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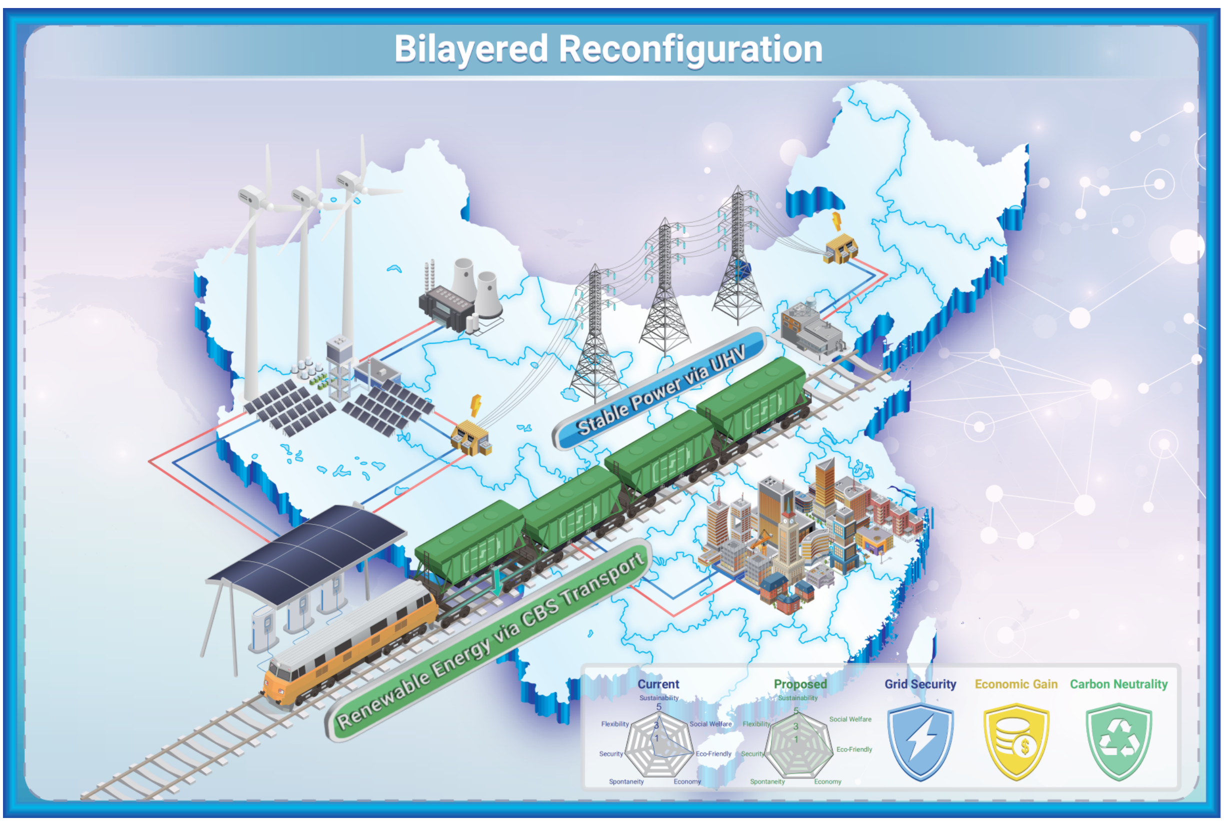
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- To address spatial power imbalance, China's current energy framework requires a 3.5 times increase in the construction of exorbitant and inflexible ultra-high voltage (UHV) lines.
- A proposed bilayered framework reconfigures the grid by storing renewable energy in containerized battery storages (CBSs) and transporting them via vacant railway capacity.
- This approach significantly reduces infrastructure needs, requiring only a 13.7% increase in new UHV lines and a 28.8% increase in new railways to meet demand that is expected to triple by 2060.
- The new CBS transportation business is projected to generate up to $0.87 trillion in transactions and could prevent the combustion of 2,061 million tonnes of coal between 2025-2060.

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Achieving carbon neutrality has been a demanding task for China, especially with the renewable-induced spatial power mismatch across provinces. Current solutions including storage co-deployment and Ultra-high-voltage (UHV) line construction impose exorbitant costs while still being insufficient in capacity, casting doubts on its long-term sustainability. Herein, we propose a bilayered reconfiguration of the current transmission framework. On the lower layer, stable power is scheduled for transmission via existing UHV lines; on the upper layer, renewable energy is physically stored and scheduled for ground transportation across the provinces via dynamic CBS sharing. CBSs relieve the transmission capacity shortage by 65.6% while achieving full renewable accommodation, meanwhile addressing renewable stochasticity and intermittency. The framework is also economic to all participants, while contributing to environmental protection, social welfare and security. Our proposal sheds light on addressing spatial power imbalance imposed by heavy renewable penetrations, and may enlighten other countries with bulk power transmission needs.

INTRODUCTION

To honor its pledge on carbon neutrality, China has increased its installation capacity of renewable generators to 758 GW as of 2022,[1] which is expected to further scale up by 15 times by 2060, with a penetration rate of 57% into the grid.[2-4] Meanwhile, the power sector is facing extreme pressure in adapting to this energy transition, one of the challenges being the spatial mismatch between the major sites of energy generation (mostly in Western/Northern provinces) and energy consumption (mostly in Eastern provinces) (See Supplemental Table S1).[5,6]

To address the spatial power mismatch, China has been carrying out a Herculean project of constructing cross-provincial Ultra-High-Voltage (UHV) transmission lines for long-distance power transmission in the past 15 years.[7] UHVs are adept at long-distance massive power transmission with minimal losses,[8] yet they are also cursed with exorbitant investment costs (0.23 million US$/km[9]), frequent maintenance and inflexible point-to-point transmission. More importantly, a higher penetration of renewables in the power industry would directly lead to frequency and voltage fluctuations in the UHV network, leading to grid insecurity and high regulation/maintenance costs.[10,11] Many provinces attempt to protect grid security through storage co-deployment, where all renewable equipment must be accompanied with 15-30 percent of energy storage installations,[12] which might discourage companies from investing in the renewable industry due to exorbitant investments.[13] Another alternative is to bundle flexible power (e.g., coal-fired power) with renewable energy before UHV transmission,[14] which in turn requires a costly capability of steep ramping from the bundled power plants,[15] and might become impractical when coal-fired power is superseded in 2060. These drawbacks lead to none of the participants profitable, whether in the site of generation, transmission or consumption, even in the presence of renewable[16] and storage[17] subsidies. Recently, another line of research focuses on converting electricity to other forms of energy, including hydrogen[18] and methane,[19] but the real-life power conversion efficiency is typically very low, raising new problems on energy utilization efficiency.

Recent developments in multiple industries of China shed light on possible alternatives to the form of cross-provincial power transmission. Many domestic battery manufacturers have announced their all-in-one Containerized Battery Storage (CBS) mass-production lineups, with large capacities, high energy densities[20-22] and affordable market prices.[23] China is also equipped with the world's second largest railway system capable of massive battery transfer.[24] Further, recent years have witnessed an emerging energy service providers including heterogeneous power sales companies[25] and storage companies.[26] It is then possible to formulate a nationwide business model of dynamically shared CBSs, by leveraging its mass production availability, battery-based energy storage transportation[27,28] and distributed service providers, to accommodate and transfer renewable energy. Throughout the line of research, we have found several papers aimed at leveraging battery transportation for power scheduling at a regional scale,[29,30] or proposes to transport batteries in order to address infrequent emergencies by rail[31] or by truck,[32] with the joint operation of power and transportation systems[33] Different from their works, the proposed business model extends the scale of battery transportation from region-wide to nation-wide to alleviate the intrinsic national power mismatch issues, and is targeted at leveraging long-range CBS transportation as a daily practice for power transmission, by taking its scalability and economic practicability as of paramount concerns.

This study focuses on the reconfiguration of the national energy transmission framework for China relying on mass-produced dynamic CBSs, to replace further UHV construction in addressing the spatial energy mismatch. Stable power, instead of renewable energy, is prioritized for transmission through UHV networks, directly increasing the power grid security. Renewable energy, on the other hand, is prioritized for mass transportation in the form of dynamically shared CBSs, with a specially-designed nationwide business model that involves a self-organized coalition of nationwide power service providers and the ground transportation systems. With the bilayered reconfiguration, fewer economical and capacity resources are required to establish this spatial energy transfer as a result of the strategic resource reallocation. In terms of distributed power participants, the reconfiguration demonstrates a lucrative solution for all participants, particularly the renewable power generation companies at an average profit of 0.071 US$/kWh. The reconfigured framework is also advantageous in environmental protection, security, as well as an enhanced level of social welfare. With adaptive improvements, the framework might even enlighten other developed countries with spatially-imbalanced power generation and consumption profiles.

METHODS / EXPERIMENTAL PROCEDURES

Classifying China's provinces into regions

The 31 provincial administrative regions of China are classified by their relative geolocation and economy into five regions: Western, Eastern, Northern, Southern and Central. Northern and western provinces feature a significantly higher share of fossil fuel and renewable resources, while their demand for energy is low; in contrast, Eastern provinces hold fewer resources but have strong power demands. Central and Southern provinces in general stand between the two extremes. See Supplemental Figure S3 for the details of regional classification.

Portraying China's provincial power balance

To estimate the provincial power balance of China's 31 provincial administrative regions through 2060, we first linearly scale the provincial power consumption and generation profiles in 2022 to years 2025-2060 (as there were no sufficient reports for years 2023 and 2024 at the time of research), based on the carbon-neutrality-driven energy outlook provided Supplemental Figure S4.

To optimally correct the power balance profile according to the proposed bilayered power transmission framework, a computational framework consisting of the following procedures is conducted in sequence:

1) Determine the provincial transmission of renewable energy (namely, wind and solar energy) based on the estimated renewable generation profiles and the net power supply/demand of provinces;

2) Compute the transmission of supporting power sources, including nuclear and hydro power, based on the estimated power generation profiles and the remaining net power surplus/deficit of provinces;

3) Compute the amount of coal-fired power transmission and coal transportation (under the proposed framework), based on the estimated amount of coal mined in provinces, capacity of UHVs, and the remaining net power surplus/deficit of provinces.

See Supplemental Note S1 for the detailed formula for each procedure.

Some special provinces, particularly Hainan and Tibet, are subject to geographical isolation or topographical barriers, and are thus excluded from the transfer of certain types of power.

Detailing the cross-provincial power transfer

We approximate the cross-provincial power transfer based on UHV transmission and CBS transportation with two constrained linear optimization models. In terms of UHVs, we first determine the UHV capacity for each outgoing province $p \in \mathcal{P}$ ($Cap^{UHV}_{p,out}$) and ingoing province $q \in \mathcal{Q}$ ($Cap^{UHV}_{q,in}$), as well as the amount of designated outgoing/ingoing power via UHVs $Trans^{UHV}_{p,out}$ and $Trans^{UHV}_{q,in}$. Then the linear model is formulated as

$$min_{Trans^{UHV}_{(p,q)}} \sum_{\substack{p \in P \\ q \in Q}} Dist(p,q)\, Trans^{UHV}_{(p,q)} \tag{1}$$

where $Dist(p,q)$ is the average distance between Provinces p and q, and $Trans^{UHV}_{(p,q)}$ is the to-be-optimized variable denoting the amount of UHV power transmitted from Province p to Province q. The linear model is then fed into a Gurobi 11.0 solver[50] for optimization to yield the optimal cross-provincial power transfer solution. The same optimization strategy applies to determining CBS-based power transfer.

Economic evaluations of the framework

Renewable power generation companies earn their revenues by selling electricity both to consumers in their own province and to external provinces, the proportion of which is determined by the total power generation and consumption profiles for each province. The unit price of electricity changes by provinces and by years, as the generation, demand, and sources of power are varied. For intra-province power sales, the majority of the power generation costs lies in the installation, operation and management of power generation devices (e.g., photovoltaics and wind turbines), referencing the open-access reports on the settlement prices of recent renewable power base projects.[51] For power sales to external provinces, additional costs are incurred, particularly the railway transportation costs where we reference the transportation costs of 40-inch containers as published by the National Railway Administration.[52] A 50% roundtrip discount is applied to the transportation costs due to the immense transportation volume. Additionally, the power generation companies pay the storage companies for CBS rentals, as well as the power sales companies for information management.

Storage companies charge 20% of the total CBS costs from the power generation companies as rental fees. The yearly CBS costs include CBS depreciation costs, operation & maintenance costs and loan interests, and the unit costs differ by the year of CBS production, attributable to the CBS manufacturing advances and state-of-health declines during the course of operation.

Power sales companies charge 1% of the total power sales revenues from the power generation companies in exchange for information management.

Details on the parameter settings in the simulation process, including electricity prices, yearly photovoltaic and wind turbine installation prices, yearly CBS installation costs and other relevant parameters can be found in Supplemental Tables S1-S4.

Evaluations on societal contributions

The amount of coal saved from combustion is computed from the unaccommodated renewable energy each year, assuming that the renewable accommodation capability linearly increases by the year. The amounts of waste gas (CO_2, SO_x and NO_x) produced, along with the amount of ash and sludge, are determined according to the coal combustion profiles. Estimations on the increases in GDPs and employments in Northern/Western underdeveloped provinces are computed from related coal industry statistics, multiplied by the coals reassigned for combustion in the provinces of coal mining. See Supplemental Table S5 for the detailed statistics.

Limitations and Future Work

We acknowledge that this study, as a macro-level strategic and economic feasibility analysis, simplifies certain operational complexities that warrant further investigation. These limitations, which we plan to address in future work, fall into two main areas. The first area is the need for more granular operational and logistical modeling. Our current study uses high-level estimates of vacant rail capacity. A valuable next step would be a detailed micro-level logistical simulation to truly validate the day-to-day operational feasibility. This would involve modeling specific train scheduling conflicts, siding availability, and hub operations like charging and dwell times. It would also allow for quantifying the specific operational costs (OPEX) related to safety, insurance, and compliance for transporting such a large battery fleet. The second area involves model robustness and scenario analysis. Our conclusions are currently drawn from a deterministic model using long-term projections. Future work would greatly benefit from a comprehensive uncertainty and sensitivity analysis on key parameters, like UHV and CBS costs, to test the framework's economic robustness. Additionally, the strategic framework could be further validated by back-testing it against historical high-curtailment periods and by exploring its resilience to disruptive future technologies, such as solid-state batteries, which are not part of our current projections.

RESULTS

The Bilayered Reconfiguration of Power Transmission

Figure 1A demonstrates the reconfigured national power transmission framework to address the spatial power mismatch, consisting of two layers of power transmission that focus on transmitting stable and renewable energy, respectively. It is important to note that our bilayered framework addresses the spatial (cross-provincial) transfer of energy. We implicitly assume that sufficient stationary storage is co-deployed at generation sites, as per current policies, to handle temporal (local) intermittency and achieve initial grid accommodation. Our framework then manages the transmission of this stabilized power.

On the lower layer, we decouple renewable energy from stable generated power (e.g., coal-fired and hydro power) in UHV transmission, and prioritize the transmission of stable power through UHVs. Raw coals, as a result, are encouraged to be combusted and converted into electricity at the site of

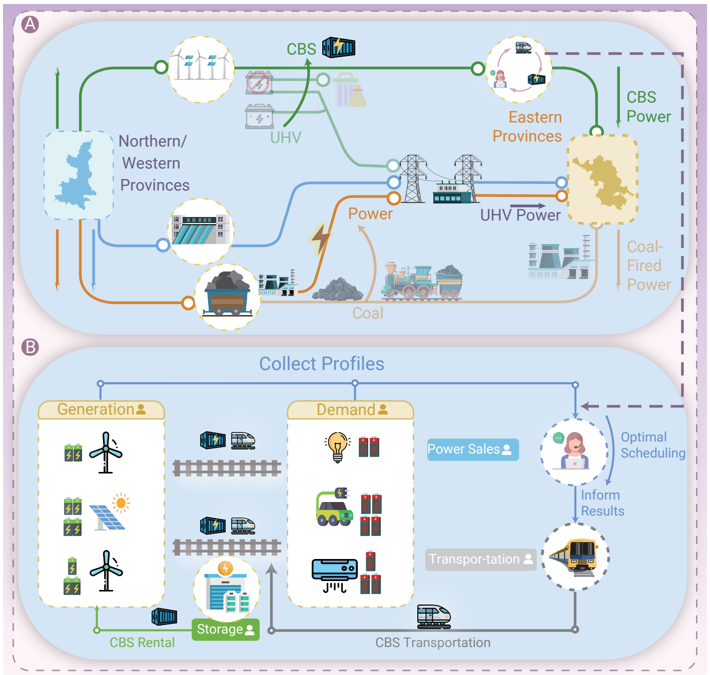

Figure 1. Reconfiguration of the national power transmission framework for China (A) The two layers of the proposed framework. Lower layer: stable power transmission (brown and blue lines) through UHVs. Upper layer: renewable power transmission (green lines) through CBSs. Translucent lines indicate the original power transmission routes intended to be phased out. (B) Details on the operational paradigm of the CBS-centered business model (purple circle in Figure 1A), where power sales, storage and transportation companies collectively assist in transporting power from the sites of generation to the sites of demand in terms of information services, storage rental services and container transportation services.

generation before UHV-based transmission to the site of generation, and are thus minimally transported through rail or other complementary ground transportation methods. Prioritizing UHVs in coordinating stable power transfer instead of renewable energy transfer significantly improves power quality, as it maximally avoids power stochasticity and intermittency issues within the power grid, directly improving frequency/voltage stability. The transition brings about further advantages to social welfare, including a higher profitability for

The transition brings about further advantages to social welfare, including a higher profitability for underdeveloped regions and a better overall solution to environmental issues, as will be further discussed in the upcoming sections.

On the upper layer, we propose a dynamic, spontaneous and self-organized solution for the remaining transmission task of renewable energy. Instead of implementing compulsive storage regulations on renewable generation companies, we encourage storage companies to provide them with CBS rental services, which will then be dynamically transported across provinces and entities through transportation systems. CBSs, where high-performance battery storages are sealed in the packaging of standardized containers, are friendly towards commercialization and mass transportation. This allows for the formation of a self-organized business model that trades energy across the nation by directly sharing and trading the CBSs with desired state-of-charges (Figure 1B).

CBSs are capable of seamlessly resolving the inherent stochasticity and intermittency of renewable energy, by charging and fixating generated energy into the battery storages before allocation. Further, with the prevalence of dynamically shared CBSs as standardized goods, a new storage market can also be created in a self-organized manner, which carries the potential to bring forth considerable business opportunities for various participants. Storage rental companies, which are already emerging in China alongside other countries, can be homogenized and aggregated into a national commercial conglomerate, by providing exclusive rental services of the standardized CBSs to the sites of electricity generation. Accordingly, power sales companies expand their information services by developing an information management system on the CBSs, keeping track of their real-time statuses such as location, state-of-charge and state-of-health. They then collect electricity generation and consumption profiles of the distributed entities, and schedule a set of optimal transportation routes for the collection of CBSs. Ground transportation systems, particularly the cross-provincial railway system, are responsible for transporting electricity in the form of dynamically-shared standardized CBSs, as per the scheduling instructions of the power sales companies. More specifically, they transport fully-charged CBSs to the sites of energy consumption for discharging, and conversely transport the drained CBSs to the sites of energy generation for charging. For the generators and consumers, only standardized sets of equipment, including rectifiers and inverters, are required for the distributed charging and discharging behavior. Renewable energy is hence physically transmitted across provinces and cities via the standardized CBSs, in the form of a dynamic storage sharing mechanism, with collaborative efforts from the energy, information and transportation networks that constitute the envisioned ecosystem. Aside from a complete decoupling from on-grid power transmission to protect the grid from frequency/voltage instability issues, the CBS ecosystem allows for all CBS participants to profit from the business model, as will be confirmed in the upcoming sections.

With the two layers of power transmission, both stable traditional energy and unstable renewable energy can be coordinatively transmitted between targeted provinces without compromising power quality in the power grid. From a broader perspective, the power transmission framework manages to allow the coalition to spontaneously balance the spatial power mismatch across provinces under the newly formulated business model, without major governmental regulation or stimuli.

The two layers of power transmission are highly flexible and interchangeable as the energy transitions come into play. For example, when the dominance of traditional power becomes superseded by renewable energy towards 2060, UHVs will also be under the task of transferring part of renewable energy. Hopefully, by then there would have been sufficient time to develop and implement more powerful storages that accommodate renewable energy at the site of generation.

Based on annual power generation and consumption data retrieved from governmental websites[2,34] (see Supplemental Table S1), simulations are performed on the cross-provincial power transformation in the upcoming years 2025-2060 under the proposed framework. During the period, as the nationwide power demand surges while coal-fired generation steadily declines, generation of renewable energy expands significantly by 7.68 times, further burdening the UHV transfer network with strong tendencies of compromising grid security. With the proposed framework, however, burdens on UHVs are significantly alleviated, diverted to more flexible ground transportation resources such as railways. According to Figure 2A which demonstrates the spatial energy transfer in 2040 (see Methods and Supplemental Note S1 for the modeling approach), a negligible 6.86% of renewable energy is transmitted via UHVs, only from a minimal number of regions with a plethora of renewable sources. Instead, UHVs shall carry a greater responsibility in transferring more stable and predictable power sources, such as coal-fired and hydro power, on the lower layer, by up to 100%. The majority of the transfer task of renewable energy shall be otherwise completed through the self-organizing CBS business model on the upper layer, the scale of which also increases steadily in time (4.47 times over the years), with a mainstream trend to transport CBSs from Northern/Western regions to Eastern regions. Particularly, energy-consuming provinces, including Shandong, Guangdong and Zhejiang, are in the greatest demands for fully-charged CBSs. On the other hand, energy-generating provinces, including Xinjiang, Ningxia and Inner Mongolia, provide the largest quantities of fully-charged CBSs. Transportation of the CBSs that start or end in these representative provinces constitute 74.3% of the total CBS trades and even 69.2% among the pool of the entire renewable energy transfer.

Strategic Resource Reallocation for Diverse Sectors

The reconfiguration of the power transmission framework brings, most importantly, a strategic reallocation of nationwide social resources, as is demonstrated in Figures 2B-E from multiple perspectives. It fully leverages the existing resources within the sectors of power transmission, ground transportation and storage services, such that a higher framework practica-

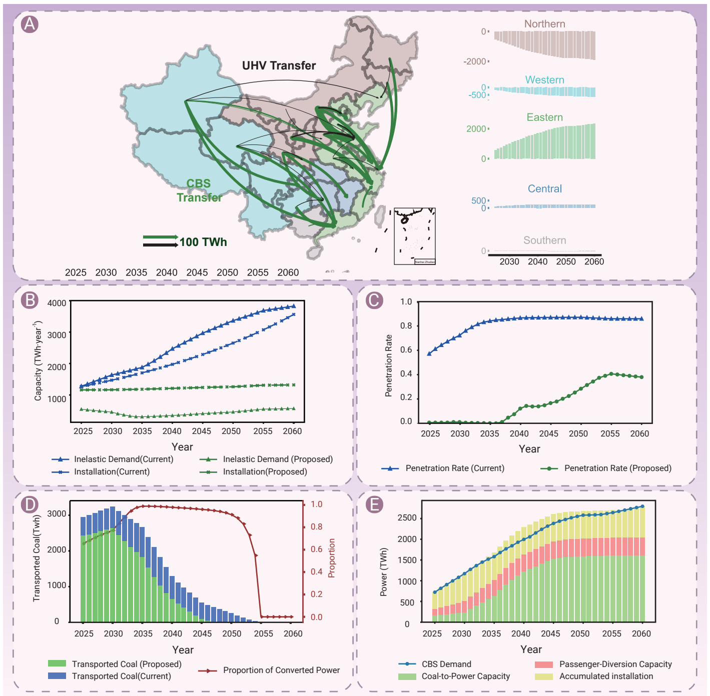

Figure 2. Changes in the dynamics of cross-provincial power transmission as per the proposed framework

bility is achieved and a lower reliability on resources is required up to 2060.

Within the power grid, the reconfiguration relieves nationwide burden to construct exorbitant cross-provincial UHVs. If the current power transmission framework continues, the accumulated UHV capacity would be highly insufficient compared with the inelastic cross-provincial renewable transfer demand (Figure 2B), even if the government constructed UHVs with an exponential capacity increase of 3% per year. With dynamically shared CBSs taking over the task of renewable energy transfer, the inelastic UHV demand now refers to the demand in stable power transfer instead, including coal-fired power and hydro power which only totals 55.1% of the installed capacity at its peak over the years. Over the period of 2025-2060, only a small increase of 13.7% is necessary for the nationwide UHV capacity (as opposed to a needs-based demand of a 200% increase for the current framework, which is calculated by our optimization model (see Methods) to meet the inelastic renewable transfer demand between specific provinces, not a simple blanket scaling assumption), and is only needed as a few nonpivotal provinces, including Anhui and Heilongjiang, lack the necessary startup capacity for stable power transfer. The relief in the capacity shortage of the UHV network, evaluated at 65.6%, leads to a significant contrast in upcoming UHV installation and maintenance costs by a factor of 2.3-7.8 times (or equivalently 45-153 billion US$). The remainder of the UHV capacity as per the proposed framework, relieved from the CBS business model, can still be fully leveraged in the transfer of elastic demands such as coal-fired power, which are a more predictable and flexible alternative for power grids.

The priority of UHVs to transfer stable power results in a lower penetration rate of renewable energy within the power transmission lines. As shown in Figure 2C, prior to 2036 the proposed framework manages to achieve a zero renewable penetration rate, as opposed to up to 84.8% for the current framework. The total renewable penetration rate across the entire period 2025-2060 has also dropped significantly by 80.8%. Considering the stochasticity and intermittency of renewable generation, this indicates a stronger security protection of the national grid and approximately an 82.8% drop in UHV maintenance fees, even in the presence of the co-deployment strategy.

Relieving UHVs from the burden of massive installation over the years naturally comes at the price of increasing the capacity of its alternative transmission strategy, namely, ground transportation. However, the required installation of transportation systems in the proposed framework is not necessarily on the same scale compared to that of UHVs in the current framework. In mainland China's railway system that already densely interconnects every two provinces (Supplemental Figure S1), we notice that passengers are rerouted to high-speed rails due to the railway electrification trend starting in the 1990s, leaving traditional rails and tracks unattended, which can be effectively resummoned for CBS transportation. On the other hand, the gradual decline in coal transportation demands in the lower layer of the proposed framework also increases the availability of more rails and tracks for CBS scheduling. More specifically, Figure 2D suggests that prior to 2055 where coal-fired power is fully eliminated, the amount of transformation from coal transportation to coal-fired power transfer reaches an average of 525 TWh as well as a maximum of 848 TWh in 2035, constituting 35.6% of the raw coal transfer and 98.8% of the total generated coal-fired power. This additional capacity, together with the capacity generated from passenger rerouting which amounts to 196 TWh, have vacated an accumulated capacity demand of 287-2,348 TWh for railways as the years progress, as has been demonstrated in Figure 2E (See Supplemental Figure S2 for the detailed capacity estimation method). The only required installation is 806 TWh of railway capacity prior to 2032, which constitutes only 28.8% of the total railway capacity towards the end of 2060. In reality, though, the required transportation capacity does not necessitate the installation of more rails and tracks: new carriages can be attached to currently installed trains, as long as the retrofitted trains meet the necessary power and safety requirements of the railway system. CBSs could also be alternatively transported by container ships between waterway-connected provinces, further relieving the railway installation needs.

The ecosystem of storage-related services on the upper layer of the framework is also expected to go through a fundamental transformation, reflected in the detailed job responsibilities of each service provider in the CBS business model, which also reshapes the bigger picture of social resource utilization. Manufacturers of storages, instead of getting involved in a cutthroat competition of storage design and pricing, now collaboratively push forward the standardization of CBSs, which in turn requires the development of high-throughput storage solutions available for mass production. Storage companies, instead of installing fixed storages at the site of generation, now provide flexible rental services of CBSs for the site of renewable generation, requiring more on CBS scheduling capabilities and less on on-site installation. Power sales companies, instead of manually coordinating the power transfer among heterogeneous entities, now only provide virtual services on information collection of generation/demand profiles and optimal scheduling of homogeneous CBSs, thus requiring less on physical labor but more on the development of geographical information systems and scheduling capabilities. From a broader perspective, the reconfigured framework requires more specialized products and supply chain management skills, meanwhile significantly reducing manual labor, attributable to the storage standardization trends across the nation. Utilization and reutilization rates of storages and storage components are also expected to be increased, from a current 6% to a full 100%, as a result of the national standardization and higher portability of CBSs.

The greatest benefit of the social resource reallocation lies in the increase of flexibility in power transfer. Renewable energy, as the predominant power source after 2040, is transferred across provinces mostly in the form of CBS transportation, a much more flexible solution against unpredictable power incidents than contract-based power transfer in the form of UHVs. The rigid outgoing UHV power contracts, for example, are responsible for the blackout in cities of the Sichuan province in 2022, even when Sichuan itself generates 368.48 TWh of hydropower that year.[35] Additionally, the standardization of CBSs indicates the strong homogenization of storage manufacturers and downstream supply chains, implying that any shortage in storages or spare parts in one place can be dynamically and efficiently remedied by another. With these unique advantages of standardized CBSs, even when taking into account the flexibility of coal transportation in the current framework, the proposed reconfiguration still manages to significantly increase the flexibility of power transmission by 2.98 times, from 31.1% to 92.6%. The higher flexibility results in a more timely and accurate response to real-time power generation and consumption requirements, and hence encourages a higher rate of power utilization.

Collective Economic Gain within All Participants

To gain an in-depth understanding of the economic structure for the CBS-

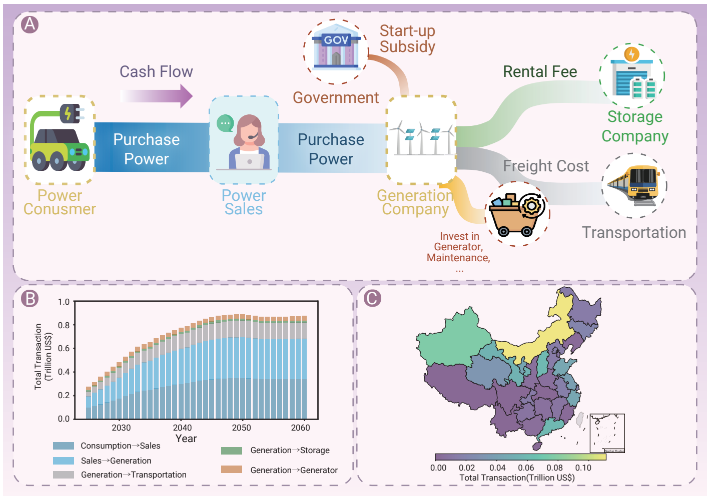

Figure 3. Details on the proposed business model embedded in the upper layer of the reconfigured framework (A) A demonstration of the operating norm of the business model, including the direction of cash flow within the major energy participants. (B) The total value of CBS-based cross-provincial power transactions across the major energy participants of the business model from 2025 to 2060. (C) The yearly average of the total CBS-based interprovincial energy transaction values within each of China's 31 provincial administrative regions.

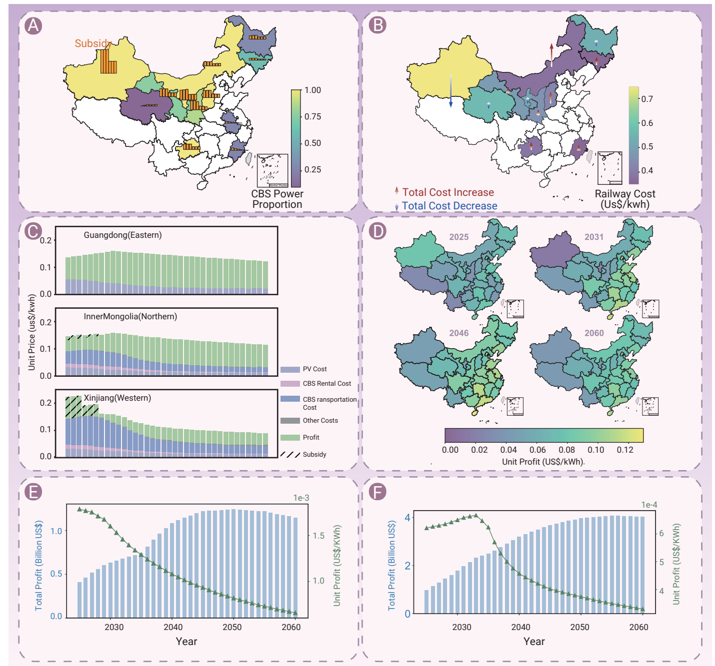

Figure 4. Economic evaluations of the reconfigured framework across provinces and years (A) Subsidies per unit of electricity (orange bars) required for particular provinces from 2025 to 2030. No subsidies are required beyond 2030. Colors on the map indicate the percentage of CBS power within the amount of renewable energy generated by each province. (B) Unit railway transportation costs of CBSs for related provinces in 2031 (colored map). Brown and blue arrows indicate the total provincial increases and decreases of railway transportation costs across as per the price adjustments, which even out across the nation, in order to incentivize the distant provinces. (C) A breakdown of revenues, costs and profits for the PV power generation companies of three representative provinces (Guangdong in the East, Inner Mongolia in the North, and Xinjiang in the West), throughout the years 2025-2060. (D) Provincial profitability of PV power generation across China's 31 provincial administrative regions in representative years 2025, 2031, 2046 and 2060. (E) Total profits (blue bars) and unit profits (green line) of the storage companies from 2025-2060. (F) Total profits (blue bars) and unit profits (green line) of the power sales companies from 2025-2060.

based business model, a visualization of the operating norm and cash flow across the participants within the business model is presented in Figure 3A. Power consumers purchase power from renewable generation companies via the power sales companies, who charge fixed-rate service fees as a middle agent providing CBS informational services and power coordination services. Renewable generation companies gain revenues from purchase orders of renewable energy and (in the first few years) subsidies from governments, meanwhile bearing the costs of storage rental fees, CBS transportation fees and generator installation/maintenance fees. Storage companies, instead of profiting from the installation and maintenance of fixed storages, now directly charge rental fees from renewable generation companies that request CBS rentals, while investing in the installation of state-of-the-art CBSs according to the latest storage generation profiles. They also manage to retrieve some of its initial investments through the recycling or second-life reutilization of the CBSs after their service periods. The transportation system, particularly the railway system, profits from the transportation of CBS as per their regular transportation services, although the prices charged per kilometer are subject to adjustments according to the CBS transportation burdens of the provinces.

On a macroeconomic scale, the new business model carries the potentials to promote nationwide economic boosts, by multiplying the turnover rates of CBSs and inviting multiple participants into the CBS-based

power transmission dynamics. The total value of interprovincial transactions within the major business participants (power consumption, power generation, power sales, storage companies and transportation) has raised from 0.27 to 0.87 trillion US$ within the time period of 2025-2060 (Figure 3B), with a maximum cash flow of 0.10 to 0.34 trillion US$ flowing from the sites of power consumption to generation. In 2025 alone, the magnitude of the transaction-induced cash flow would have accounted for 0.4% of mainland China's forecasted GDP, and the proportion is projected to increase as the years pass.[36] With the large amount of transaction value and increasing trend across the entities, a new economy would be formulated, which boosts the vitality of the current economy by creating job opportunities and interconnecting heterogeneous energy markets in the manufacturing and operation of CBSs. Particularly, the transportation and storage rental markets, two barely-profitable markets in the current stage that appear irrelevant to massive power transmission, would benefit the most from the business model, with yearly cross-provincial transactions of 42-141 and 10-14 billion US$ from 2025-2060. In terms of the spatial density of the cross-provincial transactions, the majority would take place in the Northern/Western power-outgoing provinces (e.g., Inner Mongolia and Xinjiang), with a yearly-average transaction value of as high as 111 billion US$. Eastern power-ingoing provinces come in next (e.g. Guangdong and Zhejiang), with the largest pool of expected power purchases from the power sales companies (Figure 3C).

To further quantify the economic benefits attributed to the reconfiguration, we evaluate the economic profits associated with the participants involved, throughout the timespan and geographics (see Methods for evaluation details). In terms of governmental stimulations, Figure 4A & B demonstrate the provincial start-up subsidies and CBS transportation cost adjustments, respectively, embedded in the framework to achieve collective lucrativeness across the provinces. Provincial start-up subsidies only pertain to the early years prior to 2030, and are designed to decrease over time (0.014 US$/kWh in 2025-2027 and 0.007 US$/kWh in 2028-2030) before they are phased out. Subsidies are also designed to be proportional to the average transported miles of fully-charged CBSs out of the province, such that these

provinces bear milder financial burdens in delivering the physically-stored power. Electricity-rich provinces in the Northern and Western regions, including Xinjiang (0.078 to 0.038 US$/kWh), Heilongjiang (0.010 to 0.007 US$/kWh), Shanxi (0.022 to 0.011 US$/kWh) and Shaanxi (0.029 to 0.010 US$/kWh), are therefore the biggest beneficiaries of the subsidy in its early stage of implementation; most of the other provinces, due to bearing no CBS transportation burdens, are not subject to subsidy policies in order to save governmental budgets. The railway system, on the other hand, is expected to each a same amount of profitability as traditional freight transportation, but adjusts its CBS transportation prices in favor of the more distant and CBS-reliant provinces, for example, a price reduction for Xinjiang (by 0.037 US$/kWh), Qinghai (by 0.011 US$/kWh) and Ningxia (by 0.003 US$/kWh) in 2031. Provinces with milder CBS transportation demands accordingly bear higher costs (e.g., Inner Mongolia by 0.019 US$/kWh) so that the national CBS transportation revenue evens out on the national level.

With governmental subsidies and railway price adjustments at a macroeconomic regulation level, renewable generation companies in the cities across all provinces are able to achieve collective profitability across

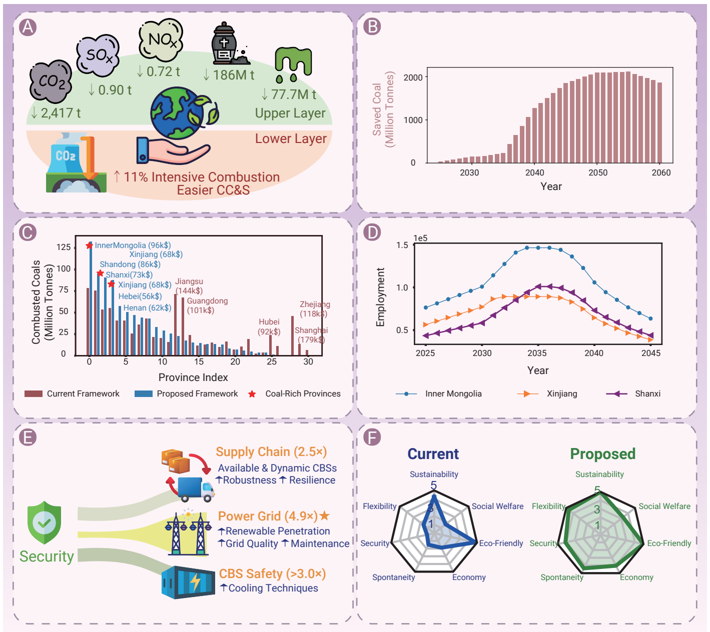

Figure 5. Evaluations of the proposed power transmission framework, particularly in terms of its contributions to the society (A) An overview of the proposed framework's contributions to the environment from both the upper and lower power transmission layers. (B) Reductions on coal combustion during the years of 2025-2060 as per the proposed framework. (C) Combusted coals across the provinces in 2045 as per the current (brown) and proposed (blue) framework. GDPs per capita of the representative provinces are listed near the respective province names. The top 3 provinces of abundant coal resources are marked with red stars. (D) Created job opportunities in the provinces of coal production (Inner Mongolia, Xinjiang and Shanxi) over the years 2025-2045, as a result of the relocation of coal-fired power generation. (E) Security enhancements embedded in the proposed framework. (F) Radar plot comparisons of the current and proposed frameworks, in terms of sustainability, flexibility, security, spontaneity, economy, eco-friendliness and social welfare. See Supplemental Note S2 for relevant evaluation metrics.

provinces during the years 2025-2060. The profit breakdowns shown in Figure 4C are calculated based on the comprehensive economic model detailed in the 'Economic evaluations of the framework' subsection of the Methods, using the cost and revenue parameters specified in Supplemental Tables S1-S4. As a demonstration, Figure 4C visualizes the profit breakdown of the PV power generation companies in three representative provinces: Guangdong as an Eastern province, Inner Mongolia as a Northern province, and Xinjiang as a Western province. Prior to 2030 when governmental subsidies are phased out, for example in 2025, faraway CBS-reliant provinces such as Xinjiang rely heavily on the subsidies (0.078 US$/kWh) and railway price adjustments (down by 0. 036 US$/kWh, embedded in the CBS transportation prices) in order to achieve lucrativeness (0.079 US$/kWh), while the representative Northern and Eastern provinces can already secure its profitability (0.053 and 0.080 US$/kWh, respectively). In the decade that follows 2030, CBS-reliant provinces featuring Xinjiang might struggle in economy without the presence of subsidies, but a minor profit can still be reached (0.013 US$/kWh in 2031) attributable to the ongoing railway price adjustments (0.106 US$/kWh in 2031), necessary to keep the power generation companies incentivized; the dilemma can be quickly phased out as the renewable transition progresses, where the unit costs for renewable generation and CBS manufacturing steadily decline (by 45.6% and 57.1%, respectively, from 2031 to 2060). By 2060 where carbon neutrality is expected to be accomplished, even Xinjiang can profit by as much as 0.030 US$/kWh, while Inner Mongolia and Guangdong can profit by 0.071 and 0.096 US$/kWh, respectively, even when the nationwide electricity price starts decaying since 2033. In terms of the nationwide profitability of renewable generation during the energy transition, Figure 4D further visualizes the PV power generation profits across the country, which increase steadily from an average of 0.061 to 0.085 US$/kWh during years 2041, and stabilized an average of 0.066 US$/kWh when the power price steadily drops to 76% of its peak value. Wind power generation companies are also expected to enjoy similar though slightly milder profits throughout the time period. In total, generation companies in all provinces can make profits across the entire time period, at an average of 0.071 US$/kWh (This profit represents the net income after deducting costs for generation, CBS rental, and transportation from the electricity sales revenue, as detailed in the Economic evaluations of the framework subsection of the Methods and Supplemental Tables S1-S4), with a favor toward Mid-Southern provinces (e.g., Hunan, Guangdong and Hainan) over Western provinces (e.g., Xinjiang and Qinghai). Those in the latter provinces, despite the financial struggle with all the long-distance CBS transportation costs, can still inherently break even with the natural benefit of spatial arbitrage: Xinjiang and Qinghai, for example, enjoy an arbitrage of 0.061 and 0.045 US$/kWh in 2031, respectively, by selling power directly to Eastern provinces.

In addition to the power generation companies, other involved participants are also expected to profit from the proposed reconfiguration of cross-provincial power transmission. The storage companies, who charge a 20 percent fixed-rate rental service cost on the standardized CBSs, are expected of an increasing total profit from 0.41 to 1.15 billion US$ across the years as the demand for renewable transmission surges, despite the exponentially decaying manufacturing costs which lowers the unit profit (Figure 4E). The increasing production of renewable energy by 2060 and the framework's preference towards CBSs to transport renewables contribute to an ever-increasing demand for the standardized CBSs, allowing for the total storage profit to grow. On the other hand, two major driving forces lead to the decrease of CBS costs: 1) a decreasing price trend in raw materials and storage manufacturing, especially when the CBS becomes mass produced and standardized in China;[37] 2) the dynamic and full-time utilization of storages from 6% to nearly 100%, which brings down the equivalent Levelized Cost of Storage (LCOS) by 16.7 times. Therefore, with the increasing demand and the lower costs across the CBS supply chain, the proposed framework manages to both ensure the appealing profits of storage companies and ensure the lucrativeness of the energy transmission industry as a whole.

The power sales companies, as the other major type of participants, live in a commission mode, providing information services of the CBS trajectories and power generation/consumption profiles of different entities, while charging 1 percent of the total power transmission revenues. Similar to the storage companies, they are also expected to be always lucrative, with total profits increasing from 0.99 to 4.03 billion US$ as a result of the surge in renewable transmission demands, in spite of the decreasing unit revenues in electricity sales for as much as 46.9% (Figure 4F). Again, a reasonable balance is achieved between the total profits of the power sales companies (by increasing demands) and the entire renewable industry (by reducing unit costs).

The central government and national power grid benefit most significantly from the reconfiguration, as now the UHVs do not need to be massively constructed to address the increasing renewable transmission demands. This effect cushions the instantaneous impacts of national power investments, as the start-up cost for the construction of UHVs (evaluated at 4.3 billion US$ for a typical ±800kV DC UHV line) is exorbitant, which will count directly towards that year's public finance even if eventually charged from the power consumers. External cost savings stem from the relief from frequent UHV maintenances for transmitting the intermittent renewable energy, as well as the secondary utilization of CBS that restores approximately 60% of the CBS installation prices.

The above analysis suggests that, even with minimal governmental subsidies for short-term kickstarts, all participants shall achieve uniform lucrativeness in all provinces and all years, and the government is relieved from the financial impacts of instantaneous investments. These two factors constitute the determining advantage for the proposed power transmission framework, and can be the major reason for all entities to operate it in a spontaneous and self-driven manner without external incentivization.

Implications for the improvement of Societal Well-Beings

Aside from bringing added values in economics and resource utility, the reconfigured framework makes substantive improvements to various aspects of the well-beings of the society, demonstrated in Figure 5.

At the forefront lies the framework's contribution to environmental protection from the design of both transmission layers. On the upper layer, the availability of dynamically-allocated CBSs on the generation side will substantially increase the accommodation of renewable energy (up to a full accommodation rate in theory), reducing the need for 3,607 TWh of coal-fired power by 2060, thus reducing greenhouse/pollutant gas emissions hard to fixate, including 2,417 tonnes of carbon dioxides, 0.90 tonnes of sulphur oxides and 0.72 tonnes of nitrogen oxides (Figure 5A).[38] Substantial solid wastes, constituting 90% of the total combustion wastes, are also eliminated, including 186 million tonnes of ashes and 77.7 million tonnes of flue-gas desulfurization sludges.[39] The amount of coal saved from combustion is accordingly multiplied from 32 million tonnes in 2025 to 2,061 million tonnes in 2056, totaling 29.4% of the total coal reserves in current mainland China (Figure 5B).[40] On the lower layer, as fossil fuel transportation has been maximally substituted with UHV-based coal-fired power transmission, coal combustions and coal-induced wastes are more concentrated on provinces that hold abundant coal resources (e.g., Inner Mongolia, Xinjiang and Shanxi, see Figure 5C), paving the way for targeted environmental restoration methods including Carbon Capture & Storage (CC&S), which are expected to cost the coal-fired power generation companies 360 billion US$ in total in the early years of energy transition. By leveraging the economies of scale, the nationwide environmental restoration costs can be substantially lowered by sharing overheads and other fixed costs across the densely located coal-fired power plants. The more intensive coal-fired power combustion also contributes to a lower need for total power reserves due to a smaller number of coal-fired power plants, hopefully reducing the total amount of coal combustion across the nation.

Considerations on social welfare are also inherently embedded in the reconfigured power transmission framework. Provinces designated for coal-fired power transmission are mostly underdeveloped in terms of GDP per capita (Figure 5C), residing near the lower end of the provincial GDP profiles (e.g., Hebei, Henan and Xinjiang), some of which are further economically reliant on the coal industry (particularly Inner Mongolia and Shanxi). By selling electricity as a secondary product instead of coals as a primary product, a much larger profit is expected in these Northern and Western underdeveloped provinces, estimated to be on an average of 0.048 US$/kWh. Job opportunities are also expected to be created in such underdeveloped provinces, especially towards 2035 where nationwide coal- fired power production is expected to be at its peak. As examples, increases of 146, 89 and 101 thousand job opportunities are expected for Inner Mongolia, Xinjiang and Shanxi, respectively (Figure 5D). The dynamic changes in provincial GDPs and job opportunities will improve the well-beings of the underdeveloped regions, thereby contributing to diminishing inter-provincial economic differences and establishing nationwide uniform prosperity.

Furthermore, the framework secures the accommodation of cross-provincial power transmission demands on three levels (Figure 5E). In terms of the CBS supply chain, the standardization of CBSs indicates that all spare parts and technologies will be readily available for mass production and emergency maintenance, reducing the lead time while boosting the robustness and resilience of the supply chain by 2.5 times. In terms of the power grid, the designation for UHVs to transmit stable power reduces the renewable penetration rate in UHVs, resulting in a 4.9 times stability boost in the power grid; the introduction of mobilized CBSs also reduces the need for coal-fired power reserves in face of sudden energy shortages. Further, with the standardization of CBSs, secure CBS operation and transportation techniques featuring water/oil-driven liquid cooling[41] can be optimally integrated into their container design, physically improving the safety of each CBS by over 3 times (see Supplemental Note S2 for the evaluation of the security boosts).

DISCUSSION

The paper outlines the possibility of a bilayered reconfiguration of power transmission across provinces, in order to adapt the power system to a renewable-predominated power system. The framework suggests transmitting stable electricity with the exorbitant while vulnerable UHVs, while transporting the intermittent renewable energy physically through dynamically-shared CBSs and an accordingly organized storage-trading business model. Figure 5F evaluates the performance of the proposed framework in the form of a radar plot (See Supplemental Note S2 for the detailed evaluation metric). As has been illustrated in the previous sections, the proposed framework is an economic, flexible, secure and eco-friendly solution, and is considerate of nationwide social welfare. The conducted economic evaluation that all participants can collectively profit in the business model also encourages the framework to pan out in a spontaneous and self-organized manner, while reaching a high level of sustainability. By contrast, the current power transmission framework (where all renewable energy is transmitted via government-installed UHVs) might reach a similar level of eco-friendliness and sustainability, but is hardly an economic, secure, flexible or spontaneous option due to the intrinsic nature of UHVs.

In addition to China, many developed countries including the United States,[42] Japan[43] and Germany,[44] who possess the world's most developed ground transportation systems, might also benefit from a similarly reconfigured CBS transportation network. In the United States, for example, the U.S. Department of Energy has already reported that the national power transmission is at its capacity limits, especially towards power-consuming provinces such as Texas.[45] Meanwhile, the spatial imbalance of power might be of minor concern for the time being, but as the U.S. approaches its promise on carbon neutrality in 2050,[46] renewables as the predominant power sources are highly likely to proliferate in less-populated states (e.g., rural utility-scale photovoltaics in Central states[47]), necessitating the transmission of inter-state power transfer. By drawing an analogy to the proposed framework in China, the U.S. could fully leverage the world's top railway system, where freight rails have almost covered across all contiguous states in high shipping densities,[48] to transport the renewable-charged CBSs between targeted states. This allows the U.S. to accommodate and coordinate the increasingly predominant renewable energy, without the construction need for UHV infrastructures which are currently lacking.[49] If further agreed and promoted by international organizations such as the International Energy Agency, it is likely that international power transportation pathways could be constructed on top of maritime shipping routes or inter-continental railways, allowing for physical trading of power between targeted countries. This further helps to break through the power operational barriers of different countries (reflected in their different voltages, frequencies, etc.), beneficial towards the worldwide accommodation of renewable energy, and boosts the economy of developing countries through a surging renewable generation and transmission business. However, the direct transferability and viability of this framework would depend on a country's specific conditions, including its railway network density, battery supply chain maturity, and existing grid infrastructure, which are critical factors not contrasted in this study.

To properly reconfigure the power transmission framework as proposed within the next few years, one has to overcome the operational barriers of different entities, including the sites of generation, consumption and service providers (including UHVs and CBSs), which are all currently operated by different stakeholders and are more sparsely interconnected as expected. One also needs to overcome the hurdles of provincial differences in nationwide operation, by means of homogenizing the various storage companies and power sales companies into nationwide franchises, allowing them to exchange standardized CBSs and information without generating unnecessary conflicts.

The government also shoulders a great responsibility in facilitating this transition. While the framework's objectives align strongly with China's high-level policies on carbon neutrality and energy security, its novel mechanism requires significant policy adaptation. The government must not only convince entities to collaborate and promote CBS standardization, but also lead the development of new regulatory pathways. Specifically, current railway transport policies are not designed for the daily transport of gigawatt-hour scale mobile energy storage. A critical pathway for implementation will be for railway authorities to develop new, robust safety and operational standards for this class of hazardous energy cargo. An appropriate amount of regulation on CBSs will also help all participants mitigate conflicts, extending the sustainability of the framework all the way to 2060.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

To retrieve exhaustive data and code sets, readers may contact the corresponding authors upon reasonable request.

SUPPLEMENTAL INFORMATION

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