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Beyond Water: Global Hydropower Futures Shaped by Interacting Hydrological and Socio-Technical Drivers

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Abstract

Hydropower is among the most consequential large-scale interventions in the water cycle, reshaping the world's river systems while supplying a substantial share of global electricity. Projections of future hydropower generation are therefore critical for water–energy planning, yet existing approaches either emphasize hydroclimatic variability or broader socio-economic-technological drivers, rarely capturing their interactions. As a result, complex interacting pathways underlying hydropower expansion remain poorly understood. We address this gap by representing multiple drivers and their interactions within a global multi-sector modeling framework. Our results show that hydropower futures emerge from distinct combinations, including electricity demand, carbon intensity pathways, and technology costs, rather than any single dominant driver. Hydrologic conditions shape regional hydropower outcomes but do not independently determine long-term expansion pathways, though their influence grows in extreme expansion scenarios later in the century. Our work provides a first step toward integrating river systems into global-scale energy and sustainability planning and decision-making.

Introduction

Hydropower occupies a unique position at the intersection of freshwater and energy systems, simultaneously reshaping riverine environments (flow regimes, sediment transport, ecosystems) [1,2] while contributing a substantial share of electricity generation and system flexibility [3–5]. Although it is a mature technology, its future remains deeply uncertain, with the potential for substantial expansion in regions characterized by rapid population and economic growth and ecologically sensitive river systems [1,6]. Projections of hydropower development therefore play a critical role in informing infrastructure investment, ecosystem and water management, and long-term energy planning [7]. Yet these projections are produced by disparate modeling communities using fundamentally different approaches: basin-scale studies emphasize hydroclimatic variability but neglect broader socio-economic-technological (SET) drivers [8], while global energy-system models capture SET change but frequently lack explicit representation of hydrologic constraints [9,10]. This is problematic because recent studies show that regional water systems are influenced not only by local hydroclimatic conditions but also by broader SET dynamics, with trans-basin drivers often exceeding the influence of local hydrologic variability [11,12]. Despite a vast body of hydropower research, existing projections rarely resolve how these interacting drivers jointly shape hydropower outcomes across scales. No internally consistent framework currently exists to support such analysis, limiting the interpretability and utility of current projections for both global assessments and regional decision-making.

Water resources and hydropower planning have traditionally been conceptualized as a water supply problem best studied at the river-basin scale [13]. Hydropower planning is no exception, with most research focused on regional systems confronting hydroclimatic uncertainty [14–18]. Basin-scale and water-energy nexus studies, including those coupling hydrologic and power system models [19,20], can improve representation of cross-sector interactions but are typically limited to regional scales and continue to emphasize hydroclimatic conditions as the primary determinant of hydropower outcomes.

Conversely, global multi-sector models, such as Integrated Assessment Models (IAMs), explicitly represent SET drivers and broad energy-water-land interactions [21–25], but often treat hydropower in simplified or exogenous ways and lack detailed representation of basin-scale hydrology and hydroclimatic uncertainty [26–28]. Taken together, these approaches do not provide a mechanistic representation of hydropower development that links basin-scale hydrology with endogenous infrastructure expansion. As a result, they cannot resolve how interacting hydrologic and socio-economic drivers shape outcomes across scales or provide a consistent basis for regional planning and cross-scale sustainability analyses. Nor do they support systematic attribution of hydropower outcomes to specific drivers or combinations of interacting factors.

We address these gaps by developing an integrated framework that couples basin-scale hydrology with the Global Change Analysis Model (GCAM) to generate a large, internally consistent ensemble of 2,160 future hydropower scenarios. Building on recent advances in representing basin-scale hydropower production within global models [6], our approach explicitly captures interactions among hydrology, socio-economic conditions, energy systems, and technology costs, systematically sampling multiple interacting drivers across these domains and propagating uncertainty through the system. Using machine-learning-based scenario discovery, we attribute hydropower outcomes to specific drivers and their combinations. Our results show that hydropower futures are shaped by multiple interacting drivers, not hydrology alone, with socio-economic and energy system factors often playing a dominant role particularly in regions where hydropower expansion is most pronounced such as parts of the Global South. Hydrologic conditions remain critical in constraining regional variability and limits to development, but do not by themselves determine long-term expansion pathways. These outcomes arise from distinct combinations of interacting drivers, rather than single dominant factors, enabling systematic identification of the conditions under which hydropower expansion is amplified, constrained, or displaced. Ultimately, by linking basin-scale freshwater systems to global dynamics, this work enables regional decision-making to be informed by global drivers while quantifying tradeoffs with other sustainability objectives. In doing so, it supports the integration of rivers into global energy and sustainability decision-making.

Results

2.1 Hydropower Futures Considering Human and Earth Systems Interactions

We develop a new class of global hydropower projections that expands the range of plausible futures beyond existing ensemble products (Figure 1). Our global-scale ensemble, among the most extensive reported to date, integrates hydrology, SET development, and energy system dynamics within a unified framework, enabling exploration of a substantially wider range of drivers and outcomes than commonly used projections [9,10] (Figures S4–S6). This expanded outcome space reveals substantial uncertainty in future hydropower deployment, as well as significant potential for expansion across many regions, with important implications for infrastructure investment, ecosystem impacts, and energy system evolution. Critically, the breadth and structure of this outcome space indicate that hydropower futures

are shaped by interacting drivers, motivating subsequent analysis of the factors and combinations that give rise to divergent trajectories (Sections 2.2 and 2.3).

Global Trends. Global hydropower generation increases across nearly all scenarios (Figure 1a), with a wide and expanding range of outcomes, while its share of total electricity generation exhibits a consistent tendency to remain stable or decline across scenarios (Figure 1b). In most scenarios (65%), generation increases while share declines, indicating that electricity demand and alternative generation technologies (e.g., solar and wind) expand faster than hydropower; in fewer scenarios, shares remain stable (31%) or increase (5%), reflecting conditions under which hydropower maintains or expands its relative importance. These patterns emerge from the combined influence of multiple interacting drivers spanning socio-economic development, energy system transformation, and hydroclimatic variability. Across the ensemble, hydropower generation increases from approximately 14.7 EJ in 2020 to between 17.1 EJ (16% increase) and 42.2 EJ (187% increase) by 2050, with an even wider divergence by 2100, corresponding to increases on the order of ~30–270% relative to present-day levels. To place this expansion in physical terms, using a global inventory of approximately 7,100 dams with hydropower as their primary purpose (GDAT) as a baseline, this range is equivalent to on the order of 1,000-12,000 additional hydropower dams by mid-century and 2,000-20,000 by 2100, assuming approximate scaling between generation and the existing hydropower fleet. In contrast, hydropower's share of global electricity, while also variable, reflects its role within a rapidly evolving energy system, spanning a factor of three by 2100 (5.7% to 16.5%), consistent with earlier projections of long-term declining hydropower share driven by demand growth, rising marginal costs and limits to further deployment, and advances in alternative technologies [4,29]. This range indicates that although declining shares are most common, hydropower can still account for a substantial portion of global electricity generation in some futures, approaching one-sixth of total supply.

Regional Trends. While global projections reveal broad patterns, regional hydropower futures are highly heterogeneous in both the timing and extent of expansion (Figures 1c and 1d). Although most regions follow the global tendency of increasing generation alongside stable or declining shares, distinct regional trajectories emerge. For example, China and Africa are projected to become the two largest hydropower-producing regions by 2100, together accounting for approximately 49% of global hydropower generation (median across scenarios), but their development pathways are shaped by distinct combinations of socio-economic, energy system, and carbon intensity drivers. In China, expansion occurs primarily before 2050, associated with rising demand and carbon-intensive generation reductions (Figure S7), while in Africa, expansion is concentrated in the latter half of the century, driven by rapid GDP growth and increasing electricity demand after 2050 (Figure S8). These differences also translate into contrasting roles for hydropower within regional energy systems, with shares increasing in China due to declining electricity demand and moderate hydropower expansion but declining in Africa as electricity generation from other sources grows more rapidly. More broadly, three patterns emerge in regional hydropower share trajectories from mid-century to 2100 (Figure 1d): increasing shares (e.g., China, Russia, Other OECD), decreasing shares (e.g., Africa, Latin America and the Caribbean), and relatively constant shares (e.g., India, Other Asia, Middle East, Europe, and the USA). These patterns

reflect differences in regional energy system dynamics, particularly the balance between hydropower expansion and overall electricity demand (Figure S9). However, these diverse regional patterns arise from interacting drivers whose individual and combined influences cannot be inferred from descriptive trends alone, motivating a systematic analysis to identify the conditions and driver combinations that lead to divergent hydropower outcomes.

2.2. Key Drivers of Future Global and Regional Hydropower Generation

To explain the global and regional patterns identified in Section 2.1, we systematically analyze the drivers of hydropower outcomes across the ensemble using machine-learning-based regression trees. At the global scale, four factors consistently emerge as dominant drivers of hydropower generation in both 2050 and 2100: socioeconomic-driven electricity demand, future scenarios with lower and higher relative carbon-intensive generation globally, the cost of combining fossil and biomass energy use with carbon capture, utilization, and storage (CCUS), and the cost of variable renewable energy (VRE) (Figure 2). These results highlight that future hydropower deployment is strongly coupled with broader energy system dynamics, rather than being determined by hydrologic conditions alone. Note that these scenarios should not be interpreted as predictive or as representing any specific policies but are intended as exploratory for providing quantitative insights into a range of drivers that underscore the connections between future global hydropower deployment and global energy systems evolution.

In contrast to the global picture, the drivers of regional hydropower generation are highly heterogeneous across space and time. By 2050, hydropower outcomes in many regions are primarily shaped by carbon intensity pathways and CCUS costs (Figure 2a), with their combined influence reaching as high as 79% of total importance in China. This indicates that near-term hydropower deployment is closely tied to decarbonization strategies, with both carbon intensity pathways and CCUS costs jointly shaping the extent of hydropower expansion across scenarios. By 2100, however, a more diverse set of drivers emerges (Figure 2b). In regions such as Africa and the United States, hydropower generation becomes increasingly influenced by socioeconomic-driven electricity demand, reflecting large uncertainties in future population and economic growth (Figures S11–S12). In contrast, hydroclimatic variability becomes more important in regions such as Latin America and India, where projected streamflow changes introduce substantial uncertainty in hydropower potential.

While our results are consistent with the importance of several drivers identified in prior studies [30,16,31], they also highlight the influence of a broader set of interacting factors across regions and scenarios. For example, although previous work emphasizes the role of declining renewable energy costs in regions such as Africa [31], our results show that socioeconomic trajectories and CCUS costs can also exert strong influences on hydropower generation. These findings motivate a more systematic analysis of how specific combinations of drivers give rise to distinct hydropower outcomes, particularly in scenarios with high levels of deployment.

2.3. Combination of Drivers of High Hydropower Expansion Scenarios

Scenarios with high hydropower deployment are of particular interest because they reveal potential risks and opportunities across socio-environmental, economic, power system, and water resource dimensions, including tradeoffs between ecological impacts and benefits such as grid stability and multi-purpose reservoir management (e.g., irrigation and flood control). To identify the conditions under which such outcomes emerge, we analyze scenarios exceeding the 90th percentile of global hydropower generation or share. Across the ensemble, over 75% of high global generation scenarios are associated with a common combination of drivers: higher VRE costs, very high electricity demand (SSP5), and a higher preference towards less carbon-intensive generation (decreasing carbon scenarios) (Figure 3a). In these cases, hydropower expands to meet growing demand while remaining competitive relative to alternative technologies, particularly when VRE and CCUS costs remain high. A smaller subset of high-generation scenarios (approximately 25%) instead arises under moderate demand growth (SSP2) combined with higher CCUS costs, further underscoring the role of technological cost constraints in driving hydropower expansion. Although similar technology cost assumptions underpin both high-generation and high-share outcomes (Figure 3b), the dominant socioeconomic drivers differ: high generation is associated with high demand (SSP5), whereas high shares more frequently occur under low demand growth (SSP3), indicating that the same system yields different driver combinations depending on whether outcomes are measured in absolute or relative terms. Together, these results show that high hydropower outcomes are not driven by any single factor, but instead emerge from distinct combinations of demand, technology costs, and carbon intensity pathways.

Regional high hydropower expansion arises from different driver combinations than those identified at the global scale. In regions such as Africa and Latin America and the Caribbean, hydroclimatic impacts on exploitable hydropower potential emerge as key drivers of high deployment scenarios (Figure 4), reflecting both substantial resource availability and large variability across streamflow projections (Figure S13). In contrast to the global results where energy system and demand-side drivers dominate, regional high-expansion scenarios depend more strongly on local hydroclimatic conditions. These results indicate that the most extreme hydropower expansion scenarios are governed by distinct combinations of global and regional drivers, with hydroclimatic variability playing a critical role in shaping upper-bound deployment even when it is not the dominant driver of overall trends.

Conclusion and Discussion

Hydropower is poised to play a critical role in future energy systems as economies shift towards renewable energy, while also shaping the sustainability of freshwater ecosystems. Projections of future hydropower development are important to water and energy planners, policymakers, and scientists studying the ecological, economic, and societal impacts of human intervention in freshwater systems.

This study represents, to our knowledge, the largest internally consistent ensemble of future hydropower projections assembled to date. By using a unified water-energy-economic modeling framework, our projections capture critical interactions between sectors and across regions, connecting basin-level impacts to global drivers. The ensemble spans both global socioeconomic and technological

uncertainties often neglected in water resources research and basin-scale hydrologic processes often absent from global energy-economic analyses, helping to bridge a long-standing gap between these communities.

While there is significant uncertainty, our results show that across a wide range of futures, hydropower is expected to expand substantially, even as its share of overall generation may fall (Figures 1a and 1b). Much of this projected expansion is concentrated in ecologically sensitive basins that have historically remained relatively undeveloped [1], raising significant concerns about tradeoffs between energy development and riverine ecosystem integrity. At the same time, much of this expansion is located in developing regions, particularly in Africa (Figure 1c), where increased access to electricity can support economic growth and improved living standards. These findings underscore the importance of evaluating hydropower expansion within a broader socio-economic and technological context, as too narrow a sectoral focus can lead to unintended consequences in planning and scientific analyses [32]. Exploratory modeling approaches are well suited to testing a wide range of futures and identifying unexpected outcomes and their underlying drivers.

Recent assessments by organizations such as the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), and International Hydropower Association (IHA) have suggested that global hydropower capacity may need to approximately double by 2050. Our results are broadly consistent with this range but also demonstrate that both substantially lower and higher levels of expansion are possible. More importantly, this work advances the global dialogue on hydropower expansion by explicitly linking underlying drivers to resulting outcomes, rather than presenting projections without context on the conditions under which expansion occurs. This perspective highlights when such targets may or may not be realized, particularly in futures where competing technologies or slower demand growth reduce the need for hydropower development, or alternatively where rapid growth and limited alternatives increase pressure on river systems.

The leading drivers of global hydropower uncertainty are concentrated in the energy sector (Figure 2), including demand-side drivers (e.g., socioeconomics) and factors affecting the relative competitiveness of hydropower (e.g., efforts to reduce carbon-intensive generation, costs of competing technologies, etc.). Projections omitting these drivers may be missing critical dynamics. However, global-scale analyses can mask important regional heterogeneity: for example, uncertainty in Africa's hydropower expansion is driven predominantly by socioeconomics, while China's is driven primarily by carbon intensive generation reductions. Yet no single set of assumptions results in high hydropower expansion everywhere, and no driver is most important in all regions. Our ensemble allows planners and scientists to focus efforts on the most important factors in a given region and to construct scenarios tied to consequences of interest.

Hydroclimatic impacts on hydropower are linked to consequential, extreme outcomes in many regions. Ensemble-average feature importance can mask a driver's role in the outcomes of most interest to planners and scientists: hydroclimatic drivers have relatively little overall impact on hydropower

expansion in Africa (Figure 3b), but every scenario with high hydropower deployment corresponds to increasing streamflow (Figure 4a). Critically, these extreme outcomes emerge from the interplay of hydrology and energy systems. Many futures resulting in high hydropower share in Latin America correspond to increasing carbon intensity scenarios, because those scenarios are associated with lower electrification in the economy (Figure 4b). Therefore, in Latin America, high hydropower shares do not necessarily indicate large hydropower deployment but instead reflect lower levels of electrification that amplify its relative contribution. Together, these findings reinforce that the most consequential hydropower outcomes cannot be understood without jointly considering hydrology and socio-economic-technological dynamics.

Hydropower will remain a critical energy resource for the foreseeable future, but its expansion also poses increasing risks to riverine ecosystems in previously undeveloped basins. Projections are therefore an essential input for planners and scientists to navigate this tradeoff. Because we use an integrated modeling framework consistent with widely used scenario products [33] and sustainability analyses (e.g., SDGs), the resulting ensemble can be readily incorporated into existing workflows. More broadly, the impact of rivers remain under-studied in global change and sustainability analyses and discussions, in part because the models and scales used to study them are often misaligned with those used in other sectors. This work helps address this gap by linking basin-scale processes to global multi-system dynamics.

Future research should focus on improving representation of hydropower systems, refining constraints on expansion, and exploring alternative energy system development pathways. A key priority is to evaluate how estimates of exploitable hydropower potential, including datasets that aim to represent more environmentally plausible potential [34], shape projected expansion and whether additional restrictions substantially alter the range of futures identified here. Expanding the ensemble to include additional energy system uncertainties will further clarify hydropower's role in evolving energy systems. This includes large-scale nuclear deployment [35], which could trade off with hydropower in supplying firm generation, and the growing role of pumped storage [36], which may shift hydropower's contribution toward flexibility rather than generation. Another promising next step is to couple our ensemble outputs with power system models such as GridPath [37,38] or PyPSA to assess grid operations, flexibility, and reliability under different hydropower deployment pathways. Additional work is also needed to represent long-term infrastructural changes, including reservoir sedimentation and hydroclimatic extremes such as drought, which affect both generation and the financial viability of dams (e.g., through debt-service risk), as well as other water-dependent technologies such as thermal and nuclear power. Finally, exploring alternative pathways, such as repowering irrigation dams, improving the performance of existing dams, expanding regional grid integration, or substituting other technologies where appropriate, will enable a more comprehensive assessment of hydropower's future role beyond conventional capacity expansion.

Methods

4.1 Global Change Analysis Model (GCAM)

We use the Global Change Analysis Model (GCAM), a subclass of integrated assessment model (i.e., global, integrated multi-sector models) that simulates the interactions and dynamics of the energy, water, agriculture and land use, economy, and the Earth system [24]. GCAM divides the world into 32 geopolitical regions, 235 water basins, and 384 land-use regions and solves for annual time steps at 5-year intervals from 2015 to 2100. GCAM uses a logit-based choice model to determine market share between competing technologies (e.g., electricity from hydropower vs. solar) based on the relative cost or choice preference of the technologies [39,40]. Ultimately, GCAM yields an equilibrium price for each commodity at which supply matches demand for each time step. Due to its ability to model the interactions across sectors, GCAM has been widely adopted in multiple regional and global studies with broad research initiatives [41,39,40,11,12].

Specifically, we use the GCAM model in which the endogenous hydropower module is implemented globally [42,1] to explore the evolving role of hydropower in response to multiple human-Earth system drivers. This implementation enables hydropower to compete with other sources of electricity generation (e.g., coal, gas, wind, geothermal, and bioenergy), facilitating the exploration of hydropower's interaction with diverse energy sources. For instance, demand for hydropower increases under scenarios with high variable renewable energy (VRE) costs as hydropower becomes an economically competitive option. For our analysis, we consider (1) hydropower generation (EJ), which indicates its absolute contribution to meeting electricity demand, and (2) hydropower share (%), which indicates its relative role in the broader energy system supplementing other energy sources. Together, hydropower generation and share provide a complementary perspective on how hydropower contributes to the broader energy mix. For more details on how the endogenous hydropower module is implemented in GCAM, the reader is referred to [43,42].

4.2 Scenario Ensemble Design

To understand how multiple human and Earth system drivers jointly influence future hydropower outcomes across scales, we sample eight drivers from three broader categories: (1) Carbon intensity and energy technology, (2) socioeconomics and demand, and (3) hydroclimatic impacts on hydropower (Table 1).

Table 1. Description of eight drivers included in the scenario ensemble generation.

Category	Driver Name	Discrete cases modeled
Carbon Intensity and Energy Technology	Carbon Intensity Scenarios	Increasing Carbon, Decreasing Carbon until 2050
	Cost of Carbon Capture, Utilization, and Storage (CCUS)	Lower costs, Higher costs
	Cost of Variable Renewable Energy (VRE)	Lower costs, Higher costs
Socioeconomics and Demand	Socioeconomics	Medium growth (e.g., SSP2), Low growth (e.g., SSP3), High growth (e.g., SSP5)
	Building Energy Demand	Lower demand, Higher demand
	Transportation Energy Demand	Lower demand, Higher demand
Hydroclimatic Impacts on Hydropower	Exploitable Hydropower Potential	30 projections based on 10 Earth System Models (ESM) and 3 SSP-Representative Concentration Pathways (RCP) scenarios [44,45]
	Hydropower Capacity Factor	

From the carbon intensity and energy technology category, we first include an ‘increasing carbon’ scenario (i.e., a reference case with continued growth in fossil fuel use) and a ‘decreasing carbon’ scenario in which global net carbon intensity is zero by 2050. We do not evaluate the likelihoods of these scenarios but instead use them to illustrate findings on future hydropower outcomes across a range of possible futures. For energy technology costs, we consider low and high costs of carbon capture, utilization, and storage (CCUS), and reference and low costs for variable renewable energy (VRE) (i.e., lower costs for solar, wind, and geothermal technologies following the Annual Technology Baseline 2021 ‘Advanced’ case in [46]). Because earth system impacts on VRE have been proven relatively insignificant in previous studies [47], we do not explicitly model its impact in this study. The socioeconomics and demand category includes socioeconomics (i.e., population and gross domestic product projections consistent with the Shared Socioeconomic Pathway (SSP) scenarios from [48]) and low and high energy demands for buildings and transportation sectors [49]. For the socioeconomic scenario, we include three possible growth projections: low growth (SSP3; 12.7 billion people with GDP per capita of $12,092 in 2100), medium growth (SSP2; 9 billion people with GDP per capita of $33,307 in 2100), and high growth (SSP5; 7.4 billion people with GDP per capita of $83,496 in 2100) [48]. Finally, for the hydroclimatic impacts on hydropower category, we consider 30 streamflow projections from the Inter-Sectoral Impact Model Intercomparison Project 3b (ISIMIP3b)’s downscaled and bias-corrected data [45]. The projections are simulated through Xanthos [50], an open-source hydrologic model that serves as the main freshwater supply component in GCAM. We consider the naturalized streamflow projections from 10 Coupled Model Intercomparison Project phase 6 Earth System Models (ESMs) coupled with 3 SSP-RCP scenarios (e.g., SSP1-2.6, SSP3-7.0, and SSP5-8.5) [45].

The current endogenous hydropower module in GCAM uses exploitable potential [44] to model future hydropower expansion, with assumptions of capacity factors [51] based on historical hydropower production and installed capacity (Figure 5a). In this study, we adopt the definition of exploitable hydropower potential from [42,44], where the potential from protected and urban lands is excluded. Therefore, exploitable hydropower potential is defined as the maximum potential that could be exploited excluding potential in environmentally protected and urban areas. Hydropower capacity factor is defined as the ratio of hydropower generation if the plant operated at full installed capacity at all times in a given land-use region [42]. We project hydroclimatic impacts on future hydropower exploitable potential and capacity factor using streamflow projections [45], in alignment with previous studies [52,53] (Figure 5b). Ultimately, we generate a 2,160-scenario ensemble of future hydropower outcomes by varying eight human and Earth system drivers from three broader categories (Figure 5c).

4.3 Classification and Regression Trees

We apply scenario discovery [54] to identify each factor's relative contribution to hydropower outcomes and the combination of factors leading to the scenarios of interest. In addition to large ensemble simulation outcomes, scenario discovery often utilizes machine learning-based algorithms to compute the relative importance of factors contributing to the scenarios of interest. Common tools adopted during this process include logistic regression [55], patient rule induction method [56], and classification and regression tree (CART) [11,40,41]. Among these algorithms, we adopt CART during scenario discovery due to its wide applicability and high interpretability of outcomes.

Specifically, we utilize the R package *randomForest* [57] to fit regression trees, and *rpart* [58] to fit classification trees to outcomes. Whereas the regression trees quantify each factor's relative contribution to the outcome (i.e., factor prioritization), classification trees identify which combination of the parameters leads to high hydropower outcomes (i.e., factor mapping). For regression trees, we compute each parameter's relative importance by the average increase in node purity across 500 trees. We use classification trees to identify the pathways leading to high global and regional hydropower expansion scenarios. We demonstrate the results from the classification trees through coverage, which represents the percentage of total high expansion scenarios falling into the specific branch. Through scenario discovery, we aim to uncover the narratives in future hydropower outcomes in response to human and Earth system drivers.

Declarations

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Data Availability Statement

The data that supports the findings of this study are openly available. Data and code used to reproduce the figures in this study are available at [59]. GCAMv5.3 is available at https://github.com/JGCRI/gcam-core/releases/tag/gcam-v5.3, and the version with the endogenous hydropower module is available at [6].

Supplementary Data

Supplementary Data is in a separate file.

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Figures

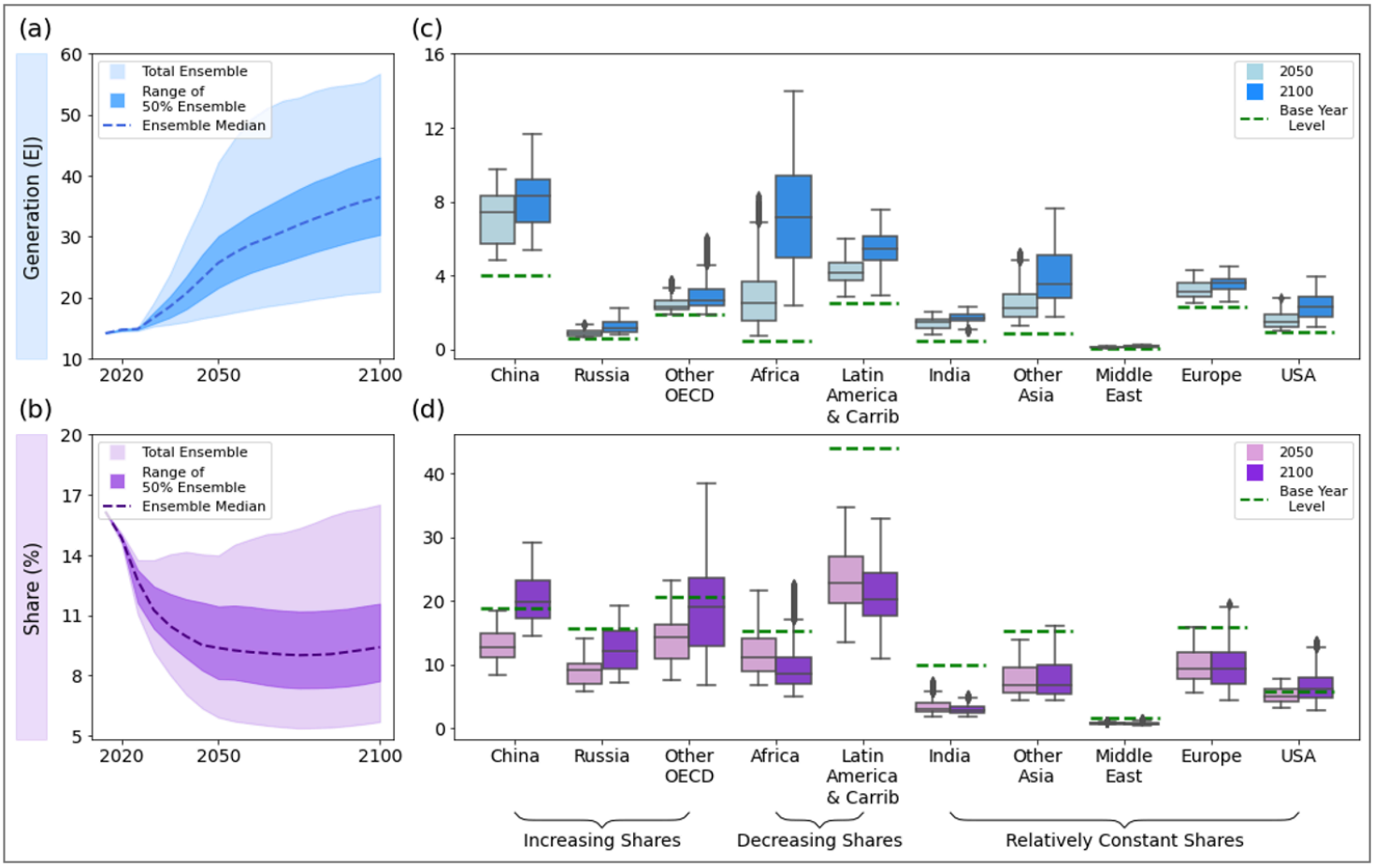


Figure 1

Projections of (a) global hydropower generation and (b) global hydropower shares over the 21st century across the full scenario ensemble, alongside (c) regional hydropower generation and (d) regionalhydropower share for 2050 and 2100. In panels (a) and (b), shaded bands represent the interquartile range (dark shading) and the full ensemble range (light shading) with the dashed line indicating the median projection. Hydropower generation represents its absolute contribution to electricity supply, whereas its share reflects its relative role in the energy mix; scenarios in which generation increases but share declines indicate that electricity demand and alternative technologies expand more rapidly than hydropower. In panels (c) and (d), base year (2015) values are shown in green dashed lines for reference. The 32 regions of the Global Change Analysis Model (GCAM) are further aggregated into 10 greater regions. “Other OECD” includes Australia, New Zealand, Canada, Japan, and South Korea; and “Other Asia” includes Pakistan, Indonesia, Central Asia, South Asia, Southeast Asia, and Taiwan.

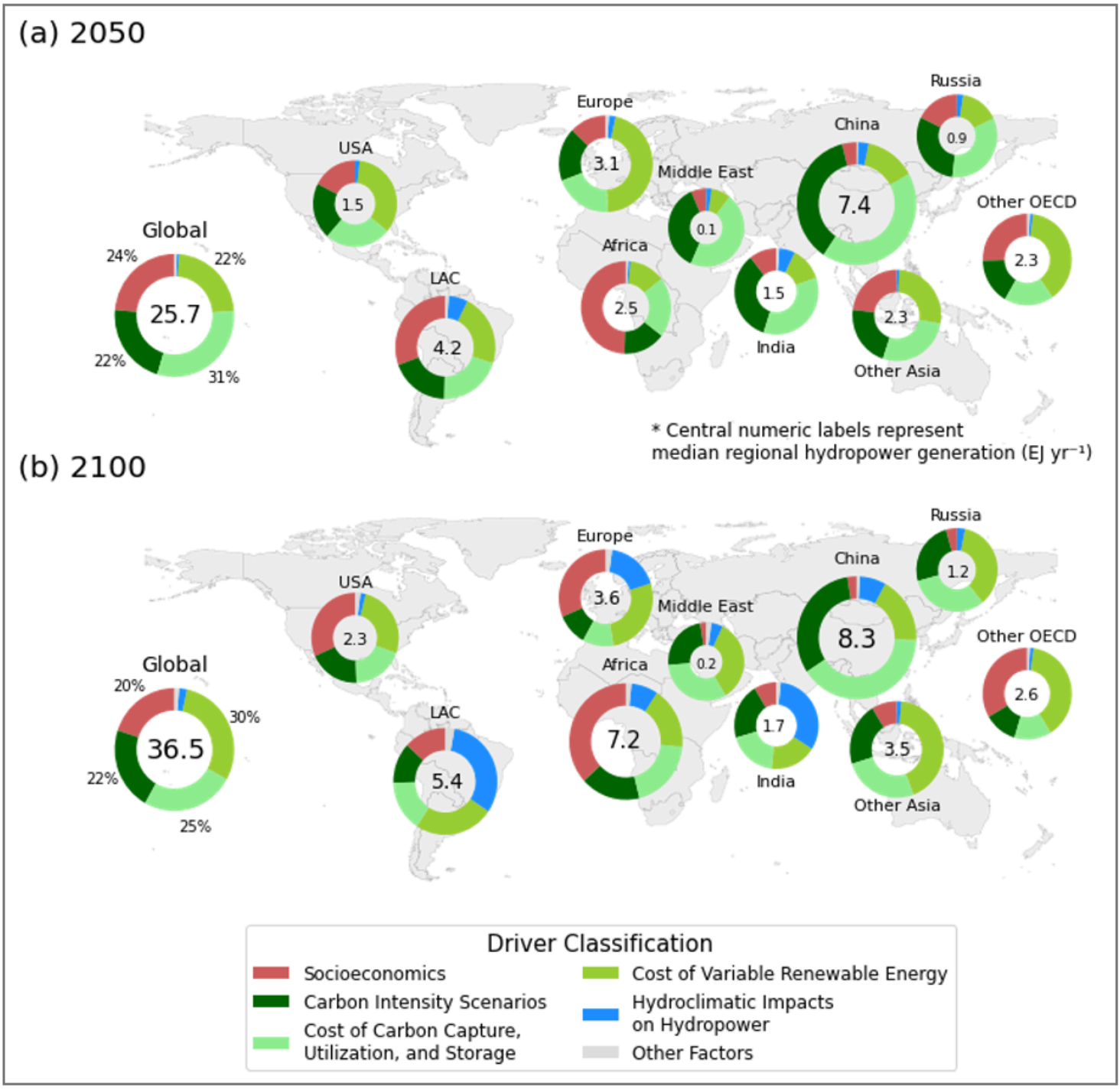


Figure 2

Relative feature importance of each human-Earth system driver on global and regional hydropower generation in (a) 2050 and (b) 2100. The size of each pie indicates the magnitude of median hydropower generation for each region and year. Refer to Supplementary Figure S10 for annotated relative feature importance heatmaps of hydropower generation and shares for all regions.

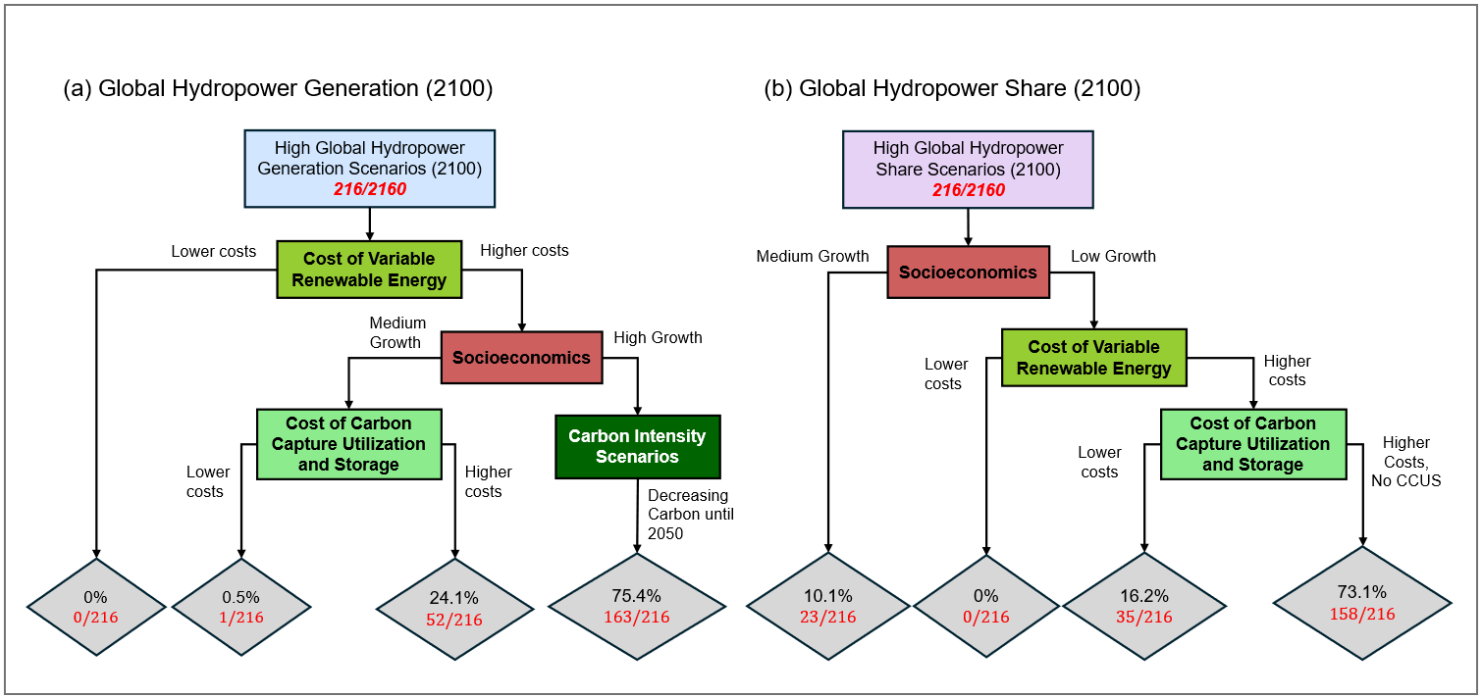


Figure 3

Simplified classification trees for scenarios leading to (a) high global hydropower generation scenarios and (b) high global hydropower share scenarios by 2100 (i.e., scenarios exceeding the 90th percentile global generation or share). Percentages in each diamond indicate coverage, defined as the proportion of scenarios meeting or exceeding the 90th percentile generation or share. Classification trees for scenarios leading to the low global hydropower generation and share scenarios (i.e., scenarios under the 10th percentile generation or share) are in Figure S13).

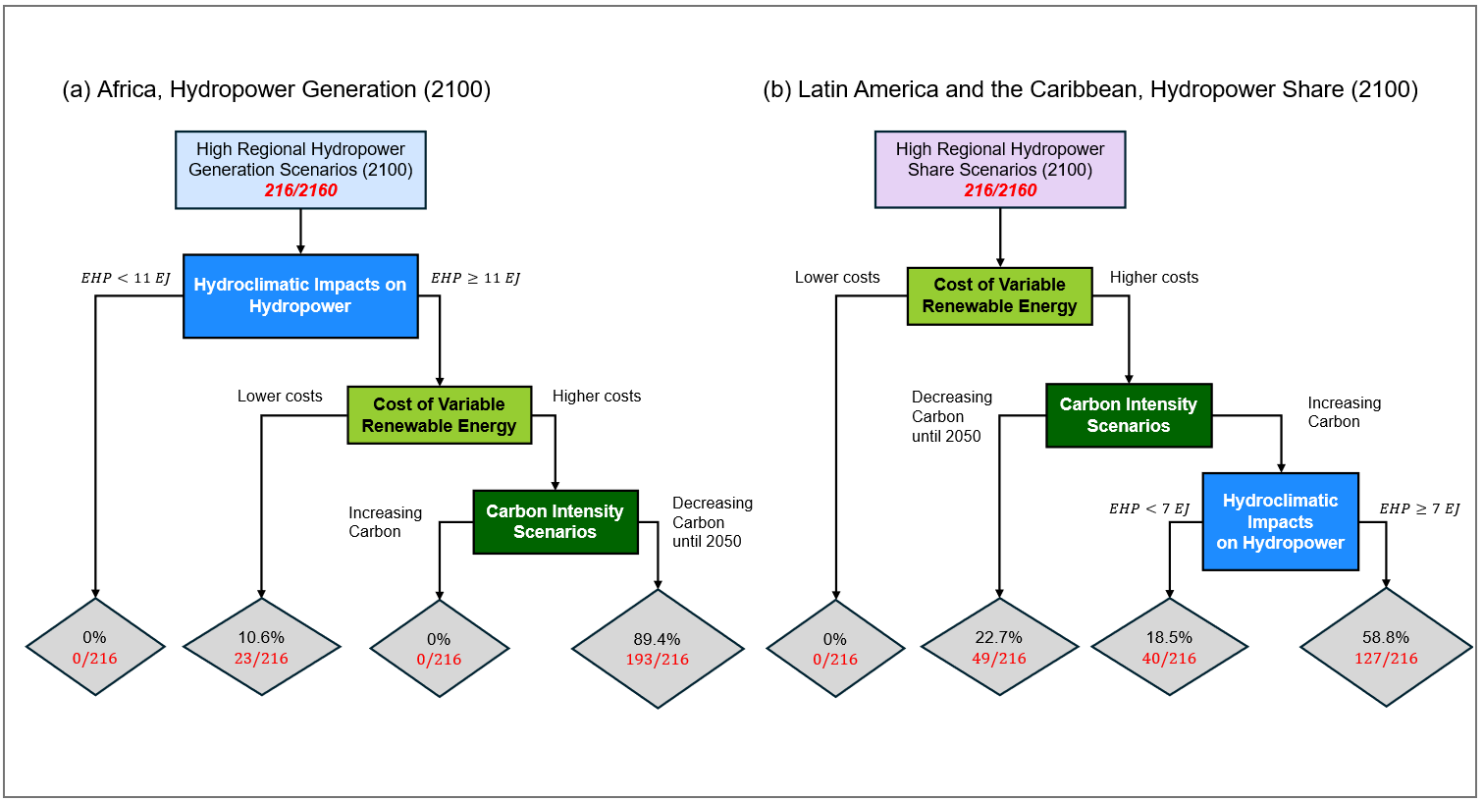


Figure 4

Simplified classification trees for scenarios leading to (a) high hydropower generation scenarios in Africa and (b) high hydropower share scenarios in Latin America and the Caribbean by 2100 (i.e., scenarios exceeding the 90th percentile regional generation or share). Percentages in each diamond indicate coverage, defined as the proportion of scenarios meeting or exceeding the 90th percentile generation or share. EHP denotes the region's total exploitable hydropower potential (EJ).

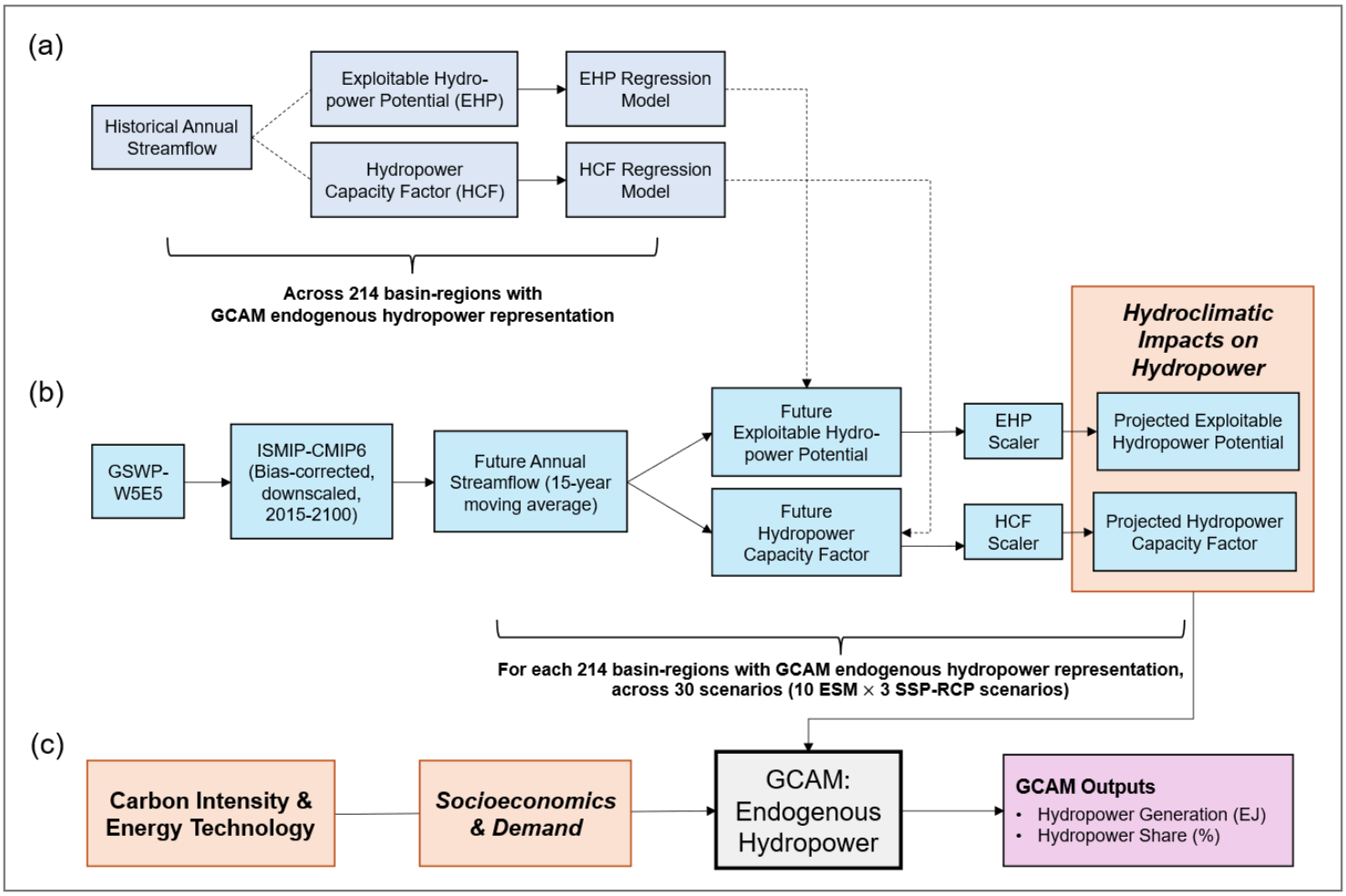


Figure 5

Overview of ensemble design. In (a), we derive the relationship between streamflow and exploitable hydropower potential and hydropower capacity factor based on historical data. In (b), we use future streamflow projections to project future exploitable hydropower potential and hydropower capacity factors. Finally, in (c), we sample eight drivers from broader human and Earth systems and generate the ensemble using GCAM. Further details on the approach we use to estimate hydroclimatic impacts on future hydropower are included Supplementary Text S1 and Figures S1-S3.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

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