LETTER

Carbon-neutral pathway to mitigating transport-power grid cross-sector effects

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Dear Editor,

The growing demand for transportation energy has brought increasing challenges to reducing greenhouse gas emissions. Currently, many countries or regions have proposed solutions to achieve carbon-neutral transportation such as the rapid expansion of the global electric vehicle (EV) market. However, these benefits are not free. Before the goal of decarbonization in electricity is achieved, the "pseudo net zero emissions" effect of the transportation sector will inevitably be accompanied by a quiet shifting of carbon responsibility.[1] This shift is undoubtedly fatal for both net zero emissions at the national level and carbon responsibility at the industry level; however, the corresponding effects have not yet been clarified.

Currently, models such as the life cycle assessment model are widely used to assess individual transportation systems; however, they rarely consider the synergy between transportation networks and power grids. Energy-focused

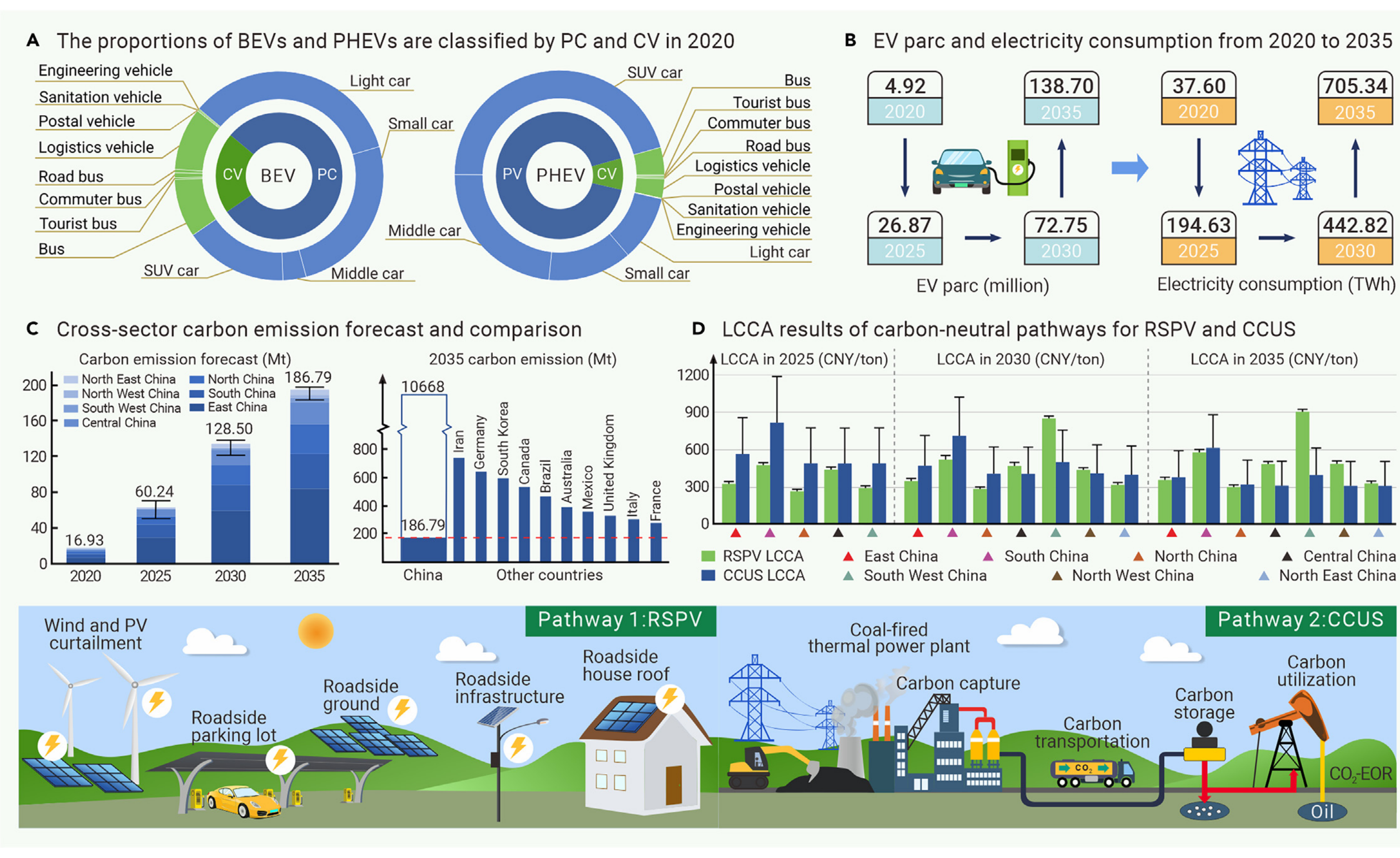

Figure 1. Cross-sector carbon emissions projections based on actual EV operation data and LCCA comparisons using RSPV and CCUS carbon-neutral pathways for seven regions in China from 2020 to 2035 (A) The proportions of battery electric vehicles (BEVs) and hybrid electric vehicles (PHEVs) are classified by passenger car (PC) and commercial vehicle (CV) in 2020. (B) EV parc and electricity consumption from 2020 to 2035. (C) EV-related cross-sector carbon emissions forecast and comparison. The stacked bar indicates the cross-sector carbon emissions in seven regions under the baseline implementation rates of the AVS and ECP100 incentive targets. The error bar defines the uncertainty range of carbon emissions under different implementation rates: the uncertainty in the AVS ranges from 20% to 30%, 40% to 50%, and 60% to 70% and the uncertainty in the ECP100 ranges from 35% to 45%, 45% to 55%, and 55% to 65% in 2025, 2030, and 2035, respectively. The reference value shown by the red dashed line is the predicted carbon emissions in 2035. (D) LCCA results of carbon-neutral pathways for RSPV and CCUS in the seven regions from 2025 to 2035. The bar indicates the LCCA for the middle-cost case, and the tops of the error bars indicate the LCCA for the high-cost case. The RSPV pathway provides road transportation assets that can be used to develop energy attributes. These assets include roadside parking lots, ground space, infrastructure, and house rooftops. CCUS technology is used to capture carbon emissions from coal-fired power plants. After being compressed, the captured carbon can be transported to an appropriate location through pipelines or tanker cars and then directly stored or utilized.

economy-wide models are often used to capture cross-systems and often include transport modules, such as the Global Change Analysis Model and computable general equilibrium models.[2] Unfortunately, power modules are usually not considered. For instance, the Regional Energy Deployment System power module, which has been introduced into the US-centric Global Change Analysis Model to check the sensitivity of solution consistency to key drivers, is not available in China.[3] The multiregional input-output model can be used as a tool to explain China's environmental impacts from an industry chain perspective but still lacks a framework for coupled intersectoral carbon flows.[4] Therefore, a unified framework is needed to quantify carbon flows between the transportation and power sectors.

To mitigate the cross-sector effects of the transport-power grid, renewable energy, which is negatively correlated with carbon emissions, is considered a panacea.[5] For the transport sector, optimizing charging methods,[6] deploying fast-charging stations,[7] and scheduling energy storage systems[8] have proven to be effective in promoting the use of renewable energy. For the power grid sector, installing carbon capture, utilization, and storage (CCUS) systems is the most straightforward strategy.[9] However, none of the literature explain cost effectiveness in different policy contexts.

Therefore, the focus of this study is to quantify the carbon emission risk posed by electrification in the transportation sector to the power sector, a risk often overlooked in existing studies, and to propose pathways to mitigate this risk. Based on the new energy vehicle (NEV) deployment plan implemented by the Chinese government, a carbon transfer model for the joint transport and power grid sectors is constructed, and the carbon emissions transferred from EV operation to the power grid sector from 2020 to 2035 are quantified. This model is based on the dynamic power module of China's decarbonization action and actual operational data of approximately 4.92 million EVs in 2020 covering seven regions, four types of passenger cars, and eight types of commercial vehicles.[10] Furthermore, two carbon-neutral pathways, namely road-side photovoltaic (RSPV) and grid-side CCUS, are proposed, and recommendations for minimizing the levelized cost of carbon abatement (LCCA) in seven regions of China are provided.

TRANSPORT-POWER GRID CROSS-SECTOR EFFECTS

Based on the carbon transfer model for joint transport-power grid sectors, this study reveals that the operation of approximately 4.92 million NEVs in China in 2020 (Figure 1A), which was expected to reduce carbon emissions in the transportation sector by approximately 8.51 Mt, forced the power grid sector to bear an additional 37.60 TWh of electricity. This situation also increased transport-power grid cross-sector carbon emissions by 16.93 Mt (Figure 1C), accounting for approximately 2.86% of the total carbon emissions from China's power grid sector.

In 2020, the Chinese government announced the development target of the NEV Industry Plan (2021–2035). Based on this target and actual EV statistics, the baseline implementation rates for the annual EV sales (AVSs) and electricity consumption per 100 km (ECP100) targets were designed. That is, the AVS targets were increased by 25%, 45%, and 65% and the ECP100 targets were decreased by 40%, 50%, and 60% by 2025, 2030, and 2035, respectively. The uncertainty range for this incentive target is 5%.

Due to the dominant role of the AVS target, cross-sector carbon emissions will rapidly increase from 2020 to 2035. Under the baseline implementation rate, even if renewable energy curtailments are prioritized for offsetting, the additional electricity consumption caused by EVs will increase by 194.63, 442.82, and 705.34 TWh in 2025, 2030, and 2035, respectively (Figure 1B). This situation results in increases of 60.24, 128.50, and 186.79 Mt in cross-sector carbon emissions, respectively. Considering the joint uncertainty of the incentive targets, the ranges of cross-sector carbon emissions are [50.24, 70.68], [119.98, 137.38], and [180.04, 193.87] Mt in 2025, 2030, and 2035, respectively (Figure 1C).

The cross-sector carbon emission effects of EVs are comparable to the annual total carbon emissions in different countries worldwide. For example, cross-sector carbon emissions in 2035 account for approximately 31.24% of South Korea's annual carbon emissions and approximately 56.60% of the United Kingdom's annual carbon emissions (Figure 1C).

TECHNO-ECONOMIC ANALYSIS OF CARBON-NEUTRAL PATHWAYS

To avoid transport-power grid cross-sector effects, two carbon-neutral pathways are proposed (Figure 1D). In pathway 1, the RSPV pathway is deployed in the transport sector to provide renewable energy electricity for EVs. In pathway 2, the CCUS pathway is deployed at coal-fired power stations in the power grid sector to reduce carbon emissions from electricity consumption caused by EVs.

Based on the regional solar radiation, power generation mix, and decarbonization actions,[10] the RSPV installed capacities required to offset the cross-sector carbon emissions in 2025, 2030, and 2035 are 131.14, 324.58, and 544.75 GW, respectively. Compared to the energy development potential of China's road assets, the development of 0.31%, 0.76%, and 1.21% of transport assets can meet the electricity demand for EVs in 2025, 2030, and 2035, respectively. The CCUS capacities required to offset cross-sector carbon emissions in 2025, 2030, and 2035 are 88.37, 187.06, and 270.20 Mt, respectively. Compared to China's geological carbon sequestration potential, the utilization of 0.73%, 1.55%, and 2.23% of its carbon sequestration potential can meet the storage demands of cross-sector carbon emissions in 2025, 2030, and 2035, respectively. In this paper, the LCCAs for two variation factors in high-cost, middle-cost, and low-cost scenarios are compared: (1) the thermal coal cost saved by replacing grid power with RSPV and (2) CCUS operation and maintenance (O&M) costs.

We find that regional RSPV LCCA differences are negatively correlated with the carbon abatement capacity of regional RSPV modules and increase as carbon reduction capacities of the modules decrease, while regional CCUS LCCA differences are positively correlated with the carbon storage distance and decrease with decreasing O&M cost (Figure 1D). In the middle-cost case, choosing RSPV instead of CCUS in East China, North China, and South China, which have longer carbon storage distances, leads to lower LCCA values of [269.1, 482.9] and [446.7, 743.3] CNY/tonne, respectively. The LCCA values for choosing CCUS instead of RSPV in Central China, Southwest China, Northwest China, and Northeast China, which have shorter carbon storage distances, are lower at [296.2, 385.0] and [334.2, 904.6] CNY/tonne, respectively. In 2035, the LCCA values for RSPV and CCUS in East China, North China, and South China will reach [295.2, 566.9] and [296.2, 592.8] CNY/tonne, respectively, while the LCCA values for Central China, Southwest China, Northwest China, and Northeast China will reach [334.2, 904.6] and [296.2, 385.0] CNY/tonne, respectively. Notably, Southwest China and Northwest China will not bear additional LCCA costs until 2025, as the electricity consumption of EVs will be completely offset by renewable energy curtailments. In addition, compared to those of the middle-cost cases, fluctuations in the high-cost and low-cost cases in the RSPV in 2025, 2030, and 2035 will be 3.50, 5.14, and 7.77 CNY/tonne, respectively, while the fluctuations in average CCUS costs will be [335.4, 454.1], [269.0, 358.0], and [219.3, 279.6] CNY/tonne, respectively.

Therefore, before 2035, the RSPV pathway is recommended for the East China, North China, and South China and the CCUS pathway is recommended for Central China, Southwest China, Northwest China, and Northeast China. Because the O&M costs of CCUS directly impact the LCCA and still have room for decline in the future, the CCUS pathway is recommended for all regions after 2035.

CONCLUSIONS AND POLICY RECOMMENDATIONS

To clarify the carbon load associated with the quiet transfer of EVs to the power grid sector, a carbon transfer model for the joint transport and power grid sector is constructed, the carbon emissions transferred from EV operation to the grid sector are quantified, and the LCCA values of the RSPV and CCUS carbon-neutral pathways in seven regions of China from 2020 to 2035 are compared.

In conclusion, this study finds, for the first time, that the transport-power grid cross-sector carbon emission effects of EVs may be comparable to the annual emissions of other countries. That is, under the baseline implementation rates of the AVS and ECP100 targets, cross-sector carbon emissions will reach 186.79 Mt in 2035, which will account for 56.60% of the United Kingdom's annual carbon emissions. Furthermore, based on the LCCA results of the two carbon-neutral pathways in seven regions of China, before 2035, the LCCA of the RSPV pathway is lower in East China, South China, and North China and the LCCA of the CCUS pathway is lower in Central China, Southwest China, Northwest China, and Northeast China. After 2035, all regions in China will have lower LCCA values according to the CCUS pathway.

One contribution of the model proposed in this paper is its ability to be extended as a basic tool for quantifying transport-power grid cross-sector effects in different countries while providing data on national renewable energy portfolios and actual EV operations. Furthermore, the regionally customized carbon-neutral pathways in this paper can be used as a complement to EV incentive policies and provide deployment options for net zero emission EV operations in China and other similar countries.

However, this paper still faces two limitations. First, although sufficient detailed operational data for vehicle-level EVs have been obtained in this paper, they ignore the impact of seasonal differences in charging curves on the power system, as accounting for this factor is beyond the scope of this study. Second, the carbon emission model proposed in this paper did not consider the impact of cross-provincial or cross-regional electricity trading on the annual carbon transfer of EVs, as assessing this impact is not the goal of this paper. In addition, considerations of interprovincial renewable energy curtailment trading and the impact of network congestion on renewable energy curtailment deserve future study.

Finally, in this paper, a summary of three policy recommendations for China and other developing countries in similar situations is provided. (1) The government should explore the possible incompatibility between new policies and the effectiveness of cross-sector carbon emission reductions. (2) Transportation policies should be coupled with other policies to accelerate the decarbonization of the power grid by offering stakeholders regulatory incentives to reduce emissions. (3) LCCA conclusions based on different regional carbon-neutral pathways can also be used as a reference for other countries; that is, in countries with high solar radiation levels, the LCCA for renewable energy upgraded to grid connectedness is relatively low, but the CCUS pathway is a more promising option as the O&M costs of CCUS gradually decrease.

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DECLARATION OF INTERESTS

The authors declare no competing interests.