Article

Intelligent Manufacturing and Autonomous Driving Technologies Are Driving the Upgrading of the US New Energy Vehicle Industry

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Abstract: This paper focuses on analyzing the transformative advantages brought by intelligent manufacturing and unmanned driving technologies within the rapidly evolving United States new energy vehicle (NEV) industry. Currently, the global and domestic NEV sectors have fundamentally evolved from being primarily based on basic electrification to being heavily dominated by economies of scale, advanced artificial intelligence, and highly coordinated development across the entire global value chain. Within this context, intelligent manufacturing serves as a critical catalyst. It can significantly enhance overall manufacturing efficiency and bolster crisis response capabilities by meticulously optimizing complex production processes, improving rigorous quality control mechanisms, and enabling seamless, real-time information sharing throughout the supply chain network. Simultaneously, the integration of autonomous driving technologies can profoundly facilitate product intelligence, drive the platformization of mobility services, and lead to the fundamental reconfiguration of traditional automotive business models. Through a comprehensive analysis of current market trends and technological advancements, this study proposes that in the forthcoming stage of industrial development, strategic efforts must be prioritized. Specifically, stakeholders should focus on the robust construction of an integrated intelligent manufacturing system, the seamless coordination of key supply chain links, the widespread popularization of autonomous driving applications, and the strengthening of government-enterprise collaboration. Ultimately, these concerted initiatives will effectively promote the US new energy vehicle industry towards achieving higher operational levels, superior product quality, and a genuinely green, sustainable developmental trajectory.

Keywords: intelligent manufacturing; autonomous driving; new energy vehicles; industrial upgrading; supply chain; sustainable development

Received: 12 March 2026
Revised: 24 April 2026
Accepted: 06 May 2026
Published: 12 May 2026

1. Introduction

The new energy vehicle industry plays a pivotal role in the transformation and advancement of the US manufacturing sector [1, 2]. As competition in the electric vehicle market intensifies, relying solely on enhancements in driving range and policy subsidies proves insufficient for ensuring sustainable growth. Intelligent manufacturing emerges as a critical solution, enabling large-scale production through the optimization of production processes, stringent quality control measures, and enhanced supply chain collaboration. Furthermore, the integration of autonomous driving technology is set to redefine vehicles, transitioning them from traditional mechanical devices into intelligent terminals and multifunctional service equipment. Exploring the mechanisms and practical implementation strategies of these advancements within the context of the US new energy vehicle industry holds significant academic and industrial value, as it addresses both technological innovation and market dynamics essential for long-term development.

2. The Realistic Foundation for the Upgrading of the US New Energy Vehicle Industry

2.1. The Phased Characteristics of the Development of the New Energy Vehicle Industry in the United States

The US new energy vehicle industry has developed through distinct phases, each marked by unique characteristics and driving factors [3]. Initially, the industry's growth was heavily reliant on government subsidies, stringent environmental protection regulations, and the strategic electrification initiatives of major enterprises. During this early phase, the primary focus was on enhancing battery performance, such as extending battery life and improving charging speeds, while simultaneously promoting the adoption of electric vehicles in the consumer market. As the industry matured and electric vehicle sales increased significantly, investments in battery technology surged, and domestic manufacturing policies were reinforced. This evolution has propelled the industry into a new phase characterized by large-scale production and a comprehensive transformation of the industrial chain. Leading automotive manufacturers, including Tesla, General Motors, and Ford, have strategically integrated battery supply chains, intelligent manufacturing processes, advanced software systems, autonomous driving technologies, and energy services into their operational frameworks. Concurrently, battery producers, chip manufacturers, and software companies have accelerated their involvement in the automotive sector, fostering a shift from competition centered on individual products to a more holistic competition encompassing the industrial chain, innovation chain, and value chain. This integrated approach has laid a robust foundation for the application of cutting-edge technologies, such as intelligent manufacturing and autonomous driving, in the ongoing industrial upgrading process. These advancements underscore the industry's transition toward a more interconnected and innovation-driven ecosystem, ensuring its continued growth and competitiveness in the global market.

2.2. The Joint Support of Intelligent Manufacturing and Autonomous Driving for Industrial Upgrading

The success of the US electric vehicle industry in achieving industrial transformation and upgrading can be attributed to a strategic shift in the manufacturing sector. This shift has moved from a sole focus on products to a dual emphasis on both products and the manufacturing process. The industry has adopted higher precision standards in areas such as battery assembly, vehicle integration, and electronic control system integration. Traditional manufacturing methods have proven inadequate to meet the growing demands for batch production, flexibility, and standardization. Consequently, intelligent manufacturing has emerged as a critical enabler for strengthening industrial foundation capabilities. Furthermore, competition among products has expanded beyond traditional electric vehicle performance metrics. Innovations in vehicle sensors, computing logic, software upgrades, and service information have become significant sources of added value. Automakers have increasingly invested in intelligent factories, vehicle-end domain controllers, advanced driving technologies, and data feedback systems [4, 5]. These advancements have not only enhanced production efficiency but also accelerated the development of automotive intelligence. This has created a positive feedback loop, fostering continuous improvement and innovation. As a result, the industry has established a robust foundation to transition from the development of electric vehicles to the broader realm of intelligent vehicle technologies, paving the way for sustained industrial progress and technological leadership.

3. The Mechanism of How Intelligent Manufacturing and Autonomous Driving Facilitate the Upgrading of the US New Energy Vehicle Industry

3.1. Intelligent Reconstruction of the Production Process and Strengthened Quality Control

The intelligent reconstruction of the production process operates through a systematic chain of "data collection - process control - quality feedback," ensuring precision and efficiency. In critical areas such as battery power, electric drive assembly, body structure, electronic control systems, and intelligent cockpits, the manufacturing process demands high precision due to the complexity of components. Even minor deviations during assembly can compromise the safety and stability of the entire vehicle. Intelligent manufacturing addresses these challenges by integrating advanced technologies such as industrial robots, machine vision, intelligent sensors, digital twins, and process management systems into the production workflow. These technologies enable real-time monitoring and dynamic control of core processes. For instance, during the welding of battery modules, white body welding, and wiring assembly, visual recognition systems can detect size deviations, suboptimal weld points, and connection defects. These detection results are immediately fed back into the production process, allowing for real-time adjustments to the robot's process parameters. This approach eliminates the traditional reliance on terminal inspections, transforming quality control into a proactive system of pre-control, online determination, and continuous repair. For the U.S. new energy vehicle industry, this advanced manufacturing methodology enhances the repeatability of large-scale production, significantly reduces rework and defect rates, and establishes a robust foundation for rapid iteration and large-scale expansion. By leveraging these intelligent systems, manufacturers can achieve higher efficiency, improved product quality, and a competitive edge in the evolving market for new energy vehicles.

3.2. Digital Supply Chain Collaboration and Local Manufacturing Support

The digitalization of the supply chain integrates data from all aspects, including procurement, production, storage, and logistics, transitioning from an experience-driven model to a data-driven one. This transformation enables real-time dynamic service capabilities that span the entire production process of new energy vehicles [3, 6]. The implementation of this model is primarily characterized by several key features. First, customer demand category information, vehicle configuration details, and market demand fluctuations are promptly fed back to the production system at the demand end. This ensures that production aligns closely with real-time consumer needs. Second, at the supply end, real-time tracking of critical components such as battery raw materials, vehicle-grade chips, and various sensors' arrival statuses facilitates two-way coordination and control of supply and demand. This synchronization minimizes delays and ensures a steady flow of essential materials. Third, at the production end, the integration of the manufacturing execution system with the supply chain system allows for dynamic adjustments to production plans based on the availability of materials. This adaptability ensures that production schedules remain efficient and responsive to potential disruptions. Furthermore, the database underpinning this system can predict delivery delays, identify factors contributing to quality changes, and assess their potential impacts. By addressing these risks proactively, scheduling plans can be adjusted before issues escalate. This collaborative approach transforms the supply chain from isolated operations into a cohesive, interconnected system, effectively mitigating problems such as information distortion and delayed responses. For the U.S. new energy vehicle industry, this model is particularly advantageous as it stabilizes the supply chain for core components and strengthens the resilience of local manufacturing systems. This, in turn, enhances the industry's capacity for sustainable development and industrial upgrading.

3.3. Autonomous Driving Promotes Product Intelligence and Business Model Reconfiguration

For the US new energy vehicle industry, the core driver of its development and evolution lies in the concurrent transformation of product characteristics and value creation methodologies. Electric vehicles serve as an optimal platform for software control, enabling the integration of autonomous driving technologies. Autonomous driving, in turn, elevates the intelligence level of new energy vehicles, shifting the competitive focus from traditional power system advantages to advanced capabilities in perception, decision-making, execution mechanisms, and data processing. These vehicles utilize cameras, radars, vehicle chips, and sophisticated algorithms to gather and analyze data on road conditions, driving behaviors, and operational statuses. Through machine learning, software updates, and remote services, the driving experience—both assisted and autonomous—undergoes continuous optimization. This iterative improvement process allows vehicles to evolve beyond static products into dynamic service platforms. Consequently, enterprises can transition from merely selling vehicles to offering ongoing services, paving the way for innovative business models. These include software subscription fees, charges for intelligent driving functionalities, fleet management fees, traffic service fees, and policy data service fees. The industry's value chain has thus expanded beyond manufacturing to encompass software, data, and service domains. Furthermore, the trajectory of industrial upgrading has shifted from merely enhancing product capabilities to constructing an intelligent ecosystem. This ecosystem integrates hardware, software, and services, fostering a holistic approach to innovation and ensuring sustained competitiveness in the rapidly evolving market landscape.

4. The Pathways for Achieving the Upgrading of the US New Energy Vehicle Industry through Intelligent Manufacturing and Autonomous Driving Technologies

4.1. Strengthening the Foundation for Large-Scale Production through the Construction of an Intelligent Manufacturing System

Building an intelligent manufacturing system to establish a robust foundation for large-scale production involves integrating digitalization, automation, and intelligence into every stage of the production process for new energy vehicles. This ensures that the entire manufacturing workflow, including battery assembly, component processing, and quality inspection, operates seamlessly and efficiently. In practice, industrial robots, fully automated welding guns, intelligent handling systems, and machine vision inspection equipment can be employed to enhance the precision of assembling power battery modules, chassis systems, and electronic control systems. Additionally, the implementation of a manufacturing execution system and a digital twin platform allows for the integration of order requirements, equipment conditions, operational parameters, inspection outcomes, and energy consumption data into a centralized production management system. This enables real-time optimization of production scheduling, immediate abnormality alerts, and process adjustments. Such a system ensures production flexibility, even amidst rapid model iterations and significant demand fluctuations, thereby maintaining a stable production capacity to support industrial upgrades. Furthermore, this approach facilitates the seamless transition to higher efficiency and quality standards, which are critical for the sustainable development of the new energy vehicle industry.

The Tesla Texas Super Factory in the United States serves as a prime example of leveraging intelligent manufacturing for large-scale production. This facility extensively utilizes automated assembly technologies, robotic welding systems, and integrated stamping processes in the production of new energy vehicles. A digital platform is employed to monitor production rhythms, component supply chains, and quality inspection data in real time [7]. During the assembly of battery packs, vehicle bodies, and electric drive systems, the production processes are order-driven. Advanced sensing technologies and visual inspection equipment are used to detect deviations in welding quality, assembly defects, and non-conformities in specific components. When quality issues arise in any process, feedback is immediately transmitted to the equipment and control systems, enabling adjustments to process parameters or the redefinition of inspection protocols. This comprehensive approach extends intelligent manufacturing from isolated equipment applications to the transformation of the entire production system. By doing so, it enhances the reliability of large-scale production for new energy vehicles, offering a practical pathway for the American automotive industry to achieve higher efficiency, superior quality, and advanced technological standards. This model underscores the potential of intelligent manufacturing to drive industrial upgrades and meet the evolving demands of the global market.

4.2. Collaboratively Enhancing the Operational Resilience of the Industrial Chain by Focusing on Key Links

To enhance the overall stability and risk-resistance of the industrial chain within the new energy vehicle industry, it is essential to integrate all critical links into a unified collaborative framework for operation. This includes raw materials for batteries, motors, vehicle components, sensor devices, assembly plants, charging infrastructure, and software systems. The traditional single-chain supply chain management model should be transformed into a collaborative management approach. Specifically, new energy vehicle enterprises in the United States should establish mechanisms for cross-enterprise information sharing and collaborative manufacturing based on vehicle demand. These mechanisms would enable timely adjustments to order forecasts, raw material procurement, component supply, production schedules, and inventory levels. Furthermore, efforts should be intensified in the research, development, and localization of key components such as batteries, intelligent control modules, laser radars, and onboard operating systems. This would mitigate the impact of external supply fluctuations on vehicle production. Additionally, supply chain visualization systems can be employed to identify risks such as delayed deliveries, price fluctuations, quality issues, and inventory backlogs. Enterprises can adopt strategies such as maintaining multi-supplier reserves, securing safety stocks of critical materials, and coordinating capacity allocation to bolster the resilience of the industrial chain. By implementing these measures, the industry can achieve a more robust and adaptive operational framework that minimizes disruptions and enhances overall efficiency.

The operational strategy of General Motors in the United States serves as a pertinent example of how the new energy vehicle industry can achieve resilience and efficiency. During its transition to electric vehicles, General Motors has not only prioritized vehicle research and development but has also actively planned the construction of battery factories to ensure a stable supply of batteries. The company has implemented digital management systems across all links of its supply chain, encompassing battery components, modules, vehicle assembly, and charging services. This comprehensive approach forms a control chain that spans the entire process from raw materials to finished products. When disruptions occur, such as changes in the delivery cycle of battery materials or specific components, the production schedule can be automatically adjusted to maintain the output of core product models. Simultaneously, supplier sourcing and spare parts adjustments can be initiated to address these challenges. By adopting this collaborative industrial chain approach, American new energy vehicle enterprises can reduce the likelihood of disruptions in key links, improve production continuity, and establish a more stable and controllable operational system. This approach also enables the industry to achieve upgrades without relying solely on singular technological advancements, thereby fostering sustainable growth and innovation.

4.3. Promoting the Extension of the Autonomous Driving Application Ecosystem to Multiple Scenarios

To advance the development of the autonomous driving application ecosystem, it is essential to extend the autonomous driving functionalities of individual vehicles to practical scenarios such as transportation, urban mobility, logistics, and public services [8–10]. In the process of application, the inherent advantages of new energy vehicles should be fully utilized. Implementation strategies should prioritize scenario-specific deployment based on safety levels, road conditions, and operational characteristics. For instance, slow unmanned driving transportation can initially be introduced in controlled environments such as parks, ports, airports, and warehouses. Concurrently, research and development efforts should focus on enhancing technologies like auxiliary driving, unmanned parking, lane keeping and lane changing, and adaptive cruise control for urban roads and highways. Furthermore, shared mobility services, ride-hailing platforms, and public buses can be integrated with high-precision maps, vehicle-road coordination systems, and cloud-based dispatch platforms to establish a comprehensive autonomous driving service ecosystem. To ensure the secure and reliable application of these technologies, it is imperative to refine testing standards, optimize information collection mechanisms, strengthen safety protocols, and develop robust liability determination frameworks.

An illustrative example of autonomous driving mobility services can be observed in Phoenix, Arizona, USA, where a relatively mature development environment for new energy vehicles equipped with autonomous driving capabilities has been established. This progress is attributed to the region's unique traffic conditions, regulatory frameworks, and urban mobility demands. Enterprises operating in this environment have successfully combined pure electric vehicles with autonomous driving technologies to offer unmanned taxi services within designated areas [3, 11]. These vehicles are equipped with various sensors that facilitate the collection and analysis of traffic data, enabling continuous system updates and improvements based on user feedback. This iterative process allows autonomous driving functionalities to adapt dynamically to real-world conditions. The transformation of new energy vehicles into intelligent transportation service platforms has not only expanded industrial profit sources but also accelerated the evolution of the U.S. new energy vehicle industry towards software-driven solutions, platform-based services, and ecosystem-oriented development. Such advancements highlight the potential for similar strategies to be adapted and implemented in other regions, fostering global innovation in autonomous driving technologies.

4.4. Formulate a Systematic Upgrading Mechanism through the Interaction of Policy Guidance and Market Feedback

To establish a systematic upgrading mechanism that integrates policy guidance and market feedback, it is essential to align the government's support measures, the scale of industrial investment, market demand, and technological advancements within a unified framework. Intelligent production and autonomous driving technologies should serve as pivotal drivers for comprehensive industrial upgrading. For instance, favorable conditions can be created to enable new energy vehicle manufacturers to expand intelligent factories, enhance battery production capacities, and intensify investments in autonomous driving research and development [12, 13]. This can be achieved through mechanisms such as tax incentives, manufacturing investment subsidies, the establishment of electric vehicle charging stations, and the enhancement of safety standards for autonomous driving systems. Concurrently, major automakers must adapt their vehicle models, intelligent driving configurations, and service offerings based on market feedback. This involves translating consumer preferences regarding range, pricing, safety, assisted driving experiences, and charging convenience into actionable product improvement strategies. Furthermore, establishing a robust communication framework among the government, enterprises, and the market is critical to ensuring that technological research and development remain closely aligned with actual consumer needs. Such coordination minimizes the risk of disconnects between innovation and practical application, fostering a more cohesive and responsive industrial ecosystem.

The new energy vehicle market in California, United States, serves as a valuable example of how policy guidance and market feedback can interact effectively. The region's high acceptance of electric vehicles, comprehensive charging infrastructure, and open testing environment for autonomous driving provide a solid foundation for industrial advancement. When introducing new energy vehicle models in this area, enterprises can refine battery capacity configurations, optimize intelligent auxiliary driving features, and adjust service fee structures based on consumer feedback regarding commuting range, assisted driving functionalities, charging durations, and software service costs [3]. Simultaneously, the government can leverage vehicle usage data, road safety statistics, and the operational load of charging facilities to refine subsidy policies, establish real-world testing protocols, and optimize infrastructure layouts. This dynamic interplay ensures that policy support, enterprise research and development investments, and market orientation remain harmonized. By fostering such a linkage, a relatively stable and sustainable development mechanism for the American new energy vehicle industry can be established. This approach not only enhances the industry's adaptability to evolving consumer demands but also strengthens its capacity for long-term growth and innovation.

5. Conclusion

Intelligent manufacturing and autonomous driving technologies have profoundly transformed the US new energy vehicle industry, driving advancements in both production processes and product capabilities. These technologies have significantly enhanced the digitalization, flexibility, and precision of manufacturing, enabling the large-scale production of new energy vehicles while maintaining stringent quality standards. Furthermore, they have expanded the scope of intelligent functionalities within vehicles, integrating software services, advanced data management systems, and intelligent transportation solutions. This has not only elevated the technological sophistication of the industry but also increased its overall economic value by fostering innovation in related sectors. Looking ahead, the industry must prioritize collaboration in the development of core components, strengthen the resilience of its supply chains, and explore new application domains to sustain growth. Additionally, the establishment of robust regulatory frameworks will be essential to harmonize technological advancements with market demands and policy objectives. By achieving a synergistic balance between innovation, market needs, and ecological sustainability, the industry can pave the way for a future characterized by high-end, intelligent, and environmentally friendly development.

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