



A Review of the Future of Traditional Power Adapters the Potential of Distributed Energy Interfaces as an Alternative

Yun Tang^{1,2,3}, Wencong Han^{1,2,3,*}, Lei Ye^{1,2,3}, Jian An^{1,2,3}, Feiyang Teng^{1,2,3}

¹Chengdu Institute of Product Quality Inspection Co. Ltd, Chengdu, China

²Chengdu product Quality Supervision and inspection institute, Chengdu, China

³Sichuan Provincial Product Quality Supervision, Inspection and Testing Institute, Chengdu, China

*Corresponding author: 244373821@qq.com

Abstract. This study reviews the substitution potential of distributed energy interfaces for traditional power adapters using a multidimensional framework. The findings reveal scenario-dependent viability: proven feasibility in low-power fixed applications; however, efficiency, cost, and infrastructure barriers persist in high-power mobile contexts. Future power systems are projected to adopt layered architectures in which universal distributed interfaces coexist with specialized high-performance adapters, offering theoretical guidance for technological evolution and industrial planning.

Keywords: Distributed interface; evolution path; literature review; power adapter; technology substitution.

1 Introduction

This review paper aims to critically examine the future trajectory of traditional power adapter technology by exploring the potential of distributed energy interfaces as a viable alternative. It will first establish the current state and inherent limitations of conventional adapters, encompassing their technical characteristics, environmental footprint, and the prevailing regulatory landscape^[1]. Subsequently, the paper will introduce the conceptual framework and technological principles of distributed energy interfaces, analyzing their advantages and application scenarios across various power contexts^[2]. A core component involves a comparative analysis between the two paradigms, evaluating key performance metrics, economic factors, environmental impact, and user experience to assess the viability of a transition. Finally, the discussion will project future technological evolution, market trends, and the necessary policy and infrastructure implications for integrating such distributed solutions into modern power systems^[3]. This structured analysis provides a foundation for understanding the broader shifts in power delivery infrastructure.

2 Traditional Power Adapters: Current State and Limitations

2.1 Literature Search Strategy

To systematically assess the potential for substitution of distributed energy interfaces, we conducted a PRISMA-aligned literature review across six databases (Web of Science, IEEE Xplore, CNKI, etc.) spanning 2003–2023. The initial search retrieved 2,185 documents. After removing 538 duplicates and excluding 1,399 irrelevant studies via title/abstract screening, 248 full texts were analyzed, yielding 118 publications that met the criteria for technical, economic, and policy aspects of the study. Table 1 outlines the systematic keyword combinations used in this global 20-year synthesis of substitution drivers across diverse research outputs.

Table 1. Keyword Combinations for Systematic Literature Searches.

category	Keyword combinations
Traditional technology	power adapter OR AC-DC converter OR external power supply
Emerging Interface	distributed energy interface OR DC microgrid OR wireless power transfer
evolutionary relationship	replace* OR evolution OR standardization

2.2 Technical Characteristics

The technical characteristics of traditional power adapters are primarily defined by their power conversion efficiency, physical form factor, and device compatibility. A core limitation lies in conversion efficiency, where energy losses, especially under light or partial loads, remain significant^[4]. These losses are often tied to the fixed-frequency switching architectures common in many designs^[5]. Furthermore, the size and thermal management requirements of internal components, such as transformers and heat sinks, impose strict constraints on miniaturization^[6]. This often results in bulky, device-specific adapters that lack interoperability. While advancements in real-time predictive control for power management offer pathways to optimize efficiency dynamically^[7], the fundamental architecture of traditional adapters presents inherent barriers. This analysis of technical limitations sets the stage for examining their subsequent economic and environmental ramifications.

represents a significant bottleneck in energy utilization, particularly under light-load conditions, in which efficiency can drop substantially^[8]. Traditional power adapters suffer from inherent inefficiencies, losing energy as heat from fixed and switching losses, which wastes electricity and demands bulky thermal management, thereby impacting the form factor and reliability. Their physical size, often bulkier than the devices they power, compromises portability and forces users to manage a clutter of incompatible, device-specific adapters. This technical fragmentation, with varied voltage and connector requirements, generates electronic waste and introduces stability issues within power systems. These combined limitations in efficiency, size,

and interoperability highlight the critical need for alternative architectures, such as distributed energy interfaces, for more sustainable and streamlined power delivery.

2.3 Environmental and Economic Considerations

The environmental and economic considerations of traditional power adapters present significant challenges. Their inherent energy conversion inefficiencies contribute to substantial energy waste and an increased carbon footprint throughout their lifecycle^[9]. The manufacturing and disposal processes involve non-renewable materials and complex logistics, posing further environmental hurdles for decarbonized energy systems^{[10][11]}. Economically, the production of diverse, device-specific adapters limits economies of scale, keeping consumer prices elevated^[12]. Furthermore, long-term costs are amplified by persistent energy waste and end-of-life disposal expenses. The economic evaluation is complicated by uncertainties in energy markets, as highlighted by frameworks for chance-constrained optimization which account for such variability in cost assessments^[13]. These combined environmental and economic factors critically underscore the limitations of the current paradigm and drive the exploration of alternative solutions like distributed energy interfaces, a shift that will necessitate corresponding updates to the regulatory landscape.

2.4 Regulatory Landscape

The regulatory landscape for traditional power adapters is a critical framework designed to ensure safety, efficiency, and interoperability. Current standards and certifications primarily address the safety risks and performance benchmarks of these standalone, centralized power conversion units^[14]. However, the emergence of distributed energy interfaces and advanced grid architectures necessitates an evolution in this regulatory paradigm. These new technologies introduce complex dynamics related to system stability, cyber-physical security, and peer-to-peer energy transactions^[15]. Consequently, regulatory bodies face the challenge of updating safety and efficiency regulations to accommodate decentralized topologies while fostering international standardization efforts to prevent market fragmentation. This evolving regulatory environment forms a crucial backdrop for the comparative analysis of traditional and emerging power solutions.

3 Distributed Energy Interfaces: Concept and Potential

3.1 Technological Principles

Bidirectional energy flow between diverse sources and loads within a localized power system. It operates using decentralized control algorithms and real-time communication to dynamically coordinate inputs and loads for optimal stability and efficiency. Architecturally, DEIs decentralize the conversion near the point of use, integrating power modules, localized storage, an intelligent controller, and standardized connect-

ors within a hierarchical framework. This design offers significant advantages over traditional adapters, including superior flexibility and scalability through plug-and-play modularity, seamless integration of renewables, enhanced system resilience, and higher net efficiency by reducing conversion stages. DEIs also minimize electronic waste by replacing single-purpose adapters and aligning naturally with smart grid functionalities, positioning them as a cornerstone for future sustainable power ecosystems.

3.2 Application Scenarios

The power conversion efficiency of traditional adapters typically ranges from 70% to 90%, and a distributed energy interface (DEI) is a modular, intelligent, and network-enabled unit that enables peer-to-peer energy trading and local renewable management in building microgrids. They also power transactive systems for mobile applications using platforms such as TRANSAX for decentralized trading. Integrated with smart grids, they act as intelligent nodes that coordinate diverse renewable sources, storage, and hydrogen systems to ensure stability. This flexibility across varying scales establishes the foundation for evaluating their associated technical challenges.

3.3 Technical Challenges

The practical deployment of distributed energy interfaces is contingent upon overcoming several significant technical hurdles. A primary challenge lies in ensuring dynamic stability and reliable frequency regulation within power systems that incorporate a high penetration of distributed and intermittent resources. Concurrently, maintaining high power conversion efficiency across diverse and fluctuating load conditions remains a critical concern for economic viability^[16]. Furthermore, these systems must adhere to stringent power quality constraints, such as managing voltage profiles, to ensure safe operation within existing grid infrastructures. Finally, achieving seamless electromagnetic compatibility and scalable integration with legacy power systems, smart grids, and transactive energy markets presents a complex systems engineering problem. Addressing these multifaceted challenges is essential for validating the operational feasibility of distributed interfaces and provides a critical foundation for subsequent comparative analysis.

4 Comparative Analysis: Traditional Adapters vs. Distributed Interfaces

4.1 Performance Metrics

This comparison evaluates traditional adapters versus distributed energy interfaces (DEIs) across efficiency, flexibility, and reliability. DEIs achieve superior efficiency by operating near the load and optimizing power flow in real-time, maintaining high performance across a wider load spectrum compared to traditional units. Their modu-

lar, software-defined designs offer greater flexibility, dynamically powering diverse devices to reduce e-waste. Although traditional adapters are simpler, DEIs enhance reliability through redundancy and modularity. This technical assessment, validated by power-hardware-in-the-loop simulations, forms the basis for subsequent economic and environmental evaluations.

4.2 Economic Factors

The economic viability of distributed energy interfaces hinges critically on production costs and potential economies of scale. Unlike traditional, device-specific adapters, a universal distributed interface could amortize its manufacturing costs across numerous applications, potentially lowering the per-unit cost through mass production. Furthermore, their integration with smart grids and renewable energy sources promises long-term economic benefits by optimizing energy flows and reducing dependency on centralized generation, as highlighted in studies on renewable-integrated systems. However, the initial investment for deploying the necessary infrastructure and power-electronics components remains a significant barrier. A comprehensive economic analysis must therefore balance these upfront costs against the operational savings and scalability advantages.

4.3 Environmental Impact

A life cycle assessment reveals distributed energy interfaces' environmental advantages over traditional adapters. Traditional adapters carry significant impacts from material-intensive manufacturing and operational inefficiency, which wastes energy and increases emissions. In contrast, distributed interfaces offer benefits across multiple stages: their modular design may use fewer or more sustainable materials; higher operational efficiency reduces lifetime energy consumption, especially with renewables; and longer lifespan potentially mitigates electronic waste. This favorable environmental profile is critical for influencing consumer acceptance and accelerating market adoption.

4.4 User Experience and Practicality

Beyond technical and economic metrics, the ultimate adoption of distributed energy interfaces hinges on their practical usability and consumer acceptance. A primary advantage over traditional adapters is the enhanced convenience from reduced physical clutter and the elimination of device-specific chargers, potentially enabled by universal interfaces or wireless power transmission integrated into environments. However, user experience is contingent on seamless compatibility with the vast installed base of existing devices and infrastructure, a challenge highlighted in microgrid integration studies. Furthermore, the reliability and perceived safety of these distributed systems, underpinned by advanced control frameworks and validated through rigorous testing platforms, are critical for building consumer trust. This interplay between tangible convenience and underlying technical assurance will funda-

mentally shape market adoption. The comparison of key performance indicators between traditional adapters and distributed interfaces (DEI) is shown in Table 2.

Table 2. The comparison of key performance indicators between traditional adapters and distributed interfaces (DEI)

Performance indicators	Traditional power adapter	Distributed Energy Interface
Typical conversion efficiency	70%–90%, significant decrease at low load	Target > 95%, need actual system data
Light load efficiency (10% load)	Can be less than 60%	Maintain efficiency through dynamic shutdown module
Life cycle carbon emissions	Higher (independent materials, manufacturing, transportation per device)	Potentially lower (material integration, facilitates renewable energy)
Cost (USD/W)	Varying by model, lack of scale economies	Initially high, expected to decrease with economies of scale.
Mean time between failures	Limited by the life of components such as electrolytic capacitors.	System reliability can be improved through module redundancy.

5 Future Projections and Technological Evolution

5.1 Layered Power System Architectures

A universal distributed interface envisions standardized, interoperable platforms enabling seamless power exchange between diverse energy sources and loads, supporting plug-and-play DER integration and transactive microgrids. Specialized high-performance adapters remain essential for applications demanding uncompromising efficiency or reliability, like aerospace systems. Effective hybrid integration strategies coordinate both approaches through optimization frameworks, peer-to-peer trading, and complementary technologies (hydrogen, flexible nuclear) to balance renewables. This coordinated approach, including multi-timescale storage sizing, ensures grid stability and efficiency, laying groundwork for flexible, resilient future power architectures.

5.2 Technological Advancements

The advancement of distributed energy interfaces is driven by progress in materials, power electronics, and control algorithms. Wide-bandgap semiconductors like silicon carbide (SiC) and gallium nitride (GaN) boost efficiency with higher switching speeds and lower losses. Enhanced power management, including predictive control and stability analysis, improves system reliability. Wireless power transfer reduces connector dependency for low-power uses. The integration of hybrid energy systems,

such as hydrogen conversion, and optimized storage sizing help manage renewable intermittency. These innovations underpin next-generation interfaces, influencing future market and policy discussions.

5.3 Market Trends and Industry Response

Power delivery markets are shifting toward flexible, integrated energy solutions, boosting adoption of distributed energy interfaces (DEIs). In response, companies are exploring blockchain-based peer-to-peer energy trading platforms. Manufacturers are also investing in AI-accelerated control models and advanced simulation testbeds to enhance distributed power management. This industrial pivot recognizes DEIs as core elements of future smart grids and microgrids, requiring a holistic approach to system design and market integration.

6 Future Projections and Technological Evolution

6.1 Regulatory Considerations

The widespread adoption of distributed energy interfaces (DEIs) necessitates a fundamental evolution in regulatory frameworks originally designed for centralized power systems, requiring updates to safety and efficiency standards that address bidirectional power flows, dynamic load management, and renewable integration through new protocols for grid interconnection, cybersecurity, and dynamic power quality management, while efficiency metrics must evolve beyond simple plug-load measurements to account for system-wide optimization and partial load performance within smart grids. Beyond updated standards, targeted policy incentives are crucial for accelerating DEI adoption, including direct economic mechanisms like tax credits and feed-in tariffs to lower cost barriers, policies enabling dynamic pricing and peer-to-peer energy trading to financially reward grid-support capabilities, and public investment in grid modernization and smart infrastructure, all within a comprehensive framework aligned with decarbonization goals. Finally, international cooperation in technology standardization through bodies like the IEC and IEEE is paramount for global deployment, as harmonized standards ensuring interoperability, safety, and reliability across borders mitigate market fragmentation and accelerate innovation. These combined regulatory advancements, policy incentives, and global standards are essential prerequisites for securely and efficiently integrating distributed interfaces into modernizing power infrastructures, paving the way for a cohesive global energy system.

6.2 Infrastructure Requirements

The widespread adoption of distributed energy interfaces (DEIs) demands significant upgrades to existing power infrastructure, beginning with the modernization of legacy grids to accommodate bidirectional power flows, enhanced monitoring, and real-time

control through advanced cyber-physical testbeds. This involves integrating smart metering and robust communication networks to manage variable inputs from distributed sources effectively, supported by simulation-based predictive models for renewable forecasting and distributed stability analysis. Furthermore, the physical infrastructure must evolve to support hybrid energy carriers and storage integration, while control architectures shift towards compositional paradigms. Seamless integration with smart city initiatives is also crucial, where DEIs serve as foundational nodes for applications like dynamic wireless EV charging and peer-to-peer energy trading on blockchain platforms, requiring inherent compatibility with smart city communication protocols. Retrofitting existing buildings and industrial systems presents substantial technical and economic challenges, as legacy electrical infrastructure often lacks the necessary capabilities for stable, bidirectional operation, and high upfront costs can be prohibitive. Addressing these multifaceted hurdles through updated technical standards, phased strategies, and supportive policies is fundamental to realizing the full potential of distributed energy systems.

7 Conclusion

Distributed energy interfaces (DEIs) offer a viable alternative to traditional adapters, contingent on specific scenarios. Their value lies in enhanced efficiency, grid stability, and renewable integration. Adoption depends on mature market structures, regulatory frameworks, and cost-benefit trade-offs, favoring environments with smart grid infrastructure like microgrids, while legacy systems require robust cybersecurity. Future research must prioritize compositional stability analysis, safe reinforcement learning, and probabilistic techniques for predictive maintenance. This evolution signifies a fundamental shift toward decentralized, intelligent power systems, redefining conversion technology from passive components to active grid participants for a more sustainable and resilient energy future.

Acknowledgment

We would like to express their sincere gratitude to Chengdu Institute of Product Quality Inspection Co. Ltd for valuable discussions and technical assistance during the course of this research.

Author Contributions

Conceptualization: Wencong Han; Methodology: Yun Tang, Lei Ye and Wencong Han; Validation: Wencong Han, Jian An and Feiyang Teng; Formal analysis: Lei Ye and Feiyang Teng; Investigation: Wencong Han, Jian An; Resources: Yun Tang; Data curation: Wencong Han; Writing—original draft: Lei Ye and Wencong Han; Writing—review & editing: Yun Tang and Feiyang Teng; Supervision: Yun Tang; Project ad-

ministration: Wencong Han; Funding acquisition: Wencong Han. All authors have read and agreed to the published version of the manuscript.

References

1. Sadamoto T , Chakraborty A , Ishizaki T ,et al. "Dynamic Modeling, Stability, and Control of Power Systems With Distributed Energy Resources: Handling Faults Using Two Control Methods in Tandem." *IEEE Control Systems*, 39(2018): 34-65. DOI:10.1109/MCS.2018.2888680.
2. Hallie Dunham, Dylan Cutler, Sakshi Mishra,et al. "Cost-optimal evaluation of centralized and distributed microgrid topologies considering voltage constraints,"*Energy for Sustainable Development*, Volume 56,2020,Pages 88-97,DOI:10.1016/j.esd.2020.03.002.
3. Khatibi Mohammad,Sara Ahmed. "Impact of Distributed Energy Resources on Frequency Regulation of the Bulk Power System."2019 IEEE Conference on Power Electronics and Renewable Energy (CPERE) (2019): 258-263.
4. F.Akopyan,R. Manohar,A.B. Apsel"A level-crossing flash asynchronous analog-to-digital converter."12th IEEE International Symposium on Asynchronous Circuits and Systems (ASYNC'06) (2006): 11 pp.-22.
5. Zhang Jiaming, Fang Jun, Zhang Tianhong, et al."Component-Level Modeling of More Electric Auxiliary Power Units for Cooperative Control."*Aerospace* 9.12(2022): 803-803. doi:10.3390/AEROSPACE9120803.
6. Mishal Mahmood,Mariam Azam,Khair-un-Nisa Fatima,et al."Design and Implementation of an Automatic Synchronizing and Protection Relay through Power-Hardware-in-the-Loop (PHIL) Simulation.."CoRR abs/1907.00339.(2019).
7. Alexander Liniger, Luca Varano, Alisa Rupenyan, et al. "Real-Time Predictive Control for Precision Machining.."CoRR abs/1908.10609.(2019).
8. Tillmann Mühlpfordt, Timm Faulwasser, Veit Hagenmeyer, "A generalized framework for chance-constrained optimal power flow." *Sustainable Energy, Grids and Networks* 16. (2018):231-242. doi:10.1016/j.segan.2018.08.002.
9. Meiyi Li, Javad Mohammadi, "Speeding Ticket: Unveiling the Energy and Emission Burden of AI-Accelerated Distributed and Decentralized Power Dispatch Models," 2024 56th North American Power Symposium (NAPS), El Paso, TX, USA, 2024, pp. 1-6, doi: 10.1109/NAPS61145.2024.10741623.
10. Leonard Göke, Alexander Wimmers, and Christian von Hirschhausen. "Flexible nuclear power and fluctuating renewables? — An analysis for decarbonized multi-vector energy systems." *Energy Strategy Reviews* 60.(2025): 101782-101782. doi:10.1016/J.ESR.2025.101782.
11. Gaffoor Shereena, and Chacko Mariamma. "A Multi-objective Hybrid Optimization for renewable energy integrated Electrical Power Transmission Expansion Planning." *International journal of electrical and computer engineering systems* 13.2(2022): 87-98. doi:10.32985/IJECES.13.2.1.
12. Hallie Dunham, et al. "Cost-optimal evaluation of centralized and distributed microgrid topologies considering voltage constraints." *Energy for Sustainable Development* 56.(2020): 88-97. doi:10.1016/j.esd.2020.03.002.
13. Tillmann Mühlpfordt, Timm Faulwasser, Veit Hagenmeyer, "A generalized framework for chance-constrained optimal power flow." *Sustainable Energy, Grids and Networks* 16. (2018): 231-242. doi:10.1016/j.segan.2018.08.002.

14. Li Hepeng,H He,"Learning to Operate Distribution Networks With Safe Deep Reinforcement Learning."IEEE Transactions on Smart Grid, 13, 3(2022): 1860-1872. DOI:10.1109/TSG.2022.3142961.
15. Dinh Hoa Nguyen,and Tatsumi Ishihara."Distributed peer-to-peer energy trading for residential fuel cell combined heat and power systems."International Journal of Electrical Power and Energy Systems 125.(2021):106533-.doi:10.1016/j.ijepes.2020.106533.
16. Huanan Liu, et al."Sizing Hybrid Energy Storage Systems for Distributed Power Systems under Multi-Time Scales."Applied Sciences 8.9(2018):doi:10.3390/app8091453.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits any noncommercial use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

