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LETTER

Accelerating power system decarbonization through the deployment of smart energy routers

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Dear Editor,

Current power systems suffer from mismatches between renewable energy supply and load demand. Interconnecting distribution networks through smart energy routers can overcome the bottlenecks in renewable energy integration, thereby accelerating the decarbonization process of power system.

INTRODUCTION

The quest for an efficient, low-carbon power system is imperative amidst global energy depletion and severe climate change.[1] Global annual renewable capacity additions increased by almost 50% to nearly 510 gigawatts (GW) in 2023, the fastest growth rate in the past two decades.[2] However, the distribution and utilization of renewable energy have not kept pace with this rapid development.[3] Existing distribution networks in power system, which operate in an open-loop radial manner, contribute to substantial energy waste due to the mismatch between energy resources and load demand, particularly as small-size distributed energy generations become more prevalent. This hinders the further integration of renewable energy.

Smart Energy Router (SER) enables cross-sectoral integration within power systems by interconnecting various energy subsystems through multiple ports. It facilitates the flexible distribution of clean electricity—derived from renewable sources—to sectors such as industry, agriculture, transportation, and residential use. Demonstration projects involving SERs have already been implemented in countries such as China[4] and the United Kingdom.[5] The project in Shandong Province described in[4] achieved an integrated energy utilization rate exceeding 80%. In academia, research on SER-based integrated systems has advanced in several directions. Reference[6] presents the energy hub as a node for producing, converting, storing, and consuming energy carriers—a promising framework for multi-energy management. In[7], the optimal scheduling of SER-based system is formulated as a tri-objective optimization problem that minimizes operational cost, pollutant emissions, and the deviation of electrical load from its desired profile. Reference[8] proposes a day-ahead scheduling method for an SER-based system, incorporating demand-side management strategies that improve customer satisfaction and increase wind power penetration by incentivizing users to adjust consumption according to the system demand profile.

These studies provide detailed and insightful analyses of the operational optimization of SER systems. However, most focus on system-level modeling and technical implementation, while few examine SER's broader role in enabling large-scale carbon reduction across multiple societal sectors. This limits our understanding of the full systemic potential of SER for achieving deep decarbonization. Furthermore, existing research typically centers on localized systems, with no comprehensive assessment of the nationwide carbon reduction potential of SER, nor an analysis of region-specific deployment strategies based on diverse industrial contexts.

In this Letter, we introduce the operating principles of SER and assess its carbon reduction performance through real-world demonstration cases. For the first time, we conduct an integrated carbon reduction assessment of SER across key sectors—hydrogen production, agriculture, heating, and electric vehicles—from a national and cross-sectoral perspective. We further propose an optimal investment strategy for SER deployment across Chinese provinces, tailored to regional industrial energy demand patterns. This work provides new insights into the scalable application of SER as a strategic enabler of multi-system integration toward carbon.

DEFINITION OF SMART ENERGY ROUTERS

SER is a versatile energy connector designed to link distribution networks across regions, leveraging power electronics to optimize electricity utilization (Figure 1A). A typical SER consists of multiple AC/DC or DC/DC converters, a common DC bus, and a central controller. Each converter links directly to a port, enabling integration with diverse energy devices and direct interfacing with regional distribution networks. It allows for the exchange of electricity through common DC buses across different distribution networks, thereby balancing the power generation and consumption. Through high-frequency power electronics and coordinated control, the SER enables flexible, bidirectional power transfer across ports, optimizing energy distribution in both space and time.

This architecture facilitates carbon reduction through three key pathways. First, by interconnecting conventionally independent sectors with the power system, the SER enables direct electrification using clean energy. This supports sectoral decarbonization, for instance by replacing fossil-fuel-based heating with electric heating, or substituting green hydrogen for carbon-intensive grey hydrogen in industrial processes. Second, the SER improves overall energy efficiency by optimizing energy flows between interconnected systems, reducing losses through coordinated multi-port control. Third, SER enhances the grid's ability to accommodate variable renewable energy, thereby reducing dependence on fossil-fuel generation. Together, these capabilities position the SER as a strategic solution for accelerating system-wide decarbonization.

APPLICATION IN DEMONSTRATION PROJECT

A demonstration project in Guizhou Province, China, is conducted to analyse the potential of SER implementation.[10] The demonstration area includes 61 residential electricity loads and 30 household distributed photovoltaic (PV) systems (Figure1B). 10 electric vehicle charging piles are installed on DC lines. Three SERs are deployed across residential, industrial, and commercial areas. Energy losses are calculated before and after SER application. Post-interconnection, the total energy loss reduction on a typical day is 280.15 kWh, a decrease of 16.68%. Of this, 170.35 kWh is saved by reducing PV energy waste. The remaining 109.80 kWh reduction resulted from decreased energy conversion and transmission losses. 87,720 kWh of electricity is saved annually with the application of SER. This leads to a 21.65% increase in renewable energy utilization efficiency and a 23.86% decrease in carbon emissions compared to previous levels. In this demonstration project, the construction cost of the SER was approximately 3×10^5 RMB. Under normal operating conditions, the investment can be recovered within 5 to 6 years, after which the system continues to generate economic benefits.

CARBON REDUTION POTENTIAL IN VARIOUS SECTORS

To assess the carbon reduction potential of SER, we developed four distinct scenarios:[10] green hydrogen production (HP), electric heating (EH), electric vehicle charging (EV), and electrified agriculture (EA). Life cycle assessment (LCA) is conducted over a 20-year period for each scenario. Developing renewable power generation (RPG) independently is set as business as usual

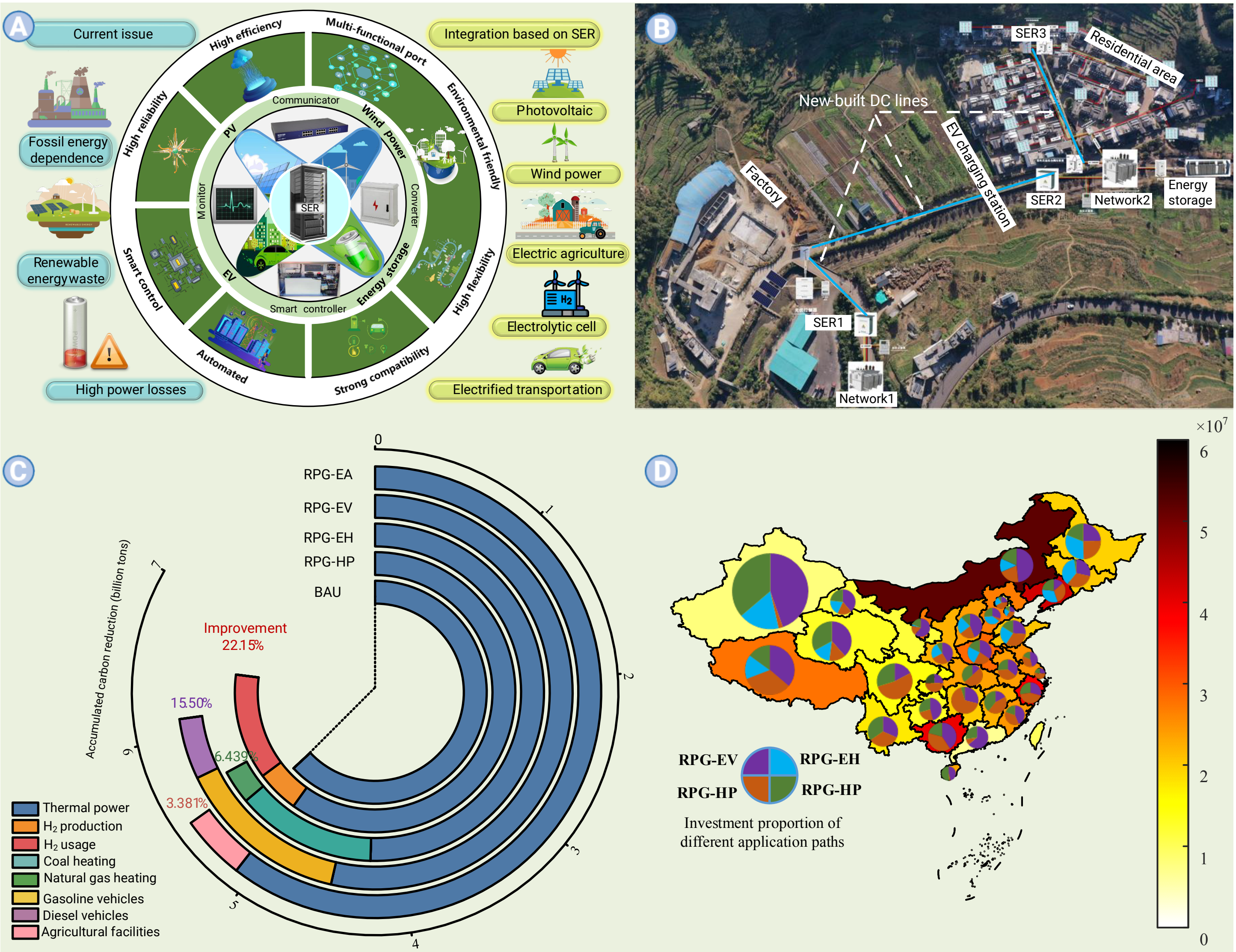

Figure 1. Typical application and demonstration project of SER (A) Energy systems of different sectors can be integrated through SER. Energy can be seamlessly transferred across various sectors to enable optimal allocation, thereby enhancing system efficiency. (B) Aerial view of the demonstration area. The detailed parameters of the demonstration project can be found in Supplementary Table 1 and Supplementary Table 2. (C) Carbon reduction improvement in different scenarios, including hydrogen production (RPG-HP), electric heating (RPG-EH), transportation (RPG-EV), electric agriculture (RPG-EA). (D) Carbon reduction after promoting SER in China, including investment allocation plans and application effectiveness for different scenarios in provinces. The data in (C) and (D) can be found in Supplementary Table 5 and Supplementary Table 6.

(BAU) case. In this case, carbon reduction will hit the bottleneck at a maximum accumulated carbon reduction of 5.296 billion tons (Figure 1C). This limitation is due to the inability to further consume renewable energy electricity. In HP scenario, renewable electricity is used for water electrolysis via SER, increasing maximum carbon reduction to 6.469 billion tons, a 22.15% improvement. In EV scenario, the reduction potential rises by 15.50% to 6.117 billion tons. Among them, a portion comes from renewable energy generation replacing thermal power generation, while another portion comes from the less usage of gasoline and diesel. Coordinated RPG and electrified agriculture through SER results in a 3.38% increase in maximum carbon reduction to 5.475 billion tons. The EH scenario, influenced by geographical and climatic factors, sees traditional coal heating replaced by renewable energy heating through SER, boosting maximum carbon reduction by 6.439%.

We further analyse the carbon reduction potential of SER based on the national situation in China. Promoting SER can enhance national carbon reduction by 18.36% compared to the sole development RPG (Figure 1D). The investment return period varies across provinces due to differences in energy demand structures. At an estimated SER cost of ¥1,000/kW, the payback period ranges from 3 to 8 years depending on the regional context. In provinces with high industrial hydrogen demand, investments should prioritize SER for green hydrogen production. In traffic intensive cities such as Beijing and Shanghai, the focus should be on promoting SER for EV charging. Provinces with cold climates should prioritize developing clean heating technology through SER. For agriculturally active provinces, emphasis should be on developing complementary PV and agricultural facilities via SER to achieve energy savings.

CONCLUSION

In this letter, we introduce an energy distribution and utilization technology that can achieve efficient clean energy promotion. We analyse the carbon reduction potential of SER across different scenarios and perform a nationwide assessment of its carbon reduction effects in China. The results demonstrate that SER plays a crucial role in driving the clean transition across various sectors. Currently, the development of SER is constrained by its cost. Due to the extensive use of power electronic devices, the investment required for SER is higher than that for conventional distribution networks[9]. As a result, energy departments remain cautious in their adoption of this technology. However, its long-term benefits—including enhanced energy efficiency, reduce environmental impact—can lead to significant cost savings over time, particularly in countries with abundant renewable energy resources and complex energy infrastructures. Given these advantages, we advocate for government interventions, such as subsidies, to stimulate the development of SER. Such measures would expedite the clean transformation of various energy systems, including the power grid, and significantly contribute to the acceleration of carbon neutrality. In the future, further research can be conducted on the policy design, energy management strategies, and market trade rules of SER-based power system.

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DECLARATION OF INTERESTS

The authors declare no competing interests.