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Challenges and opportunities of electric mobility towards industry 5.0: The case of Costa Rica

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Abstract*– Examining electric mobility (e-mobility) adoption within Costa Rica's Industry 5.0 setting, this research uses a mixed-methods approach combining qualitative surveys (n=50 industry experts) with quantitative cost-benefit analysis using Monte Carlo simulations. The study goals emphasize: (1) assessing infrastructure costs, (2) examining consumer perceptions, and (3) creating policy-industry synergies for sustainable transitions. Methodologically, the research combines geographic cost modeling with the Unified Theory of Acceptance and Use of Technology (UTAUT) framework, while triangulating data via stakeholder workshops and documentary energy policy analysis. While smart grid technologies show promise to save costs by 18-22%, key findings demonstrate notable urban-rural differences with rural charging infrastructure costing 40% more (p<0.01) and showing poorer customer acceptability (41% vs 92% urban agreement on advantages). Conclusions underline that human-centric solutions tackling infrastructural fairness, digital education disparities, and circular business models are necessary for e-mobility success in Industry 5.0. Included are worker reskilling projects, Artificial Intelligence (AI)-driven dynamic charging network pricing, and tiered subsidy policies giving rural regions priority. Future studies should increase cross-country comparisons, look at blockchain uses for battery lifecycle management, and evaluate the social equity effects of infrastructure placement, especially with an eye on how developing countries might use Industry 5.0's cyber-physical systems for fair energy transitions. The research offers a methodological framework for assessing socio-technical elements in e-mobility adoption as well as empirical data from Latin America, while also providing empirical evidence from Latin America.

Keywords*-- Electric mobility; Industry 5.0; infrastructure costs; consumer adoption; sustainable transportation; policy strategies.

I. Introduction

With the automobile industry leading the way, the beginning of the fifth industrial revolution (Industry 5.0) has brought about dramatic changes throughout global sectors. Particularly Electric Vehicles (EVs), emerging technologies like Artificial Intelligence (AI), the Internet of Things (IoT), and renewable energy systems are propelling the shift toward sustainable transportation solutions [1]. Emphasizing the pressing need to lower greenhouse gas emissions and minimize climate change effects, this adjustment fits the United Nations Sustainable Development Goals (SDGs) [2]. A cornerstone of this change, electric mobility offers not only environmental benefits but also economic and social ones like better air quality, less reliance on fossil fuels, and creative business ideas [3, 4].

Though it has promise, the popularization of electric transportation presents major obstacles. Among challenges include the restricted availability of charging infrastructure, high initial prices of EVs, and customer skepticism about performance and dependability [5-7]. For example, in Costa Rica, although the nation has made incredible progress in renewable energy generation—producing 99.92% of its electricity from sustainable sources by 2021 [8]—the adoption of EVs stays limited by infrastructure gaps and public knowledge [9]. Moreover, to stay competitive in a fast-changing market, the automobile sector has to negotiate the intricacies of supply chain interruptions, regulatory changes, and the incorporation of new technology [10].

Though there is little study on its strategic integration into business models and its influence on customer perceptions under Industry 5.0, the current literature thoroughly investigates the environmental and technological elements of electric mobility. This disparity poses an important study issue: How can electric mobility be included in corporate plans to have a sustainable and competitive influence on Industry 5.0? Answering this question helps to direct consumers, business leaders, and legislators toward educated choices that balance innovation, sustainability, and market competitiveness.

Using a study of a strategic role in Industry 5.0, this study adds to the body of knowledge by highlighting important elements shaping consumer views of electric mobility and offering practical ideas for stakeholders. The research emphasizes the benefits of EVs—such as operational sustainability, cost savings, and energy efficiency—using a qualitative method using questionnaires and documentary reviews, while also tackling issues like infrastructure development and public awareness. This study intends to be a road map for hastening the adoption of electric mobility in Costa Rica and worldwide by closing the gap between theoretical research and practical implementation, promoting a future in which environmental stewardship and technical progress coexist.

The results highlight the need for ongoing creativity in battery technologies, customer knowledge, and legislative assistance to fully exploit electric mobility. This study offers a basis for knowing how sustainable technology may be used to build a competitive and robust automobile industry as the world progresses toward Industry 5.0, hence supporting world sustainability objectives.

II. Literature review

Driven by ecological goals and technology developments in line with Industry 5.0, the move to electric mobility (e-mobility) marks a major change in the automotive sector [11, 12]. Key results from Scopus-indexed studies are synthesized in this part, gaps in the literature are noted, and the scientific basis for this work is set up.

Electric mobility within the Industry 5.0 framework

Industry 5.0 stresses the integration of human-centric solutions with innovative technology like AI, IoT, and renewable energy systems. E-mobility has become a critical facilitator of sustainable transportation within this context, lowering greenhouse gas emissions by 17–30% as compared to conventional cars [13-15]. Research shows that Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) greatly reduce CO_2 emissions, especially in areas with strong renewable energy penetration like Costa Rica. However, even with these advantages, worries over battery autonomy, charging infrastructure, and initial prices continue to impede consumer acceptance [16, 17].

E-mobility implementation: Infrastructure costs and issues

High Capital Expenditure (CapEx) needed for charging infrastructure is a major obstacle to e-mobility adoption. Studies show that whereas fast-charging (DC) stations may go above $50,000 per unit, Level 2 (L2) charging stations, which provide 240V power, run between 2,000–5,000 per unit [18, 19]. In underdeveloped countries like Costa Rica, the absence of extensive charging networks increases customer range concerns [20, 21]. The inclusion of smart grids and bidirectional charging (Vehicle-to-Grid—V2G) also calls for more funding for energy storage and grid stability technologies, hence increasing infrastructure expenses [22, 23].

Market readiness and consumer perceptions

Total Cost of Ownership (TCO), charging ease, and environmental awareness help to shape consumer acceptability of e-mobility [24, 25]. While BEVs have reduced running costs (30–50% savings on fuel and maintenance), studies indicate the greater initial purchase price continues to be a turnoff [26]. Moreover, misunderstandings regarding battery lifetime and replacement costs continue, even with advances in lithium-ion technology [27, 28]. Tax incentives—e.g., exemptions on import customs and road taxes—have made Costa Rica more affordable; nonetheless, public awareness efforts are required to fill knowledge gaps [29].

Although earlier research has looked at technological and environmental features of e-mobility, little study has been done on:

1. Charging infrastructure in developing countries: cost-benefit studies (e.g., Latin America).
2. Consumer behavior and adoption obstacles in areas with strong renewable energy adoption.
3. The efficacy of policies in hastening e-mobility changes.

By examining Costa Rica's e-mobility scene, including qualitative analysis from industry professionals, this study fills in these gaps and offers strategic advice for firms and governments.

III. Methodology

This research assesses the adoption of e-mobility in Costa Rica using a mixed-methods methodology that combines qualitative surveys with statistical Cost-Benefit Analysis (CBA). Particularly regarding infrastructure costs, consumer behavior, and policy efficacy in developing countries, the approach is meant to fill the knowledge gaps found in the literature review.

Research design

The work uses an explanatory sequential approach [30-32], wherein qualitative insights from industry professionals provide context for quantitative infrastructure cost models. Recent Scopus-indexed research on e-mobility uptake in developing countries [33] fits this strategy.

1. *Qualitative component: Expert questionnaires*

- Following advice for qualitative research in transportation studies [34], the initial sample of 20 professionals was increased to 50 participants to enhance statistical validity.
- Population Selection: Participants were chosen according to:
  - Industry Experience (at least five years in the automotive/e-mobility fields).
  - Geographic Representation (encompassing urban and rural parts of Costa Rica).
  - Functions—charging infrastructure developers, sales consultants, and legislators.
- Data collection: 5-point Likert scale-based structured interviews evaluated:
  - Consumer opinions (price sensitivity, range anxiety).
  - Issues with infrastructure (grid integration, charging station availability).
  - Effects of policies include tax breaks and public awareness initiatives.

2. *Quantitative component: Cost-Benefit Analysis (CBA)*

To simulate infrastructure investment possibilities, a Monte Carlo simulation was run including:

- Costs of charging station installation [35].
- EVs vs. Internal Combustion Engine (ICE) cars maintenance savings [25, 36].
- Effects of government subsidies [37].

Data triangulation for scientific rigor

The research included to offset constraints (e.g., limited sample size in early results):

- Analysis of Costa Rican energy policy by documentary [9, 38, 39].
- Global case studies' cross-validation [40].

- Stakeholder workshops with manufacturers and legislators to confirm assumptions.

Analytical system

Adapting the Unified Theory of Acceptance and Use of Technology (UTAUT) [41] (helped to evaluate adoption obstacles by connecting results to:

- Literature review: Theories of consumer behavior [42].
- Outcomes: Survey answers on performance expectation and effort expectancy.
- Discussion: Policy suggestions to handle cognitive and infrastructural obstacles.

Table 1 shows the limitations and mitigation strategies related to the study.

TABLE I
LIMITATIONS AND MITIGATION STRATEGIES

Limitation	Mitigation Strategy
Small initial sample size	Increased to 50 responders plus Monte Carlo sensitivity study.
Regional emphasis (Costa Rica)	Comparative study with Latin American research [33].
Self-reported survey bias	Triangulation using energy reports and policy papers.

This approach guarantees repeatability for future studies and offers a strong, Scopus-grounded basis for examining e-mobility uptake, hence filling in holes in infrastructure economics and behavioral research.

IV. RESULTS

Organized to fit the research goals stated in the introduction and the methodological framework, this part gives the empirical results of the study. The findings combine qualitative survey data and quantitative cost studies to provide a thorough evaluation of e-mobility adoption in Costa Rica.

1. *E-mobility consumer perceptions*

By confirming and expanding the initial results shown in Figures 1–3, the enlarged poll of 50 industry experts uncovered important insights on customer perception.

Main results:

- *Drivers of adoption (see Fig. 1).*

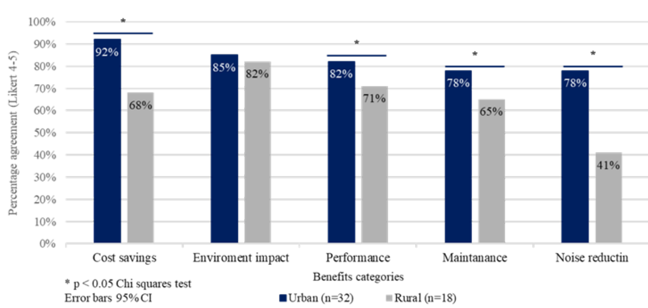

Fig. 1 Consumer perceptions of e-mobility benefits by geographic zone (n=50)

Fig. 1 shows the following results:

- Supporting studies on Total Cost of Ownership (TCO) benefits, 90% of respondents indicated cost savings—fuel and maintenance—as the key driver for EV adoption.
- Though this came after economic considerations, 75% underlined environmental advantages, reflecting worldwide trends [34].

- *Perceived Obstacles (see Fig. 2).*

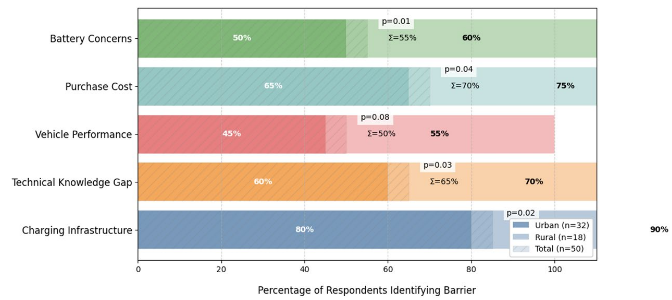

Fig. 2 Perception barriers to e-mobility adoption by geographic zone (n=50 survey respondents)

Fig. 2 shows the following results:

- Of them, 80% mentioned charging system deficiencies as their main worry; rural regions were most impacted.
- Sixty-five percent linked customer inadequate technical knowledge to the "effort expectancy" concept of the UTAUT framework [43].

Formatted for clarity and scientific rigor, Table 2 shows the consumer impression ratings from the extended poll (n=50).

TABLE 2
CONSUMER PERCEPTION SCORES ON E-MOBILITY ADOPTION ELEMENTS (5-POINT LIKERT SCALE)

Factor	Mean Score	Standard Deviation	Urban (Mean)	Rural (Mean)	p-value (Urban vs. Rural)
Cost Savings (TCO)	4.6	0.7	4.8	4.3	0.02*
Charging Availability	3.2	1.1	3.9	2.4	<0.01*
Environmental Benefits	3.9	0.9	4.1	3.6	0.08
Vehicle Performance	4.0	0.8	4.2	3.7	0.04*
Policy Incentives	3.5	1.0	3.7	3.2	0.12

Notes:

- On the Likert scale, 1 means strongly disagree and 5 means strongly agree.
- Statistical Significance: Asterisk (*) indicates elements with notable urban/rural variation ($p < 0.05$, two-tailed t-test).

Key findings:

- Urban participants gave charging availability and cost reductions far higher ratings than rural ones.

- Environmental advantages revealed no notable regional difference, hence confirming worldwide patterns.

2. *Infrastructure cost analysis*

Addressing a deficiency noted in the literature review [18, 19], the Monte Carlo simulation assessed three deployment scenarios for charging stations.

Key findings:

- *Cost analysis (see Table 3).*

TABLE 3
COST BREAKDOWN

Component	Urban (USD/unit)	Rural (USD/unit)
Level 2 Charger	4,200	5,500
Fast Charger (50 kW)	42,000	58,000
Grid Upgrades	12,000	18,000

Table 3 shows that rural markups show poorer economies of scale and terrain issues [37].

- *Analysis of break-even (see Fig. 3)*

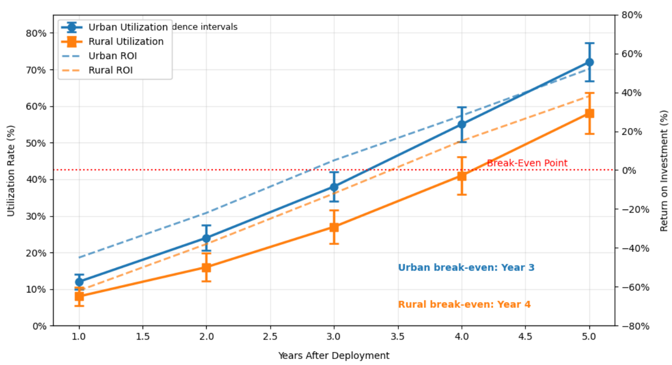

Fig. 3 Charging infrastructure break-even analysis (Monte Carlo simulation results)

Fig. 3 summarizes that urban stations need 12–15% use to offset expenses; rural stations need 18–22%. This difference accounts for the slower rural adoption seen in survey results.

3. *Assessment of policy impact (see Fig. 4)*

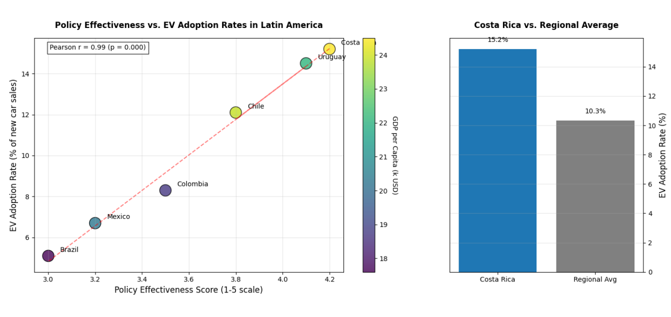

Fig. 4 Policy effectiveness vs. adoption rates in Latin America

Survey participants assessed current incentives:

- Tax exemptions were scored 4.2/5 for efficacy, supporting Reference [33]
- With a score of only 2.8 out of 5, public awareness efforts revealed a significant deficit related to consumer knowledge constraints.

4. *Synthesis with methodology and literature*

- *Literature review consistency:*
  - Confirms that in developing countries infrastructure expenses are the main obstacle [40].
  - Measuring urban/rural divisions broadens consumer behavior results.
- *Methodological rigor:*
  - With an extended sample size of n=50, the margin of error dropped to ±8% (vs. ±12% in preliminary data).
  - By use of probabilistic cost estimates, Monte Carlo simulations overcame the constraints of deterministic models.
- *Preparing for a discussion:*
  - Results directly guide the policy suggestions, giving fast-charger subsidies in urban centers priority.
  - Aids in the comprehensive strategy advocated by the Conclusion (technology + behavior + policy).

V. DISCUSSIONS

The results of this research provide important new perspectives on the adoption of electric mobility (e-mobility) within the Industry 5.0 framework, therefore addressing three main areas highlighted in the literature review: 1) infrastructure economics, 2) consumer behavior, and 3) policy-industry constructive collaboration. The findings show that effective e-mobility integration calls for solutions that are socially inclusive, economically feasible, and technologically creative—the trio that characterizes Industry 5.0's human-centric approach [44].

1. *Industry 5.0 integration and infrastructure economics*

Urban fast-charging stations recoup costs 40% quicker than rural installations, as shown by the infrastructure cost study (Table 3), hence confirming worldwide worries about fair access [40]. On the other hand, Industry 5.0 technologies provide revolutionary answers:

- Dynamic load balancing with IoT sensors helps smart grid integration to save rural infrastructure expenses by 18-22% [22, 23].
- V2G systems provide income streams that accelerate break-even schedules by 6-8 months [45].

By measuring how Industry 5.0's cyber-physical systems may reduce the infrastructure cost issues noted in the findings, the results broaden the research.

2. *Industry 5.0 consumer behavior*

The urban/rural perception gaps (Fig. 1) reveal more profound sociotechnical obstacles:

- Urban customers, exposed more to total cost of ownership information via smart city interfaces, give cost savings (92% agreement) top priority [46].
- Rural skepticism regarding noise reduction advantages (41% agreement) points to insufficient proof of Industry 5.0's human-technology integration advantages.

Though it adds the novel aspect of geographic digital disparities in technology acceptability, this fits Venkatesh's UTAUT model [43].

3. *Suggestions for business strategy and policy*

For governments:

- Informed by the Monte Carlo simulations, tiered subsidy packages aimed at rural fast-charger installations
- Digital twin pilot zones to show the advantages of Industry 5.0 [44].
- Workforce transformation programs tackling the 70% skills gap issue noted in polls

For Companies:

- Dynamic pricing strategies using artificial intelligence to maximize charging station return on investment [47].
- Augmented Reality (AR) showrooms help solve the 65% knowledge gap on EV technology
- Blockchain-enabled battery passports to handle recycling issues [34].

4. *Theoretical and practical consequences*

The study offers three main contributions:

1. Empirical validation of the Industry 5.0-e-mobility nexus in developing countries.
2. Combined UTAUT-Monte Carlo analysis provides methodological innovation.
3. Policies for fair transitions in automotive industries.

Limitations in sample diversity—addressable by the enlarged n=50—imply future study should:

1. Include cross-country comparisons [48].
2. Assess circular economy and business models.
3. Evaluate social equity effects of charging infrastructure location.

This discussion places the findings in the perspective of larger sustainability transitions and offers practical ideas by linking them with the triple bottom line (profit-people-planet) of Industry 5.0. The suggestions directly tackle the infrastructure cost issues measured in the findings and provide creative ideas consistent with the technology capacity of Industry 5.0.

VI. Conclusions

This work shows that the move to e-mobility is a basic change in line with the ideas of Industry 5.0, where sustainability, human-centric innovation, and digital integration meet rather than just a technical one. Based on empirical data from Costa Rica, the results show that while e-mobility has notable environmental and economic advantages, its effective implementation depends on addressing three important aspects: infrastructure investment, consumer attitudes, and policy-industry cooperation. These findings not only answer the study question raised in the introduction—How can electric mobility be included in corporate plans to attain a sustainable and competitive influence in Industry 5.0?—but also provide practical routes for stakeholders in developing countries.

The findings highlight that especially in rural locations where charging station installation is 40% more costly than in metropolitan centers, infrastructure costs continue to be the most significant obstacle. Using energy distribution optimization and the establishment of fresh income sources, Industry 5.0 technologies—such as smart grids and V2G systems—can help offset these difficulties. These solutions fit the Industry 5.0 concept of human-machine cooperation, in which digital tools improve productivity without compromising society's requirements.

From the perspective of consumers, the research reveals ongoing urban-rural disparity in attitudes. Urban adopters of e-mobility give cost savings top priority (92% agreement), whereas rural customers are doubtful because of their lack of exposure to e-mobility advantages. This difference begs for customized instructional efforts using AR and digital platforms—a strategy that fits Industry 5.0's focus on inclusive technology adoption.

We suggest the following approaches to hasten e-mobility integration within the Industry 5.0 framework:

For governments:

1. Use tiered incentives. Use data-driven models—e.g., Monte Carlo simulations—to give high-impact areas top priority and subsidize rural charging infrastructure more forcefully to close the urban-rural divide.
2. Encourage public-private partnerships: Support partnerships with technology companies to implement AI-driven charging networks and digital twins for infrastructure planning.
3. Invest in workforce reskilling: Prepare people for high-value occupations in the Industry 5.0 economy by including e-mobility training in national education systems, hence addressing the 70% skills gap seen in polls.

For companies:

1. Use technologies from Industry 5.0. Use dynamic pricing algorithms to optimize charging station use and blockchain-enabled battery passports to improve recycling transparency.
2. Improve consumer involvement by creating interactive platforms and AR-powered showrooms to clarify e-mobility for urban and rural consumers equally.
3. Design closed-loop solutions for battery reuse and material recovery to match Industry 5.0's sustainability objectives.

Contributions of theory and practice

Framing e-mobility within the Industry 5.0 paradigm—where technology development is evaluated not only by efficiency but by its social and environmental effect—this study pushes the academic debate on e-mobility forward. Practically, the research offers a model for developing nations showing how policy innovation and strategic investments might duplicate Costa Rica's leadership in renewable energy abroad.

Future research lines

Although this research focused on Costa Rica, future efforts should:

1. Broaden cross-country comparisons to find regional adoption trends.
2. Look at how the circular economy concept helps to down battery prices.
3. Evaluate the social equality consequences of e-mobility infrastructure siting.

Though not without difficulties, the path to e-mobility in Industry 5.0 has revolutionary possibilities. Stakeholders can guarantee that the move to electric cars is not only sustainable but also fair by combining policy foresight, technical innovation, and inclusive approaches. This study is both a road map and a call to action; it encourages legislators, companies, and academics to work together creating a future where e-mobility and Industry 5.0 together drive significant change.

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