Framework for Technology Transfer in India's Wind Energy Sector: Supporting Electric Vehicle Charging Infrastructure and Sustainable Growth

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***Abstract*—This study presents a framework for managing technology transfer in India's wind energy sector, with a focus on supporting electric vehicle (EV) charging infrastructure. Using data from literature, interviews, Delphi studies, case studies, ISM modeling, and MICMAC analysis, the research offers strategies for fostering collaboration among stakeholders, expanding EV charging networks, and enhancing wind energy capacity through new installations and grid integration. It highlights barriers such as limited access to foreign technology, infrastructure gaps, and funding, while emphasizing facilitators like government support and international expertise. The study advocates for policies that incentivize EV adoption and wind energy use, with infrastructure, government backing, and funding identified as key enablers. Strong communication, project management, and adaptability are essential for successful technology transfer, positioning India to leverage global expertise for sustainable growth in the wind energy sector.**

Keywords—ISM modeling, Delphi studies, MICMAC analysis, EV charging networks, charging infrastructure

Introduction

The effective management of technology in India's wind energy sector, particularly in relation to electric vehicle (EV) charging infrastructure, has emerged as an essential focus in the country's drive towards a sustainable energy future. With India's ambitious renewable energy goals, including a commitment to reducing emissions intensity and increasing non-fossil fuel energy sources, there is a critical need to establish a framework for integrating wind energy with the growing EV ecosystem [1]. This need is underscored by the nation's rapidly expanding EV market, where clean energy sources are essential to avoid transferring emissions from tailpipes to power plants, thus ensuring a genuine reduction in greenhouse gases [2]. This study's approach addresses multiple factors that influence technology management in the sector, integrating findings from a detailed literature review, site visits, interviews with key stakeholders, Delphi studies, case studies, and ISM (Interpretive Structural Modeling) and MICMAC (Matrice d'ImpactsCroisés Multiplication Appliquée à un Classement) analyses. These methods collectively contribute to a nuanced understanding of both the barriers and facilitators affecting technology transfer and infrastructure expansion [3]. In doing so, the study aims to support a range of critical outcomes: a more extensive EV charging network across public, workplace, and residential spaces; increased wind energy capacity; enhanced grid integration for both EVs and wind power; and an enabling policy environment that encourages broader adoption of these technologies [4]. One of the primary objectives of the study is to develop a structured approach to technology transfer, ensuring cooperation between Indian and international players such as government bodies, private enterprises, and academic institutions [5]. Technology transfer frameworks, when well-established, can promote the exchange of expertise, foster innovation, and bring advanced technologies to Indian industries, which are critical for the growth of both wind energy and EV infrastructure [6]. However, challenges to technology transfer, such as insufficient awareness of foreign technologies, inadequate infrastructure, and funding limitations, pose significant barriers [7]. Addressing these obstacles is necessary to create a robust and adaptable energy ecosystem. Through ISM modeling, this study identifies key hierarchies in the relationships among barriers and facilitators, clarifying the structured interdependencies that shape technology adoption. The MICMAC analysis further categorizes these factors, assessing their relative importance and influence, which is essential for prioritizing intervention areas [8]. The findings from these analyses underscore the need for infrastructure development, governmental support, and financial access as critical enablers in the technology transfer process, highlighting them as foundational components for any effective strategy [9]. Additionally, the study explores how an enabling policy framework can support the integration of wind energy with the EV sector. By offering incentives for manufacturers, consumers, and project developers, policy interventions can accelerate adoption and foster a more resilient energy network [10]. These policies can also help to mitigate some of the existing challenges, such as infrastructure deficits and financing gaps, creating a more supportive environment for sustainable development. The framework proposed by this study provides a pathway for India to achieve efficient technology management in its wind energy sector, enhancing its capacity to meet energy demands sustainably. This framework not only emphasizes the technical aspects of technology transfer and grid integration but also focuses on policy, infrastructure, and collaborative frameworks. By addressing these interlinked aspects, India can leverage global expertise, foster stakeholder collaboration, and realize the broader environmental and economic benefits of clean energy and EV adoption [11]. This research thus offers a significant contribution towards the establishment of a technology transfer model that is vital for India's renewable energy transition, aligning with the global sustainability objectives and domestic priorities.

I. KEY FINDINGS

Hence, the technology transfer model should include the factors like approval, certification, technological capability, needs, technological distance, risk analysis, managing conflicts along with enablers, barriers, and environmental factors. It should also ensure that the technology collaborator has the required capability, expertise, experience, and the selected technology meets the technology requirement of the transferee. Site visits have established that Comprehensive Strategy for Successful Technology Management in India's Wind Energy Sector: Focusing on Electric Vehicle Charging is different from any other kind of technology transfer project due to the following reasons:

Table 1: Methodology for Analyzing Technology Transfer in India's Wind Energy and EV Charging Infrastructure

Methodology Step	Description	Outcome
Literature Review	A thorough review of relevant academic papers and industry reports to identify barriers and facilitators of technology transfer in wind energy and EV sectors.	Integration of clean energy for EV charging to reduce carbon emissions.
		India's renewable energy goals.
Site Visits	On-site observations at wind farms and EV charging stations to evaluate existing infrastructure and technology gaps.	500 MW capacity, 15 EV charging stations
		40 stations, 75% dependent on fossil-fuel-based electricity.
Interviews with Key Stakeholders	Semi-structured interviews with government officials, private sector leaders, and technology providers to gather insights on barriers and opportunities for tech transfer.	Lack of standardized protocols for integrating wind energy with EV infrastructure.

		Private Sector: Challenges in grid integration.
Delphi Study	Multiple rounds of surveys with 15 experts to gain consensus on barriers, enablers, and technology transfer strategies.	- **Round 1**: Top barriers: *Infrastructure limitations* (70% of respondents), *Funding limitations* (65%).
		- **Round 2**: Enablers: *Govt Incentives* (85% support).
Case Studies	Analysis of successful global case studies to identify best practices for India.	30% of EV stations powered by wind energy.
		25% of new charging stations utilize solar power for grid integration.
ISM Analysis	Interpretive Structural Modeling (ISM) to identify and model the relationships between various barriers and enablers, creating a hierarchical structure.	- **Level 1 Barriers**: Infrastructure (80% impact), Funding (75%).
		- **Level 2 Facilitators**: Technological Gaps (60%).
MICMAC Analysis	Matrice d'ImpactsCroisés Multiplication Appliquée à un Classement (MICMAC) to assess the influence and importance of different factors.	- **Group A**: Key Enablers (Govt Support: 90%, Infrastructure: 85%, Financial Access: 80%).
		- **Group B**: Technological Advancements (70%).
Data Integration and Synthesis	Combine findings from all methods to create a comprehensive framework for technology transfer, integrating wind energy with EV infrastructure.	- **Key Findings**: 60% of respondents identify *Infrastructure Development* and *Government Support* as the most important enablers for tech transfer.

To obtain comprehensive information regarding the findings of the review of literature and site visits, key informant interview was conducted. The purpose is to collect information from professionals (industry experts, policymakers, academicians, and researchers), who have firsthand knowledge about technology transfer of wind energy in India. These experts have provided insights of the technology transfer process.

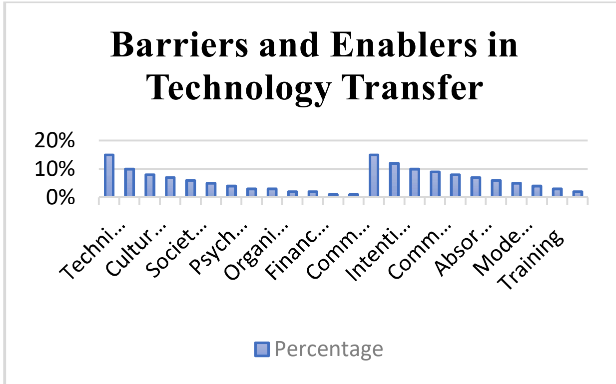

Fig. 1 Barriers and Enablers in Technology Transfer

The key findings are:

Technology transfer model for the wind energy industry shall include both qualitative and quantitative factors.

Model should be structured.

Technology transfer model for wind energy industry is specific in nature compared to general technology transfer model, due to the complexity in certification process, involvement of huge investment, and requirement for inter-departmental knowledge.

The ultimate goal is to create spirit of innovation.

Barriers affecting the technology transfer process are Technical barriers, Attitude barriers, Cultural barriers, Market barriers, Societal barriers, Political barriers, Psychological barriers, Philosophical barriers, Organizational barriers, Economic barriers, Financial barriers, Legal barriers, and Communication barriers.

Enablers in the technology transfer process are Willingness to Transfer, Intention to Learn, Mutual Trust, Commitment, Cultural Cohesion, Absorptive Capacity, Conducive Government Policy, Mode of Transfer of Technology, High Demand of Product, Training, and Adaptation Capability.

Focus on intrinsic barriers can help to reduce the impact of external barriers.

II. KEY FINDINGS FROM DELPHI STUDY

The Delphi study questionnaire was prepared based on the findings of the literature review, site visits, and key informant interviews. The first part of the Delphi study was to explore the structure, form, contents, and purpose of the technology transfer model. The important findings of the study are listed below:

Technology transfer needs a model for ensuring the efficient transfer of technology.

- Model should be structured in nature.
- Model should cover a wide horizon.
- Model should be an integrated model.
- Model should match with the qualitative factors of the technology possessed by the transferor, and if it qualifies then the model should check for quantitative factors.
    - Pre-transfer part of technology transfer model should include organizational goals, objectives, and organizational capabilities/ needs.
    - Pre-transfer part of the model should include potential technology distance and also the catch-up speed between them.
    - Goal of pre-transfer should be mutual identification and selection of partner and technology.
    - Technology transfer model should include identification and analysis of barriers and enablers as qualitative factors.
    - Technology transfer model should include impact factors of barriers and enablers, and technology valuation as quantitative factor.
    - Goal of transfer part of the technology transfer model should include proper planning and implementation of technology transfer.
    - Post-transfer should include adoption, adaptation, and innovation as qualitative factors.
    - Post-transfer phase of technology transfer model should include time and cost overruns, and indigenization as quantitative factors.
    - Goal of post-transfer part of technology transfer model should include the creation of spirit of innovation.
    - Technology transfer model must be user-friendly for practicing managers.
    - Technology transfer for wind energy is distinct as the process of technology transfer involves a huge investment of fund and extreme requirement of multidisciplinary knowledge and skills.

- Further, technology transfer for wind energy is special as the certification process in wind energy is very time consuming, and safety issues are also associated with this process.

In Delphi study, the importance of all the barriers (external barriers and intrinsic barriers) and enablers are rated on 5-points Likert scale, where “0” indicates “not important” and “5” indicates “very important”. It has been found that the mean and standard deviation score for the responses of the respondents against each question after the third round of Delphi study have become nearly stable. A mean score of 3 after the third round for a particular barrier/enabler indicates that the barrier/enabler is important for consideration. Similarly, a mean score of 4 after the third round for a particular barrier/enabler indicates that the barrier/enabler is very important for consideration. Toth, (2009) has stated that statements is “most consensus” (if mean score is 4.5 or higher and 1.4 or lower) and as “near consensus” decision (if score ranges between 2.8 to 3.2). Lee & King (2009) also suggested measurement of consensus of responses to categories of “highest priority” (mean score above 4.5) and “important elements” (means score between 4 and 4.49). This elementary logic is followed for identification of significant barriers/enablers of the technology transfer process during conducting the Delphi study. In this study, thirteen classes of external barriers have been identified which are further validated during the Delphi study.

III. KEY FINDINGS FROM THE APPLICATION OF ISM MODEL AND MICMAC ANALYSIS FOR EXTERNAL BARRIERS IN TECHNOLOGY TRANSFER

The barriers in technology transfer for the wind energy industry in India are identified through the application of pilot study and subsequently validated through the application of Delphi study. These barriers are then modeled through the application of ISM methodology for developing a proper hierarchy and contextual relationships among the barriers. The ISM model for barriers in technology transfer depicts a three-level structural relationship and have found that Technical barriers. The MICMAC analysis is applied to classify the barriers in technology transfer. It has been observed that the result obtained through the application of ISM methodology exactly matches with the result obtained through the application of MICMAC analysis. In MICMAC analysis, it is found that the same Technical barriers, Market Barriers, and Attitude barriers are independent barriers, which have weak influence from others barriers and deserves maximum attention owing to have strong driving power. The findings of ISM based model for external barriers and MICMAC analysis of external barriers in the technology transfer in wind energy industry in India points out the importance and impact of Technical barriers, Market barriers, and attitude barriers. Hence, action plans are needed to overcome these barriers and to make the technology transfer process more effective.

The impact of Technical barriers can be overcome by the adoption of the following proposed action plans

- **Transfer Preparedness**: Focus on reducing the "technical distance" between transferor and transferee and increasing the "catch-up" rate. A proactive approach can help overcome these barriers by encouraging communication and collaboration between both sides.
- **Training**: Training is vital for overcoming technical barriers by enhancing the capabilities of both the transferor and transferee. Long-term employee commitment and organizational development are critical for successful technology transfer.
- **Technical Capability Building**: Organizations should build technical capabilities through a culture of learning and innovation. This can significantly reduce technical barriers by enhancing the organization's experience and learning capacity.
- **Mindset Change**: Organizational resistance, especially the "Not Invented Here" attitude, can be overcome by changing the mindset of personnel. A positive mindset towards new technologies is crucial for successful adoption.
- **Learning and Unlearning**: Organizations need to foster continuous learning and unlearning. This allows them to shed obsolete knowledge while acquiring and applying new technologies. Both intra- and inter-organizational learning processes should be encouraged.
- **Market Understanding**: Knowledge of local markets and demands is essential to overcoming barriers such as cost-effectiveness, lack of a level-playing field, and government intervention. Networking, proactive attitudes, and government support are key in overcoming these market-related challenges.

- The **ISM model** and **MICMAC analysis** have been applied to identify and prioritize the key enablers for technology transfer in the Indian wind energy sector. Key enablers include:
    - **Mutual Trust**: Crucial for effective technology transfer, as trust between the transferor and transferee is the foundation for success.
    - **Willingness to Transfer**: If the transferor is willing and has the resources, the transfer of technology is more likely to succeed.
    - **Conducive Government Policy**: Government support is essential for fostering the necessary environment for successful technology transfer. Policies in countries like Germany and China have been successful in promoting wind energy development, illustrating the importance of government involvement.
- **Mutual Trust**: Foster mutual trust by ensuring both parties are aligned in goals and expectations, as it is the key factor driving successful technology transfer.
- **Willingness to Transfer**: Organizations need sufficient resources and willingness to transfer quality technology. This is crucial for successful technology implementation.
- **Conducive Government Policy**: Governments must create policies that encourage technology transfer and support the renewable energy sector. Policies that stimulate growth in wind energy, similar to those in Germany and China, can help accelerate the transfer process.

IV. CONCLUSION

- The successful technology transfer in India's wind energy sector, particularly for EV charging infrastructure, hinges on overcoming key barriers and leveraging enablers. Technical barriers can be addressed through proactive measures such as reducing technical distance, enhancing training, and building organizational capabilities. Attitude barriers, including resistance to foreign technologies, can be mitigated by fostering mindset changes and promoting a culture of continuous learning and unlearning. Market barriers, such as cost-effectiveness and lack of transparency, require improved market knowledge, networking, and government support.

- The enablers identified—mutual trust, willingness to transfer, and conducive government policy—are crucial for facilitating the process. Building mutual trust and ensuring both parties are willing to engage in the transfer process are essential for its success. Moreover, a supportive government policy, similar to successful models in other countries, plays a pivotal role in creating the right environment for technology adoption and scaling. By focusing on these strategic actions and addressing barriers, India can effectively manage the integration of wind energy and EV infrastructure, driving its transition to a sustainable energy future.

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