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Working Paper: Minimizing biodiversity and social impacts of hydropower, wind, and solar in Southern Africa's low-carbon electricity system

Scaling up low-carbon electricity infrastructure to meet economic growth, electrification targets, and climate goals in Southern Africa is likely to come in conflict with environmental and social values because of the significant land use requirements of wind and solar technologies and freshwater impacts of hydropower. In this study, the authors characterize wind, solar, and hydropower resources in Southern Africa under different sets of environmental and social criteria. The authors then identify least-cost electricity infrastructure investments under different sets of socio-environmental constraints and carbon emissions targets and evaluate the costs of imposing increasing environmental and social constraints on low-carbon pathways for Southern Africa's electricity system.

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Minimizing biodiversity and social impacts of hydropower, wind, and solar in Southern Africa's low-carbon electricity system
(Working paper)

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Abstract
The scale at which low-carbon electricity will need to be deployed to meet economic growth, electrification, and climate goals in Africa is unprecedented. Given the significant land use requirements of wind and solar technologies and freshwater impacts of hydropower, this infrastructure build-out may come in conflict with environmental and social values. Understanding whether and how much of the proposed and potential renewable energy resources are environmentally and socially compatible is critical for designing sustainable low-carbon pathways. In this study, we characterize wind, solar, and hydropower potential in the Southern African power pool and identify the mix of electricity generation technologies that would be cost-minimizing under different sets of socio-environmental constraints and carbon emissions targets. We find that significant potential for wind and solar remain after excluding areas with environmental and social importance and that about 60% of planned or proposed hydropower projects face potential socio-environmental conflicts. The optimal mix of generation technologies with

socio-environmental protections results in more wind, solar, and battery capacity but a reduction in hydropower capacity compared to scenarios without protections. Even under a high carbon cap (50% reductions by 2040), the total amount of cost-competitive hydropower does not exceed 55% of planned or proposed hydropower capacity—and is only 25% when considering socio-environmental protections. The combination of carbon target and land use protections results in system cost increases of 6-13%. More importantly, cost impacts vary across countries within the region depending upon which hydropower and renewable energy projects are excluded from consideration. Improving electricity trade and transmission infrastructure could mitigate costs and impacts on consumers. Further, given the region's low contribution to historical carbon emissions and considering its development needs, the international community should consider supporting the additional costs of environmentally and socially sustainable low-carbon pathways highlighted in this study.

1. Introduction

Large hydropower continues to be promoted as a cost-effective and low-carbon source of dispatchable electricity, especially in regions with abundant potential like Africa, Southeast Asia, and Latin America (Gernaat et al., 2017; IRENA, 2017; Mitchell, 2016; Sterl et al., 2020). However, hydropower development has significant negative social and environmental impacts that have historically been underestimated in power sector planning (Ansar et al., 2014; Fan et al., 2022; Moran et al., 2018; Richter et al., 2010). Wind, solar, and battery technologies with their rapidly declining costs have been viewed as promising low-carbon substitutes for new hydropower projects (Deshmukh et al., 2018; Opperman et al., 2019; Schmitt et al., 2021; Siala et al., 2021). Yet, these technologies have their own technical, environmental, and social challenges. Wind and solar generation is variable and uncertain, complicating planning and operations of future low-carbon electricity systems. Managing this variability will require large battery storage capacities, but their scale-up, especially of Lithium ion-based technologies, pose significant challenges associated with mining and recycling (Sovacool et al., 2020). Large-scale deployment of wind and solar power plants will also require a significant amount of land, which similar to hydropower dams may directly conflict with biodiversity and ecosystem services as well as negatively impact local communities. If not addressed, these conflicts arising from both hydropower and wind and solar development will likely result in project delays and cost overruns, and require mitigation and compensation costs that would affect the feasibility of new energy infrastructure critical to achieve energy security, economic growth, and climate goals of the region (Ansar et al., 2014; Dashiell et al., 2019; Sovacool et al., 2014). Careful planning of renewable energy infrastructure is thus important in order to avoid areas with high conservation and societal value (Opperman et al., 2015; Wu et al., 2020).

Hydropower planning is often performed independently of whole power systems planning. Much of the literature on the sustainable development of hydropower has focused on minimization of impacts (Almeida et al., 2022; Flecker et al., 2022), which is the second level of the mitigation hierarchy adopted for dam development after the top level of avoidance (Thieme et al., 2021). These studies strategically plan a hydropower portfolio by co-optimizing hydropower production with other socio-environmental criteria (Almeida et al., 2019; Flecker et al., 2022; Ziv et al., 2012), but they do so without considering the value of hydropower in the power system. These studies create optimal hydropower generation portfolios given a fixed amount of hydropower generation requirements, rather than optimally designing the overall technology mix which misses an opportunity to substitute higher impact hydropower plants with wind and solar generation (Almeida et al., 2019; Hurford et al., 2020; Schmitt et al., 2018). Other studies simply substitute hydropower generation on an annual generation basis using modeled solar energy generation potential in nearby locations (Waldman et al., 2019), which overlooks the dispatchable nature of hydropower generation compared to wind and solar. There has been a lack of studies assessing individual hydropower projects within a power systems planning framework where seasonal, daily, hourly, and sub hourly temporal representation of generation is needed to accurately estimate costs and value of specific technologies and projects. Here we quantify the electricity system costs and socio-environmental benefits of avoiding hydropower development, the top level within the mitigation hierarchy.

Wind and solar generation projects have also come up against conflicting social or environmental land uses (Mulvaney, 2017; Rand and Hoen, 2017). In the US, more than half of failed renewable energy projects examined were partially or entirely due to environmental impacts (Susskind et al., 2022). Failure to consider social and environmental siting criteria in both long-term energy systems planning as well as project-level planning could lead to significant overestimation of the costs, ease, and availability of developing renewable energy infrastructure (Ansar et al., 2014).

The Southern African region epitomizes the conflicts arising from hydropower development and the potential tradeoffs that would be critical for developing the vast wind and solar resources in the region. The region consists of twelve countries—Angola, Botswana, Democratic Republic of the Congo, Eswatini, Lesotho, Mozambique, Malawi, Namibia, South Africa, Tanzania, Zambia, and Zimbabwe—and accounts for 40% of Africa’s electricity demand and is expected to double its demand by 2040. Eight of the twelve countries of the Southern African Power Pool (SAPP) are dependent on hydropower for over half their electricity generation. Southern Africa is home to two of the five largest river basins in Africa—the Zambezi and Congo— with several proposed hydropower projects. With declining costs of wind and solar PV, the region also has the opportunity to scale up its renewable energy generation. At the same time, the region has large areas with high biodiversity value. Protecting these areas and avoiding social conflicts with local communities will be critical for Southern Africa to sustainably develop its renewable and hydropower resources.

In this study, we characterize wind, solar, and hydropower potential in the Southern Africa power pool and identify the mix of electricity generation technologies that would be cost-minimizing under different sets of socio-environmental constraints and carbon emissions targets. We ask, how does excluding the most socially and environmentally damaging potential wind, solar, and hydropower projects impact optimal electricity pathways and overall system costs in Southern Africa?

To create socio-environmentally constrained scenarios, we screened wind, solar, and hydropower techno-economic potential using protected areas, sensitivity areas for focal species, forested areas, free-flowing rivers, and select agricultural lands. We then supplied these hypothetical and proposed/planned renewable energy projects to a power system capacity investment model of the SAPP, GridPath, to create optimal electricity generation portfolios and identify the hydropower plants that would remain cost-competitive under each scenario (Chowdhury et al. 2022). To explore the implications of reaching conservation and climate objectives concurrently, we compare scenarios that do and do not cap greenhouse gas emissions at 50% of current emissions by 2040.

2. Results and Discussion

2.1. Environmentally and socially-constrained wind, solar, and hydropower projects

The amount of wind and solar resource potential is determined using a combination of technical, physical, economic, and socio-environmental criteria. For hydropower, using design specifications available, we modeled the reservoir footprint for 34 major planned or proposed projects. To design electricity portfolios that avoid negative environmental and social impacts of new renewable energy development, we constrained the techno-economic wind, solar and hydropower resource potential by excluding areas with varying levels of environmental and/or social importance to form the following seven screened scenarios of candidate renewable energy resources for development (see Methods for details): (1) Base in which no socio-environmental exclusions are applied (hydropower-only), (2) Legal, in which legally protected areas (e.g. IUCN I-III) are excluded from all renewable development, (3) Social in which legally protected and areas important for human livelihoods and planned hydropower plants whose reservoirs would displace more than 2000 people are excluded from development, (4) Environment in which legally protected and high conservation value areas and planned hydropower projects on large free flowing rivers are excluded, (5) Environment and Landscape in which Legal, Environment, and forested areas are excluded, (6) All Exclusions in which all Legal, Social, Environment, and Landscape areas are excluded, and (7) All Exclusions for renewable energy development and no new hydropower.

In response to socio-environmental land protections, we find that solar potential decreases significantly with less than 25% of the Base scenario potential remaining, whereas wind potential decreases less dramatically with about 72% of the Base potential remaining in the All Exclusions scenario (Fig. 1). While nearly all countries have large amounts of solar potential in the All Exclusions scenario, most of the remaining potential is concentrated in South Africa, Namibia, Botswana, and Angola (Fig 1a). Landscape (forested land) exclusions account for a significant reduction in solar potential (Fig 1d). Wind potential is also widely distributed across countries even with socio-environmental protections, though in Angola, Mozambique, and the Democratic Republic of Congo (DRC) wind potential is limited to smaller areas (Fig 1b). Planned hydropower capacity reduces to 58% of total planned potential in the All Exclusions scenario. About 12% of planned hydropower project capacity overlaps with legally protected areas, and a further 17% overlaps with areas of high conservation value or occur on free flowing rivers. In response to all combined land, river, and community protections, all countries experience a significant reduction (>50%) in planned hydropower capacity except for DRC (Fig 1f).

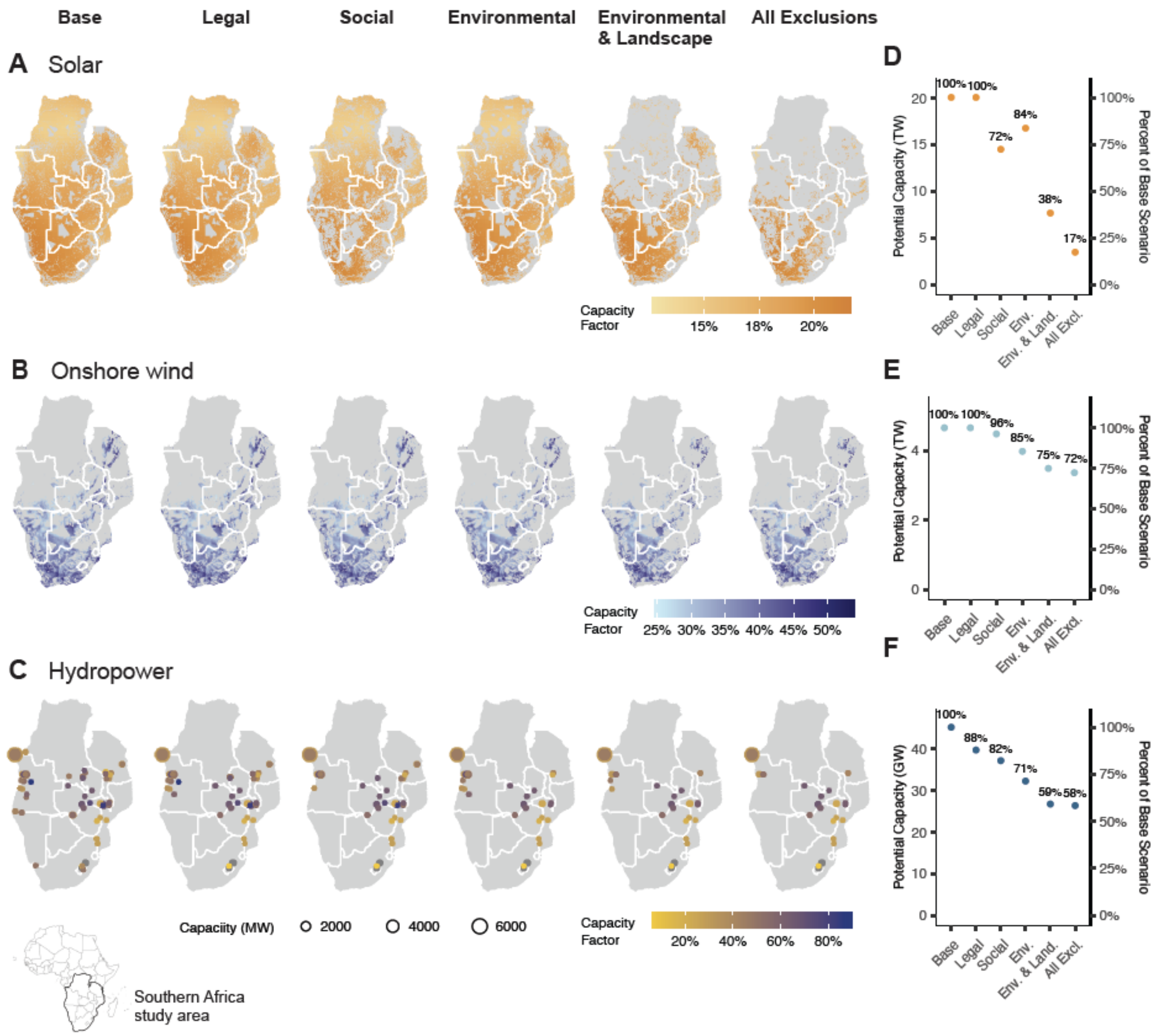

Figure 1. Renewable resource potential spatial distribution (A, B, C) and capacities and shares compared to base scenario (D, E, F) for solar photovoltaic, onshore wind, and hydropower by scenario. Base and Legal scenarios are the same for solar and onshore wind.

2.2. Optimal electricity portfolios, costs, and emissions

In order to understand how imposing renewable resources siting exclusions affect the future electricity capacity needs, electricity system costs, emissions, and impacts, we used an open source capacity expansion model, GridPath, to develop least-cost electricity pathways for Southern Africa out to 2040 (Chowdhury et al. 2022). We included an additional renewable scenario that explores the impact of a hydropower moratorium. To hold carbon emissions constant across all the scenarios in the set of runs that lacked a carbon target, we capped all other scenarios' carbon emissions using the Base scenario's annual emissions in each investment period.

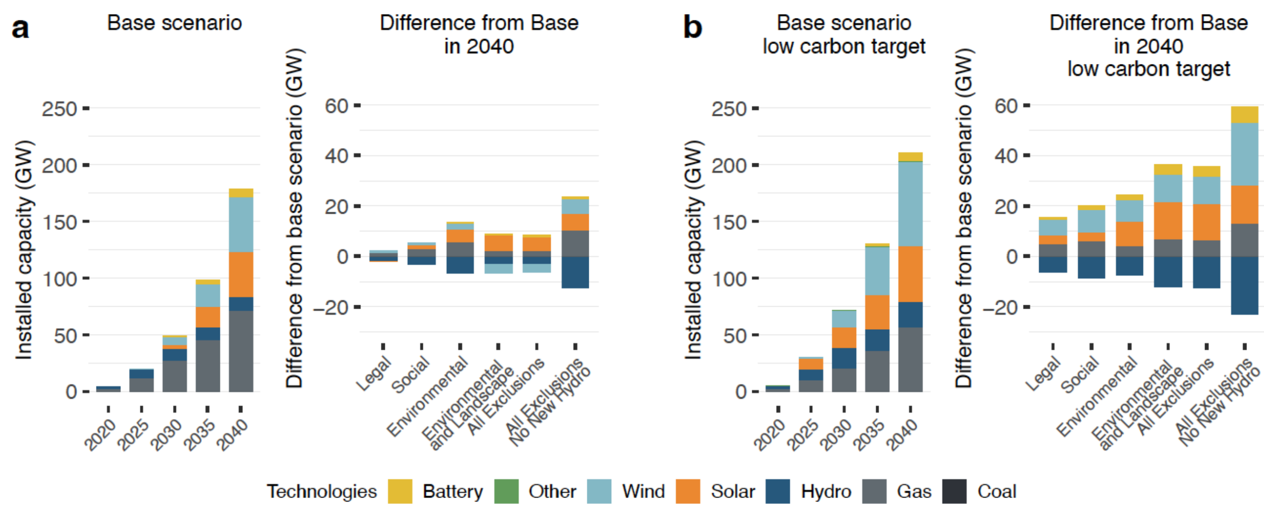

Figure 2. (a) New generation capacity installations from 2020-2040 for the Base scenario without a carbon target and differences in installed capacities in 2040 for each scenario compared to Base. (b) Same as (a) but with a low carbon emissions target trajectory that limits annual carbon emissions in 2040 to half of the Base scenario without a carbon target. Positive differences indicate greater installed capacity and negative differences indicate lower installed capacities compared to the Base scenarios.

We find that without socio-environmental siting restrictions, about 50% of new generation capacity by 2040 will come from wind and solar. Increasing environmental and social protections across all renewable technologies requires building more solar, battery, and gas, while building less hydropower, although the differences due to siting protections result in a change of less than 10% of the new capacity in the Base scenario (Fig. 2a). A hydropower moratorium, on the other hand, results in the most dramatic deviations from the Base scenario--requiring a substantial increase in wind and gas capacity (Fig. 2a), with corresponding increases in gas and wind generation, and reduction in coal generation. Increasing siting protections reduces selected wind capacity while increasing solar capacity because high quality wind sites were excluded by socio-environmental constraints. While only 3 GW of new gas capacity is added in the All Exclusions scenario, gas generation does increase to make up for the lack of load following generation due to increases in solar and the reduction in wind capacity (Fig. 2a).

A low carbon target alters the way that socio-environmental protections impact the energy portfolio. Without any additional protections in place (Base scenario), about 50 GW of additional wind, solar, and hydropower capacity (compared to the Base scenario without a carbon target) will be required to achieve a 50% reduction in carbon emissions by 2040

(Fig 2b), which fills the gap left by reduced fossil generation and capacity. Achieving an increasingly high level of socio-environmental protections and a low carbon target requires a growth of largely wind (+14%), solar (+29%), and battery (+53%) capacity, and a reduction of hydropower capacity (-54%; Fig 2b), resulting in a net gain of 11% in generation and battery capacity by 2040 in the All Exclusions scenario. Legal protections have the greatest single impact on total capacity increases (+4.2%), followed by Landscape protections (an additional 3.4 percentage points).

Unlike many other capacity expansion models which treat candidate resources as fleets of generation as opposed to individual projects, we designed the capacity investment model to identify whether or not it would be cost effective to build each planned or proposed hydropower plant. We find that without socio-environmental protections, only about 23 GW and 13 GW of hydropower will be needed in 2040 with and without a carbon target, respectively (Fig. 2). Given that 41.1 GW of planned or proposed hydropower capacity was made available to the model, we find that a large fraction of these hydropower projects are never cost competitive. Applying socio-environmental protections further reduces this selected capacity by 12.4 GW with a carbon target and 2.5 GW without, such that only 25% of planned or proposed hydropower capacity is necessary and cost-competitive by 2040.

The geographic distribution of selected, suitable but not selected, and unsuitable hydropower projects shows that some plants that are cost-competitive have negative socio and/or environmental impacts, which exclude them from development in the more protective scenarios (Fig 3). These projects are primarily found in Angola, Mozambique, Tanzania, and Zambia, with more than half of the projects in Mozambique, Zambia, and Tanzania excluded due to environmental impacts and most of the projects in Angola excluded due to landscape impacts (Fig 3D). The most cost-competitive proposed hydropower projects are concentrated in the Kwanza and Rufiji river basins. Some large hydropower projects in the Congo/DRC region (Inga series with 16-17 GW of proposed capacity) are also suitable across all scenarios, but these relatively expensive projects are selected only after the projects in the Kwanza and Rufiji river basins have already been selected and/or excluded due to socio-environmental protections (in the All Exclusions scenario).

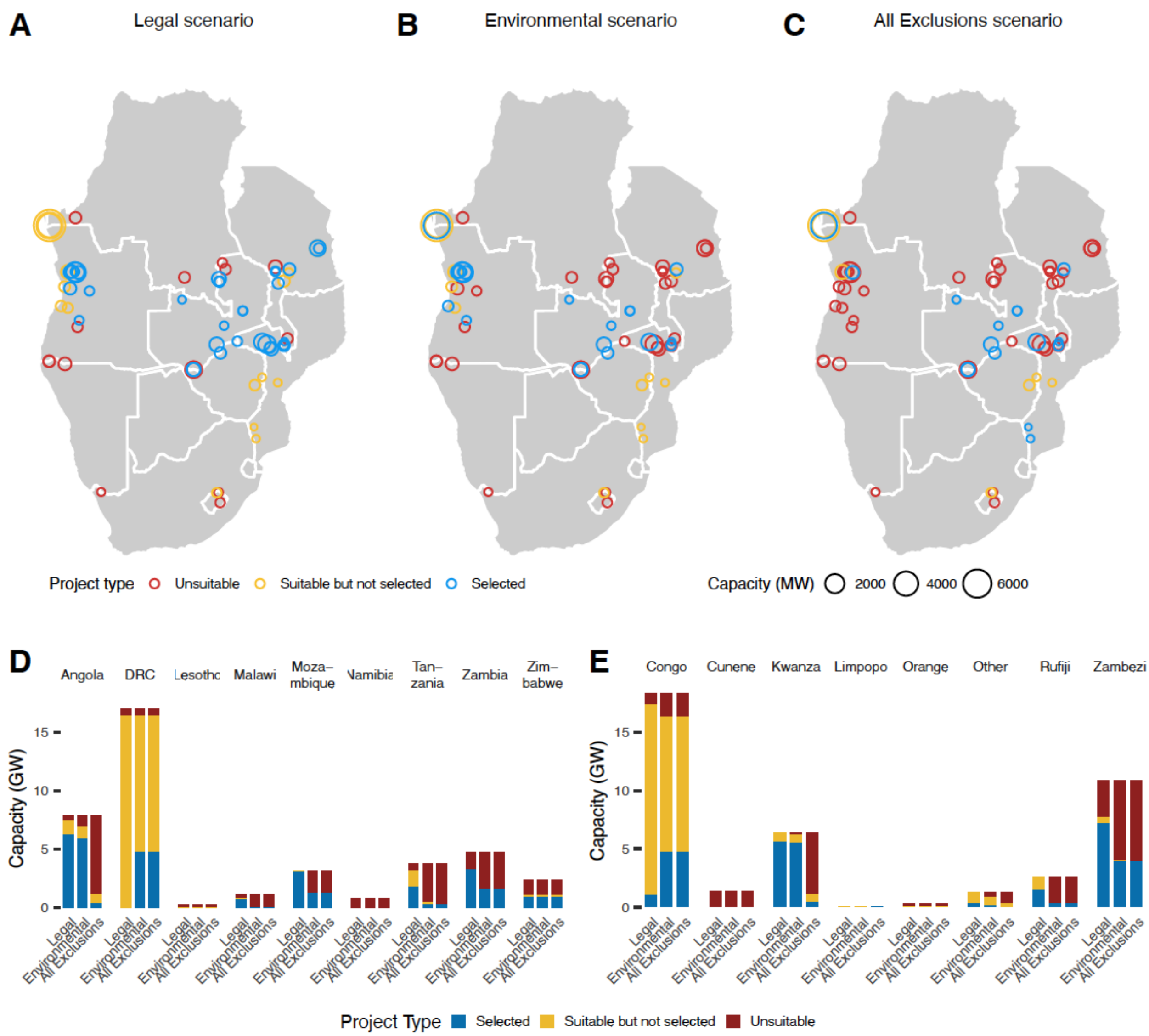

Figure 3. Spatial distribution (A, B, C), country-wise capacities (D) and basin-wise capacities (E) of unsuitable, suitable but not selected, and selected hydropower projects for Legal, Environmental, and All Exclusion scenarios.

Carbon emissions without the low-carbon cap slightly increase from 2020 to 2035 while sharply decreasing by more than 10% in 2040, largely due to coal retirements and a drop in the costs of wind and solar PV technologies (Fig. 4b). For the low-carbon scenarios, we capped emissions at levels that linearly increase with investment periods to meet a 50% emissions reduction target by 2040 compared to 2020.

Marginal electricity system costs increase in response to more socio-environmental protections. However, given the significant amount of high impact potential excluded from the model for the three renewable energy technologies, system costs only increased <1%

for Legal exclusions, 2.5% for Environmental exclusions, and up to 5.6% for All Exclusions (Fig. 5a). These cost premiums for socio-environmental protections do increase further when combined with a low carbon target, which avoids 100 million tonnes of annual CO_2 emissions by 2040 (Fig. 4a). A 6% cost increase is required under the Base scenario to achieve the low carbon target, a premium that increases up to 7% in the All Exclusions scenario. Pursuing a low carbon target and all socio-environmental protections increases costs by 13% compared to the Base scenario with no carbon target. Further, cost impacts vary across the countries within the region depending upon which hydropower and renewable energy projects are excluded from consideration. Improving electricity trade and transmission infrastructure could mitigate costs and impacts on consumers (Chowdhury et al., 2022).

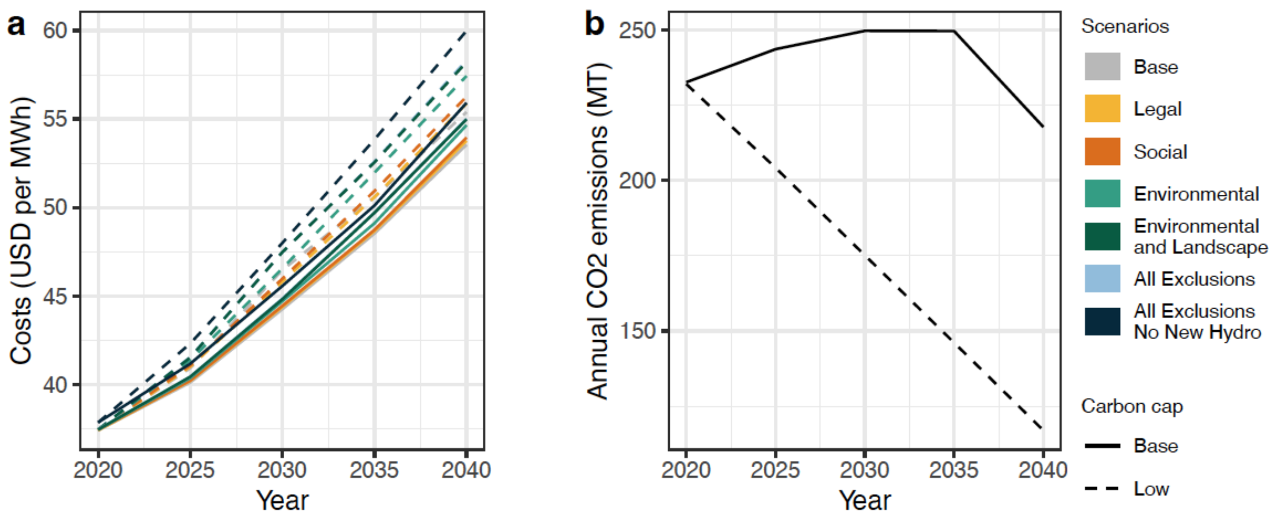

Figure 4: (a) Cost and (b) carbon emissions of Southern Africa's electricity system from 2020 to 2040 for Base and Low carbon scenarios. Carbon emissions for all scenarios are either capped at the Base scenario without a carbon cap or the Base scenario with a low carbon emissions target trajectory. Carbon emissions in the low carbon scenarios are capped at levels that linearly increase with investment periods to meet a 50% emissions reduction target by 2040 compared to 2020.

3. Methods

3.1. Environmental and social screens

We developed environmental and social screens for candidate and planned wind, solar, and hydropower projects using publicly available data. The Base scenario for wind and solar screens is the same as the Legal scenario. We included all planned hydropower plants in the Base scenario even if they overlapped with legally protected areas.

For the Legally Protected (Legal) scenario, we excluded areas identified as International Union for Conservation of Nature (IUCN) categories "Ia", "Ib", "II" in the World Database on Protected Areas (WDPA). We used this threshold to include the highest category of protected area. For example, category Ib are wilderness areas and category II are National Parks. Category Ia areas were not found in the study region. If a country did not use the IUCN categories (e.g., South Africa), we included areas designated as “National Parks” in this category. We also excluded country-specific data on National Parks, where available (e.g., DRC, Lesotho, and Tanzania).

For the Environmental scenario, we excluded areas identified as IUCN categories "III", "IV", "V", "VI". We also excluded 27 more refined designations that focus on conservation and management of natural resources (e.g., ramsar sites, which are important wetland sites identified under the international environmental treaty of the Ramsar Convention, reserves, and game management areas). Similar to legally protected areas, country specific data conservation and management areas were excluded in this scenario. We also excluded Key Biodiversity areas to account for important areas for species conservation. In the Environment and Landscape scenario, we account for intact forest by excluding areas with dense forest cover defined as areas with greater than 15% tree cover (based on ESA CCI dataset—categories 50, 60, 61, 62, 70, 80, 90, 160, and 170) and areas designated as wetlands (based on Global Lakes and Wetlands Database, WWF).

For the Human Livelihoods or Social scenario, to protect lands with social or cultural value, we excluded areas from the WDPA that focused on human livelihood benefits (e.g., world heritage sites, catchments, community conservancies and reserves). Similar to legally protected areas, we excluded country-specific data on human livelihood benefits (e.g., community forests in Namibia). Due to the strong reliance on agriculture in the region, irrigated and rainfed croplands (ESA CCI data) were also excluded in the social impact.

Lastly, we developed a sixth scenario with both Environmental and Landscape and Social scenario exclusions and a seventh scenario with the same exclusions for wind and solar but with a moratorium on new hydropower projects i.e. no new hydropower.

3.2. Wind and solar resource mapping

We adapted and built upon the Multi-criteria Analysis for Planning Renewable Energy (MapRE) modeling framework, which was first developed for and applied to regions in

Africa (Wu et al., 2017) and recently applied specifically to Southern Africa (Chowdhury et al., 2022). MapRE is a spatial energy systems modeling framework that integrates renewable resource assessment and estimation of multiple criteria for decision making analysis. Using wind and solar average resource data sets (ESMAP et al., 2019; Technical University of Denmark (DTU) et al., 2019), and applying constraints on elevation and slope (Hennig et al., 2001; Reuter et al., 2007), and the environmental and social screens, we spatially identified suitable wind and solar PV sites for the environmental and social impact scenarios across the twelve Southern African countries. We conducted the site-suitability analysis at a spatial resolution of 500 m, and then aggregated sites to 25 km and 100 km resolution for wind and solar PV, respectively.

Next, we developed hourly capacity factor time series for both wind and solar PV using the 2018 weather data. For wind, we used hourly wind speed data from ERA5 (European Centre for Medium-Range Weather Forecasts - ECMWF - Reanalysis 5) (Muñoz Sabater, 2019), adjusting the coarse spatial resolution data to match the annual average wind speeds from the finer spatial resolution Global Wind Atlas (GWA) data. We then applied a Vestas 2 MW 90 m turbine power curve to the modified hourly wind speeds to derive hourly capacity factors using the System Advisor Model (NREL, 2016a). For solar PV, we used hourly global horizontal irradiance (GHI) data from the National Solar Radiation Database (NSRDB) derived from the Meteosat satellite (NREL, 2016b). We again used the System Advisor model (NREL, 2016a) to convert GHI data to capacity factors for fixed tilt systems, setting the tilt equal to the latitude of each location. We also included costs of transmission interconnections and roads using distance of candidate projects to the nearest transmission and road infrastructure and then applying capital costs for 230 kV High Voltage Alternating Current (HVAC) transmission lines (Black & Veatch, 2019) and asphalt roads to those interconnections. For each environmental and social scenario, the list of wind and solar candidate projects and their capacities and costs were then fed to the power systems planning model.

3.3. Hydropower characterization and screening

We first mapped existing and planned hydropower projects using latitude and longitudes of project sites. We then generated energy availability data for each existing and planned hydropower project using a spatially-distributed hydrological water management model. We modeled eight river basins---Zambezi, Congo, Kwanza, Cunene, Rufiji, Orange, Limpopo, and Buzi---which encompass more than 90% of SAPP's total installed (13 GW) and projected (59 GW) hydropower capacity (SAPP, 2017).

To simulate daily runoff, evaporation, and baseflow, we first used the Variable Infiltration Capacity (VIC) hydrological model for each basin. The gridded runoff simulated by VIC was then routed through the river network by VIC-Res, a water management model that simulates daily river discharge as well as the storage and release dynamics of each hydropower project's reservoir (Dang et al., 2020). The water release for each reservoir was determined by dam-specific rule curves accounting for the reservoir water level, inflow, storage capacity, and downstream water requirements (for irrigation and other purposes). The design specifications of existing and planned reservoirs were retrieved from global reservoir and dam databases (Lehner et al., 2011; Zarfl et al., 2015), and complemented by basin-specific studies on Zambezi (Spalding-Fecher et al., 2014), Congo (Deng et al., 2020), Cunene (Moor et al., 2000), Kwanza (Hamududu and Killingtveit, 2016), Rufiji (Geressu et al., 2020), and Orange (Vonkeman et al., 2019). For more details on methodology and validation, see Chowdhury et al (2022).

To map the reservoir storage areas for each hydropower project, we used the project locations, dam and hydraulic head heights, and a 90 m Digital Elevation Model (DEM) (Lehner et al., 2008). Using Python, for each basin, we first generated a flow accumulation raster and ensured that dam locations are along flow lines. We then generated the reservoirs by filling the DEM sinks and created flow direction and accumulation rasters. We determined the elevation of each project location based on the DEM. We then estimated the reservoir height using the project elevation and the dam height. Using the reservoir height and the filled DEM, we mapped the reservoir area and calculated the reservoir volume as the change between the filled DEM and the reservoir raster. We then validated our estimated reservoir areas against reported existing and potential areas in the literature or through internet search.

To determine the suitability of each proposed hydropower project for each environmental and social scenario, we estimated the amount of mapped reservoir area that could be inundated for the criteria in each scenario (e.g., legal, environmental, social, and environmental plus social exclusions). For example, for the legally protected scenario, we excluded reservoirs that inundated sites with IUCN level I & II protection and sites designated as national parks.

For the Environmental scenario, we also examined whether the proposed dams were on a free flowing river. Using Grill et al. (2019), we identified free flowing rivers (Connectivity Status Index = 1) and classified them into two groups based on river order (determined by long-term average discharge using logarithmic progression)---small rivers were defined as rivers with average discharge < 100 m3/s (Riv_ORD> 4) and large rivers average discharge > 100 m3/s (Riv_ORD≤ 4). We then excluded proposed projects located on large free flowing rivers. To account for potential indirect impact dams and reservoirs have on free-flowing rivers, we also calculated the potential degree of regulation (DOR). DOR is a risk index that represents cumulative storage volumes in upstream reservoirs. We excluded projects that were expected to alter large free flowing rivers downstream (greater than 100 DOR). The screened lists of hydropower projects for each scenario were then fed into the power system planning model as candidate projects.

3.4. Power system planning and impacts

To identify cost-optimal electricity infrastructure investments in the SAPP for each of the scenarios, we used GridPath-SAPP model (Chowdhury et al., 2022), built on the GridPath open-source power system modeling platform (Mileva et al., 2021). Utilizing temporal and spatially-explicit demand, wind, solar, and hydro resource data along with various economic and technical constraints, GridPath's capacity-expansion functionality identifies cost-effective deployment of conventional and renewable generators, storage, and transmission lines by co-optimizing power system operations and infrastructure investments.

The GridPath-SAPP model has 12 load zones, each representing a SAPP member country. These load zones are joined by transmission corridors that have existing, planned, and candidate transmission capacities. We modeled five investment periods---2020, 2025, 2030, 2035, and 2040---each representing 5 years. To account for end effects (costs incurred beyond the model planning time horizon), we also included 2045 as an investment period representing 10 years. The model can build new infrastructure or retire existing infrastructure during an investment period. We assumed a common 7% discount rate for each investment period to calculate the net present value of costs incurred during that period.

Within each investment period, grid infrastructure is dispatched to meet load and other constraints over 24 hours during 12 days, each representing a month, and weighted appropriately to represent a full year. Energy demand and supply is balanced in each modeled hour for each load zone. Hydropower and battery storage energy availability is constrained over each day.

The model co-optimizes investments (over each 5-year period) in new system infrastructure including generation, storage, and transmission, and hourly operating costs, while meeting country-wise hourly electricity demand, technical constraints on generators, storage, and transmission lines, and other policy constraints (e.g., clean energy targets). The model assumes perfect foresight for electricity demand and technology and fuel costs. New generation capacities are selected linearly except for hydropower projects, which are discretely selected (binary decision). Annual capacity build rates for all technologies except for hydropower are not constrained. GridPath is written in Python and uses the Pyomo optimization language (Hart et al., 2011). The Gurobi solver was used for all simulations (Gurobi Optimization, LLC, 2021).

Key inputs to GridPath include projected hourly electricity demand for each investment period, installed and candidate generation capacities, hourly capacity factors of wind and solar generators, monthly energy availability of hydropower projects, and existing capacities and unit investment costs of transmission infrastructure. Hourly time series of electricity demand are based on actual 2018 data linearly extrapolated across investment periods assuming growth rates from the SAPP Plan (SAPP, 2017). Electricity demand is assumed to be inelastic and does not respond to changes in electricity costs. Existing generation capacities---mostly composed of hydropower, coal, and natural gas, with small shares of nuclear, oil, diesel, biomass, wind and solar PV ---are adopted from the SAPP Plan (SAPP, 2017). Installed coal plants are assumed to retire at an age of 55 years.

Candidate coal and gas plants are assumed only in countries with existing capacities of those technologies. Candidate wind and solar capacities and discrete hydro power plants are varied based on scenarios described earlier. Wind, solar, and battery storage costs are from the SAPP Plan (SAPP, 2017) and their trajectories are adopted from the National Renewable Energy Laboratory's Annual Technology Baseline projections (NREL, 2019). Only mid-case trajectories are considered in this study. Coal and natural gas fuel cost projections are from the SAPP Plan. Emission factors for fuels are from the Energy Information Administration (EIA, 2019).

Other techno-economic parameters of the generators including fixed operating and maintenance (O&M) costs, variable O&M costs, heat rates, fuel costs, start-up costs, ramp rates, minimum operating levels, minimum up and down times, capital costs, plant lifetimes, emission per unit generation, storage charging and discharging efficiencies, and transmission losses are adopted from the SAPP Plan (SAPP, 2017), South Africa's Integrated Resource Plan (DOE, 2019), and (Chowdhury et al., 2022). Primary reserve margin (PRM) of 15% over peak demand is imposed as a constraint for new capacity investments. Only dispatchable generation and storage technologies and only 10% of wind capacity can contribute to PRM.

We assumed full coordination among the SAPP countries, with only transmission losses and transfer capacities as constraints to electricity trade. Existing interconnection transfer capacities are adopted from the SAPP (SAPP, 2020a, 2020b). GridPath optimally builds new transmission capacities along existing and planned transmission corridors. Lengths of the interconnectors are estimated using the centroids of countries. Investment costs for new transmission lines and substations are from the Western Electricity Coordinating Council (Black & Veatch, 2019). We assume bulk transmission losses of 1% per 100 miles (Eurek et al., 2016).

Major outputs are new-built capacities of generation, storage, and transmission, hourly electricity dispatch, curtailment, and transmission losses, exports and imports among the countries, operating and investment costs, and CO_2 emissions.

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References

Almeida, R.M., Schmitt, R.J., Castelletti, A., Flecker, A.S., Harou, J.J., Heilpern, S.A., Kittner, N., Mathias Kondolf, G., Opperman, J.J., Shi, Q., Gomes, C.P., McIntyre, P.B., 2022. Strategic planning of hydropower development: balancing benefits and socioenvironmental costs. Curr. Opin. Environ. Sustain. 56, 101175. https://doi.org/10.1016/j.cosust.2022.101175

Almeida, R.M., Shi, Q., Gomes-Selman, J.M., Wu, X., Xue, Y., Angarita, H., Barros, N., Forsberg, B.R., García-Villacorta, R., Hamilton, S.K., Melack, J.M., Montoya, M., Perez, G., Sethi, S.A., Gomes, C.P., Flecker, A.S., 2019. Reducing greenhouse gas emissions of Amazon hydropower with strategic dam planning. Nat. Commun. 10, 4281. https://doi.org/10.1038/s41467-019-12179-5

Ansar, A., Flyvbjerg, B., Budzier, A., Lunn, D., 2014. Should we build more large dams? The actual costs of hydropower megaproject development. Energy Policy 69, 43–56. https://doi.org/10.1016/j.enpol.2013.10.069

Black & Veatch, 2019. WECC 2019 Transmission Capital Cost Tool.

Chowdhury, A.F.M.K., Deshmukh, R., Wu, G.C., Uppal, A., Mileva, A., Curry, T., Armstrong, L., Galelli, S., Ndhlukula, K., 2022. Enabling a low-carbon electricity system for Southern Africa. Joule. https://doi.org/10.1016/j.joule.2022.06.030

Dang, T.D., Chowdhury, A.K., Galelli, S., 2020. On the representation of water reservoir storage and operations in large-scale hydrological models: implications on model parameterization and climate change impact assessments. Hydrol. Earth Syst. Sci. 24, 397–416. https://doi.org/10.5194/hess-24-397-2020

Dashiell, S.L., Buckley, M., Mulvaney, D., 2019. Green Light Study: Economic and Conservation Benefits of Low-Impact Solar Siting in California. The Nature Conservancy.

Deng, C., Song, F., Chen, Z., 2020. Preliminary study on the exploitation plan of the mega hydropower base in the lower reaches of Congo River. Glob. Energy Interconnect. 3, 12–22. https://doi.org/10.1016/j.gloei.2020.03.008

Deshmukh, R., Mileva, A., Wu, G.C., 2018. Renewable energy alternatives to mega hydropower: a case study of Inga 3 for Southern Africa. Environ. Res. Lett. 13, 064020. https://doi.org/10.1088/1748-9326/aabf60

DOE, 2019. Integrated Resource Plan (IRP2019). Department of Energy Republic of South Africa.

EIA, 2019. How much carbon is produced when different fuels are burned? Energy Information Administration.

ESMAP, Solargis, World Bank, 2019. Global Solar Atlas 2.0. World Bank.

Eurek, K., Cole, W., Bielen, D., Blair, N., Cohen, S., Frew, B., Ho, J., Krishnan, V., Mai, T., Sigrin, B., Steinberg, D., 2016. Regional Energy Deployment System (ReEDS) Model Documentation: version 2016. National Renewable Energy Laboratory (NREL), 15013 Denver West Parkway Golden, CO 80401, U.S.

Fan, P., Cho, M.S., Lin, Z., Ouyang, Z., Qi, J., Chen, J., Moran, E.F., 2022. Recently constructed hydropower dams were associated with reduced economic production, population, and greenness in nearby areas. Proc. Natl. Acad. Sci. 119, e2108038119. https://doi.org/10.1073/pnas.2108038119

Flecker, A.S., Shi, Q., Almeida, R.M., Angarita, H., Gomes-Selman, J.M., García-Villacorta, R., Sethi, S.A., Thomas, S.A., Poff, N.L., Forsberg, B.R.,

Heilpern, S.A., Hamilton, S.K., Abad, J.D., Anderson, E.P., Barros, N., Bernal, I.C., Bernstein, R., Cañas, C.M., Dangles, O., Encalada, A.C., Fleischmann, A.S., Goulding, M., Higgins, J., Jézéquel, C., Larson, E.I., McIntyre, P.B., Melack, J.M., Montoya, M., Oberdorff, T., Paiva, R., Perez, G., Rappazzo, B.H., Steinschneider, S., Torres, S., Varese, M., Walter, M.T., Wu, X., Xue, Y., Zapata-Ríos, X.E., Gomes, C.P., 2022. Reducing adverse impacts of Amazon hydropower expansion. Science 375, 753–760. https://doi.org/10.1126/science.abj4017
Geressu, R., Siderius, C., Harou, J.J., Kashaigili, J., Pettinotti, L., Conway, D., 2020. Assessing River Basin Development Given Water-Energy-Food-Environment Interdependencies. Earths Future 8, e2019EF001464. https://doi.org/10.1029/2019EF001464
Gernaat, D.E.H.J., Bogaart, P.W., Vuuren, D.P. van, Biemans, H., Niessink, R., 2017. High-resolution assessment of global technical and economic hydropower potential. Nat. Energy 2, 821–828. https://doi.org/10.1038/s41560-017-0006-y
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, M.E., Meng, J., Mulligan, M., Nilsson, C., Olden, J.D., Opperman, J.J., Petry, P., Reidy Liermann, C., Sáenz, L., Salinas-Rodríguez, S., Schelle, P., Schmitt, R.J.P., Snider, J., Tan, F., Tockner, K., Valdujo, P.H., van Soesbergen, A., Zarfl, C., 2019. Mapping the world's free-flowing rivers. Nature 569, 215–221. https://doi.org/10.1038/s41586-019-1111-9
Gurobi Optimization, LLC, 2021. Gurobi Optimizer Reference Manual.
Hamududu, B.H., Killingtveit, A., 2016. Hydropower Production in Future Climate Scenarios: The Case for Kwanza River, Angola. Energies 9. https://doi.org/10.3390/en9050363
Hart, W.E., Paul, W.J., David, L.W., 2011. Pyomo: Modeling and Solving Mathematical Programs in Python. Math. Program. Comput. 3, 219–260.
Hennig, T.A., Kretsch, J.L., Pessagno, C.J., Salamonowicz, P.H., Stein, W.L., Westort, C.Y., 2001. The Shuttle Radar Topography Mission, Digital Earth Moving. National Aeronautics and Space Administration (NASA), Berlin, Heidelberg.
Hurford, A.P., McCartney, M.P., Harou, J.J., Dalton, J., Smith, D.M., Odada, E., 2020. Balancing services from built and natural assets via river basin trade-off analysis. Ecosyst. Serv. 45, 101144. https://doi.org/10.1016/j.ecoser.2020.101144
IRENA, 2017. Planning for the renewable future: Long-term modelling and tools to expand variable renewable power in emerging economies 136.
Lehner, B., Liermann, C.R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., others, 2011. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Front. Ecol. Environ. 9, 494–502.
Lehner, B., Verdin, K., Jarvis, A., 2008. New Global Hydrography Derived From Spaceborne Elevation Data. Eos Trans. Am. Geophys. Union 89, 93–94. https://doi.org/10.1029/2008EO100001
Mileva, A., De Moor, G., Deshmukh, R., 2021. GridPath.
Mitchell, C., 2016. Momentum is increasing towards a flexible electricity system based on renewables. Nat. Energy 1, 15030. https://doi.org/10.1038/nenergy.2015.30
Moor, F. de, Barber-James, H.M., Harrison, A.D., Lugo-Ortiz, C.R., 2000. The

macroinvertebrates of the Cunene River from the Ruacana Falls to the river mouth and assessment of the conservation status of the river. Afr. J. Aquat. Sci. 25, 105–122. https://doi.org/10.2989/160859100780177857
Moran, E.F., Lopez, M.C., Moore, N., Müller, N., Hyndman, D.W., 2018. Sustainable hydropower in the 21st century. Proc. Natl. Acad. Sci. 115, 11891–11898. https://doi.org/10.1073/pnas.1809426115
Mulvaney, D., 2017. Identifying the roots of Green Civil War over utility-scale solar energy projects on public lands across the American Southwest. J. Land Use Sci. 12, 493–515. https://doi.org/10.1080/1747423X.2017.1379566
Muñoz Sabater, J., 2019. ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS).
NREL, 2019. Annual Technology Baseline (ATB) Data 2019. National Renewable Energy Laboratory (NREL).
NREL, 2016a. System Advisor Model (SAM). National Renewable Energy Laboratory.
NREL, 2016b. National Solar Radiation Database. National Renewable Energy Laboratory.
Opperman, J., Grill, G., Hartmann, J., 2015. The Power of Rivers: Finding balance between energy and conservation in hydropower development. The Nature Conservancy.
Opperman, J.J., Baruch-Mordo, S., Carvallo, J.P., Kammen, D., Kiesecker, J., Weber, C., 2019. Sustaining the Last Rivers: The renewable revolution could keep dams off the world’s remaining free-flowing rivers. Am. Sci. 107, 302–306.
Rand, J., Hoen, B., 2017. Thirty years of North American wind energy acceptance research: What have we learned? Energy Res. Soc. Sci. 29, 135–148. https://doi.org/10.1016/j.erss.2017.05.019
Reuter, H.I., Nelson, A., Jarvis, A., 2007. An evaluation of void filling interpolation methods for SRTM data. Int. J. Geogr. Inf. Sci. 21, 983–1008.
Richter, B.D., Postel, S., Revenga, C., Scudder, T., Lehner, B., Churchill, A., Chow, M., 2010. Lost in development’s shadow: The downstream human consequences of dams. Water Altern. 3, 14.
SAPP, 2020a. Transfer limits. Southern African Power Pool (SAPP).
SAPP, 2020b. Interconnectors. Southern African Power Pool (SAPP).
SAPP, 2017. SAPP Pool Plan 2017. Southern African Power Pool (SAPP), 24 Golden Stairs Road, EmeraldHill, Harare, Zimbabwe.
Schmitt, R.J.P., Bizzi, S., Castelletti, A., Kondolf, G.M., 2018. Improved trade-offs of hydropower and sand connectivity by strategic dam planning in the Mekong. Nat. Sustain. 1, 96–104. https://doi.org/10.1038/s41893-018-0022-3
Schmitt, R.J.P., Kittner, N., Kondolf, G.M., Kammen, D.M., 2021. Joint strategic energy and river basin planning to reduce dam impacts on rivers in Myanmar. Environ. Res. Lett. 16, 054054. https://doi.org/10.1088/1748-9326/abe329
Siala, K., Chowdhury, A.K., Dang, T., Galelli, S., 2021. Solar energy and regional coordination as a feasible alternative to large hydropower in Southeast Asia. Nat. Commun. 12.
Sovacool, B.K., Ali, S.H., Bazilian, M., Radley, B., Nemery, B., Okatz, J., Mulvaney, D., 2020. Sustainable minerals and metals for a low-carbon future. Science 367, 30–33. https://doi.org/10.1126/science.aaz6003

Sovacool, B.K., Gilbert, A., Nugent, D., 2014. An international comparative assessment of construction cost overruns for electricity infrastructure. Energy Res. Soc. Sci. 3, 152–160. https://doi.org/10.1016/j.erss.2014.07.016
Spalding-Fecher, R., Yamba, F., Walimwipi, H., Kling, H., Tembo, B., Nyambe, I., Chapman, A., Cuamba, B., 2014. Water supply and demand scenarios for the Zambezi river basin – climate change and upstream development impacts on new hydropower projects in the Zambezi project, Report for Climate and Development Knowledge Network. University of Cape Town.
Sterl, S., Vanderkelen, I., Chawanda, C.J., Russo, D., Brecha, R.J., van Griensven, A., van Lipzig, N.P.M., Thiery, W., 2020. Smart renewable electricity portfolios in West Africa. Nat. Sustain. 3, 710–719. https://doi.org/10.1038/s41893-020-0539-0
Susskind, L., Chun, J., Gant, A., Hodgkins, C., Cohen, J., Lohmar, S., 2022. Sources of opposition to renewable energy projects in the United States. Energy Policy 165, 112922. https://doi.org/10.1016/j.enpol.2022.112922
Technical University of Denmark (DTU), World Bank, Energy Sector Management Assistance Program (ESMAP), 2019. Global Wind Atlas 3.0. World Bank.
Thieme, M.L., Tickner, D., Grill, G., Carvallo, J.P., Goichot, M., Hartmann, J., Higgins, J., Lehner, B., Mulligan, M., Nilsson, C., Tockner, K., Zarfl, C., Opperman, J., 2021. Navigating trade-offs between dams and river conservation. Glob. Sustain. 4. https://doi.org/10.1017/sus.2021.15
Vonkeman, J.K., Bosman, D.E., Basson, G.R., 2019. Investigation of the impacts of the proposed Noordoewer Vioolsdrift dam on the Orange river estuary in Namibia and South Africa. Department of Civil Engineering, Stellenbosch University, Stellenbosch 7600, South Africa.
Waldman, J., Sharma, S., Afshari, S., Fekete, B., 2019. Solar-power replacement as a solution for hydropower foregone in US dam removals. Nat. Sustain. 2, 872–878. https://doi.org/10.1038/s41893-019-0362-7
Wu, G.C., Deshmukh, R., Ndhlukula, K., Radojicic, T., Reilly-Moman, J., Phadke, A., Kammen, D.M., Callaway, D.S., 2017. Strategic siting and regional grid interconnections key to low-carbon futures in African countries. Proc. Natl. Acad. Sci. 114, E3004–E3012. https://doi.org/10.1073/pnas.1611845114
Wu, G.C., Leslie, E., Sawyerr, O., Cameron, D.R., Brand, E., Cohen, B., Allen, D., Ochoa, M., Olson, A., 2020. Low-impact land use pathways to deep decarbonization of electricity. Environ. Res. Lett. 15, 074044. https://doi.org/10.1088/1748-9326/ab87d1
Zarfl, C., Lumsdon, A.E., Berlekamp, J., Tydecks, L., Tockner, K., 2015. A global boom in hydropower dam construction. Aquat. Sci. 77, 161–170. https://doi.org/10.1007/s00027-014-0377-0
Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I., Levin, S.A., 2012. Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. Proc. Natl. Acad. Sci. 109, 5609–5614.

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