communications earth & environment

Article

https://doi.org/10.1038/s43247-024-01363-1

China Southern Power Grid's decarbonization likely to impact cropland and transboundary rivers

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Decarbonizing the electricity sector requires massive investments in generation and transmission infrastructures that may impact both water and land resources. Characterizing these effects is key to ensure a sustainable energy transition. Here, we identify and quantify the unintended consequences of decarbonizing the China Southern Power Grid, China's second-largest grid. We show that reaching carbon neutrality by 2060 is feasible; yet, doing so requires converting 40,000 square kilometers of land to support solar and wind as well as tapping on rivers to build ~32 gigawatts of hydropower. The impact of wind and solar development would span across multiple sectors, since crop and grassland constitute 90% of the identified sites. The construction of new dams may carry major externalities and trickle down to nearby countries, as most dams are located in transboundary rivers. Curbing the international footprint of this decarbonization effort would require additional investments (~12 billion United States dollars) in carbon capture technologies.

The decarbonization of the electricity sector is a major pillar of the policies adopted by several countries to limit global warming[1]. China, the world's largest emitter of carbon dioxide, is no exception: to overcome the twin challenge of reaching carbon neutrality by 2060 while meeting an increase in electricity demand[2], China has long started to invest in renewables, especially in water, wind, and solar resources[3]. This is the beginning of a long pathway that is expected to yield a profound transformation of the electricity system[4–7]. However, the deep interconnections between human and natural systems[8] may compound such decarbonization plans with unintended consequences. Hydropower, for instance, is characterized by major externalities that span from the displacement of large communities to the alteration of hydrological and ecological processes[9–11]. Wind and solar, on the other hand, require vast amounts of land, with potential social and ecological impacts that spurred the so-called "green vs. green" conflicts[12], some of which are already perceived in China[13]. Identifying and quantifying the unintended consequences of decarbonization policies is therefore key to ensuring the sustainability of major infrastructural developments.

So far, research efforts have predominantly focussed on the relationship between specific types of renewables and their unintended consequences[14]. Beginning with solar and wind, previous studies have quantified land use requirements[15,16] and shown that the use of siting constraints and appropriate pace can make the energy transition affordable and more sustainable[17]. As for hydropower, emphasis has been placed predominantly on the use of wind and solar resources to cap the construction of new dams[18–21]; knowledge about the relationship between CO_2 emission targets and dam development pathways is limited. There are two additional matters, related to hydropower, that make such characterizations challenging. First, global warming may alter important system drivers, such as water demand or hydropower production[22], which in turn affect investments in power grid expansion. Second, hydropower resources are often located in transboundary river basins; this implies that the externalities associated with the construction of dams are complicated by tensions arising between riparian countries[23]. Because of these complexities, it is important to devise grid decarbonization plans that explicitly account for their impact across sectors (i.e., land and water) and countries, a matter that, to date, has not been explored.

Here, we identify the unintended consequences that could be caused by the implementation of carbon-neutrality targets in China. We focus, in particular, on the China Southern Power Grid (CSPG), China's one of two wide-area synchronous grids (Fig. 1). Its current situation is indeed emblematic of the aforementioned complexities. The CSPG already serves a total of almost 300 million customers; yet, it is expected to serve a rapidly increasing load in the next decades—the annual electricity demand is projected to more than double by 2060 (from 1177 TWh in 2020 to 2579 TWh

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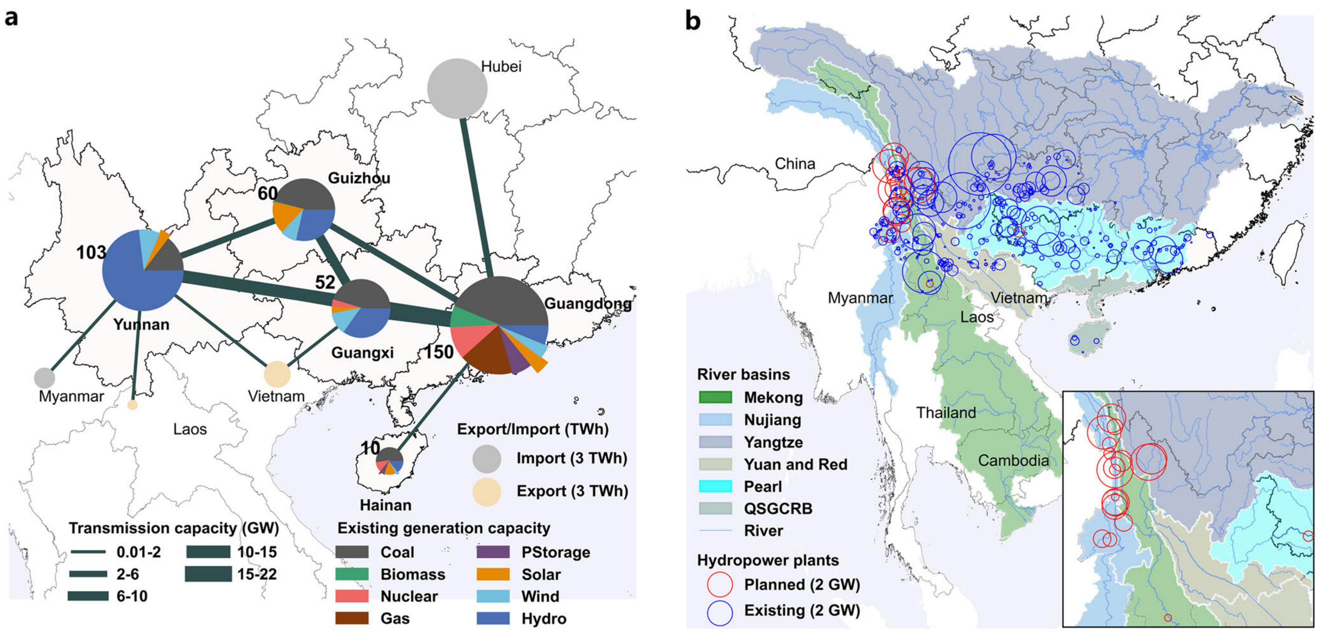

Fig. 1 | Study site. a Spatial representation of the CSPG power system infrastructure. The snow-white areas are the regions under the CSPG jurisdiction. Segments represent existing interconnections. The pie charts illustrate the existing capacity mix for each province and are proportional to their province-wise capacity (shown beside each pie). All components of the power grid are modeled with GridPath. **b** The map illustrates the river basins whose hydropower dams feed the China Southern Power Grid (CSPG). These basins are the Mekong, Nujiang, and Red (transboundary) and the Yangtze, Pearl, Qionglei and Southeast Guangxi Coastal river basins (QSGCRB). All riparian countries in which the transboundary basins flow are shown on the map. Existing (operated in 2020) and planned dams are represented by blue and red circles, respectively. The inset provides a more detailed illustration of the dams planned in the Mekong, Nujiang, and Yangtze.

in 2060)[24,25]. To emancipate the grid from its reliance on coal and achieve carbon neutrality, radical changes to the generation and transmission facilities are planned. This includes the expansion of solar and wind plants, as well as a massive expansion of the hydropower fleet that will add more than 32 GW of installed hydropower capacity. Apart from the Yangtze, most of this capacity (78%) will be added to transboundary rivers, namely the Mekong and Nujiang (also known as the Salween) (Fig. 1). The questions of interest are therefore the following: What are the land requirements for achieving carbon neutrality? What is the amount of additional hydropower that is needed to support the decarbonization of the CSPG? How does protecting transboundary river basins impact decarbonization pathways and land requirements?

Table 1 | Core scenarios and associated assumptions

Name	Carbon neutrality	Transb. hydro.	Available renewable capacity (GW)		
			Hydro.	Solar	Wind
Reference	No decarb. target	Yes	32.34	340	94
Decarb. 2060	By 2060	Yes	32.34	340	94
Decarb. 2050	By 2050	Yes	32.34	340	94
Decarb. 2040	By 2040	Yes	32.34	340	94
Decarb. 2060 WTH[a]	By 2060	No	7.34	340	94
Decarb. 2050 WTH[a]	By 2050	No	7.34	340	94
Decarb. 2040 WTH[a]	By 2040	No	7.34	340	94

The available capacity for hydropower refers to the capacity that could be installed at the planned dams; the capacity for solar and wind indicates the potential of the candidate sites. The remaining scenarios are described in Table S1.

[a]Without Transboundary Hydropower (WTH) dams.

To answer these questions, we adopted a modeling framework that explicitly captures the spatio-temporal details of the CSPG's generation, storage, and transmission resources. The core of our framework is GridPath[26], a modeling platform that we set up for the five provinces of the CSPG and through which we co-optimize capacity expansion and energy operations for generators, storage, and transmission across multiple investment periods with various techno-economic and operational constraints. GridPath integrates high-resolution wind, solar, and hydropower availability data, which are produced by three additional models. Hydropower availability at existing and planned dams is estimated by Xanthos[27], a global hydrological and water management model. As for solar and wind resources, we first used REZoning[28]—an interactive, global geospatial datasets-based platform—to identify candidate wind and solar sites and estimate their potential. We then calculated time series of hourly power availability at the candidate sites with pyGRETA[29].

We examined a wide range of scenarios to explore the impact of decarbonization policies, dam development on transboundary basins, and changes in hydropower availability caused by global warming. The core scenarios consist of seven elements (Table 1). In the Reference scenario, we assume that carbon-neutrality targets are not imposed; an assumption that allows us to estimate the costs associated to the decarbonization of the CSPG. The impact of decarbonization policies (in terms of both costs and unintended consequences) is assessed through a scenario that imposes the achievement of carbon-neutrality by 2060—as pledged by the Chinese government[30]—plus two additional scenarios that anticipate the target to 2050 and 2040. To isolate the effects of transboundary hydropower projects, we implemented three additional scenarios in which we target carbon-neutrality (in 2060, 2050, and 2040), but without the aid of dams in transboundary rivers. All aforementioned scenarios are also implemented for projected hydrological conditions that reflect the impact of climate change on hydropower resources (Table S1). Banking on the high-resolution output provided by GridPath, we finally pin down, for each scenario, the effect of dam expansion on individual rivers and estimate the land use requirements associated to the expansion of wind and solar.

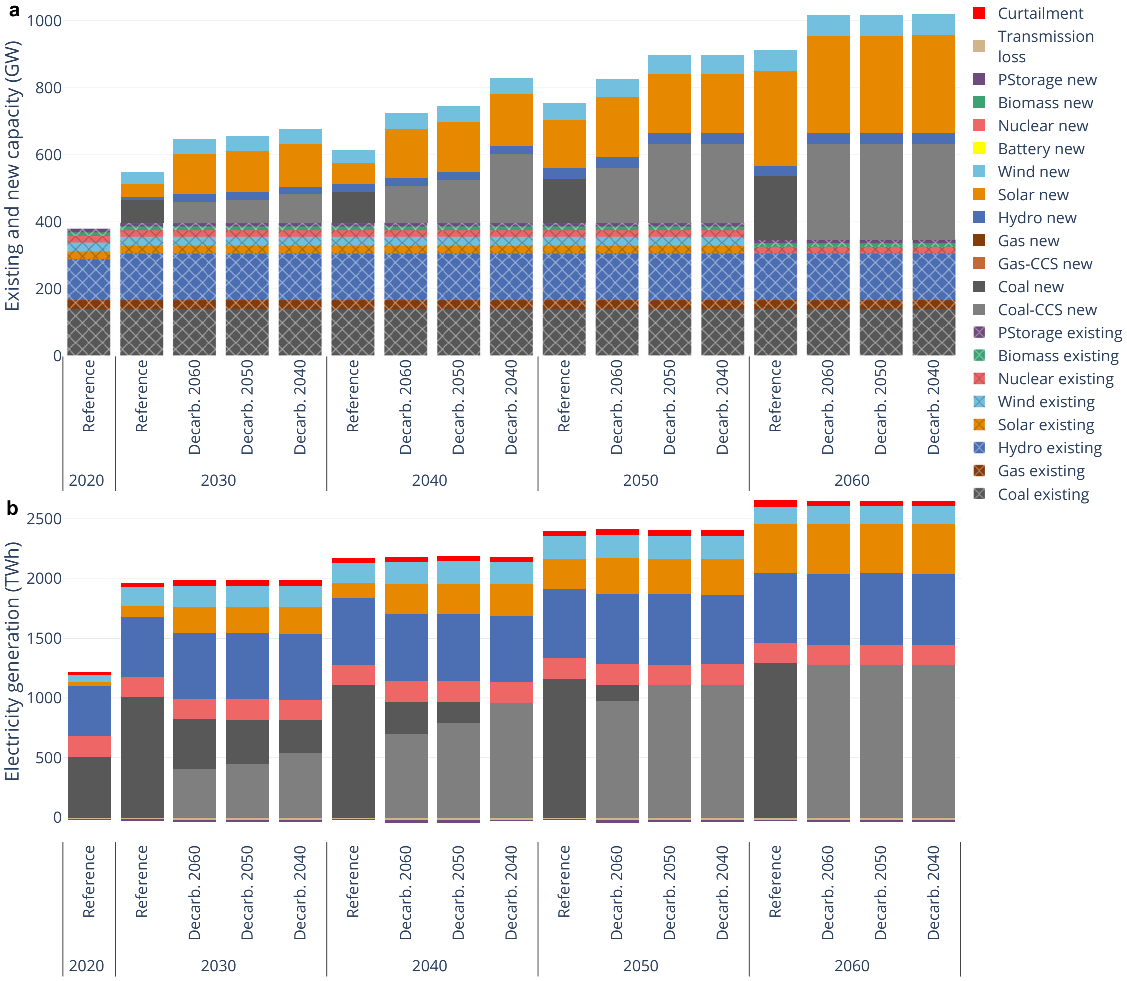

Fig. 2 | Capacity and generation mix over the period 2020–2060 in the CSPG. **a** Existing (hatched bars) and new (solid bars) capacity mix and **b** generation mix for four core scenarios, namely the Reference scenario and three scenarios with carbon neutrality targets set for the years 2040, 2050, and 2060. The capacity (only existing) and generation in 2020 are the same across all scenarios, and hence, shown only for the Reference scenario.

Results

Capacity expansion plans under decarbonization targets

Coal power plants have historically been the dominant source of electricity for the CSPG (Fig. 1). Importantly, their role does not change significantly if grid decarbonization policies are excluded: in the Reference scenario (Table 1), coal still accounts for 33% of new capacity and about half of the generation mix in 2060 (Fig. 2). New coal power plants are mainly located in Guangdong and Guizhou (Fig. S1) because of the vast electricity demand in Guangdong (Table S7) and the limited availability of variable renewables in Guizhou (Table S19). The explanation for the dominance of coal plants in the generation fleet must be sought in the cost competitiveness of this technology, especially before 2040 (Table S9). The deployment of new renewables is indeed gradual during the first part of the planning period, followed by a quick increase after 2040. By 2060, 283 GW and 62 GW of solar and wind, respectively, are deployed. Taken together, they account for 21% of the generation mix. Another hefty fraction of the generation mix (roughly 22%) is accounted for by hydropower, with more than 32 GW deployed by 2060. In other words, 83%, 66%, and 100% of the available (new) capacity for solar, wind, and hydropower is exploited by 2060.

The condition depicted above completely changes when carbon neutrality targets are taken into account (Fig. 2a). Beginning with the Decarb. 2060 scenario, we note a quick expansion of wind and solar in 2030, with a newly invested capacity of 163 GW—roughly twice the one of the Reference scenario (74 GW). The expansion of wind and solar continues until 2060, when these two technologies comprise the largest share of new capacity (62 GW of wind and 291 GW of solar). Hydropower plants maintain an important role, with a total capacity of 172 GW (32.34 GW of new capacity), yielding about a fourth of the total generation in 2060. Interestingly, we also note substantial investments in coal plants combined with carbon capture and storage (coal-CCS hereafter) technology, which is necessary to replace the supply guaranteed by conventional coal plants (Fig. 2b) and complement the generation of renewable resources. Since the available capacity of wind, solar, and hydropower is almost entirely exploited, this suggests that the capacity of renewables is not enough to meet the double goal of meeting an increasing demand while decarbonizing the power grid. Our results also indicate that it is also possible to implement more ‘ambitious’ decarbonization policies, as shown in the Decarb. 2050 and Decarb. 2040 scenarios, which target carbon neutrality in 2050 and 2040. This is achieved by anticipating investments in solar, wind, and coal-CCS. For instance, the wind and solar capacities for Decarb. 2060, Decarb. 2050, and Decarb. 2040 scenarios vary from 163 GW to 171 GW in 2030, while coal-CCS ranges from 64 GW to 86 GW.

The impact of the decarbonization policies is also reflected in the transmission capacity, which is expanded to address the load-generation imbalance across the CSPG. All core scenarios show an increase in transmission capacity (from 96% to 134%, compared to the 2020 level, see Fig. S1 and Tables S2–S3), but the expansion partially occurs in different interprovincial corridors in the carbon-neutral scenarios compared to the Reference one—since dropping traditional coal plants requires tapping on more geographically distributed resources. In particular, the corridor

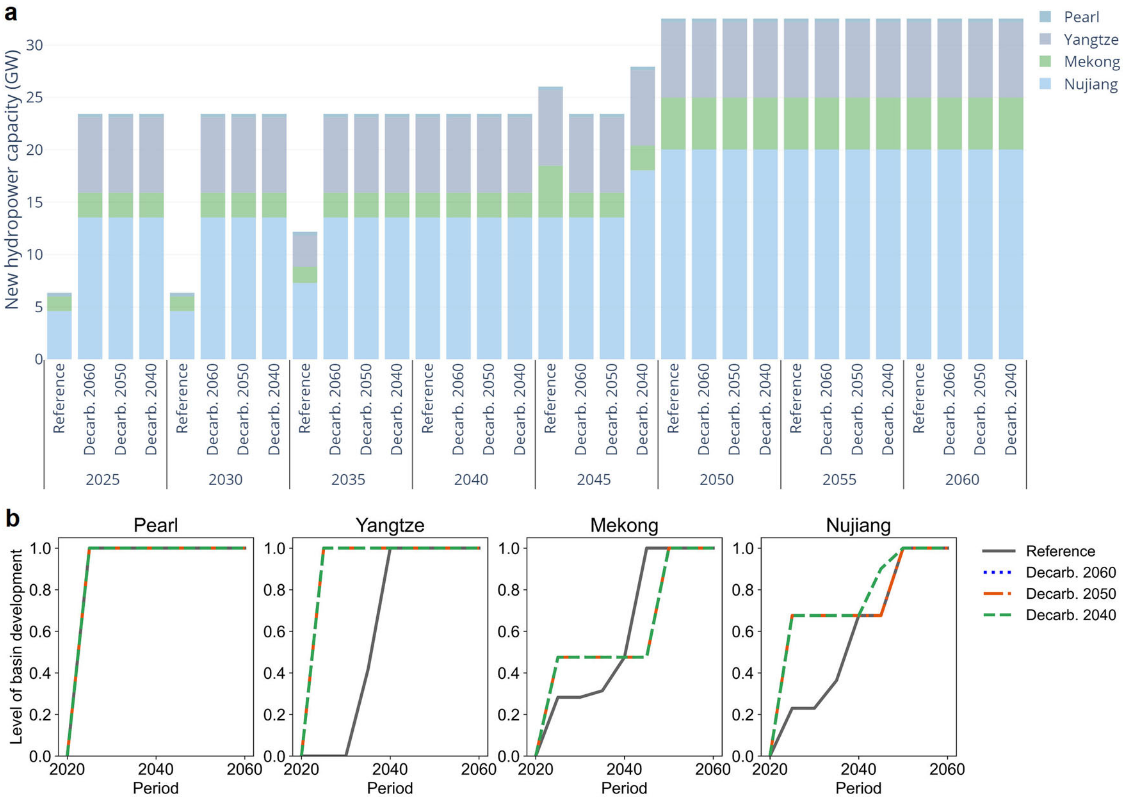

Fig. 3 | Basin-wise selected new hydropower capacity and level of basin development over the period 2020–2060. a Selected new hydropower capacity corresponding to each planning stage, core scenario, and basin. Note that both Nujiang and Mekong are transboundary. **b** Level of basin-wise hydropower development, defined as the ratio between the available and developed capacity.

connecting Yunnan to Guizhou is expanded to provide access to more hydropower generation; moreover, additional interconnections in the eastern part of the CSPG are necessary to provide greater access to solar and wind resources. In turn, the expansion of transmission corridors substantially increases inter-provincial electricity trade (Fig. S2). Overall, these results indicate that the 2060 carbon neutrality target set by the Chinese government[30] is feasible, charting a pathway whose feasibility banks on solar, wind, hydropower, coal-CCS, and electricity trade. However, this pathway and its more ambitious alternatives may impact land requirements and transboundary river basins of key ecological and geo-political importance.

Impact of decarbonization policies on water and land resources

Our results show that by 2060 the entire candidate hydropower capacity of 32.34 GW (Table S14) will be fully exploited regardless of the adopted decarbonization policy (Fig. 3a). 78% of this capacity is provided by two transboundary river basins (i.e., Mekong and Nujiang), with the Pearl and Yangtze providing the rest. A key aspect to consider here is the timing with which such development is carried out, a major difference between the Reference scenario and the decarbonization ones. In the former case, the construction of new dams happens gradually, particularly in the earlier phases of the planning period—before 2040, only 12 GW of new hydropower are required to meet the increase in electricity demand. In contrast, all decarbonization scenarios require a quicker development of dams, with 23 GW of new hydropower deployed by 2025. The basins contributing the most are the Mekong, Nujiang, and Yangtze (Figure S6), which must commit 48%, 68%, and 100% of the candidate capacity by 2025 (Fig. 3b).

Insights regarding the impact of wind and solar are offered in Fig. 4. A key point to notice is the total requirement for land in 2060: taken together, solar and wind will require roughly 40,000 km^2 of land. This is a rather sizeable area, corresponding to roughly one-fourth of Guangdong's total area. While this specific requirement is similar across the scenarios, the pace with which land use changes is radically different when decarbonization is taken into account (Tables S4 and S5). In 2030, for instance, the land requirements of wind and solar (scenarios Decarb. 2060, 2050, and 2040) are 1.3 times and 3 times the ones characterizing the Reference scenario—and would thus require to anticipate the conversion of about 10,000 km^2 of land. Two other points also deserved to be stressed. First, the deployment of solar and wind plants reflects the geographical distribution of these resources, but may also lead to unfair land use requirements; in this specific case, the sole province of Guangxi should support 43% of the total land requirements across the CSPG (Table S4). Second, the social and ecological costs associated to the construction of solar and wind plants may not be negligible, since crop and grassland constitute the vast majority of the land that will undergo such rapid transformations (Table S6).

Limiting the impact on transboundary rivers

Is it possible to decarbonize the electricity system without impacting transboundary resources? To answer this question, we consider three additional decarbonization scenarios in which the construction of transboundary hydropower plants is entirely excluded (Table 1). Our results indicate that it may not be necessary to choose between curbing CO$_2$ emissions and limiting the construction of new dams; alternative pathways exist. The technology that makes these pathways feasible is coal-CCS. For the scenario Decarb. 2060 WTH, for example, we find that the capacity expansion plan is cost-optimally met with an additional 20 GW of coal-CCS with respect to the Decarb. 2060 scenario (Fig. S3). In fact, it is even possible to implement more ambitious decarbonization policies (Decarb. 2050 WTH and Decarb. 2040 WTH), which require, however, additional and quicker investments in coal-CCS (Fig. S3). Importantly, this also leads to a more aggressive deployment of wind and solar resources, which in turn impose a faster conversion of land use, especially before 2030 (Fig. S7).

A final aspect that is worth analyzing are the CO$_2$ emissions and costs associated to all decarbonization scenarios, which are compared in Fig. 5

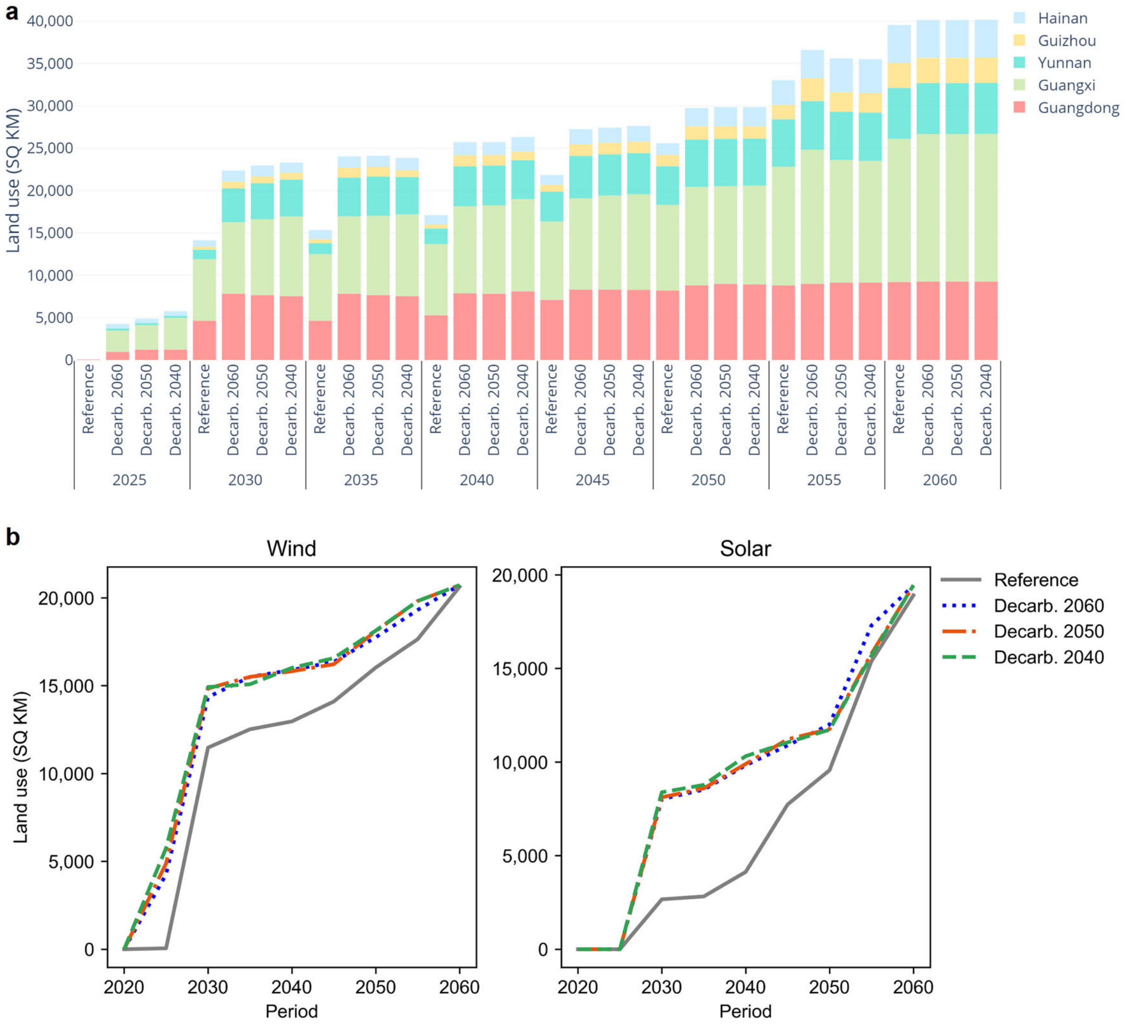

Fig. 4 | Land requirements for wind and solar over the period 2020–2060. a Required province-wise land area for wind and solar corresponding to each planning stage. **b** Temporal development of land area requirements for wind and solar.

against the ones of the Reference scenario. A first pattern emerging from this comparison is the relationship between CO_2 emission reductions and investment and operating costs over the period 2020–2060: the decarbonization scenario could reduce future emissions by 74 to 86% (corresponding to 6254 and 7246 Mt CO_2) while increasing costs by 'only' 6.3–10.6% compared to the Reference scenario. That corresponds to a range of 76–127 billion USD. Second, halting the construction of transboundary hydropower plants would not dramatically increase the total system costs; we found that exerting this option never increases costs by more than 1% (corresponding to about 12 billion dollars) compared to the corresponding scenarios with future development in transboundary river basins. In sum, there might be tangible opportunities for decarbonizing the CSPG without necessarily impacting transboundary resources.

Discussion

Our analysis shows that, given the current electricity demand projections, the pledge of reaching carbon neutrality by 2060 may be feasible in the provinces served by CSPG; in fact, it might even be possible to anticipate the target year for carbon neutrality to 2050 or 2040. However, a 100% transition to wind, water, and solar may not be feasible, since their capacity is not sufficient to meet the expected growth in electricity demand—unless actions aimed at curbing such growth are taken. The implementation of the pathways we identified would still lead to a profound transformation of the power generation and transmission infrastructure, yielding a system hinged on renewables, coal-CCS, and electricity trade—a result in line with other recent studies on China's grids[4–7,31]. In other words, CSPG's old conventional fossil fuel-based power system would be partially replaced by new components, with renewables at its core and dispatchable generators providing additional flexibility.

Importantly, our analysis indicates that the decarbonization plans require very rapid investments in renewables, with major requirements for water and land resources. The hydropower sector would expand its fleet with 20 large dams—with a total new installed capacity of about 32 GW—the vast majority of which should be deployed in the coming decade. However, these planned dams are located in river basins of key ecological importance, namely the Yangtze, Mekong, and Nujiang[32]. The first two basins already carry the consequences of dam development, so one could easily foresee that the construction of new dams may exacerbate a variety of problems, such as the fragmentation of the river network, alteration of sediment and nutrient dynamics, obstruction of migratory routes of aquatic species, or hydrological alterations[33–36]. The situation of the Nujiang is even more concerning, since this is one of the remaining free-flowing rivers in Southeast Asia[37]; the construction of new dams in its upper reaches may carry environmental impacts similar to those observed in the Mekong and Yangtze. Another element worth stressing is that almost 80% of the planned dams are located in transboundary basins (i.e., Mekong and Nujiang). More dams may thus carry two geo-political issues. First, they may aggravate the tensions between China and the Lower Mekong countries[38]. Second, they might expand the tensions to Myanmar, where the downstream portion of the Nujiang flows. On the flipside, the CSPG decarbonization process may

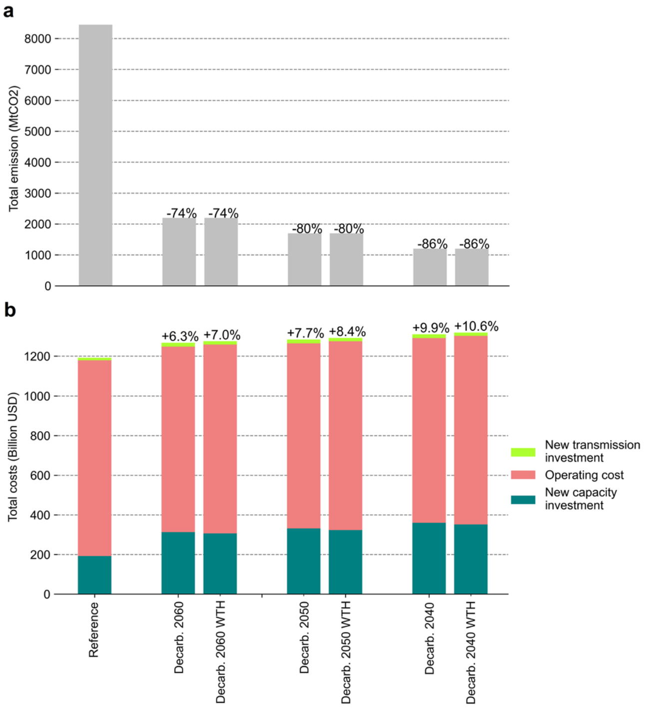

Fig. 5 | Emissions and costs cumulated over the period 2020–2060. **a** Total CO_2 emissions. Numbers over the bars indicate changes in the carbon-neutral scenarios with respect to the Reference scenario. **b** Total costs resulting from the combination of operating costs and investments in new generation and transmission capacity.

present new opportunities for transboundary collaboration between China and other countries in jointly developing the Nujiang basin, akin to Lancang-Mekong Cooperation and the Belt and Road Initiative[39,40]. This necessitates the implementation of sustained policy support by China and other Southeast Asian countries to underpin the cooperative mechanism.

The requirements for land dedicated to solar and wind are also remarkable, with roughly 40,000 km^2 needed by 2060; more than 11 times the amount of land converted by 2015 (about 3500 km^2). What is perhaps even more interesting is the pace of this development, as more ambitious decarbonization plans require more land in the early phases of the planning period. In addition to the sheer size of land requirements and associated pace of development, a third element worth considering is the current use of the land resources that are likely to undergo such rapid transformations. 90% of wind and solar resources are indeed located in cultivated land, grassland, and shrubland, so one can easily foresee the emergence of major socio-ecological trade-offs. On one hand, rapid land use changes may affect agricultural productivity and natural ecosystems, leading to problems such as the loss of wildlife linkages, soil compaction, and fragmentation of agroecosystems[17]. In this regard, it is worth stressing that wind and solar facilities have a typical service life of about 30 years, but their impacts on land and local ecology are more long-term and also pose challenges for reversal[13]. A sudden expansion of solar and wind plants would therefore further encroach croplands, especially in provinces, like Guangdong, where electricity demand is higher. On the other hand, the exploitation of wind and solar resources will not only contribute to the grid decarbonization process, but also to the local economy. Adequate land planning practices should therefore be adopted to address the emergence of these trade-offs. Examples include land use policies, stricter environmental regulations, the use of ecological-friendly siting design (e.g., agrivoltaic systems[41]), or improvements in land-use efficiency (e.g., construction of integrated solar systems[13]).

Another point worth discussing here is the fact that the impact of the decarbonization policies on transboundary river basins could be curbed—or even halted—but this would increase the total system costs (by roughly 12 billion dollars) and, importantly, further expand the reliance on coal-CCS.

The use of carbon capture and storage technologies is indeed a pillar of all CSPG's decarbonization pathways—a solution that has been recently suggested for a variety of regions[6,42–47], including China[6,47]. In particular[47], identified CCS has a pivotal element of China's efforts to limit global warming below 1.5 °C. It should be stressed, however, that CCS has yet to be deployed at such large spatial scales, like the one implied by our study, so questions concerning the actual feasibility of such pathways are relevant. On one hand, we note that CCS has great potential[42,45], which includes the retrofitting of existing conventional fossil-fuel-based plants[48]. On the other hand, there are various challenges that may impede the widespread adoption of CCS technologies, such as uncertainty in future costs, technology immaturity risk, environmental concerns, and potential policy restrictions. Investments and research in CCS are therefore necessary, especially in regions—like the provinces served by the CSPG—that are constrained in terms of water and land resources.

Looking at our modeling approach, it is worth stressing that its chief working assumption is the resolution of an optimization problem conceived to find the future grid configurations that minimize costs while meeting carbon emission targets. This assumption is relevant because it characterizes the current macro-energy modeling landscape, and it can thus help us understand what the optimization of a single objective entails. Specifically, we do not know how the decarbonization of large power grids could affect land and water resources; to answer such question, solving a single-objective optimization problem and then looking into its unintended consequences is a simpler, practical, and realistic strategy—since decarbonization efforts are often based on the single of goal of reducing CO_2 emissions. In turn, creating a knowledge base of these unintended consequences will help broadening the formulation of decarbonization plans, for instance through the formulation of multi-objective problems[49]. Another modeling aspect warranting future investigations is the study of 'alternative' solutions placed near the one(s) found via cost-minimization: the minimum in complex cost optimization models is typically very shallow; so, future grid configurations can be altered quite a bit with minimum consequences for the total system costs. Policy makers may thus work with a larger decision space, and the actual transition path will likely not correspond to the system costs minimum[50].

In sum, our work contributes to the ongoing debate on the unintended effects of decarbonization plans by showing that these effects span across multiple resources (water and land) and trickle down to nearby countries. Looking forward, it would be relevant to understand how these impacts on land and water resources would impact the economy and different social groups, or how such impacts would be amplified by the electrification of important sectors (e.g., transportation, industry). Naturally, completely avoiding the environmental impacts we identified—as well as their cascading consequences—may not be possible; instead, we ought to identify them before large-scale infrastructure are planned and devise trade-off solutions that help us meet carbon-neutrality targets while minimizing socio-ecological conflicts[51,52].

Methods

Electricity system model and data

To simulate the long-term development of the CSPG's electricity system, we used an open-source power system modeling platform (GridPath)[26,53]. This multi-period planning model co-optimizes power system operations and capacity expansion to identify the cost-effective allocation of conventional and renewable generators, storage devices, and transmission lines in different target years. Beginning with the temporal domain, we set up GridPath-CSPG for the period 2020–2060, for which decarbonization pledges and projections of electricity demand are publicly available[24,25,30]. In this 40-year timeline, we consider multiple investment periods, each representing five years, and during which the model can build new infrastructures or retire existing ones. This is a rather common choice in grid expansion problems[20,54]. To account for end effects (costs incurred beyond the model planning time horizon), we also included 2065 as an investment period representing 10 years. As for the spatial resolution, we opted for a total of nine load zones, five representing the provinces served by CSPG and four representing provinces and states that trade electricity with the CSPG (Fig. 1a). These load zones are interconnected by transmission corridors, including existing and planned (for future development) transmission lines. The choice of this spatial resolution was chiefly driven by data availability; as explained below, not all grid data are available with finer granularity. This is a frequent challenge in macro-scale modeling studies for developing regions[20,21,55,56], including China[5,6,31]. It is also worth noting that the adoption of such spatial resolution does not affect the model reliability, a point to which we will return later.

As mentioned above, GridPath models not only capacity expansion decisions, but also operational ones, since the latter influence the former. Within each investment period, electricity is dispatched to meet load and other constraints over 24 h during 12 days, each representing a month, and weighted appropriately to represent a full year. Energy demand and supply are balanced in each modeled hour for each load zone. For the year 2020, we first created the province-wise average month-hourly time series based on real and detailed quarter-hour data (96 × 365 time-points) available for each province. As shown in Fig. S11, the load demand pattern in each representative day varies in different provinces and seasons, reflecting the demographic and industrial structure difference and seasonality effects. Note that the load demand encompasses various sectors, including residential (e.g., air conditioning loads and heating), industrial, commercial, and transportation (e.g., electric vehicles). To produce time series of future electricity demand, we linearly extrapolated the observed demand time series into the full planning periods using projected growth rates for each province—the growth rates were derived from the Report on CSPG's Action Plan for Building a New Power System (2020–2030)[25] and the forecasted data by State Grid Corporation of China (SGCC)[24] (Table S7). Specifically, for 2020–2030, we employed a growth rate of 6.5% from 2020 to 2025, and a growth rate of 3.5% from 2025 to 2030 for each province; for 2030–2060, the load demand is projected to increase at a growth rate of 1% (Fig. S12). We also collected 2020 cross-border import/export data from the Power Exchange Center (PEC) of Yunnan and Guangxi, and electricity trade data between the CSPG and Hubei from the PEC of Guangdong. Due to the unavailability of data on future projections of electricity trade in these links, we assumed that trade will remain at the 2020 level across the full planning periods. To account for the annual peak demand not captured in the representative days for each planning period, we introduced a planning reserve margin (PRM) of 15% of the peak demands in each representative day (monthly-averaged). The PRM in this study is mainly provided by dispatchable generators and storage, which could also buffer the intermittency of wind and solar technologies.

In addition to the observed and projected electricity demand, major inputs to GridPath are the existing power infrastructure (generators, transmission lines, storage), planned expansion projects, hourly capacity factors of identified wind and solar sites, monthly hydropower availability (on a plant-specific basis), carbon emission targets, and other techno-economic parameters (e.g., investment and maintenance costs, fuel costs, emission per unit generation, storage operation efficiencies, ramping, heat rates, and transmission losses). Beginning with the power supply fleet, we consider eleven kinds of generator and storage technologies, namely wind, solar, hydro, nuclear, coal, gas, biomass, coal-CCS, gas-CCS, pumped storage hydropower (PSH), and battery storage. Existing generation capacities—mostly consisting of hydropower and coal, with a small share of gas, nuclear, biomass, PSH, wind, and solar—were retrieved from the China Electricity Council[57] and PEC of each province in the CSPG. We consider candidate capacities for coal, gas, biomass, nuclear, and PSH that have existing installed capacities. We also consider candidate capacities for coal-CCS and gas-CCS as low-carbon technologies. About 32 GW of conventional[58] and 53 GW of PSH[25,59] hydropower are planned to be deployed in CSPG, which we consider as candidate projects. Wind and solar are rich in resource availability and could largely contribute to future decarbonization as their cost-competitiveness increases, whereas battery storage could be an important catalyst for integrating such variable renewable resources. Generators and storage are dispatched to meet load demand at an hourly resolution on each representative day within the planning periods for each load zone. The operations of non-renewable generators (e.g., coal, coal-CCS, gas, gas-CCS, and nuclear) are constrained by techno-economic characteristics (e.g., ramping, heat rates, fuel costs, minimum operating levels). Hydropower is constrained by daily energy availability over each day. The hydropower availability varies with a monthly time-step according to seasonal hydro-climatic variability (see the description of the Hydrological and water management model). Storage (PSH and battery) is dispatched based on daily energy availability, as both PSH and battery can be flexibly charged and discharged for storing and generating electricity in a day. The capital costs of renewables (i.e., hydro, wind, and solar) and biomass are derived from the Manual of Renewable Energy Data[60], and the capital costs of wind and solar in 2020 are consistent with IRENA's Renewable Power Generation Costs report in 2022[61]. The capital costs of other technologies are adopted from previous China's electricity system capacity expansion plan studies[5,6,62]. Other techno-economic parameters (e.g., heat rate, ramp rate, lifetime) are presented in Table S8. The capital cost for all technologies is assumed to be static across time, except for wind, solar, battery, coal-CCS, and gas-CCS, for which we use the 'mid' time-varying capital cost projections (Table S9) of the NREL's ATB-2022[63]. For fuel costs of coal and gas, we use the projections (Table S10) from the NREL's ATB-2019[64]; fuel costs of biomass and nuclear are assumed to remain static at the 2020 level. We extracted emission factors (Table S11) for each fuel from the Energy Information Administration[65].

We collected the existing transmission facilities data for 2020 from ref. 59 and ref. 66. The operational characteristics of the transmission lines include capacity, transmission loss, and line length. We assume that the capacity of the existing transmission lines could be linearly and cost-optimally expanded from 2025 onward, except for the lines between the CSPG and other provinces in China and the cross-border lines—whose capacity is kept constant across the full planning period. The length of the inter-provincial lines is estimated using centroids of provinces/countries. We applied a transmission loss of 1% per 100 miles for all transmission lines[67]. Further information on the capital costs of the transmission lines collected from the Electric Power Planning & Engineering Institute[68,69] is given in Table S12. The carbon emissions in 2020 are set based on the data reported by the China Electricity Council[57], while the decarbonization scenarios are modeled by taking the 2020 emissions and linearly decreasing them until the target year (i.e., 2060, 2050, or 2040).

The model selects future generators, storage, and transmission lines for each 5-year period (except 2020, which operates the system using only existing infrastructure) with the objective of minimizing the system costs (i.e., investment and operating costs) over the entire planning period (i.e., 2020–2060). Each planning period employs a discount factor of 7% to estimate the net present value of costs incurred, in line with previous capacity expansion studies[20,70,71]. New capacities of conventional generators and battery storage are selected linearly from province-wise candidate resources. New capacities of wind and solar projects are selected from the spatially-distributed candidate sites (see "Wind and solar resource data"), and are therefore modeled as binary decision variables. For hydropower and PSH projects, new capacities are modeled as binary decisions (i.e., the model decides whether to build, or not, a given project). Mathematically, GridPath-CSPG's solves a mixed-integer linear program to minimize the costs associated with the expansion and operation of the energy system, subject to various economic and technical constraints. The model is written in Python/Pyomo[72] and the problem is solved using Gurobi[73]. Major outputs are the new capacities (generators, transmission lines, storage), hourly operation of the system, the grid expansion and operating costs, power curtailment, imports and exports, and carbon emissions for each planning period.

Finally, we note that GridPath-CSPG was validated against the generation mix and carbon emission data for 2020 (Table S13), reported by the China Electricity Council[57] and PEC of each province. This type of validation—still uncommon in macro-scale energy studies—ensures that GridPath-CSPG correctly captures decisions currently made within the grid, thereby providing a suitable basis for studying its future expansion. We also tested the model sensitivity with respect to different hydropower availability conditions caused by global warming (Figs. S4, S5, and S8).

Hydrological and water management model

To simulate hydropower availability at each dam, we use Xanthos, a global hydrologic and water management model[27,74]. The core component of Xanthos incorporates modules for estimating potential evapotranspiration, runoff generation, and river routing. Key inputs to these modules include gridded monthly downscaled, and bias-corrected, projection of temperature and precipitation from the Norwegian Earth System Model (NorESM1-M)[75], and a maximum soil water storage capacity map. Following the recent applications of Xanthos to South America[76–78] and West Africa[79], in this study, Xanthos is forced with the WFDEI bias-corrected reanalysis dataset[80] to simulate streamflow and hydropower generation for global existing dams[81] at a monthly time-step (1970–2010), and with a spatial resolution of 0.5 degrees. The simulation covers six basins across the CSPG, i.e., Mekong, Nujiang, Yangtze, Yuan and Red, Pearl, and QSGCRB, which encompass more than 120 GW of existing hydropower capacity and 32 GW of projected hydropower capacity [58] (Table S14). We used the monthly hydropower generation to calculate the average monthly capacity factors for the existing hydropower plants (Table S15). To estimate the capacity factor of planned hydropower projects, we rely on a nearest-neighbor approach—given the coordinates and installed capacity of a planned dam, we look for nearby existing dams with similar features within the same basin and adopt the capacity factor of the most similar dam. To assess the sensitivity of the hydropower availability (and, hence, of the power system dynamics) to future climatic conditions, we use hydropower availability for the 2020–2060 period, simulated by Xanthos under two climate change scenarios that represent two global climate models and two representative concentration pathways (RCP 4.5 and RCP 8.5) (see Fig. S9).

For all core and sensitivity scenarios (Table 1), we use the same set of monthly capacity factors across all investment periods. For sensitivity scenarios related to the impact of climate change on hydropower production, we adopt historical capacity factors for the year 2020, while the monthly capacity factors for the period 2025–2060 vary according to the future climatic conditions. The average monthly capacity factors so obtained are then used as input to GridPath-CSPG.

Wind and solar resource data

To identify candidate wind and solar sites and their potential capacity, we use the Renewable Energy Zoning (REZoning), an interactive, web-based, platform[28] based on the Multi-criteria Analysis for Planning Renewable Energy (MapRE) model[82]. REZoning allows users to choose the region of interest and estimate the technical and economic potentials of candidate wind and solar sites through spatial analysis. The analysis consists of three steps, namely the estimation of technical and economic potential, followed by a multi-criteria (and prioritization) analysis. The first step estimates the technical potential for development by accounting for geophysical constraints (topographic limitations and land-use constraints) and system performance. The second step leads to the estimation of the levelized cost of electricity (LCOE) for the zones resulting from the previous step. Finally, the multi-criteria and prioritization analysis selects and prioritizes candidate renewable energy sites by applying various criteria and factors (monetized and non-monetized) in addition to the LCOE. The data sources that these steps rely on are listed in Table S16.

REZoning first implements the aforementioned analysis at a spatial resolution of 500 m, and then aggregates it to a 50 km resolution. Geophysical constraints include various land cover types, which are used to filter the sites suitable for the construction of wind and solar (Table S17). Cut-off values for elevation, slope, and capacity factor are based on recent studies on renewable resource assessment[6,20]. As for the value of other parameters (i.e., installed capacity area factor, distance to transmission lines, and distance to roads), we first implemented a sensitivity analysis, which led to the identification of their final values (Table S18). Overall, this helped us identify 94 candidate wind sites and 340 candidate solar sites from a total of 593 sites (i.e., grids) across the CSPG (Table S19). Then, to match the reported existing wind and solar capacity, we assumed that the existing wind and solar farms are distributed across each candidate wind and solar site in proportion to their development potential value. Finally, we deducted the derived existing wind and solar capacity by spatially matching it with the potential of the candidate sites and obtained the final wind and solar potential (Fig. S10). The land use requirements impacted by wind and solar development were estimated using the land use factor (or installed capacity area factor, MW/km^2)[15,17,83].

To estimate hourly wind and solar power availability in the identified sites, we adopted pyGRETA (Python Generator of Renewable Time Series and Map[29]), which has been used for wind and solar availability simulation in Europe[84] and Southeast Asia[18]. pyGRETA requires irradiation, temperature, and wind speed time series to simulate wind and solar power availability. We used the Modern-Era Retrospective analysis for Research and Application, Version-2 (MERRA-2) reanalysis product to force pyGRETA. Specifically, we used hourly global horizontal irradiance (GHI), top of the atmosphere irradiance (TOA), and air temperature 2 m above the ground as key inputs for deriving solar capacity factor time series for the year 2020. As for wind, we used hourly northward wind velocity at 50 m and eastward wind velocity at 50 m as key inputs to derive wind capacity factor time series for the year 2020. We assume the deployment of single-axis tracker technology (by setting the tilt equal to latitude) for solar, and GE 2.5 MW wind turbine with a 100 m high hub for wind. The simulated wind and solar average capacity factors were similar to those reported for 2020 (Table S20).

Data availability

The data generated in this study have been deposited in Zenodo under the accession code https://zenodo.org/record/8278149. The source data file behind the Figures can be found in Figureshare[85].

Code availability

The electricity system model GridPath is available at https://github.com/blue-marble/gridpath. The hydrological-water management model Xanthos is available at https://github.com/JGCRI/xanthos. The renewable energy development potential assessment platform REZoning is available at https://rezoning.energydata.info/. The renewable energy availability modeling framework pyGRETA is available at https://github.com/tum-ens/pyGRETA.

Received: 9 January 2024; Accepted: 2 April 2024;

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Acknowledgements

This research is supported by the National Science Foundation of China (No. 52239001). The first author is sponsored by the China Scholarship Council for his visit to the Singapore University of Technology and Design, Singapore. A.F.M.K.C. is supported by the US National Science Foundation under Grant No. 1855982. The authors acknowledge Dr. Franklyn Kanyako for sharing the hydropower data.

Author contributions

X.Y.J., S.G. and A.F.M.K.C. designed the research; X.Y.J. performed the research. S.G., X.Y.J. and A.F.M.K.C. analyzed data and wrote the paper. B.L. and C.T.C. reviewed and edited the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-024-01363-1.

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Peer review information *Communications Earth & Environment* thanks the anonymous reviewers for their contribution to the peer review of this work. Primary Handling Editors: Martina Grecequet. A peer review file is available.