



Geophysical Constraints on Decarbonized Systems—Building Spatio-Temporal Uncertainties into Future Electricity Grid Planning

AFM Kamal Chowdhury¹ · Thomas Wild^{1,2} · Ranjit Deshmukh^{3,4} · Gokul Iyer² · Stefano Galelli⁵

Accepted: 9 November 2023

© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2023

Abstract

Purpose of Review Future electricity grids will be characterized by the high penetration of renewables to support the decarbonization process. Yet, this transition will further expose grids to a broad spectrum of geophysical forces, such as weather and climate or the availability of land and minerals. Here, we synthesize the current body of knowledge on the relationship between geophysical constraints and electricity grid planning.

Recent Findings We show that there have been promising advances in the data, methods, and modelling tools needed to incorporate the effect of geophysical constraints on demand, resource availability, and grid operations. However, current research efforts are typically focused on the effect of a single constraint, thereby lacking a broader view of the problem.

Summary More system-specific and finer-scale analyses are necessary to better understand how spatio-temporal variability in geophysical forces affects grid planning. Moreover, we need a broader focus on the multi-sectoral implications of decarbonization efforts, including the societal consequences of grid management decisions. Importantly, all these efforts are challenged by the computational requirements of existing power system models, which often limit our ability to characterize uncertainty and scale analyses across larger domains.

Keywords Geophysical constraints · Power grid · Decarbonization · Weather and climate · Land and space · Minerals and materials

Introduction

Decarbonizing the electricity sector is one of the most important strategies in achieving a carbon-free economy, because

of not only its present contribution to carbon emissions, but also its potential for providing the low-carbon ‘fuel’ needed to decarbonize several end-use sectors (e.g., buildings, industry, and transportation). The specific pathways to grid decarbonization are many; yet, they are all punctuated by major challenges. First, electricity demand is expected to grow significantly over the next few decades as a result of the electrification of end-use sectors, as well as the increasing electricity access and standards of living brought about by socio-economic development [1–4]. Second, the evolution of the electricity grid faces a range of geophysical, techno-economic, socio-cultural, institutional, and ecological constraints, which in turn limit our ability to integrate clean energy resources without significantly impacting other domains of interest, such as the conservation of land and water resources, protection of terrestrial and aquatic ecosystems, and preservation of cultural sites [5–8]. The timing and extent of grid-decarbonization efforts will therefore be shaped by these challenges, to which one must add the implementation of global and national pledges [9–11]. Here, we focus on a specific element of these challenges, namely the

✉ AFM Kamal Chowdhury
kchy@umd.edu

✉ Stefano Galelli
galelli@cornell.edu

¹ Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD 20740, USA

² Joint Global Change Research Institute (JGCRI), Pacific Northwest National Laboratory (PNNL), College Park, MD 20740, USA

³ Environmental Studies Program, University of California Santa Barbara, Santa Barbara, CA 93106, USA

⁴ Bren School of Environmental Science and Management, University of California Santa Barbara, Santa Barbara, CA 93106, USA

⁵ School of Civil and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA

constraints imposed by geophysical forces: weather, climate, land, and the availability of minerals significantly affect grid planning and operations [12], so their presence requires careful considerations to support a timely and just transition to low-carbon grids.

Scientific and policy analyses, largely based on computational models, provide useful insights into future decarbonization pathways. Although these analyses and models have come a long way to adequately represent the processes and constraints related to grid-decarbonization [13–16], many of them still struggle with the representation of geophysical constraints, in turn limiting the value of the decarbonization scenarios, or pathways, so identified [17, 18]. Indeed, the relevant literature generally presents a partial view of how such constraints should be accounted for. Some studies, for instance, focused on the effects of geophysical forces on specific clean energy technologies (e.g., wind [19], solar [20], or both [21, 22]), while others focused on the response of electricity systems to changes in a single, specific, force (e.g., climate change impacts on renewable resources [12, 23]). In this article, we synthesize the current state-of-the-art with the aim of first presenting a more holistic view of the geophysical forces constraining grid decarbonization efforts (“[An Overview of Key Geophysical Constraints](#)”), and then identifying the most pressing issues and opportunities for energy systems modelling (“[Representation of Geophysical Constraints into Grid Planning Models](#)” - “[Opportunities to Alleviate Geophysical Constraints](#)”). We finally conclude with a call for action that will ideally span across multiple communities (“[Call for Action](#)”).

An Overview of Key Geophysical Constraints

Multiple geophysical processes influence electricity systems at both resource potential and operational levels (Fig. 1). Resource potential generally refers to the annual energy availability of a renewable resource. The exploitable limits of the major renewable resources—hydro, wind, solar, and bioenergy—are largely constrained by climatic processes (e.g., hydropower predominantly depends on precipitation, solar power on solar radiation) and land (e.g., availability and suitability of land for the construction of dams or solar farms), whereas other renewables (e.g., geothermal, tidal) are mostly limited by the availability of economically feasible resources. Accordingly, the exploitable potential could vary under different climate change impacts as well as different levels of socio-ecological conservation criteria (e.g., protection of sites with high biodiversity value or cultural importance) [23, 24].

On the other hand, the production of many renewable resources—particularly hydropower, wind, and solar—significantly varies at seasonal to sub-hourly scales, with

substantial effects on grid operations. Since hydropower, wind, and solar are widely anticipated to contribute a large share of future electricity generation [25, 26], such temporal variability could significantly affect grid reliability and costs. Hence, the operation of grids characterized by high penetration of renewables will likely require massive deployment of utility-scale battery storage, which is in turn constrained by the availability of critical minerals (i.e., lithium, cobalt, nickel, and manganese [27–29]). In fact, the large deployment of renewable generation infrastructure (e.g., solar modules, wind turbines, and associated transmission expansion) will also require a major supply of various minerals and materials, such as iron, copper, and aluminum [28–31].

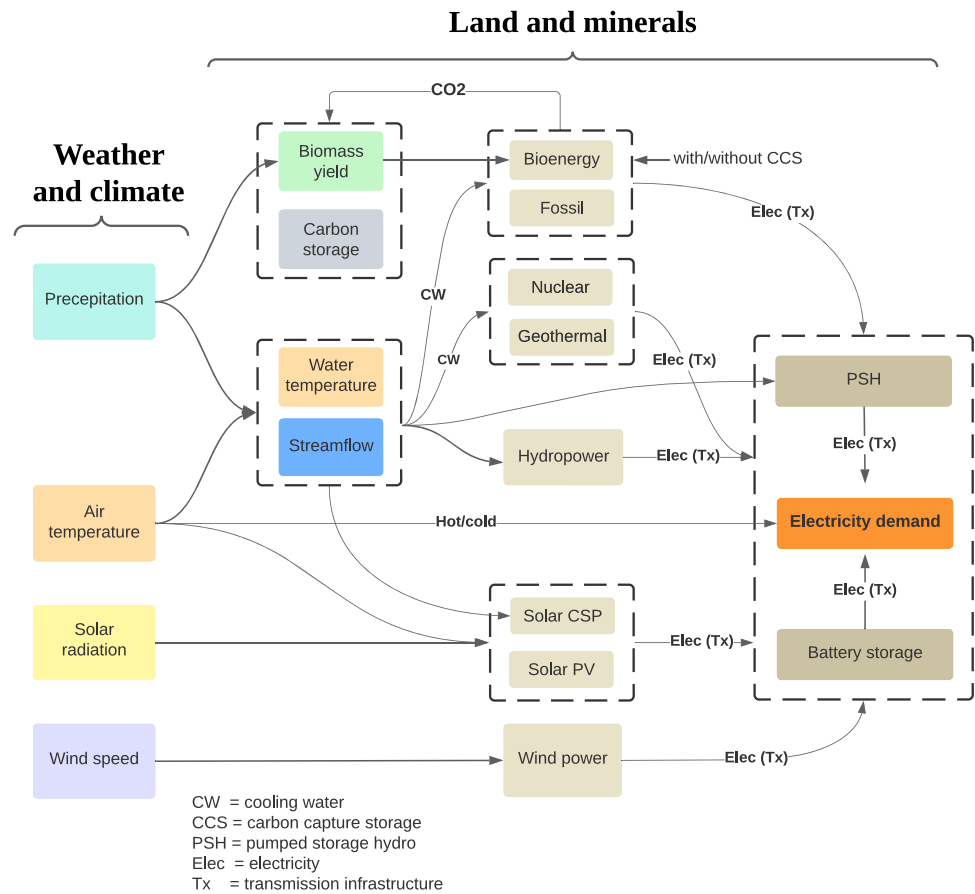
The constraints imposed by geophysical forces affect low-carbon thermo-electric plants as well, including biomass and nuclear plants. There are at least two constraints worth considering here. First, the need for cooling water links the output of these plants to variability in hydro-climatological processes, including limited water availability and intake water temperature that reduce efficiency of thermal plants [32–35]. Second, the cooling process affects the temperature of downstream water bodies and aquatic ecosystems, and is indeed subject to regulations that, while seldom enforced, can constrain operations [36–38]. Importantly, higher air temperatures and heatwaves will also constrain the performance of thermo-electric plants relying on fossil fuels, including coal and gas [39, 40]. While relatively less discussed in the literature, we note that the water consumption of certain renewable technologies (e.g., storage hydropower or concentrating solar power) could also be critical for decarbonized grids [41]; on the other hand, floating solar PV could have water-saving effects [42].

The electricity demand, finally, largely depends on temperature patterns [43, 44], which could vary significantly with climate change conditions [45, 46]—although it is worth noting that future demand growth will also be affected by socio-economic changes and end-use electrification [1, 4]. Looking forward, all linkages mentioned here will largely shape our ability to decarbonize the power grid, although their influence on both supply and demand will vary significantly from region to region. In the next sections, we will go deeper into these linkages, explore the latest scientific and policy advances, and identify the main gaps that will drive future research efforts.

Representation of Geophysical Constraints into Grid Planning Models

Both policy and scientific analyses of future grid planning are mostly based on computational models. While there have been promising advances in open and non-proprietary

Fig. 1 Major linkages between geophysical forces and electricity systems. Weather and climatic forces influence energy resource potential, as well as grid operations and electricity demand. The availability of land and minerals predominantly influences the resource potential of a few clean energy resources and provision for future infrastructure development. The biomass yield can be influenced by elevated atmospheric CO₂ concentrations, a phenomenon known as CO₂-fertilization. Note that items of similar type (e.g., all power plant technologies) are shown in identical colors



data and tools [47–49], there is still a compelling need for additional steps on the representation of geophysical constraints in computational models. In particular, we discuss the constraints and their representation in three main areas, namely electricity demand, generation resources, and grid operations. Note that, while geophysical constraints are our key focus, we also discuss other constraints (e.g., socio-environmental) that could have significant influences on certain components of future decarbonized grids. Moreover, by grid planning models, we refer to the electricity system models that consider both the development (e.g., capacity expansion) and operations of future grids.

Electricity Demand

Temperature is the key geophysical variable that influences electricity demand [43, 44], with humidity playing a more marginal role [50]. Existing electricity system models generally use statistical methods (e.g., binning method [51], polynomial fit [52]), machine learning [43]) to take into account the effects of temperature on electricity demand. While the methods for modelling the temperature-demand relationships are quite well-established, electricity system models are often unable to incorporate the full range of

demand variability, mainly due to computational limitations. In particular, capacity expansion models for long-term planning generally consider electricity demand for only a few representative hours (peak and off-peak hours) and days (e.g., one or two days for each month), thus neglecting the full range of demand variability that might unfold over one or multiple years [53, 54]. Also, models often operate with lumped electricity demand over large spatial domains (regional to national scales) with simplified representation of grid infrastructure, and, thus, may not properly incorporate the effects of finer-scale spatial variability of temperature (e.g., urban heat islands) on electricity demand and transmission-distribution [55, 56]. This is indeed an important gap: we lack a complete understanding of how such assumptions for demand modelling (e.g., choice of representative days or meteorological conditions) will impact future grid planning. Literature has mainly focused on how a simplified spatio-temporal representation of electricity generation resources, particularly the variable renewable energy resources, could affect the outputs (e.g., generation mix, costs) of capacity expansion models [57, 58]. Moreover, the literature provides a shallow characterization of the compound effects of climate extremes on both demand and supply sides [59]**; this is yet another critical issue, par-

ticularly in future decarbonized grids with high penetration of renewables and end-use electrification. This matter is well exemplified by Texas' 2021 blackout, when the cold weather conditions amplified demand and limited the ability to supply electricity [51].

Looking forward, we foresee two other important research directions regarding the impact of geophysical constraints on electricity demand. First, despite considerable studies to understand climate change's impact on future electricity demand (see [44] and references therein), additional efforts are necessary to narrow the uncertainty in peak demand associated with future temperature projections. Second, the effects of geophysical constraints, especially temperature extremes, need to be further evaluated under enhanced growth in electricity demand due to socio-economic development as well as end-use electrification. Air-conditioning demand in regions with hotter climates will increasingly stress electricity grids, both with increasing affordability of air conditioners and increasing temperatures. At the same time, demand due to electrification of heating loads in colder climates may experience interactions in opposite directions, i.e., electrification of heating systems could make a future grid more vulnerable during cold seasons but less vulnerable as winter temperatures become milder with global climate change (e.g., post 2050). The existing literature, apparently, has a limited understanding of how future decarbonized grids with enhanced electricity demand could behave under temperature extremes [60].

Generation Resources

The decarbonization of future electricity grids will largely depend on the integration of renewable energy resources, whose availability is constrained by geophysical forces, such as climate, land, and minerals (Fig. 1). Future projections of the electricity generation mix generally consider exploitable limits of renewable resources [61–63] or specific candidate projects [64, 65] to identify the extent of renewable integration under different constraints (technical, economic, policy, and climatic conditions). The estimation of the resource availability substantially varies with the methods adopted for representing geophysical, techno-economic, and socio-environmental constraints, as well as future climate projections. Despite the recent advances, the current literature still lacks comprehensive databases on the exploitable, or projected, renewable resources under different constraints, which is in turn a major limitation for adequately representing them in future grid planning.

Hydropower

Hydropower resources are mainly constrained by water availability, suitable topographic conditions, and availability of

land for the construction of dams and reservoirs. While these constraints shape the techno-economically feasible limits of the hydro-resources, the exploitable limits are determined by further considerations on the socio-environmental impacts of dams and reservoirs, which could substantially vary depending on the adopted conservation criteria [24, 66, 67]. The future hydropower potential in a region could also significantly reduce or increase under climate change conditions [23], as well as changes in land cover (e.g., forestation) [68]. Several studies (see [69] and references therein) evaluated the effects of climate change on hydropower availability and its role in future electricity systems; yet, further analysis is necessary given the large uncertainties associated with climate change projections.

While exploitable hydropower potentials are useful for long-term planning (e.g., system evolution until the end of the century) that generally considers maximum resource potential, short-term decision-making (e.g., capacity expansion for few decades) requires project-level details, a type of data that is still very rare in the public domain. One of the few comprehensive global datasets of future hydropower projects (under construction and planning) was compiled by Zarfl et al. [70], while Zhang and Gu [71] recently compiled a dataset of potential dam sites across the globe. Other efforts to compile similar datasets for specific river basins have also been made [72, 73]. These datasets generally include projected capacity with dam locations, but do not include other techno-economic (e.g., capital and O&M costs) and physical (type of dam, reservoir area, hydraulic head) characteristics of the dams that are critically important to model and analyze future operational conditions, and, thus, their role in the power grid.

With widespread concerns over potential negative impacts of hydropower dams on riverine biodiversity and ecosystem services [74–79], a great deal of recent focus has been directed to strategic planning [80]** and optimized reservoir operations [81] as opportunities to more efficiently achieve objectives (e.g., energy production) with the fewest environmental impacts. Yet, we still have a limited quantitative understanding of how different levels of hydropower development will affect riverine biodiversity and ecosystem services. This knowledge gap exists for two reasons. First, previous literature [74–76] mostly relied on implicit metrics (e.g., loss of river connectivity, degree of flow regulation) to quantify the negative impacts; only a few studies [78, 79] have so far attempted to explicitly quantify the socio-ecological impacts of dams most directly related to human well-being (e.g., population displacement, loss of income, change in terrestrial and aquatic species). Second, dam planning studies typically neglect the role that dams play within the power grid, and so they are likely to propose dam expansion plans that are less harmful to the environment but not necessarily feasible from a power system perspective.

Moreover, while hydropower is generally considered as a low-carbon resource, recent studies [82, 83] showed that greenhouse gas emissions from hydropower reservoirs are not negligible, particularly in the tropics. Recent dam planning studies have attempted to explicitly optimize dam locations to minimize the emission from reservoirs [84], although additional research may be needed to reduce the uncertainty associated with emission estimates [85] and thus include this important aspect into grid expansion models. Despite these growing concerns, hydropower could still expand substantially in many regions under different energy-economic conditions, including multi-sector decarbonization efforts [86, 87]. Continuous development of the data related to future hydropower resources could thus support the integration of this renewable into future decarbonized grids. Accordingly, continuous improvement is necessary for hydropower simulation models as well, although this field has substantially advanced in recent years to incorporate weather and climate-driven influences on hydropower for grid operations and planning at both global to sub-national scales [35, 88].

Hydropower's role in decarbonized electricity systems needs to be evaluated by considering its multi-sectoral interaction with other water and land uses [89, 90]. While grid decarbonization could require substantial deployment of hydropower, little is known about its potential influence on water demand for agriculture and urban supply, as well as the effects of new reservoirs on land use. For example, Zeng et al. [91] showed that only 8% of global installed hydropower complements irrigation water supply, with more than half of them affecting water availability for irrigation. A similar analysis for future hydropower is not available. Our understanding of how future dams will impact sediment flows and water systems is also limited [92–94]. On the other hand, while hydropower could provide important flexibility in operations of future decarbonized grids with a high share of variable renewable energy [95, 96], the cost-competitiveness of hydropower could increasingly be challenged by a rapid decline in the costs of other renewables and battery storage in at least some regions [87, 97, 98]. In turn, this requires further understanding of the trade-offs between the land-water implications of hydropower vs the land implications of other renewables (wind, solar, and bioenergy). Hydropower's interaction with other water and land uses could have far-reaching socio-environmental consequences and potential conflicts. Electricity system models, so far, have had limited ability to adequately represent the multi-sectoral interactions of hydropower, and associated water and land constraints. Multi-sectoral models, such as integrated assessment models, could play an important role in incorporating such dynamics into the planning of future decarbonized grids [86], although the representation of water and land dynamics in these models is still under development.

Moreover, multi-sector models generally operate at coarser spatio-temporal scales (e.g., global-to-regional and annual), and, hence, potential coupling of multi-sector models with finer-scale (e.g., grid and hourly) electricity system models will require careful harmonization of spatio-temporal data.

Wind, Solar, and Battery Storage

Wind and solar power are predominantly dependent on wind speed and solar radiation, respectively, whereas their availability in a region is generally constrained by topographical conditions and availability of land and water areas [6, 21, 99]. Most decarbonization studies suggest a large-scale build-out of wind and solar technologies because of their declining costs and large potential, often greater than future expected electricity demand [26, 100, 101]. Because their spatial footprint is generally greater than most conventional technologies, wind and solar-dominated future electricity systems are expected to require a substantial amount of land and water areas [6, 102, 103]. Moreover, in many regions, significant solar PV and wind resources are typically located on agricultural lands, and the concentrating solar power (CSP) resources in water-stressed areas, which could limit their future deployments, especially if best practices of co-use and revenue sharing are not followed [20, 104, 105]. For example, different levels of siting ordinances on land availability can reduce wind and solar resources by up to 87% and 38% in the US [106]. Societal acceptance and potential socio-environmental impacts of wind and solar deployments also need to be carefully incorporated in future grid planning to ensure a just and equitable low-carbon transition [107–109], which could further constrain available wind and solar resources. In addition, topographic suitability, land availability, and economic feasibility of new transmission facilities to access wind and solar resources—especially those farther from existing grid infrastructure—could significantly affect their future deployment in some regions [110, 111]. Because only a few studies [5, 6, 112] focused on identifying strategic and low-impact siting of wind and solar to minimize their land, space, and socio-environmental impacts, more region-specific analyses are necessary. Future research could also explore the extent and feasibility of relevant alternative techniques and technologies for better space utilization, such as agri-voltaic [20] and floating solar PV systems [42, 113], respectively.

Energy generation from wind and solar varies across time and space, and the spatio-temporal representation of existing and future deployments can significantly affect the outputs of energy system models (e.g., generation mix, storage requirements, costs, emissions). Capacity expansion or planning models that cost-optimally select generation, storage, and transmission assets across several future investment years often simplify the spatio-temporal representation of wind

and solar due to computational limitations [57, 58]. Some studies consider hourly wind and solar data for representative days to account for diurnal variability of wind and solar power, whereas others consider hourly data averaged over a month or year—a choice that could result in under- or over-estimation of the reliability of wind and solar resources in future grid planning [114]. Further research is thus necessary to understand how these spatio-temporal simplifications could affect the planning of future electricity grids, especially in under-studied regions across the world. Combining capacity planning studies with probabilistic/stochastic analysis could help design more resilient electricity systems, especially against climatic extremes [115, 116]. Importantly, such analyses require detailed multi-year datasets.

Global datasets of wind and solar potentials at high spatial resolution (e.g., global atlases for wind: <https://globalwindatlas.info/en>, and solar: <https://globalsolaratlas.info/map>), some available through web-based interactive platforms (e.g., REZoning: <https://rezoning.energydata.info/about> [112, 117], reV: <https://www.nrel.gov/gis/renewable-energy-potential.html> [118]), are helping identify candidate wind and solar sites for future deployment. Hourly data sets for wind and solar energy production with global coverage have been useful for multi-year analysis of future electricity systems (Renewables.ninja: <https://www.renewables.ninja/about> [119, 120]). At the same time, uncertainties introduced by land-use and other parameter assumptions need to be accounted for in long-term energy systems models [63]. Lastly, uncertainties from climate change effects on variable renewable energy, which are larger for wind power availability than solar [23, 121], need to be adequately represented in energy planning models to ensure electricity system reliability. While previous studies have incorporated data from global and regional climate models to explore the impacts of long-term variability in wind and solar generation [23, 122], climate datasets with historical and future meteorological conditions tailored for energy systems models [122] and consistent modeling frameworks [12] are essential for adequately assessing climate change impacts on future energy systems. Enhancing modeling initiatives to address these challenges could critically help understand geophysical constraints on the future decarbonized grids with high penetration of renewables.

A relatively less-discussed geophysical constraint is the availability of certain minerals for renewable technologies and grid infrastructure. Particularly, the availability of lithium, cobalt, nickel, and manganese is critical for battery storage [27–29], one of the widely anticipated measures for grid-reliability in future decarbonized grids with high penetration of variable renewable energy. Moreover, the future availability of solar PV and wind turbines could also be substantially constrained by the availability of iron, copper, and aluminum [28–31]. Because these minerals and materials are

available in only a few countries and regions, their availability in the global market could be largely influenced by geopolitical decisions [123–125], whose implications are still not well-understood in future grid planning.

Bioenergy

While the role of bioenergy in future decarbonized grids could largely depend on techno-economic and policy conditions, their availability is directly related to terrestrial vegetation, which, in turn, is linked with the availability of land and water. Moreover, the uncertainty in future availability of bioenergy is associated with a phenomenon called the CO₂-fertilization effect, which refers to increased photosynthesis due to elevated atmospheric CO₂ concentrations [23]. The persistent increase in greening over a large fraction of the global vegetated area over the last few decades has predominantly been driven by the CO₂-fertilization effect [126–128]. However, increased ambient temperature and droughts under changed climate could largely reduce the future effects of CO₂-fertilization in many regions [129]. Yet, the future effect of the phenomenon on global vegetation productivity remains quite uncertain, largely due to the inability of existing data and models to quantify how plant ecosystems may adapt to the carbon, nitrogen, and phosphorus cycles as climate changes [130].

Electricity system models, and the policies derived from them, have varied approaches to account for the emissions from bioenergy generators, particularly from the ones without carbon capture and storage (CCS). Many countries consider bioenergy (e.g., burning wood) as a carbon-neutral fuel and subsidize it to replace coal in meeting their renewable energy targets [131]. However, the carbon emission intensity of bioenergy generators is generally higher than most of the fossil-fuel-based generators, including coal, whereas neutralization of the emissions through forest regrowth is uncertain and could take decades to centuries [131, 132]. Bioenergy with CCS (BECCS), on the other hand, could have negative global warming potential [133, 134]. Although BECCS plants are included in many modeling studies in order to meet deep decarbonization targets, commercial BECCS projects are still not common. Hence, further research is necessary to better understand the role of bioenergy (with or without CCS) in future decarbonized grids.

Grid Operations

The operations of future decarbonized grids could be substantially constrained by weather and climatic forces. Here, a positive aspect is that natural hydro-climatic variability (from inter-annual to hourly) is increasingly getting better represented in production cost models (see reviews by [14, 15]); the most recent advances even include the incorporation

of seasonal to sub-seasonal climate forecasts into grid operations [135]. While substantial attention has so far been paid to understanding the effect of geophysical constraints on the operations of specific grid components (e.g., hydropower), a growing body of literature has started assessing these effects more holistically at the grid scale (e.g., [136–138]). Typically, this is accomplished by soft-coupling electricity system models with separate models simulating the impact of climate variability on hydropower, wind, solar, and other climate-dependent generators. Only a few recent studies have started evaluating the benefits of multi-model hard-coupling [139], which could be further evaluated for decarbonized grids. Going forward, further research is necessary to better understand the resilience and reliability of decarbonized grids under multi-sectoral electricity demands for net-zero transitions. Continuous scientific and policy focus is also necessary for the effects of geophysical forces on transmission facilities. On one hand, coordinated investment in transmission is critical to harness the maximum benefit of climate-dependent generators (e.g., hydropower), whose production could substantially vary at seasonal to sub-seasonal scales [140]. On the other hand, the resilience of transmission and distribution systems against weather and climatic extreme events (e.g., flood, snow, heatwave, wildfire) could be a growing concern in a changing climate [141–143].

Although some studies anticipated that the transition to electricity systems 100%-based on renewables is feasible [100, 144–146], the grid-decarbonization process of some regions may still rely on thermal generators, including bioenergy, nuclear, as well as fossil-based thermal generators with carbon capture and storage technologies [147]. While the future cost-effectiveness of these technologies will be limited by the availability and costs of the respective fuels (e.g., coal, gas, oil), the operational availability of these generators could be substantially constrained by temperature extremes and droughts, given that the cooling systems of fossil-based generators depend on air and water. Importantly, the literature on the water implications of global energy decarbonization generally presents a ‘partial’ or ‘too wide’ view of future uncertainties of the energy transition. As an example of the ‘partial’ view, Lohmann et al. [33] focused only on the water use by thermal power plants, and showed that associated global water withdrawal and consumption could be decreased by 95% and 98% (by 2050) in a ‘Best Policy Scenario’ with 100% renewable energy compatible to 1.5 °C targets. This emphasized the water-saving potentials of renewable-based energy transition, but overlooked the water consumption of certain renewable resources, such as hydropower and solar CSP [41]. On the other hand, Fricko et al. [32] showed that the end-of-century global energy-related water withdrawal and consumption could vary over quite a wide range (10–611% and 146–747% relative to 2000 level, respectively) in decarbonization scenarios under different demand growth

(low, mid, high), development of transportation fleets (conventional vs electric/hydrogen vehicles), portfolios of supply technologies (varying CCS, RE, etc.), and cooling technologies (baseline vs phase-out once-through). While this is an important contribution, the ranges of uncertainties may still be ‘too broad’ to fully support decision-making processes. Future studies could focus on narrowing these uncertainties by incorporating dynamics that are critically important for electricity systems and excluding relatively less likely factors. Involving different stakeholders, including policy-makers, in designing model scenarios could be a way of identifying the ‘important’ and ‘less likely’ factors.

Opportunities to Alleviate Geophysical Constraints

The geophysical constraints we identified above are a direct consequence of the systemic interconnections that exist between power supply systems, hydro-climatic variability, and availability of natural resources. Given the depth and breadth of these interconnections, it is perhaps unrealistic to depict a future in which these systems will be fully decoupled. Instead, we ought to imagine a future in which the effects of geophysical constraints are alleviated through the implementation of complementary *de-risking* strategies.

Investment Diversification

Investment diversification is typically seen as a management strategy to limit dependence-related problems—the overall risk to energy supply is smaller if there is a diversified portfolio of suppliers [111, 148]. This concept is well exemplified by REPowerEU, the plan envisioned by the European Commission to make the EU energy and power supply less dependent on Russia [149]. Investment diversification is, however, less adopted in relation to geophysical constraints. Yet, the risks associated with the effect of geophysical constraints on poorly diversified power systems are non-negligible, as demonstrated, for instance, by the impact of the 2003 heat wave on France’s nuclear sector, which at the time supplied ~85% of the country’s electricity demand [150]. Investment diversification is, therefore, a necessary aspect of grid planning: by promoting a diverse power generation mix, we acknowledge the presence of hazards and curb the associated vulnerabilities, ultimately reducing the risks of power shortfalls—or other negative effects of geophysical hazards on grid operations. We note that such ‘paradigm shift’ will likely be a result of decarbonization policies that heavily rely on renewables and, in particular, on solar, wind, and hydropower. Most countries will indeed require combining all these resources as they progress towards net-zero energy systems (e.g., [100, 151–153]). Importantly, diver-

sification must go beyond generation capacity and include regional to intercontinental trade, which is facilitated by high-voltage transmission lines. Expanding the transmission capacity is not only a means to facilitate the integration of renewables [64, 98, 154, 155]; it also allows us to tap external resources during extreme conditions [156]. Finally, given that the demand for critical minerals for clean energy technologies is set to increase rapidly, the diversification of supply sources requires more attention. The activities for the exploration of known minerals, as well as identifications of new alternative minerals, could also be accelerated [28, 29].

Deeper Integration of Renewables

Future grids will be dominated by large shares of renewables, so designing planning and management solutions that integrate their variable, non-dispatchable production is a means to limit the effect of geophysical constraints and thus ensure a more reliable supply of electricity. Here, there are at least three technological solutions deserving our attention. First, we need to keep developing energy storage technologies, whose role in large and interconnected grids will become pivotal in the next two or three decades [157]. In this regard, energy storage should be seen as a portfolio of technologies that includes not only the rapidly growing utility-scale (short-duration or diurnal scale Lithium Ion) battery technologies to drive their costs down, but also other solutions such as flywheels, flow batteries, and hydrogen energy storage [158]. Compared to Lithium Ion battery technologies, flow batteries and power-to-gas hydrogen storage technologies have the potential to provide multi-day to seasonal long-duration storage more cost-effectively because of their ability to decouple energy and power capacity [159]. Hydrogen generation technologies can also enable coupling with the transportation, industry, and heating sectors. Another important long-duration storage technology is pumped-hydro energy storage (PHES), which has a massive, and largely unexploited, capacity [160]. In this case, though, major barriers to the implementation of PHES are not technological limits or costs, but rather the environmental impact of dams [161]—yet another form of geophysical and societal constraint. A second strategy for the integration of renewables banks on the fact that renewables are characterized by different peak operating times, so one could exploit their complementarity. This can be achieved by combining two or multiple energy sources into a single power station (*hybridization*, see [162]) or by devising hydropower operational plans that explicitly account for the variability of solar and wind resources [139, 163]. Finally, we need to focus not only on utility-scale renewables, but also on distributed energy resources, including distributed generation, demand response, and distributed energy stor-

age. Their increased presence could further facilitate the decarbonization of the power grid while limiting land-use impacts [164]. Further technological breakthroughs across the energy-economic sectors could also accelerate the transition to low-carbon grids [165–167].

Call for Action

Our analysis of geophysical constraints on decarbonized power systems leads to the identification of a few key gaps that could serve as focal points for future research.

Computational Requirements of Power System Models The current class of planning and operational models may not be able to fully characterize the impact of geophysical constraints on power grids. Setting aside the specific technical challenges on which we elaborated in “[Representation of Geophysical Constraints into Grid Planning Models](#)”, an important point worth stressing here is the conflict between the computational requirements of power system models and the number of runs needed to study the effect of geophysical constraints—determining the impact of hydro-climatic variability on grid reliability, for instance, easily requires thousands of model evaluations [59, 168]. This problem exacerbates in studies spanning across large spatio-temporal domains or adopting a high-resolution representation of the power grid. The solutions to this problem are, potentially, many; examples include the re-formulation of the mathematical programs underpinning the models, the development of faster solvers [169], or the identification of fast model surrogates [170]. We therefore need to fully investigate these solutions, generalize them, and adopt the most promising ones.

Multi-sector Impacts The problem of decarbonizing the grid—while limiting the impact of geophysical constraints—is an important guiding principle that may, however, have a myopic nature: if we focus on one (e.g., decarbonization) or a few macro objectives, we may accidentally overlook the unintended consequences of our decisions. The construction of dams, for instance, helps reduce CO₂ emissions (at least in non-tropical locations; see “[Hydropower](#)”) and better integrate other forms of renewables, but carries several externalities that have been the subject of harsh criticisms on dam development [171]. Adopting a perspective that goes beyond the (still) central role of power systems is therefore paramount, as demonstrated by the growing interest in multi-sector studies [172]. We therefore need to expand the capability of the existing class of computational models, which should account not only for the presence of geophysical constraints, but also for the main multi-sector consequences caused by grid management decisions.

Justice and Equity A focal point for future research that relates to both geophysical constraints and multi-sector impacts are the concepts of justice and equity. Could geophysical constraints impede a just transition to carbon-neutral power systems? Which communities are affected by adverse air quality, land use changes, and mineral extraction, and to what extent? The vast majority of grid modelling frameworks is unable, to date, to answer these questions. Yet, very recent research has shown that inequities in exposure to pollution are common in a variety of situations, such as the increased emissions from power plants during droughts or the phasing out of nuclear plants [173, 174]. Going forward, we therefore call for the development of frameworks that explicitly link grid management decisions to their societal consequences, such as changes in air quality standards, changes in land use, or affected communities.

Closure

In this review, we synthesized the current body of knowledge on the relationship between geophysical forces and grid decarbonization efforts. We show that present and future grids are, and will be, exposed to a variety of constraints, ranging from changes in electricity demand and resource availability (driven by global warming) to the limited availability of land for wind, solar, and transmission lines. The current class of data, methodological approaches, and modelling tools are not fully equipped to address these challenges. Substantial research efforts are therefore necessary to improve the representation of geophysical constraints in computational models, enable faster analyses, and expand the focus of grid decarbonization studies to include multi-sector impacts as well as elements of justice and equity.

Acknowledgements A.F.M.K.C., T.W., and G.I. are supported by the US National Science Foundation under Grant No. 1855982.

Author Contributions A.F.M.K.C. drafted the manuscript. T.W., R.D., G.I., and S.G. contributed to the literature review and manuscript revisions.

Declarations

Conflict of Interest The authors declare no conflict of interest.

Competing interests The authors declare no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

- Castillo VZ, Boer H-Sd, Muñoz RM, Gernaat DEHJ, Benders R, Vuuren D. Future global electricity demand load curves. *Energy*. 2022;258:124741. <https://doi.org/10.1016/j.energy.2022.124741>. Accessed 21 Aug 2023
- Xu G, Yang H, Schwarz P. A strengthened relationship between electricity and economic growth in China: an empirical study with a structural equation model. *Energy*. 2022;241:122905. <https://doi.org/10.1016/j.energy.2021.122905>. Accessed 21 Aug 2023.
- Binsted M. An electrified road to climate goals. *Nat Energy*. 2022;7(1):9–10. <https://doi.org/10.1038/s41560-021-00974-8>. Number: 1 Publisher: Nature Publishing Group. Accessed 22 Aug 2023.
- Li X, Lepour D, Heymann F, Maréchal F. Electrification and digitalization effects on sectoral energy demand and consumption: a prospective study towards 2050. *Energy*. 2023;279:127992. <https://doi.org/10.1016/j.energy.2023.127992>. Accessed 21 Aug 2023.
- Wu GC, Leslie E, Sawyerr O, Cameron DR, Brand E, Cohen B, Allen D, Ochoa M, Olson A. Low-impact land use pathways to deep decarbonization of electricity. *Environ Res Lett*. 2020;15(7):074044. <https://doi.org/10.1088/1748-9326/ab87d1>. Publisher: IOP Publishing. Accessed 14 July 2023.
- Wu GC, Jones RA, Leslie E, Williams JH, Pascale A, Brand E, Parker SS, Cohen BS, Fargione JE, Souder J, Batres M, Gleason MG, Schindel MH, Stanley CK. Minimizing habitat conflicts in meeting net-zero energy targets in the western United States. *Proc Natl Acad Sci*. 2023;120(4):2204098120. <https://doi.org/10.1073/pnas.2204098120>. Publisher: Proceedings of the National Academy of Sciences. Accessed 14 July 2023.
- Best J. Anthropogenic stresses on the world's big rivers. *Nat Geosci*. 2019;12(1):7–21. <https://doi.org/10.1038/s41561-018-0262-x>. Accessed 16 April 2023.
- Su G, Logez M, Xu J, Tao S, Villéger S, Brosse S. Human impacts on global freshwater fish biodiversity. *Science*. 2021;371(6531):835–8. <https://doi.org/10.1126/science.abd3369>. Publisher: American Association for the Advancement of Science. Accessed 14 April 2023.
- IEA: Net Zero by 2050 - a roadmap for the global energy sector. Technical report, International Energy Agency (IEA): Paris; 2021. <https://www.iea.org/reports/net-zero-by-2050>. Accessed 17 April 2023
- Ou Y, Iyer G, Clarke L, Edmonds J, Fawcett AA, Hultman N, McFarland JR, Binsted M, Cui R, Fyson C, Geiges A, Gonzales-Zuñiga S, Gidden MJ, Höhne N, Jeffery L, Kuramochi T, Lewis J, Meinshausen M, Nicholls Z, Patel P, Ragnauth S, Rogelj J, Waldhoff S, Yu S, McJeon H. Can updated climate pledges limit warming well below 2°C? *Science*. 2021;374(6568):693–5. <https://doi.org/10.1126/science.abl8976>. Publisher: American Association for the Advancement of Science. Accessed 13 July 2023.
- Bistline J, Abhyankar N, Blanford G, Clarke L, Fakhry R, McJeon H, Reilly J, Roney C, Wilson T, Yuan M, Zhao A. Actions for reducing US emissions at least 50% by 2030. *Science*. 2022;376(6596):922–4. <https://doi.org/10.1126/science.abn0661>. Publisher: American Association for the Advancement of Science. Accessed 13 July 2023.
- Yalew SG, Vliet MTH, Gernaat DEHJ, Ludwig F, Miara A, Park C, Byers E, De Cian E, Piontek F, Iyer G, Mouratiadou I, Glynn J, Hejazi M, Dessens O, Rochedo P, Pietzcker R, Schaeffer R, Fujimori S, Dasgupta S, Mima S, Silva SRS, Chaturvedi V, Vautard R, Vuuren DP. Impacts of climate change on energy systems in global and regional scenarios. *Nat Energy*. 2020;5(10):794–802.

- <https://doi.org/10.1038/s41560-020-0664-z>. Number: 10 Publisher: Nature Publishing Group. Accessed 13 Mar 2023.
13. Gupta A, Davis M, Kumar A. An integrated assessment framework for the decarbonization of the electricity generation sector. *Appl Energy*. 2021;288: 116634. <https://doi.org/10.1016/j.apenergy.2021.116634>. Accessed 19 Mar 2023.
 14. Fodstad M, Granado P, Hellemo L, Knudsen BR, Pisciella P, Silvast A, Bordin C, Schmidt S, Straus J. Next frontiers in energy system modelling: a review on challenges and the state of the art. *Renew Sustain Energy Rev*. 2022;160:112246. <https://doi.org/10.1016/j.rser.2022.112246>. Accessed 14 July 2023.
 15. Guzović Z, Duic N, Piacentino A, Markovska N, Mathiesen BV, Lund H. Recent advances in methods, policies and technologies at sustainable energy systems development. *Energy*. 2022;245: 123276. <https://doi.org/10.1016/j.energy.2022.123276>. Accessed 14 July 2023.
 16. Moglen R, Chawla KP, Levi P, Sun Y, Phillips O, Leibowicz BD, Jenkins JD, Grubert EA. The state of macro-energy systems research: common critiques, current progress, and research priorities. *iScience*. 2023;26(4):106325. <https://doi.org/10.1016/j.isci.2023.106325>. Accessed 14 July 2023.
 17. Kriegler E, Luderer G, Bauer N, Baumstark L, Fujimori S, Popp A, Rogelj J, Streffer J, Vuuren DP. Pathways limiting warming to 1.5°C: a tale of turning around in no time? *Phil Trans R Soc A Math Phys Eng Sci*. 2018;376(2119):20160457. <https://doi.org/10.1098/rsta.2016.0457>. Publisher: Royal Society. Accessed 14 July 2023.
 18. Rogelj J, Popp A, Calvin KV, Luderer G, Emmerling J, Gernaat D, Fujimori S, Streffer J, Hasegawa T, Marangoni G, Krey V, Kriegler E, Riahi K, Vuuren DP, Doelman J, Drouet L, Edmonds J, Fricko O, Harmsen M, Havlík P, Humpenöder F, Stehfest E, Tavoni M. Scenarios towards limiting global mean temperature increase below 1.5°C. *Nat Clim Chang*. 2018;8(4):325–332. <https://doi.org/10.1038/s41558-018-0091-3>. Number: 4 Publisher: Nature Publishing Group. Accessed 14 July 2023.
 19. Marvel K, Kravitz B, Caldeira K. Geophysical limits to global wind power. *Nat Clim Chang*. 2013;3(2):118–21. <https://doi.org/10.1038/nclimate1683>. Number: 2 Publisher: Nature Publishing Group. Accessed 13 Mar 2023.
 20. Adeh EH, Good SP, Calaf M, Higgins CW. Solar PV power potential is greatest over croplands. *Sci Rep*. 2019;9(1):11442. <https://doi.org/10.1038/s41598-019-47803-3>. Number: 1 Publisher: Nature Publishing Group. Accessed 13 Mar 2023.
 21. Shaner MR, Davis SJ, Lewis NS, Caldeira K. Geophysical constraints on the reliability of solar and wind power in the United States. *Energy Environ Sci*. 2018;11(4):914–25. <https://doi.org/10.1039/C7EE03029K>. Publisher: Royal Society of Chemistry. Accessed 13 Mar 2023.
 22. Tong D, Farnham DJ, Duan L, Zhang Q, Lewis NS, Caldeira K, Davis SJ. Geophysical constraints on the reliability of solar and wind power worldwide. *Nat Commun*. 2021;12(1):6146. <https://doi.org/10.1038/s41467-021-26355-z>. Number: 1 Publisher: Nature Publishing Group. Accessed 13 Mar 2023.
 23. Gernaat DEHJ, Boer HS, Daioglou V, Yalew SG, Müller C, Vuuren DP. Climate change impacts on renewable energy supply. *Nat Clim Chang*. 2021;11(2):119–25. <https://doi.org/10.1038/s41558-020-00949-9>. Number: 2 Publisher: Nature Publishing Group. Accessed 13 Mar 2023.
 24. Zhou Y, Hejazi M, Smith S, Edmonds J, Li H, Clarke L, Calvin K, Thomson A. A comprehensive view of global potential for hydro-generated electricity. *Energy Environ Sci*. 2015;8(9):2622–33. <https://doi.org/10.1039/C5EE00888C>. Accessed 14 Jan 2023.
 25. Bogdanov D, Farfan J, Sadovskaia K, Aghahosseini A, Child M, Gulagi A, Oyewo AS, Souza Noel Simas Barbosa L, Breyer C. Radical transformation pathway towards sustainable electricity via evolutionary steps. *Nat Commun*. 2019;10(1):1077. <https://doi.org/10.1038/s41467-019-08855-1>. Number: 1 Publisher: Nature Publishing Group.
 26. Larson E, Greig C, Jenkins JD, Mayfield E, Pascale A, Zhang C, Drossman J. Net-zero America: potential pathways, infrastructure, and impacts. Technical report, Princeton, NJ, Princeton University; 2021.
 27. Wang H, Feng K, Wang P, Yang Y, Sun L, Yang F, Chen W-Q, Zhang Y, Li J. China's electric vehicle and climate ambitions jeopardized by surging critical material prices. *Nat Commun*. 2023;14(1):1246. <https://doi.org/10.1038/s41467-023-36957-4>. Number: 1 Publisher: Nature Publishing Group. Accessed 14 Mar 2023.
 28. Moerenhout T, Lee LY, Glynn J. Critical mineral supply constraints and their impact on energy system models. Technical report, center on global energy policy at Columbia University: New York; 2023.
 29. IEA: Critical Minerals Market Review 2023. Technical report, international energy agency (IEA): Paris; 2023.
 30. Fu R, Peng K, Wang P, Zhong H, Chen B, Zhang P, Zhang Y, Chen D, Liu X, Feng K, Li J. Tracing metal footprints via global renewable power value chains. *Nat Commun*. 2023;14(1):3703. <https://doi.org/10.1038/s41467-023-39356-x>. Number: 1 Publisher: Nature Publishing Group. Accessed 14 July 2023.
 31. Wang S, Hausfather Z, Davis S, Lloyd J, Olson EB, Liebermann L, Núñez-Mujica GD, McBride J. Future demand for electricity generation materials under different climate mitigation scenarios. *Joule*. 2023;7(2):309–32. <https://doi.org/10.1016/j.joule.2023.01.001>. Publisher: Elsevier. Accessed 21 Aug 2023.
 32. Fricko O, Parkinson SC, Johnson N, Strubegger M, Vliet MTv, Riahi K. Energy sector water use implications of a 2 °C climate policy. *Environ Res Lett*. 2016;11(3):034011. <https://doi.org/10.1088/1748-9326/11/3/034011>. Publisher: IOP Publishing. Accessed 27 Mar 2023.
 33. Lohrmann A, Farfan J, Caldera U, Lohrmann C, Breyer C. Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. *Nature Energy*. 2019;4(12):1040–8. <https://doi.org/10.1038/s41560-019-0501-4>. Number: 12 Publisher: Nature Publishing Group. Accessed 19 Mar 2023.
 34. Byers EA, Coxon G, Freer J, Hall JW. Drought and climate change impacts on cooling water shortages and electricity prices in Great Britain. *Nat Commun*. 2020;11(1):2239. <https://doi.org/10.1038/s41467-020-16012-2>. Number: 1 Publisher: Nature Publishing Group. Accessed 17 Mar 2023.
 35. Chowdhury AFMK, Dang TD, Nguyen HTT, Koh R, Galelli S. The Greater Mekong's climate-water-energy nexus: how ENSO-triggered regional droughts affect power supply and CO2 emissions. *Earth's Future*. 2021;9(3):2020–001814. <https://onlinelibrary.wiley.com/doi/pdf/10.1029/2020EF001814>.
 36. Badr L, Boardman G, Bigger J. Review of water use in U.S. Thermoelectric power plants. *J Energy Eng*. 2012;138(4):246–57. [https://doi.org/10.1061/\(ASCE\)EY.1943-7897.0000076](https://doi.org/10.1061/(ASCE)EY.1943-7897.0000076). Publisher: American Society of Civil Engineers. Accessed 22 Aug 2023.
 37. Madden N, Lewis A, Davis M. Thermal effluent from the power sector: an analysis of once-through cooling system impacts on surface water temperature. *Environ Res Lett*. 2013;8(3): 035006. <https://doi.org/10.1088/1748-9326/8/3/035006>. Publisher: IOP Publishing. Accessed 22 Aug 2023.
 38. Raptis CE, Vliet MTHv, Pfister S. Global thermal pollution of rivers from thermoelectric power plants. *Environ Res Lett*. 2016;11(10):104011. <https://doi.org/10.1088/1748-9326/11/10/104011>. Publisher: IOP Publishing. Accessed 22 Aug 2023.
 39. Penmetsa V, Holbert KE. Climate change effects on thermal power generation and projected losses in generation and income in the U.S. for the period 2020–2050. In: 2020 52nd North American

- power symposium (NAPS). IEEE, Tempe, AZ: USA;2021. pp. 1–6. <https://doi.org/10.1109/NAPS50074.2021.9449688>. <https://ieeexplore.ieee.org/document/9449688/>. Accessed 22 Aug 2023
40. Amell AA, Cadavid FJ. Influence of the relative humidity on the air cooling thermal load in gas turbine power plant. *Appl Therm Eng*. 2002;22(13):1529–33. [https://doi.org/10.1016/S1359-4311\(02\)00063-7](https://doi.org/10.1016/S1359-4311(02)00063-7). Accessed 22 Aug 2023.
 41. Jin Y, Behrens P, Tukker A, Scherer L. Water use of electricity technologies: a global meta-analysis. *Renew Sust Energ Rev*. 2019;115: 109391. <https://doi.org/10.1016/j.rser.2019.109391>. Accessed 22 Aug 2023.
 42. Jin Y, Hu S, Ziegler AD, Gibson L, Campbell JE, Xu R, Chen D, Zhu K, Zheng Y, Ye B, Ye F, Zeng Z. Energy production and water savings from floating solar photovoltaics on global reservoirs. *Nat Sustain*. 2023;1–10. <https://doi.org/10.1038/s41893-023-01089-6>. Publisher: Nature Publishing Group. Accessed 17 Mar 2023
 43. Alipour P, Mukherjee S, Nateghi R. Assessing climate sensitivity of peak electricity load for resilient power systems planning and operation: a study applied to the Texas region. *Energy*. 2019;185:1143–53. <https://doi.org/10.1016/j.energy.2019.07.074>. Accessed 12 Aug 2023.
 44. Doss-Gollin J, Amonkar Y, Schmeltzer K, Cohan D. Improving the representation of climate risks in long-term electricity systems planning: a critical review. *Curr Sustain/Renew Energy Rep*. 2023. <https://doi.org/10.1007/s40518-023-00224-3>. Accessed 23 Aug 2023.
 45. Auffhammer M, Baylis P, Hausman CH. Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. *Proc Natl Acad Sci*. 2017;114(8):1886–91. <https://doi.org/10.1073/pnas.1613193114>. Publisher: Proceedings of the National Academy of Sciences. Accessed 12 Aug 2023.
 46. Romitti Y, Sue Wing I. Heterogeneous climate change impacts on electricity demand in world cities circa mid-century. *Sci Rep*. 2022;12(1):4280. <https://doi.org/10.1038/s41598-022-07922-w>. Number: 1 Publisher: Nature Publishing Group. Accessed 12 Aug 2023.
 47. Pfenninger S, DeCarolis J, Hirth L, Quoilin S, Staffell I. The importance of open data and software: is energy research lagging behind? *Energy Policy*. 2017;101:211–5. <https://doi.org/10.1016/j.enpol.2016.11.046>. Accessed 26 Aug 2023.
 48. Manfren M, Nastasi B, Groppi D, Astiaso Garcia D. Open data and energy analytics - an analysis of essential information for energy system planning, design and operation. *Energy*. 2020;213: 118803. <https://doi.org/10.1016/j.energy.2020.118803>. Accessed 26 Aug 2023.
 49. Kazmi H, Munne-Collado I, Mehmood F, Syed TA, Driesen J. Towards data-driven energy communities: a review of open-source datasets, models and tools. *Renew Sust Energ Rev*. 2021;148: 111290. <https://doi.org/10.1016/j.rser.2021.111290>. Accessed 26 Aug 2023.
 50. Maia-Silva D, Kumar R, Nateghi R. The critical role of humidity in modeling summer electricity demand across the United States. *Nat Commun*. 2020;11(1):1686. <https://doi.org/10.1038/s41467-020-15393-8>. Number: 1 Publisher: Nature Publishing Group. Accessed 12 Aug 2023.
 51. Shaffer B, Quintero D, Rhodes J. Changing sensitivity to cold weather in Texas power demand. *iScience*. 2022;25(4). <https://doi.org/10.1016/j.isci.2022.104173>. Publisher: Elsevier. Accessed 13 Aug 2023
 52. Lee J, Dessler AE. The impact of neglecting climate change and variability on ERCOT's forecasts of electricity demand in Texas. *Weather Clim Soc*. 2022;14(2):499–505. <https://doi.org/10.1175/WCAS-D-21-0140.1>. Publisher: American Meteorological Society Section: Weather, Climate, and Society. Accessed 13 Aug 2023
 53. Merrick JH. On representation of temporal variability in electricity capacity planning models. *Energy Econ*. 2016;59:261–74. <https://doi.org/10.1016/j.eneco.2016.08.001>. Accessed 13 Aug 2023.
 54. Liu Y, Sioshansi R, Conejo AJ. Hierarchical clustering to find representative operating periods for capacity-expansion modeling. *IEEE Trans Power Syst*. 2018;33(3):3029–39. <https://doi.org/10.1109/TPWRS.2017.2746379>. Conference Name: IEEE Transactions on Power Systems.
 55. Santamouris M, Cartalis C, Synnefa A, Kolokotsa D. On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings-a review. *Energy Build*. 2015;98:119–24. <https://doi.org/10.1016/j.enbuild.2014.09.052>. Accessed 22 Aug 2023.
 56. Li X, Zhou Y, Yu S, Jia G, Li H, Li W. Urban heat island impacts on building energy consumption: a review of approaches and findings. *Energy*. 2019;174:407–19. <https://doi.org/10.1016/j.energy.2019.02.183>. Accessed 22 Aug 2023.
 57. Reichenberg L, Hedenus F. The error induced by using representative periods in capacity expansion models: system cost, total capacity mix and regional capacity mix. *Energy Syst*. 2022. <https://doi.org/10.1007/s12667-022-00533-4>. Accessed 13 Aug 2023.
 58. Kuepper LE, Teichgraber H, Baumgärtner N, Bardow A, Brandt AR. Wind data introduce error in time-series reduction for capacity expansion modelling. *Energy*. 2022;256: 124467. <https://doi.org/10.1016/j.energy.2022.124467>. Accessed 13 Aug 2023.
 59. Turner SWD, Voisin N, Fazio J, Hua D, Jourabchi M. Compound climate events transform electrical power shortfall risk in the Pacific Northwest. *Nat Commun*. 2019;10(1):8. <https://doi.org/10.1038/s41467-018-07894-4>. Number: 1 Publisher: Nature Publishing Group. Accessed 17 Mar 2023.
 60. Levin T, Botterud A, Mann WN, Kwon J, Zhou Z. Extreme weather and electricity markets: key lessons from the February 2021 Texas crisis. *Joule*. 2022;6(1):1–7. <https://doi.org/10.1016/j.joule.2021.12.015>. Accessed 22 Aug 2023.
 61. Bataille C, Waisman H, Briand Y, Svensson J, Vogt-Schilb A, Jaramillo M, Delgado R, Arguello R, Clarke L, Wild T, Lallana F, Bravo G, Nadal G, Le Treut G, Godínez G, Quiros-Tortos J, Pereira E, Howells M, Buira D, Tovilla J, Farbes J, Ryan J, De La Torre Ugarte D, Collado M, Requejo F, Gomez X, Soria R, Villamar D, Rochedo P, Imperio M. Net-zero deep decarbonization pathways in Latin America: challenges and opportunities. *Energy Strategy Rev*. 2020;30:100510. <https://doi.org/10.1016/j.esr.2020.100510>.
 62. Binsted M, Iyer G, Edmonds J, Vogt-Schilb A, Arguello R, Cadena A, Delgado R, Feijoo F, Lucena AFP, McJeon H, Miralles-Wilhelm F, Sharma A. Stranded asset implications of the Paris Agreement in Latin America and the Caribbean. *Environ Res Lett*. 2020;15(4):044026. <https://doi.org/10.1088/1748-9326/ab506d>. Publisher: IOP Publishing
 63. Silva SR, Hejazi MI, Iyer G, Wild TB, Binsted M, Miralles-Wilhelm F, Patel P, Snyder AC, Vernon CR. Power sector investment implications of climate impacts on renewable resources in Latin America and the Caribbean. *Nat Commun*. 2021;12(1):1276. <https://doi.org/10.1038/s41467-021-21502-y>. Number: 1 Publisher: Nature Publishing Group.
 64. Chowdhury AFMK, Deshmukh R, Wu GC, Uppal A, Mileva A, Curry T, Armstrong L, Galelli S, Ndhlukula K. Enabling a low-carbon electricity system for Southern Africa. *Joule*. 2022. <https://doi.org/10.1016/j.joule.2022.06.030>.
 65. Deshmukh R, Phadke A, Callaway DS. Least-cost targets and avoided fossil fuel capacity in India's pursuit of renewable energy. *Proc Natl Acad Sci*. 2021;118(13):2008128118. <https://doi.org/10.1073/pnas.2008128118>. Publisher: Proceedings of the National Academy of Sciences. Accessed 02 Mar 2023.

66. Gernaat DEHJ, Bogaart PW, Vuuren DPv, Biemans H, Niessink R. High-resolution assessment of global technical and economic hydropower potential. *Nat Energy*. 2017;2(10):821–8. <https://doi.org/10.1038/s41560-017-0006-y>. Number: 10 Publisher: Nature Publishing Group
67. ...Xu R, Zeng Z, Pan M, Ziegler AD, Holden J, Spracklen DV, Brown LE, He X, Chen D, Ye B, Xu H, Jerez S, Zheng C, Liu J, Lin P, Yang Y, Zou J, Wang D, Gu M, Yang Z, Li D, Huang J, Lakshmi V, Wood EF. A global-scale framework for hydropower development incorporating strict environmental constraints. *Nat Water*. 2023;1(1):113–22. <https://doi.org/10.1038/s44221-022-00004-1>. Accessed 14 Feb 2023
68. Arias ME, Farinosi F, Lee E, Livino A, Briscoe J, Moorcroft PR. Impacts of climate change and deforestation on hydropower planning in the Brazilian Amazon. *Nat Sustain*. 2020;3(6):430–6. <https://doi.org/10.1038/s41893-020-0492-y>. Number: 6 Publisher: Nature Publishing Group. Accessed 28 Feb 2023.
69. Wasti A, Ray P, Wi S, Folch C, Ubierna M, Karki P. Climate change and the hydropower sector: a global review. *WIREs Clim Chan*. 2022;13(2):757. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/wcc.757>
70. Zarfl C, Lumsdon AE, Berlekamp J, Tydecks L, Tockner K. A global boom in hydropower dam construction. *Aquat Sci*. 2015;77(1):161–70. <https://doi.org/10.1007/00027-014-0377-0>. 01267. Accessed 19 Oct 2021.
71. Zhang AT, Gu VX. Global Dam Tracker: a database of more than 35,000 dams with location, catchment, and attribute information. *Sci Data*. 2023;10(1):111. <https://doi.org/10.1038/s41597-023-02008-2>. Number: 1 Publisher: Nature Publishing Group. Accessed 28 Feb 2023.
72. Hennig T, Harlan T, Tilt B, Magee D. Hydropower development in South Asia: data challenges, new approaches, and implications for decision-making. *WIREs Water*. 2023;10(4):654. <https://doi.org/10.1002/wat2.1654>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/wat2.1654>. Accessed 13 Aug 2023
73. Tiwari AD, Pokhrel Y, Kramer D, Akhter T, Tang Q, Liu J, Qi J, Loc HH, Lakshmi V. A synthesis of hydroclimatic, ecological, and socioeconomic data for transdisciplinary research in the Mekong. *Sci Data*. 2023;10(1):283. <https://doi.org/10.1038/s41597-023-02193-0>. Number: 1 Publisher: Nature Publishing Group. Accessed 13 Aug 2023.
74. Grill G, Lehner B, Thieme M, Geenen B, Tickner D, Antonelli F, Babu S, Borrelli P, Cheng L, Crochetiere H, Ehalt Macedo H, Filgueiras R, Goichot M, Higgins J, Hogan Z, Lip B, McClain ME, Meng J, Mulligan M, Nilsson C, Olden JD, Opperman JJ, Petry P, Reidy Liermann C, Sáenz L, Salinas-Rodríguez S, Schelle P, Schmitt RJP, Snider J, Tan F, Tockner K, Valdujo PH, Soesbergen A, Zarfl C. Mapping the world's free-flowing rivers. *Nature*. 2019;569(7755):215–21. <https://doi.org/10.1038/s41586-019-1111-9>
75. Flecker AS, Shi Q, Almeida RM, Angarita H, Gomes-Selman JM, García-Villacorta R, Sethi SA, Thomas SA, Poff NL, Forsberg BR, Heilpern SA, Hamilton SK, Abad JD, Anderson EP, Barros N, Bernal IC, Bernstein R, Cañas CM, Dangles O, Encalada AC, Fleischmann AS, Goulding M, Higgins J, Jézéquel C, Larson EI, McIntyre PB, Melack JM, Montoya M, Oberdorff T, Paiva R, Perez G, Rappazzo BH, Steinschneider S, Torres S, Varese M, Walter MT, Wu X, Xue Y, Zapata-Ríos XE, Gomes CP. Reducing adverse impacts of Amazon hydropower expansion. *Science*. 2022;375(6582):753–60. <https://doi.org/10.1126/science.abj4017>. Publisher: American Association for the Advancement of Science.
76. Barbarossa V, Schmitt RJP, Huijbregts MAJ, Zarfl C, King H, Schipper AM. Impacts of current and future large dams on the geographic range connectivity of freshwater fish worldwide. *Proc Natl Acad Sci*. 2020;117(7):3648–55. <https://doi.org/10.1073/pnas.1912776117>. Publisher: Proceedings of the National Academy of Sciences. Accessed 15 Feb 2023.
77. Zarfl C, Berlekamp J, He F, Jähnig SC, Darwall W, Tockner K. Future large hydropower dams impact global freshwater megafauna. *Scie Rep*. 2019;9(1):18531. <https://doi.org/10.1038/s41598-019-54980-8>. Number: 1 Publisher: Nature Publishing Group. Accessed 14 April 2023.
78. Fan P, Cho MS, Lin Z, Ouyang Z, Qi J, Chen J, Moran EF. Recently constructed hydropower dams were associated with reduced economic production, population, and greenness in nearby areas. *Proc Natl Acad Sci*. 2022;119(8):2108038119. <https://doi.org/10.1073/pnas.2108038119>. Publisher: Proceedings of the National Academy of Sciences. Accessed 15 Feb 2023.
79. Dorber M, Arvesen A, Gernaat D, Verones F. Controlling biodiversity impacts of future global hydropower reservoirs by strategic site selection. *Sci Rep*. 2020;10(1):21777. <https://doi.org/10.1038/s41598-020-78444-6>. Accessed 14 Jan 2023.
80. Opperman JJ, Carvallo JP, Kelman R, Schmitt RJP, Almeida R, Chapin E, Flecker A, Goichot M, Grill G, Harou JJ, Hartmann J, Higgins J, Kammen D, Martin E, Martins T, Newsock A, Rogéliz C, Raeppele J, Sada R, Thieme ML, Harrison D. Balancing renewable energy and river resources by moving from individual assessments of hydropower projects to energy system planning. *Front Environ Sci*. 2023;10. Accessed 27 Feb 2023
81. Galelli S, Dang TD, Ng JY, Chowdhury AFMK, Arias ME. Opportunities to curb hydrological alterations via dam re-operation in the Mekong. *Nat Sustain*. 2022;5(12):1058–69. <https://doi.org/10.1038/s41893-022-00971-z>. Number: 12 Publisher: Nature Publishing Group. Accessed 16 Feb 2023.
82. Keller PS, Marcé R, Obrador B, Koschorreck M. Global carbon budget of reservoirs is overturned by the quantification of drawdown areas. *Nat Geosci*. 2021;14(6):402–8. <https://doi.org/10.1038/s41561-021-00734-z>. Number: 6 Publisher: Nature Publishing Group. Accessed 15 Aug 2023.
83. Faria FAMd, Jaramillo P, Sawakuchi HO, Richey JE, Barros N. Estimating greenhouse gas emissions from future Amazonian hydroelectric reservoirs. *Environ Res Lett*. 2015;10(12):124019. <https://doi.org/10.1088/1748-9326/10/12/124019>. Publisher: IOP Publishing. Accessed 15 Aug 2023
84. Almeida RM, Shi Q, Gomes-Selman JM, Wu X, Xue Y, Angarita H, Barros N, Forsberg BR, García-Villacorta R, Hamilton SK, Melack JM, Montoya M, Perez G, Sethi SA, Gomes CP, Flecker AS. Reducing greenhouse gas emissions of Amazon hydropower with strategic dam planning. *Nat Commun*. 2019;10(1):4281. <https://doi.org/10.1038/s41467-019-12179-5>. Number: 1 Publisher: Nature Publishing Group. Accessed 28 Feb 2023
85. Räsänen TA, Varis O, Scherer L, Kumm M. Greenhouse gas emissions of hydropower in the Mekong River Basin. *Environ Res Lett*. 2018;13(3): 034030. <https://doi.org/10.1088/1748-9326/aaa817>. Publisher: IOP Publishing. Accessed 06 Sept 2023.
86. Zhang Y, Binsted M, Iyer G, Kim S, Wild T, Zhao M. Long-term basin-scale hydropower expansion under alternative scenarios in a global multisector model. *Environ Res Lett*. 2022;17(11): 114029. <https://doi.org/10.1088/1748-9326/ac9ac9>. Accessed 14 Jan 2023.
87. Chowdhury AK, Wild T, Zhang Y, Binsted M, Iyer G, Kim S, Lamontagne J. Future hydropower expansion in eco-sensitive river basins under global energy-economic change. In: Review July 2023. <https://doi.org/10.21203/rs.3.rs-3089500/v1>. <https://www.researchsquare.com/article/rs-3089500/v1>. Accessed 14 Aug 2023
88. Turner SWD, Voisin N. Simulation of hydropower at subcontinental to global scales: a state-of-the-art review. *Environ Res Lett*. 2022;17(2): 023002. <https://doi.org/10.1088/1748-9326/ac4e38>. Publisher: IOP Publishing. Accessed 23 May 2023.

89. Wild TB, Khan Z, Zhao M, Suriano M, Bereslawski JL, Roberts P, Casado J, Gaviño-Novillo M, Clarke L, Hejazi M, Miralles-Wilhelm F, Muñoz-Castillo R, Vernon C, Snyder A, Yarlagaadda B, Birnbaum A, Lamontagne J, White D, Ojeda-Matos, G.: The implications of global change for the co-evolution of Argentina's integrated energy-water-land systems. *Earth's Future*. 2021;9(8). <https://doi.org/10.1029/2020EF001970>
90. Khan Z, Wild TB, Silva Carrazzone ME, Gaudioso R, Mascari MP, Bianchi F, Weinstein F, Pérez F, Pérez W, Miralles-Wilhelm F, Clarke L, Hejazi M, Vernon CR, Kyle P, Edmonds J, Muñoz-Castillo R. Integrated energy-water-land nexus planning to guide national policy: an example from Uruguay. *Environ Res Lett*. 2020;15(9): 094014. <https://doi.org/10.1088/1748-9326/ab9389>.
91. Zeng R, Cai X, Ringler C, Zhu T. Hydropower versus irrigation-an analysis of global patterns. *Environ Res Lett*. 2017;12(3): 034006. <https://doi.org/10.1088/1748-9326/aa5f3f>. Publisher: IOP Publishing. Accessed 07 Mar 2023.
92. Wild TB, Loucks DP, Annandale GW, Kaini P. Maintaining sediment flows through hydropower dams in the Mekong River Basin. *J Water Resour Plan Manag*. 2016;142(1):05015004. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000560](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000560). Publisher: American Society of Civil Engineers.
93. Schmitt RJP, Bizzi S, Castelletti A, Opperman JJ, Kondolf GM. Planning dam portfolios for low sediment trapping shows limits for sustainable hydropower in the Mekong. *Sci Adv*. 2019;5(10):2175. <https://doi.org/10.1126/sciadv.aaw2175>. Publisher: American Association for the Advancement of Science. Accessed 18 Feb 2023.
94. Schmitt RJP, Kittner N, Kondolf GM, Kammen DM. Joint strategic energy and river basin planning to reduce dam impacts on rivers in Myanmar. *Environ Res Lett*. 2021;16(5): 054054. <https://doi.org/10.1088/1748-9326/abe329>. Publisher: IOP Publishing. Accessed 15 Feb 2023.
95. Sterl S, Vanderkelen I, Chawanda CJ, Russo D, Brecha RJ, Griensven A, Lipzig NPM, Thiery W. Smart renewable electricity portfolios in West Africa. *Nat Sustain*. 2020;3(9):710–9. <https://doi.org/10.1038/s41893-020-0539-0>. Number: 9 Publisher: Nature Publishing Group. Accessed 28 Feb 2023.
96. Sterl S, Fadly D, Liersch S, Koch H, Thiery W. Linking solar and wind power in eastern Africa with operation of the Grand Ethiopian Renaissance Dam. *Nat Energy*. 2021;6(4):407–18. <https://doi.org/10.1038/s41560-021-00799-5>. Number: 4 Publisher: Nature Publishing Group. Accessed 28 Feb 2023.
97. Carlino A, Wildemeersch M, Chawanda CJ, Giuliani M, Sterl S, Thiery W, Griensven A, Castelletti A. Declining cost of renewables and climate change curb the need for African hydropower expansion. *Science*. 2023;381(6658):5848. <https://doi.org/10.1126/science.adf5848>. Publisher: American Association for the Advancement of Science. Accessed 11 Aug 2023.
98. Siala K, Chowdhury AK, Dang T, Galelli S. Solar energy and regional coordination as a feasible alternative to large hydropower in Southeast Asia. *Nat Commun*. 2021;12(4159):00003.
99. Hernandez RR, Hoffacker MK, Murphy-Mariscal ML, Wu GC, Allen MF. Solar energy development impacts on land cover change and protected areas. *Proc Natl Acad Sci*. 2015;112(44):13579–84. <https://doi.org/10.1073/pnas.1517656112>. Publisher: Proceedings of the National Academy of Sciences. Accessed 14 July 2023.
100. Jacobson MZ, Krauland A-Kv, Coughlin SJ, Dukas E, Nelson AJH, Palmer FC, Rasmussen KR. Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries. *Energy Environ Sci*. 2022. <https://doi.org/10.1039/D2EE00722C>. Publisher: The Royal Society of Chemistry
101. Williams JH, Jones RA, Haley B, Kwok G, Hargreaves J, Farbes J, Torn MS. Carbon-neutral pathways for the United States. *AGU Advances*. 2021;2(1). <https://doi.org/10.1029/2020AV000284>. Accessed 26 Aug 2023
102. Wu GC, Torn MS, Williams JH. Incorporating land-use requirements and environmental constraints in low-carbon electricity planning for California. *Environ Sci Technol*. 2015;49(4):2013–21. <https://doi.org/10.1021/es502979v>. Publisher: American Chemical Society. Accessed 14 July 2023.
103. Nøland JK, Auxepaules J, Rousset A, Perney B, Falletti G. Spatial energy density of large-scale electricity generation from power sources worldwide. *Sci Rep*. 2022;12(1):21280. <https://doi.org/10.1038/s41598-022-25341-9>. Number: 1 Publisher: Nature Publishing Group. Accessed 13 Mar 2023.
104. Deshmukh R, Wu GC, Callaway DS, Phadke A. Geospatial and techno-economic analysis of wind and solar resources in India. *Renew Energy*. 2019;134:947–60. <https://doi.org/10.1016/j.renene.2018.11.073>. Accessed 14 July 2023.
105. Schomberg AC, Bringezu S, Flörke M, Biederbick H. Spatially explicit life cycle assessments reveal hotspots of environmental impacts from renewable electricity generation. *Commun Earth Environ*. 2022;3(1):1–14. <https://doi.org/10.1038/s43247-022-00521-7>. Number: 1 Publisher: Nature Publishing Group. Accessed 13 Mar 2023.
106. Lopez A, Cole W, Sergi B, Levine A, Carey J, Mangan C, Mai T, Williams T, Pinchuk P, Gu J. Impact of siting ordinances on land availability for wind and solar development. *Nat Energy*. 2023. <https://doi.org/10.1038/s41560-023-01319-3>. Accessed 26 Aug 2023.
107. Sovacool BK, Lakshmi Ratan P. Conceptualizing the acceptance of wind and solar electricity. *Renew Sustain Energy Rev*. 2012;16(7):5268–79. <https://doi.org/10.1016/j.rser.2012.04.048>. Accessed 26 Aug 2023.
108. Gorayeb A, Brannstrom C, De Andrade Meireles AJ, De Sousa Mendes J. Wind power gone bad: critiquing wind power planning processes in northeastern Brazil. *Energy Res Soc Sci*. 2018;40:82–8. <https://doi.org/10.1016/j.erss.2017.11.027>. Accessed 26 Aug 2023.
109. Ross E, Day M, Ivanova C, McLeod A, Lockshin J. Intersections of disadvantaged communities and renewable energy potential: data set and analysis to inform equitable investment prioritization in the United States. *Renew Energy Focus*. 2022;41:1–14. <https://doi.org/10.1016/j.ref.2022.02.002>. Accessed 26 Aug 2023.
110. Sterl S, Hussain B, Miketa A, Li Y, Merven B, Ben Ticha MB, Elabbas MAE, Thiery W, Russo D. An all-Africa dataset of energy model “supply regions” for solar photovoltaic and wind power. *Sci Data*. 2022;9(1):664. <https://doi.org/10.1038/s41597-022-01786-5>. Number: 1 Publisher: Nature Publishing Group. Accessed 13 Aug 2023.
111. Chowdhury AFMK, Wessel J, Wild T, Lamontagne J, Kanyako F. Exploring sustainable electricity system development pathways in South America's MERCOSUR sub-region. *Energy Strateg Rev*. 2023;49: 101150. <https://doi.org/10.1016/j.esr.2023.101150>. Accessed 21 Aug 2023.
112. Wu GC, Deshmukh R, Ndhukula K, Radojicic T, Reilly-Moman J, Phadke A, Kammen DM, Callaway DS. Strategic siting and regional grid interconnections key to low-carbon futures in African countries. *Proc Natl Acad Sci*. 2017;114(15):3004–12. <https://doi.org/10.1073/pnas.1611845114>. Publisher: Proceedings of the National Academy of Sciences. Accessed 14 July 2023.
113. Kowsar A, Hassan M, Rana MT, Haque N, Faruque MH, Ahsan S, Alam F. Optimization and techno-economic assessment of 50 MW floating solar power plant on Hakaluki marsh land in Bangladesh. *Renew Energy*. 2023;216: 119077. <https://doi.org/10.1016/j.renene.2023.119077>. Accessed 29 Aug 2023.
114. Blanford GJ, Merrick JH, Bistline JET, Young DT. Simulating annual variation in load, wind, and solar by representative

- hour selection. *Energy J.* 2018;39(3). <https://doi.org/10.5547/01956574.39.3.gbla>. Accessed 26 Aug 2023
115. Akdemir KZ, Kern JD, Lamontagne J. Assessing risks for New England's wholesale electricity market from wind power losses during extreme winter storms. *Energy.* 2022;251: 123886. <https://doi.org/10.1016/j.energy.2022.123886>. Accessed 26 Aug 2023.
 116. Wessel J, Kern JD, Voisin N, Oikonomou K, Haas J. Technology pathways could help drive the U.S. west coast grid's exposure to hydrometeorological uncertainty. *Earth's Future.* 2022;10(1). <https://doi.org/10.1029/2021EF002187>. Accessed 26 Aug 2023
 117. Energy Sector Management Assistance Program (ESMAP): REZoning: the renewable energy zoning tool; 2022. <https://rezoning.energydata.info>. Accessed 26 Aug 2023
 118. Maclaurin G, Grue N, Anthony L, Heimiller D, Rossol M, Buster G, Williams T. The renewable energy potential (reV) model: a geospatial platform for technical potential and supply curve modeling. Technical Report NREL/TP-6A20-73067, National Renewable Energy Laboratory, Golden: CO; 2019. <https://www.nrel.gov/docs/fy19osti/73067.pdf>
 119. Pfenninger S, Staffell I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy.* 2016;114:1251–65. <https://doi.org/10.1016/j.energy.2016.08.060>.
 120. Staffell I, Pfenninger S. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy.* 2016;114:1224–39. <https://doi.org/10.1016/j.energy.2016.08.068>. Accessed 26 Aug 2023.
 121. Kanyako F, Baker E. Uncertainty analysis of the future cost of wind energy on climate change mitigation. *Climatic Change.* 2021;166(1–2):10. <https://doi.org/10.1007/s10584-021-03105-0>.
 122. Craig MT, Carreño IL, Rossol M, Hodge B-M, Brancucci C. Effects on power system operations of potential changes in wind and solar generation potential under climate change. *Environ Res Lett.* 2019;14(3): 034014. <https://doi.org/10.1088/1748-9326/aaf93b>. Publisher: IOP Publishing. Accessed 28 Aug 2023.
 123. Islam MM, Sohag K, Mariev O. Geopolitical risks and mineral-driven renewable energy generation in China: a decomposed analysis. *Resour Policy.* 2023;80: 103229. <https://doi.org/10.1016/j.resourpol.2022.103229>. Accessed 26 Aug 2023.
 124. Manberger A, Johansson B. The geopolitics of metals and metalloids used for the renewable energy transition. *Energy Strateg Rev.* 2019;26: 100394. <https://doi.org/10.1016/j.esr.2019.100394>. Accessed 26 Aug 2023.
 125. Overland I. The geopolitics of renewable energy: debunking four emerging myths. *Energy Res Soc Sci.* 2019;49:36–40. <https://doi.org/10.1016/j.erss.2018.10.018>. Accessed 26 Aug 2023.
 126. Zhu Z, Piao S, Myneni RB, Huang M, Zeng Z, Canadell JG, Ciais P, Sitch S, Friedlingstein P, Arneeth A, Cao C, Cheng L, Kato E, Koven C, Li Y, Lian X, Liu Y, Liu R, Mao J, Pan Y, Peng S, Peñuelas J, Poulter B, Pugh TAM, Stocker BD, Viovy N, Wang X, Wang Y, Xiao Z, Yang H, Zaehle S, Zeng N. Greening of the Earth and its drivers. *Nat Clim Chang.* 2016;6(8):791–5. <https://doi.org/10.1038/nclimate3004>. Number: 8 Publisher: Nature Publishing Group. Accessed 23 June 2023.
 127. Chen C, Riley WJ, Prentice IC, Keenan TF. CO₂ fertilization of terrestrial photosynthesis inferred from site to global scales. *Proc Natl Acad Sci.* 2022;119(10):2115627119. <https://doi.org/10.1073/pnas.2115627119>. Publisher: Proceedings of the National Academy of Sciences. Accessed 23 June 2023.
 128. Wang S, Zhang Y, Ju W, Chen JM, Ciais P, Cescatti A, Sardans J, Janssens IA, Wu M, Berry JA, Campbell E, Fernández-Martínez M, Alkama R, Sitch S, Friedlingstein P, Smith WK, Yuan W, He W, Lombardozzi D, Kautz M, Zhu D, Lienert S, Kato E, Poulter B, Sanders TGM, Krüger I, Wang R, Zeng N, Tian H, Vuichard N, Jain AK, Wiltshire A, Haverd V, Goll DS, Peñuelas J. Recent global decline of CO₂ fertilization effects on vegetation photosynthesis. *Science.* 2020;370(6522):1295–300. <https://doi.org/10.1126/science.abb7772>. Publisher: American Association for the Advancement of Science. Accessed 23 June 2023.
 129. Yarlagadda B, Wild T, Zhao X, Clarke L, Cui R, Khan Z, Birnbaum A, Lamontagne J. Trade and climate mitigation interactions create agro-economic opportunities with social and environmental trade-offs in Latin America and the Caribbean. *Earth's Future.* 2023;11(4):2022–003063. <https://doi.org/10.1029/2022EF003063>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1029/2022EF003063>. Accessed 26 Sept 2023
 130. Huntingford C, Oliver RJ. Constraints on estimating the CO₂ fertilization effect emerge. *Nature.* 2021;600(7888):224–5. <https://doi.org/10.1038/d41586-021-03560-w>. Bandiera_abtest: a Cg_type: News And Views Number: 7888 Publisher: Nature Publishing Group Subject_term: Climate change, Climate sciences. Accessed 23 June 2023
 131. Sterman J, Moomaw W, Rooney-Varga JN, Siegel L. Does wood bioenergy help or harm the climate? *Bull At Sci.* 2022;78(3):128–38. <https://doi.org/10.1080/00963402.2022.2062933>. Publisher: Routledge. Accessed 22 Aug 2023
 132. Buchholz T, Prisle S, Marland G, Canham C, Sampson N. Uncertainty in projecting GHG emissions from bioenergy. *Nat Clim Chang.* 2014;4(12):1045–7. <https://doi.org/10.1038/nclimate2418>. Number: 12 Publisher: Nature Publishing Group. Accessed 22 Aug 2023.
 133. Bauer N, Rose SK, Fujimori S, Vuuren DP, Weyant J, Wise M, Cui Y, Daioglou V, Gidden MJ, Kato E, Kitous A, Leblanc F, Sands R, Sano F, Streffer J, Tsutsui J, Bibas R, Fricko O, Hasegawa T, Klein D, Kurosawa A, Mima S, Muratori M. Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Clim Chang.* 2020;163(3):1553–68. <https://doi.org/10.1007/s10584-018-2226-y>. Accessed 22 Aug 2023.
 134. Withey P, Johnston C, Guo J. Quantifying the global warming potential of carbon dioxide emissions from bioenergy with carbon capture and storage. *Renew Sustain Energy Rev.* 2019;115: 109408. <https://doi.org/10.1016/j.rser.2019.109408>. Accessed 22 Aug 2023.
 135. Koh R, Galelli S. Evaluating streamflow forecasts in hydro-dominated power systems—when and why they matter. preprint, Preprints August 2023. <https://doi.org/10.22541/essoar.169143870.00652382/v1>. <https://essopenarchive.org/users/646330/articles/658304-evaluating-streamflow-forecasts-in-hydro-dominated-power-systems-when-and-why-they-matter?commit=60d1785eca0a73730f9a447441ec47014891690c>. Accessed 14 Aug 2023
 136. Chowdhury AFMK, Kern J, Dang TD, Galelli S. PowNet: a network-constrained unit commitment/economic dispatch model for large-scale power systems analysis. 2020;8(1):5. <https://doi.org/10.5334/jors.302>. Number: 1 Publisher: Ubiquity Press. Accessed 14 Aug 2023
 137. Su Y, Kern JD, Denaro S, Hill J, Reed P, Sun Y, Cohen J, Characklis GW. An open source model for quantifying risks in bulk electric power systems from spatially and temporally correlated hydrometeorological processes. *Environ Model Softw.* 2020;126: 104667. <https://doi.org/10.1016/j.envsoft.2020.104667>. Accessed 14 Aug 2023.
 138. O'Connell Voisin N, Macknick Fu. Sensitivity of Western U.S. power system dynamics to droughts compounded with fuel price variability. *Appl Energy.* 2019;247:745–54. <https://doi.org/10.1016/j.apenergy.2019.01.156>. Accessed 14 Aug 2023
 139. Koh R, Kern J, Galelli S. Hard-coupling water and power system models increases the complementarity of renewable energy sources. *Appl Energy.* 2022;321: 119386. <https://doi.org/10.1016/j.apenergy.2022.119386>. Accessed 14 Aug 2023.

140. Chowdhury AFMK, Dang TD, Bagchi A, Galelli S. Expected benefits of Laos' hydropower development curbed by hydroclimatic variability and limited transmission capacity: opportunities to reform. *J Water Resour Plan Manag.* 2020;146(10):05020019. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0001279](https://doi.org/10.1061/(ASCE)WR.1943-5452.0001279). Publisher: American Society of Civil Engineers.
141. Bartos M, Chester M, Johnson N, Gorman B, Eisenberg D, Linkov I, Bates M. Impacts of rising air temperatures on electric transmission ampacity and peak electricity load in the United States. *Environ Res Lett.* 2016;11(11): 114008. <https://doi.org/10.1088/1748-9326/11/11/114008>. Publisher: IOP Publishing. Accessed 14 Aug 2023.
142. Feng X, Yang J, Luo C, Sun Y, Liu M, Tang Y. A risk evaluation method for cascading failure considering transmission line icing. In: *IEEE Innovative smart grid technologies - Asia (ISGT ASIA)*. IEEE, Bangkok: Thailand; 2015. pp. 1–4. <https://doi.org/10.1109/ISGT-Asia.2015.7387014>. <http://ieeexplore.ieee.org/document/7387014/>. Accessed 14 Aug 2023
143. Dian S, Cheng P, Ye Q, Wu J, Luo R, Wang C, Hui D, Zhou N, Zou D, Yu Q, Gong X. Integrating wildfires propagation prediction into early warning of electrical transmission line outages. *IEEE Access.* 2019;7:27586–603. <https://doi.org/10.1109/ACCESS.2019.2894141>. Conference Name: IEEE Access.
144. Ram M, Bogdanov D, Aghahosseini A, Gulagi A, Oyewo AS, Odai Mensah TN, Child M, Caldera U, Sadovskaia K, Barbosa LDSNS, Fasihi M, Khalili S, Traber T, Breyer C. Global energy transition to 100% renewables by 2050: not fiction, but much needed impetus for developing economies to leapfrog into a sustainable future. *Energy.* 2022;246:123419. <https://doi.org/10.1016/j.energy.2022.123419>. Accessed 14 Aug 2023
145. Diesendorf M, Elliston B. The feasibility of 100% renewable electricity systems: a response to critics. *Renew Sustain Energy Rev.* 2018;93:318–30. <https://doi.org/10.1016/j.rser.2018.05.042>. Accessed 14 Aug 2023.
146. Khalili S, Breyer C. Review on 100% renewable energy system analyses-a bibliometric perspective. *IEEE Access.* 2022;10:125792–834. <https://doi.org/10.1109/ACCESS.2022.3221155>. Conference Name: IEEE Access.
147. Fuhrman J, Bergero C, Weber M, Monteith S, Wang FM, Clarens AF, Doney SC, Shobe V, McJeon H. Diverse carbon dioxide removal approaches could reduce impacts on the energy-water-land system. *Nat Clim Chang.* 2023;1–10. <https://doi.org/10.1038/s41558-023-01604-9>. Publisher: Nature Publishing Group. Accessed 13 Mar 2023
148. Cohen G, Joutz F, Loungani P. Measuring energy security: trends in the diversification of oil and natural gas supplies. *Energy Policy.* 2011;39(9):4860–9. <https://doi.org/10.1016/j.enpol.2011.06.034>. Accessed 21 Aug 2023.
149. Rosenow J. Europe on the way to net zero: what challenges and opportunities? *PLOS Clim.* 2022;1(7):0000058. <https://doi.org/10.1371/journal.pclm.0000058>. Accessed 21 Aug 2023
150. Poumadère M, Mays C, Le Mer S, Blong R. The 2003 heat wave in France: dangerous climate change here and now. *Risk Anal.* 2005;25(6):1483–94. <https://doi.org/10.1111/j.1539-6924.2005.00694.x>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1539-6924.2005.00694.x>. Accessed 2023-08-21
151. Jenkins JD, Luke M, Thernstrom S. Getting to zero carbon emissions in the electric power sector. *Joule.* 2018;2(12):2498–510. <https://doi.org/10.1016/j.joule.2018.11.013>. Accessed 13 Mar 2023.
152. Davis SJ, Lewis NS, Shaner M, Aggarwal S, Arent D, Azevedo IL, Benson SM, Bradley T, Brouwer J, Chiang Y-M, Clark CTM, Cohen A, Doig S, Edmonds J, Fennell P, Field CB, Hannegan B, Hodge B-M, Hoffert MI, Ingersoll E, Jaramillo P, Lackner KS, Mach KJ, Mastrandrea M, Ogden J, Peterson PF, Sanchez DL, Sperling D, Stagner J, Trancik JE, Yang C-J, Caldeira K. Net-zero emissions energy systems. *Science.* 2018;360(6396):9793. <https://doi.org/10.1126/science.aas9793>. Publisher: American Association for the Advancement of Science. Accessed 14 Mar 2023.
153. DeAngelo J, Azevedo I, Bistline J, Clarke L, Luderer G, Byers E, Davis SJ. Energy systems in scenarios at net-zero CO2 emissions. *Nat Commun.* 2021;12(1):6096. <https://doi.org/10.1038/s41467-021-26356-y>. Number: 1 Publisher: Nature Publishing Group. Accessed 13 Mar 2023.
154. Grams CM, Beerli R, Pfenninger S, Staffell I, Wernli H. Balancing Europe's wind-power output through spatial deployment informed by weather regimes. *Nat Clim Chang.* 2017;7(8):557–62. <https://doi.org/10.1038/nclimate3338>. Number: 8 Publisher: Nature Publishing Group. Accessed 21 Aug 2023.
155. Poumadère T, Lilliestam J, Marelli S, Pfenninger S. Trade-offs between geographic scale, cost, and infrastructure requirements for fully renewable electricity in Europe. *Joule.* 2020;4(9):1929–48. <https://doi.org/10.1016/j.joule.2020.07.018>. Accessed 21 Aug 2023.
156. Busby JW, Baker K, Bazilian MD, Gilbert AQ, Grubert E, Rai V, Rhodes JD, Shidore S, Smith CA, Webber ME. Cascading risks: understanding the 2021 winter blackout in Texas. *Energy Res Soc Sci.* 2021;77: 102106. <https://doi.org/10.1016/j.erss.2021.102106>. Accessed 21 Aug 2023.
157. Golombek R, Lind A, Ringkjøb H-K, Seljom P. The role of transmission and energy storage in European decarbonization towards 2050. *Energy.* 2022;239: 122159. <https://doi.org/10.1016/j.energy.2021.122159>. Accessed 21 Aug 2023.
158. Koohi-Fayegh S, Rosen MA. A review of energy storage types, applications and recent developments. *J Energy Storage.* 2020;27: 101047. <https://doi.org/10.1016/j.est.2019.101047>. Accessed 21 Aug 2023.
159. Shan R, Reagan J, Castellanos S, Kurtz S, Kittner N. Evaluating emerging long-duration energy storage technologies. *Renew Sustain Energy Rev.* 2022;159: 112240. <https://doi.org/10.1016/j.rser.2022.112240>. Accessed 30 Oct 2023.
160. Hunt JD, Byers E, Wada Y, Parkinson S, Gernaat DEHJ, Langan S, Vuuren DP, Riahi K. Global resource potential of seasonal pumped hydropower storage for energy and water storage. *Nat Commun.* 2020;11(1):947. <https://doi.org/10.1038/s41467-020-14555-y>. Number: 1 Publisher: Nature Publishing Group. Accessed 21 Aug 2023.
161. Yang C-J, Jackson RB. Opportunities and barriers to pumped-hydro energy storage in the United States. *Renew Sustain Energy Rev.* 2011;15(1):839–44. <https://doi.org/10.1016/j.rser.2010.09.020>. Accessed 21 Aug 2023.
162. Jurasz J, Canales FA, Kies A, Guezgouz M, Beluco A. A review on the complementarity of renewable energy sources: concept, metrics, application and future research directions. *Sol Energy.* 2020;195:703–24. <https://doi.org/10.1016/j.solener.2019.11.087>. Accessed 21 Aug 2023.
163. François B, Hingray B, Raynaud D, Borga M, Creutin JD. Increasing climate-related-energy penetration by integrating run-of-the-river hydropower to wind/solar mix. *Renew Energy.* 2016;87:686–96. <https://doi.org/10.1016/j.renene.2015.10.064>. Accessed 21 Aug 2023.
164. Shen B, Kahrl F, Satchwell AJ. Facilitating power grid decarbonization with distributed energy resources: lessons from the United States. *Annu Rev Environ Resour.* 2021;46(1):349–75. <https://doi.org/10.1146/annurev-environ-111320-071618>. Accessed 21 Aug 2023
165. Knuth S. Breakthroughs for a green economy? Financialization and clean energy transition. *Energy Res Soc Sci.* 2018;41:220–9. <https://doi.org/10.1016/j.erss.2018.04.024>. Accessed 27 Aug 2023.

166. Bazilian M, Bradshaw M, Gabriel J, Goldthau A, Westphal K. Four scenarios of the energy transition: drivers, consequences, and implications for geopolitics. *WIREs Clim Chang*. 2020;11(2):625. <https://doi.org/10.1002/wcc.625>. _eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/wcc.625>. Accessed 27 Aug 2023
167. Hainsch K, Löffler K, Burandt T, Auer H, Granado P, Pesciella P, Zwickl-Bernhard S. Energy transition scenarios: what policies, societal attitudes, and technology developments will realize the EU Green Deal? *Energy*. 2022;239: 122067. <https://doi.org/10.1016/j.energy.2021.122067>. Accessed 27 Aug 2023.
168. Su Y, Kern JD, Reed PM, Characklis GW. Compound hydrometeorological extremes across multiple timescales drive volatility in California electricity market prices and emissions. *Appl Energy*. 2020;276: 115541. <https://doi.org/10.1016/j.apenergy.2020.115541>. Accessed 21 Aug 2023.
169. Flores-Quiroz A, Palma-Behnke R, Zakeri G, Moreno R. A column generation approach for solving generation expansion planning problems with high renewable energy penetration. *Electr Power Syst Res*. 2016;136:232–41. <https://doi.org/10.1016/j.epsr.2016.02.011>. Accessed 21 Aug 2023.
170. Van Hentenryck P. Machine learning for optimal power flows. In: Carlsson JG, Shier D, Greenberg HJ, editors. *Tutorials in operations research: Emerging optimization methods and modeling techniques with applications*. INFORMS: ???; 2021. <https://doi.org/10.1287/educ.2021.0234>. <http://pubsonline.informs.org/doi/10.1287/educ.2021.0234>. Accessed 21 Aug 2023
171. Winemiller KO, McIntyre PB, Castello L, Fluet-Chouinard E, Giarrizzo T, Nam S, Baird IG, Darwall W, Lujan NK, Harrison I, Stiassny MLJ, Silvano RAM, Fitzgerald DB, Pelicice FM, Agostinho AA, Gomes LC, Albert JS, Baran E, Petrere MJr, Zarfl C, Mulligan M, Sullivan JP, Arantes CC, Sousa LM, Koning AA, Hoeinghaus DJ, Sabaj M, Lundberg JG, Armbruster J, Thieme ML, Petry P, Zuanon J, Vilara GT, Snoeks J, Ou C, Rainboth W, Pavanelli CS, Akama A, Soesbergen Av, Sáenz L. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science*. 2016. <https://doi.org/10.1126/science.aac7082>. Publisher: American Association for the Advancement of Science. Accessed 30 Dec 2021
172. Reed PM, Hadjimichael A, Moss RH, Brelsford C, Burleyson CD, Cohen S, Dyreson A, Gold DF, Gupta RS, Keller K, Konar M, Monier E, Morris J, Srikrishnan V, Voisin N, Yoon J. Multisector dynamics: advancing the science of complex adaptive human-earth systems. *Earth's Future*. 2022;10(3):2021–002621. <https://doi.org/10.1029/2021EF002621>. _eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1029/2021EF002621>. Accessed 21 Aug 2023
173. Zeighami A, Kern J, Yates AJ, Weber P, Bruno AA. U.S. West Coast droughts and heat waves exacerbate pollution inequality and can evade emission control policies. *Nat Commun*. 2023;14(1):1415. <https://doi.org/10.1038/s41467-023-37080-0>. Number: 1 Publisher: Nature Publishing Group. Accessed 25 April 2023
174. Freese LM, Chossière GP, Eastham SD, Jenn A, Selin NE. Nuclear power generation phase-outs redistribute US air quality and climate-related mortality risk. *Nat Energy*. 2023;8(5):492–503. <https://doi.org/10.1038/s41560-023-01241-8>. Number: 5 Publisher: Nature Publishing Group. Accessed 21 Aug 2023.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.