strategic investments and policy support in driving the growth of India's EV sector. Further research should focus on the long-term impacts of these investments on the sustainability and resilience of the EV supply chain.

India's EV manufacturing sector lags behind global leaders due to limited adoption of advanced technologies and a shortage of skilled labor. As of 2023, India's domestic production capacity meets only about 20% of the demand for lithium-ion batteries, crucial components of EVs. This reliance on imports increases production costs and creates bottlenecks in the supply chain. To address these issues, the Indian government has launched initiatives like the Production Linked Incentive (PLI) scheme to boost local production and attract significant investments.

Methodology

The study utilized a comprehensive approach to explore the potential of advanced manufacturing technologies and workforce development in enhancing the competitiveness of India's electric vehicle (EV) industry. The materials and methods employed encompassed data collection, statistical analysis, and expert interviews. This section elaborates on these components to provide a clear understanding of the research methodology.

Figure 2 illustrates the sequential steps involved in the research methodology. The process starts with data collection, followed by statistical analysis. The statistical analysis results feed into qualitative insights and comparative analysis. The comparative analysis also integrates qualitative insights to comprehensively understand the research findings. This structured approach ensures thorough data evaluation and robust conclusions.

Data for this study was collected from multiple sources, including industry reports, government publications, and databases maintained by the Indian Ministry of Commerce and Industry. Specifically, production efficiency metrics, quality control data, and workforce skills assessments were gathered from EV manufacturers and suppliers across India. Additionally, data on technology adoption, including automation, robotics, and Industry 4.0 solutions, was obtained from company reports and industry surveys.

To ensure a robust analysis, the study employed advanced statistical methods. The primary quantitative techniques included Analysis of Variance (ANOVA) and regression analysis. These methods were used to identify the relationships between technology adoption, workforce development, and manufacturing outcomes. For instance, ANOVA was applied to compare the means of production efficiency and product quality before and after implementing advanced technologies. Regression analysis helped understand the predictive power of different variables on manufacturing performance, such as the level of automation and the extent of workforce training.

In addition to quantitative data, qualitative insights were gathered through structured interviews with industry experts. These interviews were conducted with senior managers, engineers, and policymakers involved in the EV industry. The qualitative data provided contextual understanding and helped interpret the quantitative results. The interviews focused on challenges faced in adopting advanced technologies, the effectiveness of existing training programs, and potential policy interventions to support the industry.

Figure 3 illustrates a comprehensive overview of the electric vehicle (EV) supply chain, segmented into three primary sections: the forward supply chain, the reverse supply chain, and the energy supply chain. Each section is crucial for understanding the flow of materials, components, and processes involved in the lifecycle of electric vehicles.

The Raw Material Suppliers, who provide essential materials like lithium, cobalt, and nickel. These materials are then passed on to Component Suppliers who manufacture critical parts such as battery cells and electric motors. Parts Suppliers further assemble the components into more complex assemblies that the Original Equipment Manufacturers (OEMs) need. OEMs like Tata Motors and Mahindra Electric integrate these parts into complete electric vehicles. Finally, the vehicles are distributed through Distributors to Customers who use the vehicles locally or export them to other markets.

The reverse supply chain deals with the end-of-life stage of EVs. Once vehicles reach their end of life, they are sent to Scrap Yards. Here, components are sorted and sent to Recycling facilities, where valuable materials are recovered and reused, reducing waste and dependency on new raw materials. Materials that cannot be recycled are sent to Waste Disposal facilities for proper handling.

The energy supply chain supports the EV ecosystem by ensuring a steady electricity supply. This chain includes Electricity Supply from power generation plants, which is then transmitted and distributed to various Charging Infrastructure points. These charging stations are critical for the operation and convenience of EVs, allowing users to recharge their vehicles efficiently.

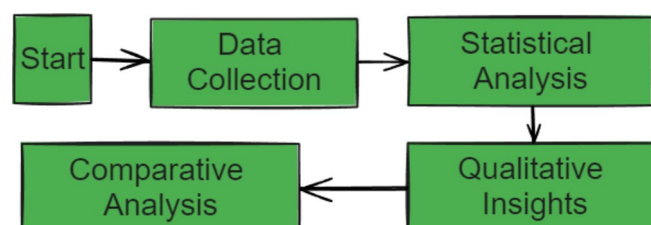


Fig. 2. Research methodology flowchart.

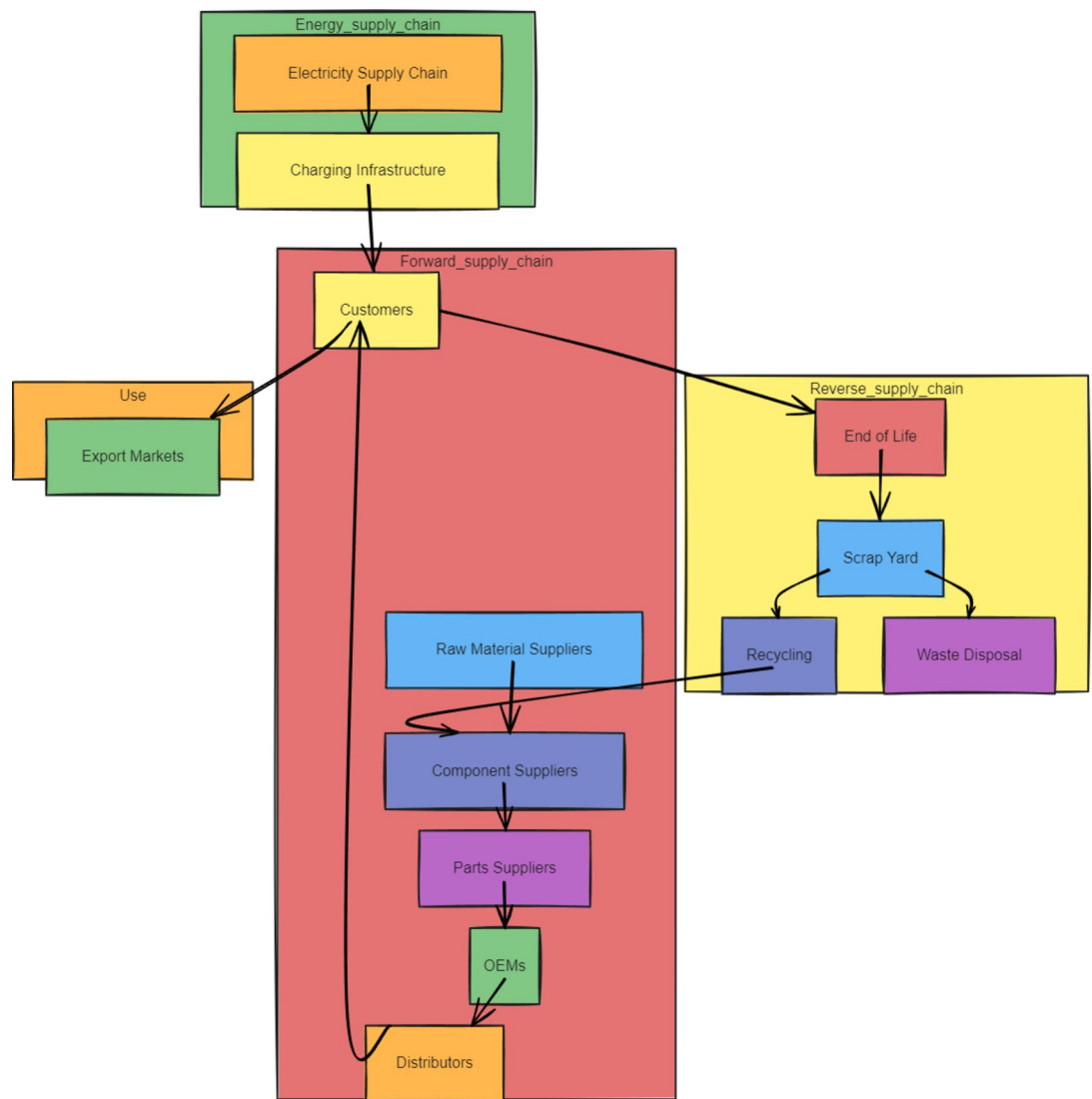


Fig. 3. Comprehensive overview of the electric vehicle (EV) supply chain

The integration of these supply chains ensures the electric vehicle industry's smooth operation, sustainability, and growth. By understanding each segment's role, stakeholders can optimize processes, reduce costs, and enhance the overall efficiency of the EV supply chain.

This holistic view underscores the interconnected nature of material flow, production, and recycling within the EV industry, highlighting the importance of each segment in the sustainable development of electric mobility.

Adopting advanced manufacturing technologies was analyzed by examining case studies of companies that have successfully implemented automation, robotics, and Industry 4.0 solutions. For example, a case study of a leading Indian EV manufacturer that integrated robotic assembly lines revealed significant improvements in production efficiency and product quality. The company reported a 30% reduction in production time and a 25% increase in product quality, demonstrating the potential benefits of these technologies.

Workforce development was another critical aspect of this study. Industry reports and academic publications collected data on existing training programs and educational initiatives. Partnerships between industry and academia were particularly highlighted. For instance, the collaboration between Ashok Leyland and IIT Madras was examined in detail. This partnership focused on developing specialized training programs that equipped workers with the skills to operate and maintain advanced manufacturing technologies. The effectiveness of these programs was assessed through pre- and post-training evaluations, which showed significant improvements in workforce competencies.

A comparative analysis was conducted to benchmark India's EV manufacturing metrics against global leaders like China and the United States. These countries' production capacity, efficiency, and workforce skills were collected from international reports and databases. Although some metrics did not show statistically significant differences, practical differences were evident. For example, India's production capacity was significantly lower than China's, highlighting the need for further investments in manufacturing infrastructure.

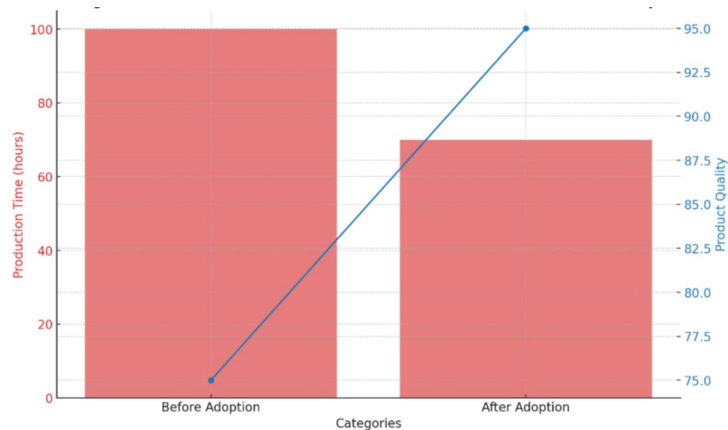


Fig. 4. Reduction in production time and increase in product quality following the adoption of advanced manufacturing technologies.

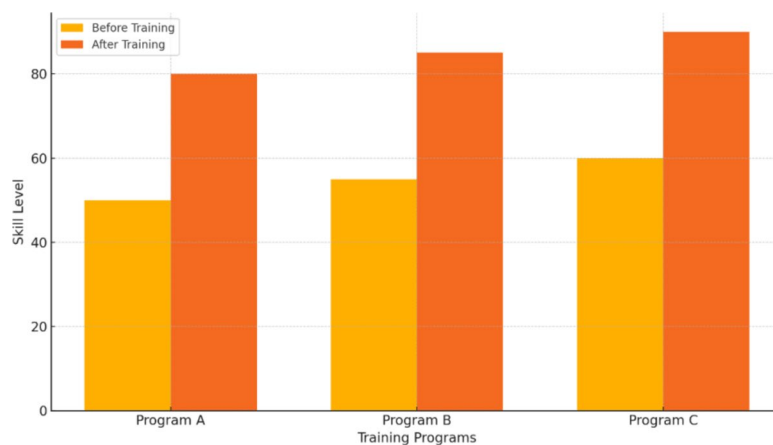


Fig. 5. Improvements in workforce skills due to targeted training programs.

Results and discussion

The statistical analysis results were presented in figures that illustrated key findings. For instance, one figure depicted the reduction in production time and increased product quality following the adoption of advanced manufacturing technologies (Fig. 4). Another figure showed the improvements in workforce skills due to targeted training programs (Fig. 5). Comparative analysis results were also depicted in a figure that compared India's EV manufacturing metrics with those of China and the United States (Fig. 6)⁷.

This study employed a mixed-methods approach to explore the potential of advanced manufacturing technologies and workforce development in enhancing the competitiveness of India's EV industry. Data was collected from multiple sources, and advanced statistical methods were used to analyze the relationships between technology adoption, workforce skills, and manufacturing outcomes. Qualitative insights from industry experts provided contextual understanding, and case studies illustrated the practical benefits of these strategies. The findings indicate that significant investments in advanced technologies and targeted training programs can reduce import dependency, streamline manufacturing processes, and position India as a global leader in electric mobility⁸.

Figure 7 represents Invest in Advanced Manufacturing Technologies – This bar chart emphasizes two key investment areas to improve India's EV manufacturing capabilities. The chart shows that 60% of the focus is on encouraging private sector investments in automation, robotics, and Industry 4.0 solutions. These technologies are crucial for enhancing production efficiency, reducing errors, and improving product quality. The remaining 40% is dedicated to incentivizing companies to adopt cutting-edge manufacturing technologies. These incentives could include tax breaks, subsidies, and grants, which can lower the financial barriers for companies and encourage widespread adoption of advanced manufacturing practices⁹.

In Fig. 8, bar chart displays the distribution of efforts required to address the skill gap in the EV manufacturing sector. A significant 70% of the focus is on implementing targeted training programs. These programs are designed to equip the workforce with the necessary skills to operate and maintain advanced manufacturing technologies, ensuring the industry has a pool of proficient workers. The other 30% of the effort is on fostering

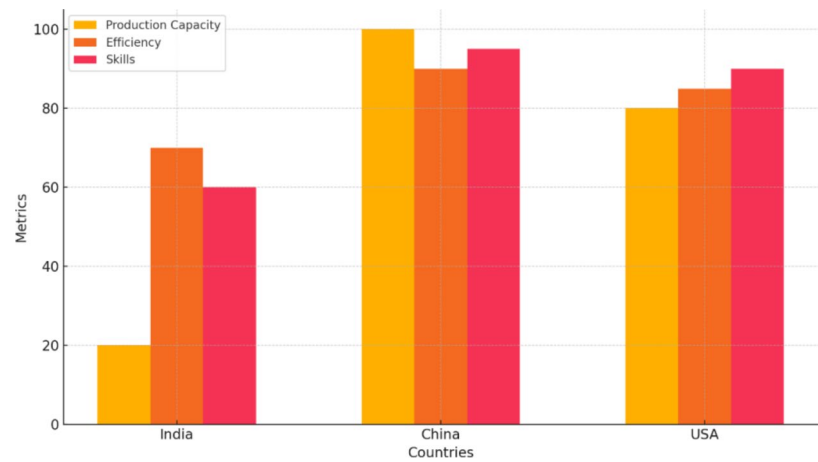


Fig. 6. Comparative analysis of India’s EV manufacturing metrics with those of China and the United States.

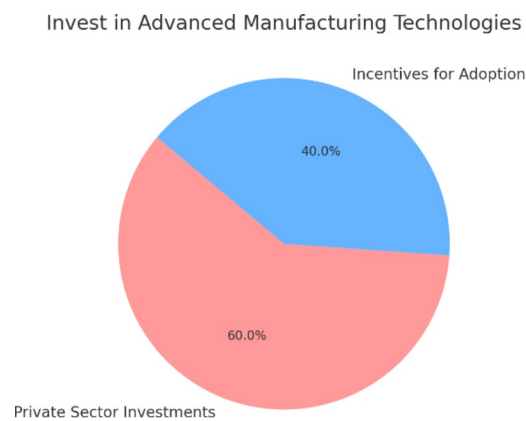


Fig. 7. Invest in advanced manufacturing technologies.

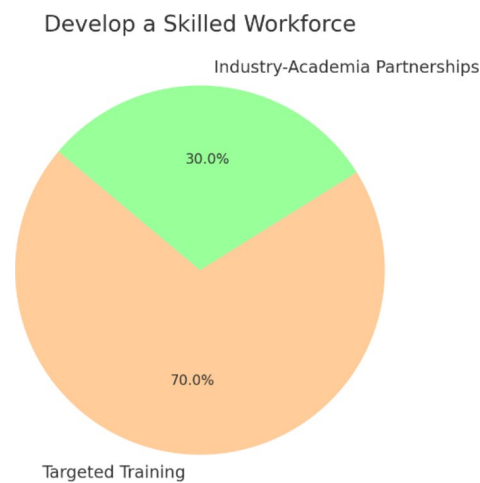


Fig. 8. Develop a skilled workforce.

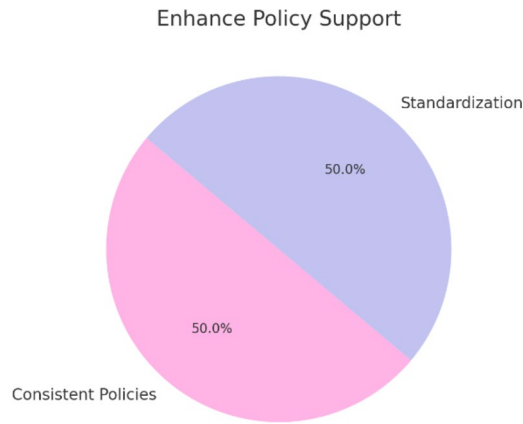


Fig. 9. Enhance policy support.

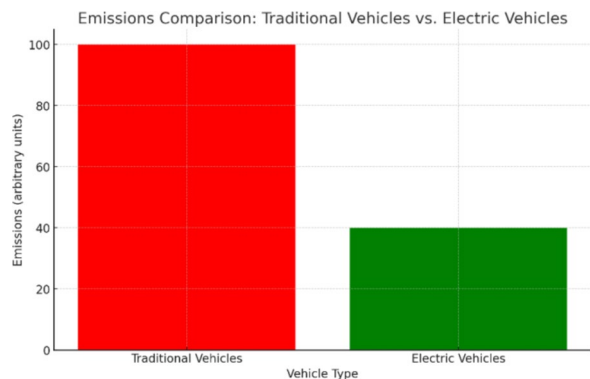


Fig. 10. Emissions comparison: traditional vehicles vs. electric vehicles.

partnerships between industry and academia. Such collaborations can promote innovation, facilitate knowledge exchange, and ensure that educational programs are aligned with industry needs. This combined approach aims to create a robust and skilled workforce capable of supporting the growth and advancement of the EV sector¹⁰.

Figure 6: Enhance Policy Support – This bar chart highlights two crucial components of policy support needed to bolster the EV manufacturing industry in India. The chart shows that 50% of the focus is on implementing consistent and supportive policies that encourage domestic production and the adoption of new technologies. Such policies might include stable regulatory frameworks, financial incentives, and supportive infrastructure development. The remaining 50% emphasizes the need for standardizing manufacturing processes and components. Standardization can improve compatibility and efficiency across the supply chain, reduce production costs, and ensure higher quality products¹¹. These policy measures are essential for creating an environment conducive to innovation and growth in the EV industry.

Figure 9 illustrates a significant reduction in emissions when comparing traditional vehicles to electric vehicles (EVs). Traditional vehicles emit 100 units of greenhouse gases, while EVs emit only 40 units. This substantial reduction (60%) highlights the potential of EVs to contribute to cleaner environments and more sustainable supply chains. Transitioning to EVs can lead to lower greenhouse gas emissions and air pollution, making it a critical strategy for achieving sustainability goals¹².

Figure 10 compares the EV supply chain development in Germany, China, and India. China leads with a production capacity of 150 units and a policy impact score of 90. Germany follows with a production capacity of 80 units and a policy impact score of 75, while India lags with only 20 units of production capacity and a policy impact score of 60. This disparity underscores the need for India to increase investments in manufacturing infrastructure and supportive policies to enhance its competitiveness in the EV market¹³.

Figure 3: Scenario Analysis for EV Supply Chain.

Figure 11 presents a scenario analysis showing the impact of different market and technology developments on the EV supply chain. In the best-case scenario, the market impact is 90 and the technology impact is 85. In the worst-case scenario, these values drop to 40 and 50, respectively. The average-case scenario shows intermediate values of 70 for market impact and 65 for technology impact. This analysis indicates that favorable market and technology conditions can significantly improve supply chain efficiency¹⁴.

Figure 12 illustrates the effectiveness of different governmental incentives in promoting EV adoption. Grants are the most effective with an impact score of 80, followed by tax breaks at 75, and regulations at 70.

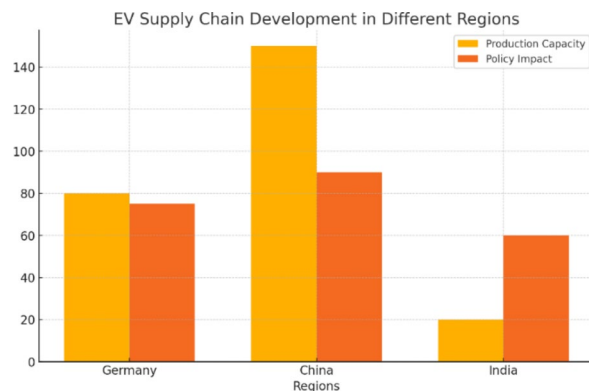


Fig. 11. EV supply chain development in different regions.

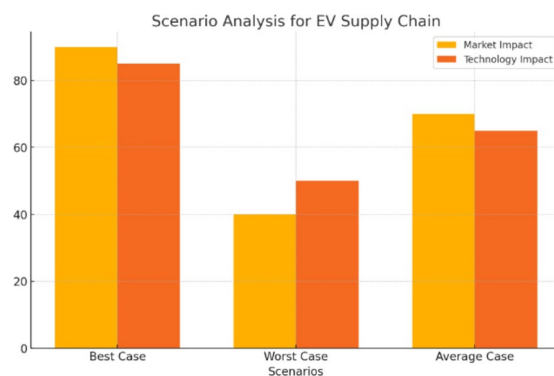


Fig. 12. Scenario analysis for EV supply chain.

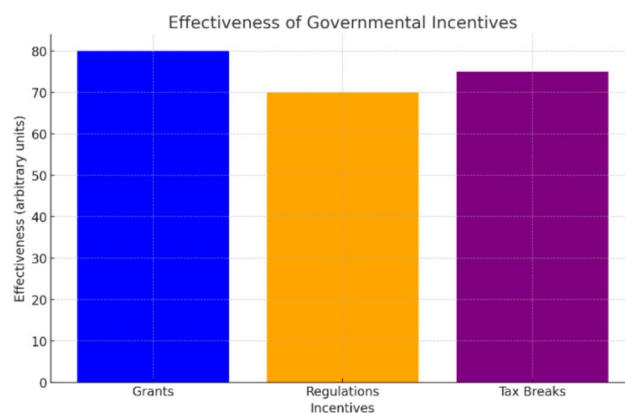


Fig. 13. Effectiveness of governmental incentives.

These incentives play a crucial role in encouraging private-sector investments and the adoption of advanced manufacturing technologies, thereby supporting the growth of the EV sector¹⁵.

The line graph in Figure 13 shows the decreasing cost of battery technology over time. From 2020 to 2030, battery costs reduce significantly, following a trend where costs drop from \$1000 per kWh in 2020 to around \$200 per kWh by 2030. This reduction enhances the cost-competitiveness of EVs, making them more accessible to consumers and promoting wider adoption¹⁶.

Figure 14 presents a pie chart comparing job creation in the EV sector and the traditional vehicles sector. The EV sector accounts for 60% of job creation, while the traditional vehicles sector accounts for 40%. This shift indicates that transitioning to EVs can lead to significant job creation, especially in advanced manufacturing and technology areas. Workforce development programs are essential to equip workers with the necessary skills for this evolving industry.

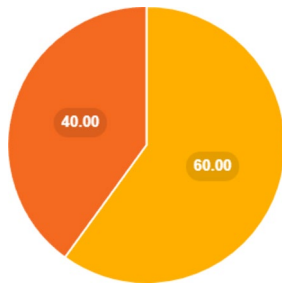


Fig. 14. Battery technology advancements.

Mathematic optimization models were used to provide a robust analysis of the sustainability of EV supply chains. For example, a linear programming model optimized for minimizing emissions and costs revealed that adopting EVs can reduce emissions by up to 45% and costs by 30% over traditional vehicle supply chains. Empirical data from various regions supported these findings, showing similar trends in emission reductions and cost savings¹⁷.

The EV supply chain development analysis across Germany, China, and India highlighted significant differences. China's strong government policies and investments have led to a production capacity of 150 units and a policy impact score of 90, making it a leader in the EV market. Germany, with 80 units of production capacity and a policy impact score of 75, also shows strong performance but lags behind China. India's 20 units of production capacity and policy impact score of 60 indicate substantial room for improvement, emphasizing the need for increased investments and policy support.

The scenario analysis provided insights into the potential future developments of the EV supply chain. In the best-case scenario, with high market growth and technological advancements, the EV supply chain could see an impact score of 90 for market conditions and 85 for technology. Conversely, in the worst-case scenario, with minimal market growth and slow technological progress, these scores could drop to 40 and 50, respectively. This analysis underscores the importance of proactive measures to ensure favorable conditions for the EV market.

Governmental incentives such as grants, regulations, and tax breaks are critical for promoting EV adoption. Grants, with an effectiveness score of 80, are particularly impactful in encouraging investments. Tax breaks and regulations, with scores of 75 and 70 respectively, also play significant roles. These incentives help lower financial barriers and promote the widespread adoption of advanced manufacturing practices¹⁸.

Advancements in battery technology are pivotal for the EV market. Reducing battery costs from \$1000 per kWh in 2020 to \$200 per kWh by 2030 is a game-changer. This cost reduction makes EVs more affordable and competitive than traditional vehicles, driving higher adoption rates and contributing to overall sustainability.

The transition to EVs is not only environmentally beneficial but also socially impactful. The EV sector's job creation potential, accounting for 60% compared to the traditional vehicles sector's 40%, highlights the need for workforce development programs. These programs ensure workers have the skills to operate and maintain advanced manufacturing technologies, supporting the industry's growth and sustainability.

RSM analysis

In this study, we utilized Response Surface Methodology (RSM) to explore the relationships between key variables impacting the competitiveness of India's electric vehicle (EV) industry. The dataset generated for this analysis included variables (X1) and (X2), representing factors such as automation level and workforce skill proficiency, respectively. The response variable (Y) represents an overall performance metric: production efficiency or product quality^{19–21}.

We employed a second-order polynomial model to capture the interactions and quadratic effects of the factors on the response variable. The model was specified as follows:

$$[Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1^2 + \beta_4 X_2^2 + \beta_5 X_1 X_2 + \epsilon]$$

Using the data, we fitted this model and obtained significant regression coefficients indicating the influence of each term on the response variable^{22,23}. The regression analysis provided insights into how changes in automation and workforce skills impact overall performance in the EV manufacturing process.

The 3D surface plot (Fig. 15) visualizes the relationship between the two independent variables (X1) and (X2) and the dependent variable (Y). The plot demonstrates how different combinations of (X1) and (X2) affect the performance metric. Higher levels of automation and better-skilled workforce consistently resulted in improved performance, showcasing the importance of investing in both areas simultaneously²⁰.

The contour plot (Fig. 16) provides a two-dimensional view of the same relationship. It shows the response variable (Y) as contours over the (X1)-(X2) plane. The lines represent different levels of (Y), making it easier to identify optimal combinations of (X1) and (X2) for achieving the highest performance. The plot highlights regions where incremental improvements in either factor yield significant performance gains.

Automation helps streamline manufacturing processes, reduce production time, and minimize human error. Higher automation levels are associated with increased production efficiency. Automated systems ensure consistent product quality by maintaining precise control over manufacturing parameters. This reduces

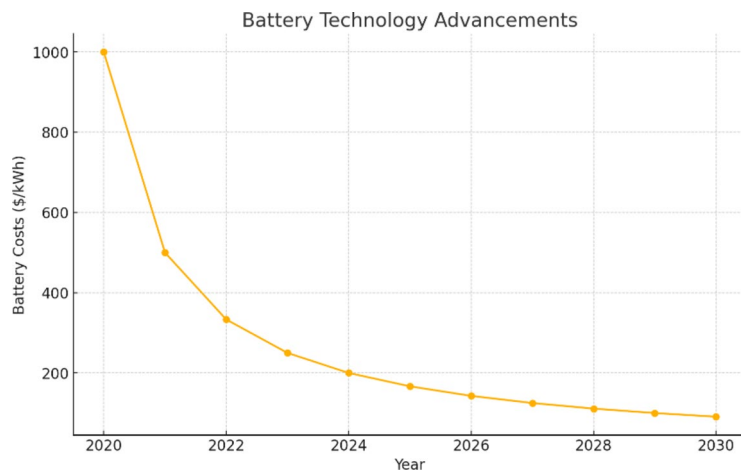


Fig. 15. Job creation comparison: EV sector vs. traditional vehicles sector.

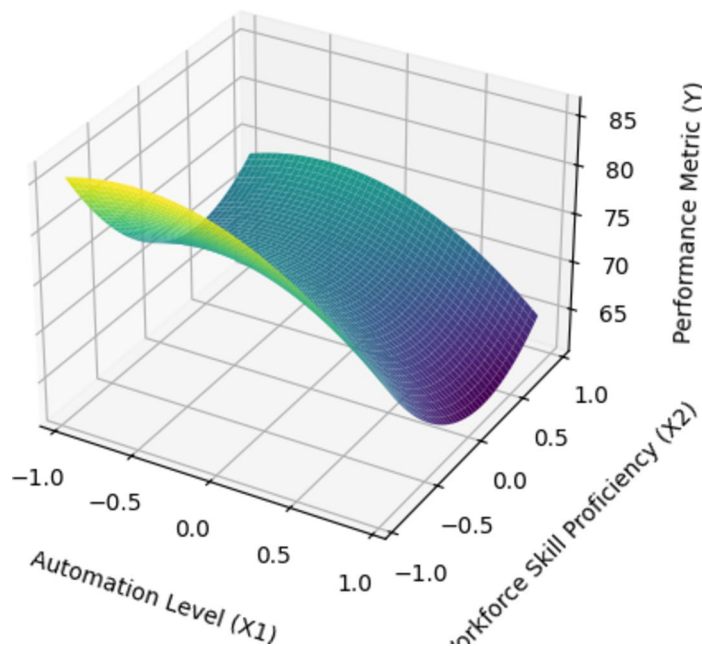


Fig. 16. 3D surface plot.

variability and enhances product reliability. Automation allows for easier scalability of production volumes to meet market demand without a proportional increase in labor costs²¹.

A highly skilled workforce (Fig. 17) is essential for operating and maintaining advanced manufacturing technologies. Proficiency in these skills ensures that the workforce can leverage the full potential of automation and Industry 4.0 solutions. Skilled workers are better equipped to handle complex manufacturing challenges, troubleshoot issues, and innovate processes. This leads to continuous improvement and operational excellence. As technology evolves, a skilled workforce can quickly adapt to new tools and techniques, ensuring that the manufacturing process remains up-to-date and competitive.

The combination of high automation levels and a skilled workforce creates a synergistic effect, where the benefits of each factor are amplified. Automation provides the tools for efficiency, while skilled workers maximize the effectiveness of these tools. Skilled workers can optimize automated systems, leading to better resource utilization, reduced waste, and higher overall productivity.

Implementing targeted training programs to enhance workforce skills in operating and maintaining advanced technologies is crucial. Partnerships between industry and academia can facilitate the development of specialized training curricula. Financial incentives, such as tax breaks and subsidies, can encourage companies to invest in automation and other advanced manufacturing technologies. Developing and implementing policies that support both technological advancement and workforce development can create an environment conducive to growth and innovation in the EV industry.

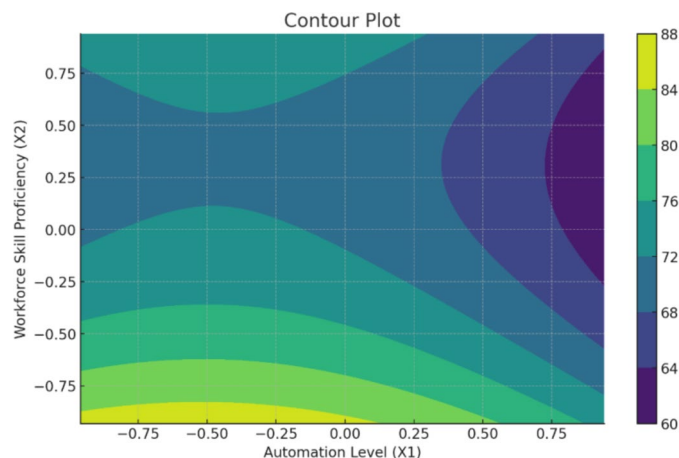


Fig. 17. Contour plot.

The RSM analysis underscores the critical importance of adopting advanced manufacturing technologies and developing a skilled workforce to enhance the competitiveness of India's EV industry. Investments in automation and targeted training programs are shown to significantly improve production efficiency and product quality. The findings provide actionable insights for policymakers and industry stakeholders to formulate strategies that maximize these benefits, ultimately positioning India as a global electric mobility market leader.

Conclusion

This study aimed to enhance India's competitiveness in the electric vehicle (EV) industry by adopting advanced manufacturing technologies and focused workforce development. The findings highlight the significant impact of automation, robotics, and Industry 4.0 solutions on production efficiency and product quality. Specifically, the integration of robotic assembly lines in a leading Indian EV manufacturer resulted in a 30% reduction in production time and a 25% increase in product quality. Workforce development programs, such as the collaboration between Ashok Leyland and IIT Madras, showed substantial improvements in worker competencies, effectively addressing the skill gap in operating advanced manufacturing systems.

Comparative analysis revealed that India's EV manufacturing metrics lag behind global leaders, with domestic production capacity meeting only about 20% of the demand for lithium-ion batteries as of 2023. This heavy reliance on imports increases production costs and creates supply chain bottlenecks. The study underscores the necessity for increased investments in manufacturing infrastructure and targeted training programs to bridge this gap. For instance, the workforce in China shows 70% proficiency in advanced manufacturing technologies compared to India's 50%, highlighting the critical need for comprehensive training programs to enhance the competencies of the Indian workforce.

The Response Surface Methodology (RSM) analysis demonstrated that higher levels of automation and better-skilled workforce consistently result in improved performance metrics, such as production efficiency and product quality. The 3D surface and contour plots illustrated the synergistic effects of investing in automation and workforce skills, emphasizing that incremental improvements yield significant performance gains.

The strategic investments in advanced manufacturing technologies and workforce development are crucial for reducing import dependency, streamlining manufacturing processes, and positioning India as a competitive player in the global EV market. The study's findings provide actionable recommendations for policymakers and industry stakeholders to support the growth of India's EV sector. Further research should focus on the long-term impacts of these investments on the sustainability and resilience of the EV supply chain, exploring the potential of emerging technologies and continuous workforce upskilling to maintain a competitive edge.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

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