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# From theoretical to sustainable potential for run-of-river hydropower development in the upper Indus basin

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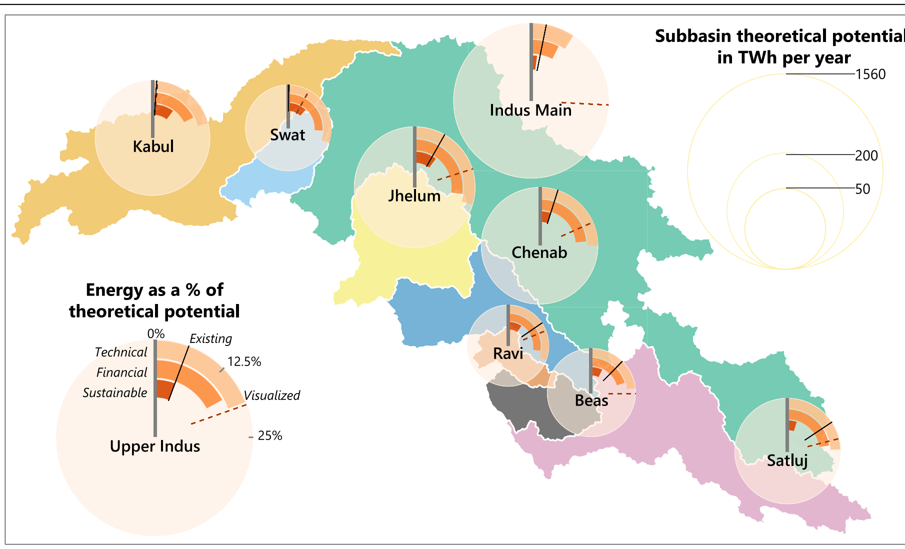
## GRAPHICAL ABSTRACT




**Graphical Abstract 1: Sub-basin wise hydropower potential as a percentage of theoretical run-of-river (RoR) potential for the full mixed scenario with risk-averse geo-hazard representation.** Circle sizes indicate modelled theoretical potential while orange radial bars indicate modelled theoretical, technical, financial and sustainable potential under three energy focus scenarios. Existing (solid black line) and visualized (dotted brown line) potentials are shown by lines.

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## ABSTRACT

A comprehensive assessment of hydropower resource potential considering factors beyond technical and financial parameters is missing for the upper Indus basin (UIB). Our framework takes a systems approach

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to quantify the theoretical to sustainable hydropower potential by successively considering natural, technical, financial, anthropogenic, environmental, and geo-hazard risk constraints on hydropower at individual sites as well as at the basin-scale. Theoretical potential of the UIB is 1564 TWh/yr at 500-m resolution. Across three energy focus and three geo-hazard risk scenarios, our cost-minimization model finds that technical (12%–19%), financial (6%–17%) and sustainable (2%–10%) potential are a small portion of the theoretical value. Mixed development combining plants of various size, cost and configuration provides the highest potential with the best spatial coverage. Alongside, our review of 20 datasets reveals a visualized potential exceeding 300 TWh/yr from 447 hydropower plants across the UIB, with only a quarter of the potential materialized by mostly large plants in the mainstreams. Hydropower cost curves show that Swat and Kabul sub-basins have a larger proportion of cost-effective and sustainable potential untapped by the visualized potential. Water use for other sectors represents the strongest constraints, reducing a third of the technical potential when evaluating sustainable potential. Ultimately, human decisions regarding scale, configuration and sustainability have a larger influence on hydropower potential than model parameter assumptions. In quantifying hydropower potential under many policy scenarios, we demonstrate the need for defining hydropower sustainability from a basin-scale perspective towards energy justice and balanced fulfilment of Sustainable Development Goals for water and energy across the Indus.

## 1. Introduction

In the last century, hydropower developed in the Indus basin as a subsidiary benefit of reservoirs built for irrigation [1,2]. However, since the 2000s, interest in hydropower has increased exponentially here like in other basins in Asia [3,4]. The mountains of the upper Indus provide ample opportunity for cost-effective hydropower generation. Reliable energy access is a precursor for economic growth and for achieving the sustainable development goals (SDGs), especially for remote communities in the mountains [5]. Hence, hydropower is considered a key solution to fulfil increasing electricity demands and to increase renewable energy[1] sources [1]. In Pakistan alone, hydropower generation doubled between 2000 and 2020 [6,7]. Alongside, electricity demands nearly tripled, with over 27% of the load shed on average in the last decade [8]. Hence, Pakistan's integrated generation capacity expansion plan (IGCEP) proposes a four-fold increase in hydropower from 2020 to 2040 [8].

Such ambitious hydropower expansion plans need to be scrutinized holistically for their impacts beyond techno-economic performance in energy generation. India and Pakistan already have national policies requiring the use of energy expansion modelling to optimize hydropower planning [1,8,9]. These models however, only consider the scheduling of shortlisted plants prioritized by the central government to maximize power capacity and minimize costs to meet national demands. As such, the plants considered by these national models propagate political and financial interests in large hydropower plants [4,10]. The World Commission on Dams (2000) highlights past usage of such a biased set of initial options as a key fallacy leading to poor hydropower decisions. A comprehensive initial assessment considering factors beyond technical and financial parameters is recommended to make decision-makers aware of broader implications of hydropower development from the start. More recently, Vaidya et al. [12] also argue that the sustainability of hydropower development in South Asia depends on the extent to which potential can not only be harnessed cost-effectively but also in a socially and environmentally just manner.

A localized assessment of all potential options for hydropower development in the Indus basin remains missing. Some global assessments [13–15] can provide an initial estimate for the hydropower resources available in the Indus. However, these have coarse spatial resolution that are particularly poorly at representing the complex hydrology of mountainous basins like the Indus [16–18]. Furthermore, global assessments do not capture local constraints and preferences for hydropower design that can significantly vary the technical, financial or social viability of hydropower sites [19]. Thus, a high-resolution systematic identification of viable hydropower options considering local hydrology and other constraints is necessary to inform the sustainable development of hydropower in the Indus.

[1] 'Energy' refers to electricity throughout the paper unless specified otherwise.

Current discussions on hydropower sustainability focus primarily on individual plants [20–22]. Meanwhile, hydropower policies are made at national scale and socio-environmental impacts are felt across the basin [23]. For transboundary basins like the Indus, an integrated river basin management (IRBM) approach can bridge this gap between plant, national and basin scale perspectives in long-term hydropower planning [12,24]. Under IRBM, hydropower portfolios incorporating all plants within the basin should be evaluated together to consider synergies and trade-offs between different sectors under the water–energy–food–environment nexus (WEFE) that all rely on the Indus water. Rasul [25], Vaidya et al. [12], MRC et al. [24], Couto and Olden [23] only present qualitative frameworks. However, quantitative assessments are needed to facilitate evidence-based water sharing between the upper and lower Indus basin (UIB and LIB) where the Indus Water Treaty (IWT 1960) decrees that new hydropower plants may not affect existing water usage across the riparian countries [27]. Our earlier review [28] highlighted how recent basin-scale studies on hydropower are using spatially dis-aggregated data to quantify non-traditional factors such as nexus water usage, environmental value, social preferences, value for community and proximity to farmland, forests or settlements in assessing the feasibility of hydropower sites [15,29–33]. In particular, Gernaat et al. [15] provides a modular framework that can be combined with emerging spatial data to incorporate IRBM in hydropower planning.

Specifically in the UIB, two other factors plague hydropower planning. First, socio-political preferences vary for the scale of hydropower development [28,34]. Technocratic national agendas remain biased towards large hydropower plants like Diamer-Basha and Dasu as instruments of political, financial and territorial power while serving as symbols of masculinity, modernity and prestige [35–39]. In contrast, bottoms-up electrification of remote mountain villages in the UIB favours small hydropower plants [40,41], which are proliferating under the global Clean Development Mechanism [42,43]. A quantitative analysis of how different scales of hydropower development can be combined at the basin-level is missing. Second, hydropower interests in the region are increasingly shifting to upstream headwaters [2,44] where the susceptibility to geo-hazards are higher; but geo-hazard risks are not receiving increasing attention in hydropower planning. Earthquake-induced landslides were the leading cause of historical damages to hydropower infrastructure [45]. More than half of the hydropower plants in the region are already on pathways of glacial lake outburst floods (GLOFs) [46] while over 10% of the rivers are highly susceptible to significant seismic damage [45]. Increasing atmospheric warming, cryosphere degradation, and mountain landscape instability under climate change is expected to increase these geo-hazards [47,48]. The compounding impact of cascading geo-hazards will be even higher, as witnessed in the 2013 Kedarnath disaster where extreme rainfall triggered landslides, lake outbursts and floods damaging over 10 hydropower plants [47]. Given these escalating occurrences of geo-hazards, it is imperative to incorporate spatial variation in geo-hazard risks in hydropower planning.

To promote sustainable hydropower planning in the Indus, the aim of our study is to expand traditional approaches for techno-economical assessment of individual hydropower plants to consider a basin-scale hydropower planning including socio-environmental constraints, policy implications and hazard risk. Initially, we develop an inventory of hydropower plants in the UIB by reviewing global and national databases. Thereafter, we implement the Hydropower Potential exploration (HyPE) model for the UIB that we conceptualized in Dhaubanjar et al. [28] to quantify the various classes of hydropower potential in the UIB. As one of the first spatially-explicit and comprehensive study focusing on the UIB, we present several improvements to current approaches for hydropower potential assessment. First, we use a high-resolution cryosphere-hydrology model to improve runoff simulation, which is considered the primary source of uncertainty in hydropower assessments [49]. Second, our model optimizes small and large hydropower plants in two run-of-river (RoR) hydropower configurations simultaneously; existing studies focus on one configuration and/or scale [28]. Third, we present quantitative strategies to include the missing geo-hazard consideration in hydropower assessments. With these improvements, our model offers important insights into the spatial variations in hydropower potential across the UIB and the implications of policies choices on development scale and geo-hazard risks. Our model formulation also demonstrates innovative ways to integrate diverse datasets to better represent society–nature interactions that influence the sustainability of hydropower.

## 2. Methods

This study implements our conceptual framework for hydropower exploration presented in Dhaubanjar et al. [28] for the UIB to quantify five classes of hydropower potential introduced therein: visualized, theoretical, technical, financial and sustainable. Potential is defined in terms of annual hydropower energy generation. Visualized potential refers to the energy generation by hydropower plants that are existing or planned for future development by national governments. Theoretical potential is modelled based on physical equations while a cost-minimization model is used to estimate the technical, financial and sustainable potentials under multiple policy scenarios.

### *2.1. Inventory of visualized hydropower potential*

To quantify visualized potential, a hydropower inventory was developed for the UIB by collating publicly available information on hydropower plants in the UIB using a three-step process. First, we reviewed literature and engaged with stakeholders to identify and evaluate global and national datasets. Through engagement with hydropower practitioners, policymakers and global hydropower researchers, we shortlisted 9 global and 11 national datasets as key sources (Table 1). Next, we assessed the methods, database structure, and parameter definitions used across these sources to develop strategies for automated and manual merging of plant information. The majority of the global databases collate secondary data from other sources or national documents. These tend to focus on hydropower plants within specific plant dimensions (capacity, dam size or reservoir size), functionality or development status. National documents generally contain a limited number of parameters focusing on plant size and performance. In India, plants > 25 MW are centrally managed while in Pakistan the cut-off is at 50 MW, hence these larger plants are better documented. We started with the global hydropower database by Byers et al. [50] which combines multiple global databases. To this, we merged unique information from other global databases using data wrangling. Information from national documents were merged manually. For conflicting values, data from the latest national documents were considered most reliable.

Thereafter, we manually validated four parameters relevant to our model: location (latitude–longitude), development status, plant capacity and annual energy generation. First, for validating location, we used geo-reference satellite imagery in Google Earth to visually locate the dam or the intake point on the river where available, else we located the powerhouse. For future plants, we used published reports to identify the tentative dam or powerhouse location where available. Otherwise, some future plants use the location of tentative administrative units as listed in the global future hydropower database [51]. Development status indicated in contemporary national reports [8,9,52,53] was used to classify each plant as: existing, under-construction, planned or raw. ‘Planned’ indicates plants in government pipelines while ‘raw’ indicates plants that appear in at least one key source with no further information. Plant capacity information was largely consistent across global and national sources. In contrast, multiple definitions were found for annual energy generation. For larger existing plants, actual energy generation for 2018–19 or 2019–20 was reported by WAPDA [52,54]. For some under-construction and planned plants, we found design energy generation in planning documents. For the remainder, we estimated energy generation by using an exponential regression between plant capacity in MW and actual energy generation in GWh/yr separately for 39 plants<=50 MW and 47 plants> 50 MW [50,55]. We found limited information in both global and national sources for the typification of plants based on their configuration, especially for future plants. National documents sometimes identify plants with large reservoirs or dams. These were classified as “Storage” type while the remaining plants were classified as “Other”. See Supplement C for a detailed documentation of the inventory. Overall, these quality checks focused on plants > 5 MW classified as existing or under-construction.

### *2.2. Hydropower potential exploration (HyPE) model*

Our previous review of hydropower estimation methods [28] found that existing approaches either considered a global or continental analysis focused on strategic resource assessment or a site-specific analysis focused on optimal design of individual plants. Some basin and sub-basin scale studies exist, however these also lack the systematic and comprehensive approach of global analysis and the representation of local constraints of site-specific analysis. Hence, combining the advances in literature, review of local policy documents and co-creation with hydropower experts from the region, we developed a conceptual framework for hydropower potential exploration for the context of the UIB that is implemented here as the HyPE model. A brief summary of the model is presented in the sections below while a comprehensive description of each hydropower potential class is presented in Dhaubanjar et al. [28]. The framework uses simulated runoff from a state-of-the-art cryosphere-hydrology model with a 5-km spatial resolution based on SPHY [56]. Considering the importance of cryospheric processes to discharge simulation in the UIB, the high resolution model was calibrated using a 3-step approach explicitly considering parameters related to snow sublimation, snow cover and melt processes using a combination of in-situ observed and satellite remote sensing parameters. Khanal et al. [56] have calibrated and validated the model to improve the discharge simulation at two stations in the UIB. The 40-year long-term monthly average runoff (1979–2018) simulated by Khanal et al. [56] has been downscaled using Gernaat et al. [15]’s discharge routing algorithm to generate discharge forcing at 500-m for the HyPE model. Grid cells with annual average discharge $\geq$ $0.1\ m^3 s^{-1}$ are selected as streams suitable for hydropower (see Supplement B.1). The model explores the following types of potential along these streams:

#### *2.2.1. Theoretical potential*

The theoretical potential ($P_{theoretical}$) is estimated using the gravitational potential energy as the maximum amount of energy that can be generated by RoR hydropower exploitation. Focusing on RoR potential, we use the discharge-weighted elevation difference to evaluate potential at each river segment:

$$P_{theoretical} = \rho g (Z_{upstream} - Z_{downstream}) Q_{yr,upstream} \times \eta \times t \qquad (1)$$

**Table 1**
Key global and national sources shortlisted for initial development of the visualized hydropower inventory for UIB.

| | Dataset | Year published | # Records | Focus of dataset | Geo-referenced | Method |
|---|---|---|---|---|---|---|
| GLOBAL SOURCES | | | | | | |
| GLOBAL | FAO Geo-referenced Database on Dams for Central and South East Asia [57] | 2014 | 14,500 | Medium to large | Partial | Self reporting by countries in during update cycles |
| | Future Hydropower Reservoirs and Dams Database [51] | 2015 | 3,700 | ≥ 1MW | Yes | Manual inspection, validation and collation of information from research articles, grey literature and internet |
| | Power-generation system vulnerability and adaptation to changes in climate and water resources* [55] | 2016 | 24,515 | 0.001–812 MW | Yes | Combines capacity data from WEPP with location data from CARMA/SEDAC based on plant name. Other information was gathered from GRaND |
| | OpenStreetMap (OSM) Power | 2017 | 54,308 | – | Yes | Global dam data based on OSM tags |
| | International Commission on Large Dams (ICOLD)** | 2018 | 59,071 | ≥ 15 m, or 5–15 m with reservoir ≥0.03 $km^3$ | No | Self reporting by member countries |
| | WRI "A Global Database of Power Plants" [50] | 2019 | 30,000+ plants in 164 countries | ≥ 1 MW | Yes | Automated collaction of machine-readable global (WEPP, GEO and CARMA) and national data sources and manual collation from other sources |
| | GlObal geOreferenced Database of Dams [58] | 2020 | 38,660 | Medium to large | Yes | Manually digitized visible dams in satellite images. No plant specific information available beyond georeference |
| | Global Reservoir and Dam Database [59] | v1.3 – 2019 | v1.3 – 7000+ | Large (≥0.1 $km^3$ | Yes | Manual inspection, validation and collation of information from research articles, grey literature and internet |
| NATIONAL SOURCES | | | | | | |
| | Dataset | Year published | # Records | Focus of dataset | Geo-referenced | Method |
| PAKISTAN | WAPDA Annual Reports [52,54] | every year | 22 existing large plants | >1 MW | No | Annual national reporting on performance |
| | Hydropower Resources of Pakistan [60] | 2011 | 479 plants in AJK, GB and KP | >0.01 MW | In PDF | Manual collation of sub-national databases |
| | Indicative Generation Capacity Expansion Plan 2018–2040 [8] | 2019 | 17 existing; 4 Under construction; 23 Candidate | >30 MW | No | Manual collation of information from relevant agencies on existing, committed and candidate plants |
| CHINA | Major dams in China [61] | 2014 | 183 in all of china | | Partial | Manual collation |
| | Tibetian plateau dam list[62] | 2010 | 39 in Tibet | | Partial | Manual collation |
| INDIA | National Electricity Plan: Volume I Annex 5.1 [9] | 2018 | 13 in Ladakh, JK and HP states | | No | Only under construction or comissioned plants most likely to benefit during 2017–22 |
| | National registry on large dams [63] | 2018 | 37 in Ladakh, JK and HP states | no info on HP capacity | Partial | National reporting on large dams, existing and future |
| | Statewise hydropower profile 2020 Annex 2.1 [53] | 2020 | 201 in Ladakh, JK and HP states | >25 MW | No | National reporting on statewise info on status of hydropower plants, existing and future |
| | Review of Performance of Hydropower Stations 2018–19 (CEA 2019) | 2019 | 37 major dams w 44 HP plants | >25 MW | No | National reporting on existing plants |
| | Annual Electricity Generation Target [64] | 2020 | | >25 MW | No | National planning of power production |
| | CEA Annual Report 2019–20 Annex 5A [65] | every year | | | No | Annual national reporting on performance |

* Source not used because no plant name or other identifier available to match this dataset to others.
** Source not used because it is not freely available.

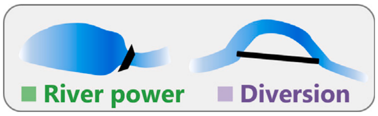


**Fig. 1.** **Two RoR hydropower configurations—river power plant (RP) and diversion canal plant (DP) considered in this study.**

where $Z$ is the elevation (m) at the upstream and downstream ends of a river segment; $Q_{yr,upstream}$ is the simulated annual average discharge ($m^3/s$) entering the segment; $\rho$ is the density of water ($kg/m^3$); $g$ is the gravitational acceleration (9.8 $m/s^2$); $t$ is hours of plant operation (8760 h/yr) and $\eta$ is the plant efficiency considered 100% assuming that the theoretical plant can run at full capacity year-round. Eq. (1) is applied by breaking the streams into river segments of equal-lengths varying from 500 m to 100 km.

### 2.2.2. Technical, financial and sustainable potential

We quantify technical potential as the energy that can be generated by cost-optimal development of RoR plants throughout the UIB. Technical potential is estimated as done by Gernaat et al. [15] using cost functions developed by the Norwegian [66,67] and US hydropower industry [68]. We improve Gernaat et al. [15]'s method by using the latest physical and socio-economic datasets for the UIB and adding local design preferences. The model considers two RoR hydropower configurations—river power plant (RP) and diversion canal plant (DP)–that are preferable for mountainous terrains (Fig. 1). DPs have an upstream intake diverting a portion of discharge into a powerhouse downstream while RPs have a small dam that allows for peaking RoR hydropower generation. At each site, the model first performs a spatial search upstream for all possible diversion inlets for the DP configurations and then a sizing of dam-reservoir for RP. The RP and DP plants identified by the cost-optimal sizing at individual sites are then compared to select the optimal combination of the two configurations to minimize production costs at the basin-scale.

The annual energy generation (Wh) at each RP and DP is evaluated using:

$$P_{RP} = \rho g(Z_{headwater} - Z_{tailwater}) \times Q_{design,RP} \times \eta_{gen,RD} \times \eta_{dist,gridtype} \times t \times CF_{RP} \quad (2)$$

$$P_{DP} = \rho g(Z_{inlet} - Z_{powerhouse} - h_f) \times Q_{design,DP} \times \eta_{gen,DP} \times \eta_{dist,gridtype} \times t \times CF_{DP} \quad (3)$$

Here, $Z$s are the elevations representing head-drop (m). $h_f$ is the friction losses in the diversion pipe for DPs (m). $Q_{design}$ and $CF$s are design discharge ($m^3s^{-1}$) and annual average plant capacity factor (unitless) calculated based on monthly discharge and the flow exceedance threshold selected for plant design. $\eta_{gen}$ and $\eta_{dist}$ are electricity generation and distribution efficiencies where the latter further distinguishes between on and off grid plants.

The per-unit energy production cost for each plant is evaluated as the ratio of annualized capital costs and annual average energy generation. The algorithm explicitly considers the cost of civil infrastructure, turbine, electromechanical equipment, transmission–distribution lines, access road, land acquisition, agricultural loss, forest loss, resettlement, community compensation, fish passage, provincial water use fee, operation and maintenance, and owners fees (Table 3). See Gernaat et al. [15], NVE [66,67] for cost functions used. All costs are adjusted to the 2010 US dollar level (USD2010).

For RPs, the infrastructure costs consider a Reinforced Concrete (RCC) dam, steel penstock and underground powerhouse. Dam size is limited by setting the regulating capability factor (RCF) to $\leq$ 5%, i.e. a reservoir storage limit of 5% of the annual discharge volume. RCF $\leq$ 5% is applicable for pondage reservoirs not large enough to have seasonal storage [95]. Meanwhile, large DP infrastructure include a desanding basin, tunnel blasting, underground penstock and powerhouse and distribution costs of connection to the nearest transmission grid. Small DPs (< 50 MW based on GoP [96]) consider surface penstock and powerhouse with an off-grid distribution to the nearest settlement. Table 2 lists the source and resolution of 32 datasets used in the model while Table 3 summarizes the model parameters. Cost components and parameters were selected in discussion with stakeholders on standard practice and review of design documents of plants in Pakistan. Thereafter, we quantify the financial potential by considering a subset of plants from the technical potential with a production cost $\leq$ 0.10 USD2021/KWh. This threshold represents the globally cost-competitive price for hydropower energy [97,98] and is also comparable to costs for other energy sources in Pakistan [6,99] and India [7].

Furthermore, sustainable potential is quantified as energy that can be generated if we also consider other non-technical and non-economic constraints that affect the long-term sustainability of hydropower development. We consider three factors for the sustainability of hydropower: water use, land use and geo-hazard risk. Hydropower is one of many users of available natural resources under the WEFE nexus. Hence, we consider balancing the sharing of available resource with other users and minimizing conflicts with other sectors as a key aspect of hydropower sustainability. For sustainable water use, we evaluate sustainable design discharge based on water available for hydropower development after deducting consumptive water use for domestic, industrial and irrigation purposes as estimated by Smolenaars et al. [82,100]. Additionally, we impose an environmental flow (e-flow) requirement, set as a percentage of discharge, to consider water required for environmental protection. For sustainable land use, we do not allow hydropower development in national and international cultural and natural heritage sites [92–94] with appropriate buffers as indicated in Table 3. Geo-hazard risk representation is presented in Section 2.3.2. Additionally, we compute the full and remaining technical, financial and sustainable potential. Full potential assumes that there is no hydropower developed yet. Remaining potential explores hydropower potential outside of grid cells where dams and reservoirs already exist from our visualized hydropower inventory.

### 2.2.3. Stakeholder consultations

Using the Delphi technique [101], multiple online discussions were held with hydropower experts from Pakistan, Afghanistan and Nepal in 2020–2021 to adjust the model to the local context. The first discussion series focused on the conceptualization of the model framework while the second series focused on plausibility of model parameters, setup and scenarios. Both discussion series [102] were held iteratively in groups of 2–3 participants. All methodological assumptions and parameters (Table 3) were thus developed with feedback from regional hydropower and energy experts. The sensitivity and scenario analysis were designed to represent the range of perspectives offered by stakeholders.

## 2.3. Policy scenario analysis

### 2.3.1. Energy focus scenarios

We model three energy development scenarios capturing the difference in stakeholder interests regarding the scale of hydropower development [28]. In Pakistan and India, the central government is responsible for the large plants. Private developers are only interested in medium to large plants close to existing transmission grids. In the largely remote parts of the UIB, communities and provincial governments want to develop small off-grid plants that are close to communities. These varying interests are quantified through three scenarios focused on large, medium and mixed plant sizes. The scenarios use different river segment lengths based on the response of theoretical potential to different lengths.

In the ***Large focus*** scenario, all rivers are split into 25-km segments to focus the cost algorithm on searching for large RPs and DP targeting the interests of the central government. It represents the dominant hydropower aspirations in Asia pursuing mega plants [2]. In the Medium

**Table 2**
Various datasets used to set up the hydropower potential exploration model.

| | Dataset | Sources | Spatial | Temporal | Units | Format |
|---|---|---|---|---|---|---|
| 1 | Historical monthly average runoff grid | SPHY glacial-hydrology model [56] | 5 km | 40yr monthly average (1979–2018) | $m^3/s$ | raster |
| 2 | Finer DEM for dam sizing | HydroSHEDS v1.2 [69] | 3” | 2008 | m | raster |
| 3 | Main DEM | | 15” | | m | raster |
| 4 | Flow accumulation | Self-generated using 500 m HydroSHEDs DEM | 500 m | 2008 | Number of cells | raster |
| 5 | Flow direction | | | | Direction indices | |
| 6 | Lakes and reservoirs | HydroLAKES v1.0 [70] | polygons | 2016 | – | vector |
| 7 | Glaciers | Randolph Glacier Inventory v6.0 [71] | polygons | 2017 | – | vector |
| 8 | Glacial lake | [72] | polylines | 2005 | – | vector |
| 9 | Power transmission network | OverpassTurbo [73] | polylines | 2020 | – | vector |
| 10 | Global road network | GRIP4 by [74] | polylines | 2018 | – | vector |
| 11 | National road network | [75,76] | National PDF | Pakistan 2013<br>Afghanistan 2018 | – | vector |
| 12 | Settlements | [77] | points | 2001 | – | vector |
| 13 | Land use land cover | CCI-LC v2.0.7 by [78] | 300 m | 2015 | 31 classes | raster |
| 14 | Local land and tree prices | [79,80] | Per category | 2020 | USD per $km^2$ for 8 land types | vector |
| 15 | Tree density map | [81] | 1 km | 2015 | Number of trees per $km^2$ | raster |
| 16 | Annual agricultural crop production | Smolenaars et al. [82] | 5’ | 10yr average<br>(2001–2010) | Tonne per $km^2$ for 13 crop classes | raster |
| 17 | Average annual crop prices | [83] | Per crop for India & Pakistan | 10yr average<br>(2001–2010) | USD per tonne for 27 crops | vector |
| 18 | Population density | HYDE v3.2 by [84] | 5’ | 2015 | Number of people per $km^2$ | raster |
| 19 | National GDP (PPP) | Smolenaars et al. [82] | Per country | 2019 | USD per capita | vector |
| 20 | National boundaries | GADM v3.4 [85] | polygons | 2018 | – | vector |
| 21 | Water demand for irrigation | Smolenaars et al. [82] | 5’ | 10yr monthly average (2005–2015) | $m^3$ per month | raster |
| 22 | Water demand for household and industries | Smolenaars et al. [82] | | | | raster |
| 23 | Global seismic hazard | Global Seismic Hazards program (GSHAP) by Giardini et al. [86] | 0.1° × 0.1° | 2003 | Peak Ground Acceleration (in $m/s^2$) | raster |
| 24 | Past earthquakes inventory | USGS Earthquake Hazards Program [87] | points | 2008–2018 | | vector |
| 25 | Thrust and fault inventory | Mohadjer et al. [88] | polylines | 2016 | – | vector |
| 26 | Landslide susceptibility map | Emberson et al. [89] | 30”~1 km | 2020 | 5 classes | raster |
| 27 | Past landslides inventory | NASA Global Landslide Catalog (GLC) [90] | points | 2008–2018 in the UIB | – | raster |
| 28 | Hazardous glacial lakes | [91] | per lake | 2012 | – | vector |
| 29 | World heritage sites | [92] | per heritage | 2020 | – | vector |
| 30 | National cultural heritages | [93] | per heritage | 1997 | – | vector |
| 31 | Natural heritages | WDPA v1.6 by [94] | polygons | 2019 | – | vector |
| 32 | Inventory of current and planned hydropower project | Self-compilation of national and international databases documented in Supplement C | per project | – | – | vector |

All datasets were re-sampled to 500 m using Geospatial Data Abstraction Library (GDAL). A detailed discussion of data processing and model parameterization is provided in Dhaubanjar et al. [28].

**Table 3**
Parameter values selected for the three energy focus scenarios based on literature review, stakeholder discussion and the hydropower inventory.

| | Component | River Power Plant | Diversion Canal Plant | |
|---|---|---|---|---|
| | | | Large | Small |
| Technical parameters | Search on streams | Primary | Primary and Secondary | Tertiary |
| | Minimum head (m) | 4 m | 4 m | 20 m |
| | Minimum distance between intake and powerhouse | – | 500 m | 500 m |
| | Search radius based on maximum distance between intake and power house | – | 3 km [103] | 1.5 km |
| | Minimum distance between two plants | 1 km | | 500 m |
| | River segment length | 4 km | | 2 km |
| | Minimum design flow | 1.0 $m^3/s$ | 1.0 $m^3/s$ | 0.1 $m^3/s$ |
| | *Channels are cells with annual discharge > 0.1* $m^3/s$ | | | |
| | Design flow (QXX = flow exceeded xx % of the time) | Q40 | Q30 | Q80 |
| | Reservoir storage limit or RCF (as % of annual average inflow volume) | 5% [95] | – | – |
| | Generation efficiency | 90% | 85% | 80% |
| | Transmission and distribution efficiency | 85% [104] | 85% [104] | 96% [105] |
| Capital cost parameters | Blasted headrace tunnel | | ✓ | |
| | De-sanding basin | | ✓ | ✓ |
| | Steel penstock | ✓ | ✓ | ✓ |
| | RCC Dam | ✓ | | |
| | Fish passage | ✓ | ✓ | |
| | Underground powerhouse | ✓ | ✓ | |
| | Turbine | ✓ | ✓ | ✓ |
| | Electro-technical equipment | ✓ | ✓ | ✓ |
| | Miscellaneous mechanical equipment | ✓ | ✓ | |
| | Road access | ✓ | ✓ | |
| | Transmission line connection | On-grid | On-grid | Off-grid |
| | Land acquisition | Land value +15% [106] | | – |
| | Agricultural losses | ✓ | | – |
| | Loss of trees | ✓ | | – |
| | Resettlement per capita | 3*GDP | | – |
| | Community compensation (as % of resettlement costs) | 10% | 10% | – |
| Other cost parameters | Provincial Water Use charge | PAK 0.425/kWh [107] | | – |
| | Discount rate | 10% | | |
| | Lifetime | 40 years [15] | 30 years [30] | 15 years [108] |
| | Owner's cost (as % of capital investment) | 20% [98] | 10% [98] | – |
| | Operation & maintenance (as % of capital investment) | 2.5% [15] | 3% | 3.50% |
| Sustainability constrains | Environmental flow requirement (as % of annual average discharge) | 30% [15,31] | | – |
| | Hazard risk mitigation cost (as % of capital investment) | 2%–10% across 5 levels | +1% to the RP rate | – |
| | Buffer around thrusts and faults | 1 km | | |
| | Buffer around GLOFs | 0.5 km | | |
| | Buffer for cultural heritages | 1 km [109] | | |
| | Buffer for natural heritages | 2 km [109] | | |

focus scenario, the streams are split into smaller 4-km segments to focus searches on medium plants accommodating the interests of private investors. Finally, in the ***Mixed focus*** scenario, we apply a three-tier search across three river classes to distinguish between large RPs, small DPs and large DPs. The annual discharge was used to classify rivers into three bins (see Supplement B.1). Primary rivers (6% of rivers) are high flow mainstreams where we search for large RPs and DPs. Secondary rivers (28%) are the tributaries upstream of the mainstreams where we search for medium to large DPs. Tertiary rivers (66%) are even smaller headwaters where we search for small RPs of interest to local communities. The primary and secondary streams are split into 4-km river segments while tertiary streams are split into 2-km segments. The parameters listed in Table 3 are also differentiated between the three river classes to search for different plants. As such, our use of varying river segment lengths in the three energy focus scenarios is not a strict constraint limiting the search to a fixed range of plant sizes. In a cost-minimization framework like ours, large plants will inherently have low unit production cost and higher probability of being selected as optimal. Using smaller segments limits the number of large plants shortlisted by the search, allowing smaller plants to emerge. Additionally, in the mixed focus scenario, we use different cost functions for small plants < 50 MW to account for the difference in cost scaling between small and large plants as in [66,67].

#### 2.3.2. Geo-hazard risk representations

We consider the risk of three major geo-hazards in the UIB (earthquake, landslide and GLOF), using multiple datasets as proxies to categorize hazard susceptibility into 5 probability levels (very low, low, medium, high, very high). For earthquake risk, seismic zone definitions in national building codes [110,111], peak ground acceleration (PGA) seismicity [86] and location of existing thrusts & faults [88] are used to classify susceptibility of earthquake occurrence. For landslide, we use the latest global landslide susceptibility map by Emberson et al. [89]. For both earthquake and landslide risks, we reclassify the global risk classes to visually align with locations for historical earthquake [87] and landslide [90] occurrences as shown in Supplement B.2. Similarly, we consider locations of potentially dangerous glacial lakes and probable maximum travel paths downstream of these glacial lakes as having very high susceptibility to GLOF occurrence. Travel paths are defined using empirical functions based on slope [112].

Considering the need to balance hydropower development and geo-hazard risks, we formulate three geo-hazard risk strategies differing in the degree of risk-aversion applied to the mixed sustainable scenario (Table 4):

- **Cost-based:** Geo-hazard mitigation costs are applied throughout the basin as 2–10% of capital investment costs scaled based on maximum-hazard risk level across the three geo-hazards.
- **Risk-averse:** Areas with "very high" risk for any of the three geo-hazards are excluded from hydropower development while mitigation costs are incorporated for other levels.
- **Multi-hazard:** Areas with "high" or "very high" multi-hazard risk composite of the three geo-hazards are excluded from hydropower development while mitigation costs are added to other levels.

The cost-based representation reflects the status quo where all hazard risks are considered acceptable if they can be financially reconciled. The risk-averse representation considers the damages caused by recent geological disasters in the region [113] and calls for more conservative planning of large infrastructure by avoiding any known disaster prone areas [46]. Here, the maximum-hazard risk levels across any of the three hazards is used as the exclusion criterion. In contrast, the multi-hazard risk representation emphasizes areas where multiple cascading disasters can trigger higher damages than a single disaster [114]. To this end, we develop a composite multi-hazard risk map as the equal-weighted sum of the individual hazard susceptibility maps that is re-scaled to five risk levels.

### 2.4. Sensitivity analysis

Hydropower policies in the basin countries do not explicitly specify design discharge thresholds. However, experts shared desirable ranges of thresholds for the three plant configurations. Table 5 shows the design discharge thresholds for each of the three plant configurations that were used to generate 27 combinations. For seven other parameters listed in Table 6, we conduct a one-at-a-time sensitivity analysis changing parameters in both directions. The mixed scenario with the risk-averse hazard representation is considered the default.

## 3. Results

### 3.1. Visualized hydropower potential

Our inventory identified 210 existing plants with 22.2 GW capacity and 89.3 TWh/yr of hydropower in the UIB (Fig. 2B). This is comparable to the 25 GW reported recently by Harlan and Hennig [2] for the entire Indus. The total visualized hydropower potential in our inventory is four-times the existing value at 369.4 TWh/yr (90.9 GW). Our values are much higher than the 6.72 and 60 GW reported for existing and total visualized hydropower potential for Pakistan alone in 2012 [115]. A quarter of the visualized potential comes from just 40 under-construction plants while half the visualized potential is from planned or raw plants. Of the 468 unique hydropower plants in the inventory, nearly half are missing precise geo-reference. These are predominantly planned and raw plants for which locations have not been finalized or existing plants ≤5 MW that are difficult to identify in satellite imagery. Only geo-referenced plants, totalling 307 TWh/yr, are mapped in Fig. 2C.

Visualized plants vary in size and plant configuration. Plants range from 0.35–23,135 GWh/yr (0.05–4866 MW) and are concentrated in the south of the UIB (Fig. 2C). The largest plants lie along the main branch of the Indus as also observed by Siddiqi et al. [115]. Small plants are scattered in the north and along other tributaries. Nine storage type plants represent ~40% of the existing potential. Eleven other storage plants are planned. In total, these storage plants with 63 TWh/yr contribute only ~17% of the total visualized potential (Fig. 2B). Therefore, other plant configurations dominate the inventory. These 447 other plants with 306 TWh/yr potential are considered the visualized RoR potential from hereon. Note that for a majority of the plants, we only have design or estimated energy (Fig. 2B). Lack of actual generation data and inconsistency across national reports adds uncertainty to our visualized RoR potential [115].

### 3.2. Theoretical hydropower potential

The theoretical RoR potential for the UIB is 1564 TWh/yr when streams with $Q \geq 0.1$ $m^3s^{-1}$ are divided into 500-m river segments (Fig. 2C). If we consider all cells in the UIB, the potential increases to 1798 TWh/yr.[2] In Fig. 2C, high theoretical potential segments overlap with large visualized plants especially in the Indus main, Jhelum and Chenab tributaries. However, theoretical potential in the Kabul river and the upstream areas of the Satluj and Indus main tributaries remain unexploited. Some visualized plants are larger than the theoretical RoR potential because they may have large reservoirs that span beyond one 500-m segment.

Fig. 3 shows that theoretical potential portfolios vary with river segment lengths. The theoretical potential decreases by about 44% to 880 TWh/yr when a coarser 100-km river segmentation is used compared to the 500-m. The distribution of plant size also changes. At 100-km, 68% of the theoretical potential comes from mega plants while only 10% of the plants in the portfolio are classified as small (< 50 MW). The proportion of small plants is notably higher for river

[2] Our approach uses discharge-weighted elevation difference to estimate theoretical potential (See Eq. (1)). Some studies estimate gross theoretical potential using runoff-weighted elevation difference without using runoff routing to obtain discharge. Doing so yields the theoretical potential of the UIB at 1855 TWh/yr.

**Table 4**
Combination of different classes of potential with energy focus scenarios and geo-hazard risk representations.

| | | | | Energy focus scenarios | | |
|---|---|---|---|---|---|---|
| | | | | Large | Medium | Mixed |
| Constraint type | Technical | | | x | x | x |
| | Financial | | | x | x | x |
| | Sustainable | **Geo-hazard risk representation** | Risk-averse | x | x | x |
| | | | Multi-hazard | | | x |
| | | | Cost-based | | | x |

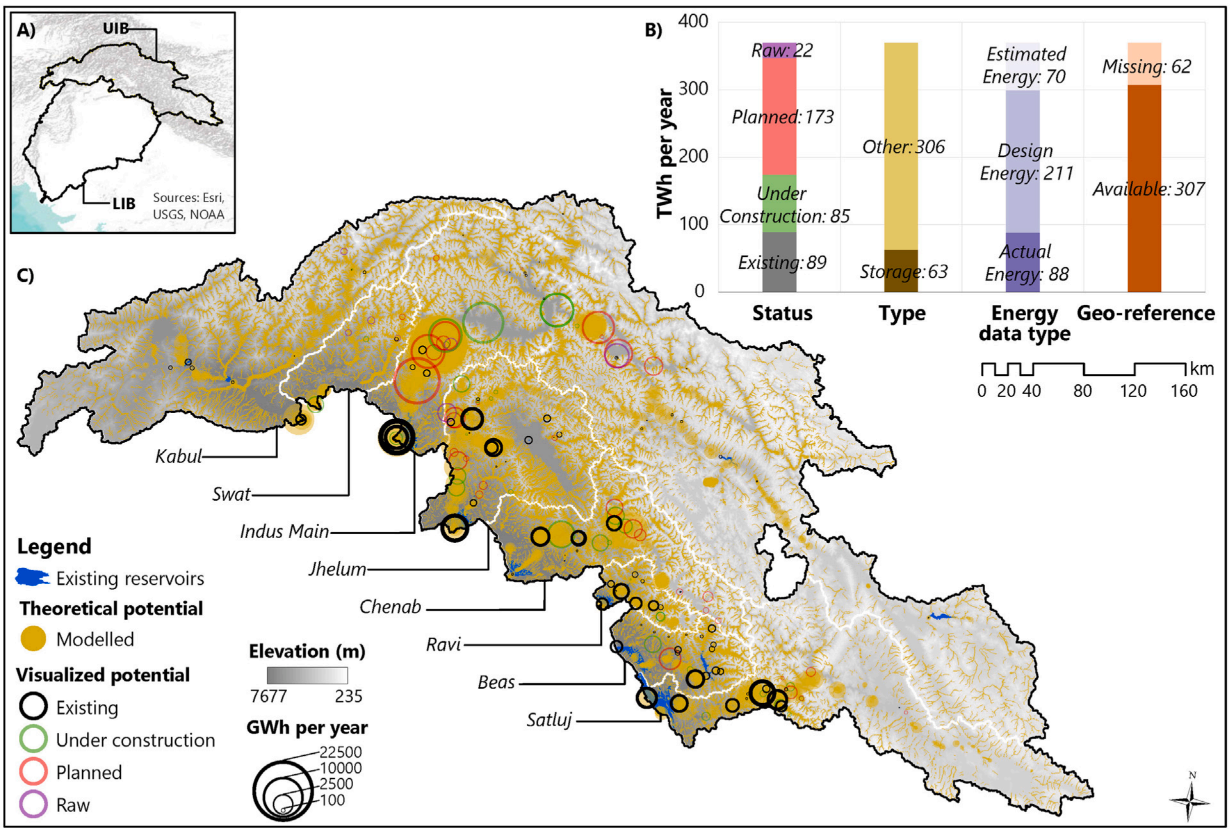


**Fig. 2. Comparison of visualized and theoretical potential.** (A) Inset map shows the location of lower and upper Indus basin (LIB and UIB) in South Asia. (B) Inset bar chart summarizes the energy generation (in TWh per year) for all visualized plants in our inventory grouped by current status, type of plant, type of energy data and availability of geo-reference for either the powerhouse, intake or dam location. (C) Circle outlines in the map indicate location and status for only the visualized plants with geo-referencing. Yellow circles show the theoretical RoR potential along 500 m river segments across the upper Indus. Circle sizes indicate the energy generation at each plant in GWh per year. Check our story map for an interactive map.

**Table 5**
Design discharge thresholds for the three plant configurations for sensitivity analysis. RP = River power plan, DP = Diversion canal plant and QXX = flow exceeded xx % of the time.

| Plant configuration | | (–) | Default | (+) |
|---|---|---|---|---|
| RP | | Q50 | Q40 | Q30 |
| DP | Large | Q40 | Q30 | Q25 |
| | Small | Q90 | Q80 | Q70 |

segment < 20-km with the average plant size for these cases falling below 50 MW. When the search distance is large, identification of large plants is prioritized and vice versa [14]. Coarse analysis misses out on the energy that can be generated by utilizing discharge where it is generated in between the segments. This effect will be smaller for small segments or for river basins where discharge does not change considerably with elevation. Nonetheless, Fig. 3 also shows that hydropower in the UIB will be maximized by using a combination of small and large plants to utilize the steep elevation and high discharge across the basin.

**Table 6**
Values for seven parameters for one-at-a-time sensitivity analysis. Reservoir storage limit is applied as a percentage to the annual average discharge volume while environmental flow is applied to the monthly discharge.

| | Parameter | Configuration | (–) | Default | (+) |
|---|---|---|---|---|---|
| 1 | Minimum head (m) | Small DP | 5 | 20 | 35 |
| 2 | Generation Efficiency (%) | Small DP | 70 | 80 | 90 |
| 3 | | Large DP | 75 | 85 | 95 |
| 4 | | RP | 80 | 90 | 100 |
| 5 | Reservoir storage limit (%) | RP | 2 | 5 | 10 |
| 6 | Interest rate (%) | RP & DP | 5 | 10 | 15 |
| 7 | Environmental flow (%) | RP & DP | 20 | 30 | 40 |

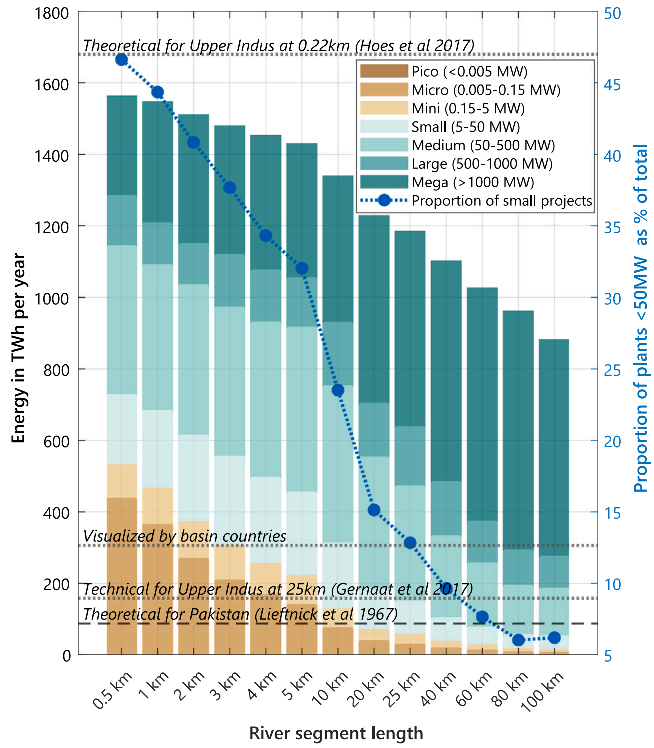


**Fig. 3. Variation in the size of hydropower plants in the theoretical potential portfolio as a function of river segment lengths ranging from 0.5–100 km.** The stacked bars show the cumulative theoretical potential for seven hydropower plant size classes [115] while the blue line shows the proportion of small plants < 50 MW as a percentage of the total. We use plant capacity based hydropower classes recommended by Siddiqi et al. [115] and convert the MW to TWh/yr assuming year round production at full capacity.

### *3.3. Technical, financial and sustainable potential*

#### *3.3.1. Energy focus scenarios*

Only a small portion of the theoretical potential (Fig. 4A) can be realized by the three energy focus scenarios. The mixed focus scenario has the highest potential for both RP and DP plant configurations with technical, financial and sustainable potentials totalling 300 (19% of theoretical), 266 (17%) and 90 (6%) TWh/yr respectively. The medium focus scenario has slightly lower values with technical, financial and sustainable potential at 264 (18%), 188 (12%) and 64 TWh/yr (4%). The potential in the large scenario is even lower with the sustainable potential being only a third of the mixed scenario at 32 TWh/yr (2%). Exclusion of existing hydropower plants under remaining potential results in a larger decline in the RP potential (9.7–46 TWh/yr) than in the DP potential (0.4–9.8 TWh/yr) but only a small decline in the number of plants. The decrease can be attributed to the existing large storage plants in the Indus. These plants in the high flow streams in the south (Fig. 2) currently generate about 35.5 TWh/yr which is comparable to the difference between full and remaining RP potentials.

The spatial distribution (Supplement B.4) and number (Fig. 4A) of RP and DP plants vary under the three scenarios. Under the large scenario, RP plants are generally concentrated along the main tributaries while some RPs emerge in secondary streams in the medium scenario. RP potential dominates the large and medium scenario but is comparable to DP potential in the mixed scenario. The number of plants increases drastically in the medium and mixed scenarios because of the finer river segmentation. Especially in the south, many small plants emerge to use the elevation changes between the mountain and the plains. The number of DPs is much higher than RPs in the mixed scenario because it prioritizes DPs in secondary and tertiary rivers that make up 94% of the streams while only the primary rivers (6% of streams) are open to RPs. Between the technical and sustainable potential, the density of plants decreases throughout the basin and especially in the northeast where the geo-hazard risk is high. However, unlike in the large and medium scenario, the number of RPs in the mixed scenario remains similar under technical, financial and sustainable potential indicating that the financial and sustainability criteria result in smaller RPs here. Therefore, the mixed scenario combining small and large plants best utilizes the variation in theoretical potential (Fig. 3) to maximize these potential classes.

Fig. 4B explores the 70% decline from technical to sustainable potential under the mixed scenario as various financial and sustainability constraints are applied. The addition of a cost threshold reduces the technical potential by about 11%. Thereafter, addition of sustainable discharge constraints (other water uses) results in a 28% drop, mostly attributable to e-flow requirements. Next, exclusion of heritage areas and areas with very high geo-hazard risk reduces the technical potential by 6% and 24% respectively. Sustainable discharge causes a higher reduction in RP potential than DP while, the other constraints cause a higher decrease in DP potential. Overall, other water uses and geo-hazard risk aversion emerge as major bottlenecks for sustainable hydropower development. Note that the gap between technical and financial potential is much higher in the large and medium scenario as compared to the mixed scenario because their cost curves (Fig. 8) are much steeper with individual plant costs changing rapidly. Financial constrains may be more important for these.

#### *3.3.2. Geo-hazard risk representations*

In Fig. 4B, the combined impact of the three geo-hazards on hydropower potential under the risk-averse representation causes a 72 TWh/yr drop in potential. In contrast, Fig. 4C, accounting for earthquake, landslide and GLOF individually lowers the potential by 6, 11 and 53 TWh/yr respectively. Though both landslide and earthquake risks are above "Medium" level for nearly 80% of the basin, landslide emerges as the dominant geo-hazard as landslide risk areas fall in high hydropower potential areas of the Indus main. The impact of all geo-hazards together is also higher than the sum of the individual geo-hazards because the geo-hazards risks do not necessarily coincide spatially (SupplementB.2). Due to the spatial variation in the three geo-hazard susceptibilities, there is notable difference in the maximum- and multi- hazard risk maps (Supplement B.3). In the multi-hazard risk map, only about 2% of the UIB falls in the "High" or "Very high" category. In contrast, in the maximum-hazard risk map nearly 45% falls under the "Medium" category and 8% falls in the "Very high" category. These show that the majority of the UIB is at risk for a single disaster while few areas are at high risk for multiple disasters.

Fig. 4D shows the total potential when using the maximum- or multi- hazard risk maps under the three geo-hazard risk representations. The cost-based risk representation increases the default mixed sustainable risk-averse potential by 78% to 161 TWh/yr while multi-hazard representation causes a 68% increase. These correspond to a 39% and 45% drop from financial to sustainable potential as opposed to the 66% drop in the risk-averse case. The risk-averse representation has only half as much DPs, in both potential and number, than that in the cost-based and multi-hazard representations because many small DP plants in the north are rejected under the risk-averse representation (see Supplement B.5). In contrast, changes in RPs are subtle with a few big plants being added when hazard constraints are relaxed in the cost-based or multi-hazard representation. As such, multi-hazard risk representation provides a middle ground by preventing hydropower development in high multi-hazard risk areas and requiring higher investment in disaster mitigation and regular maintenance in areas with single-hazard risks.

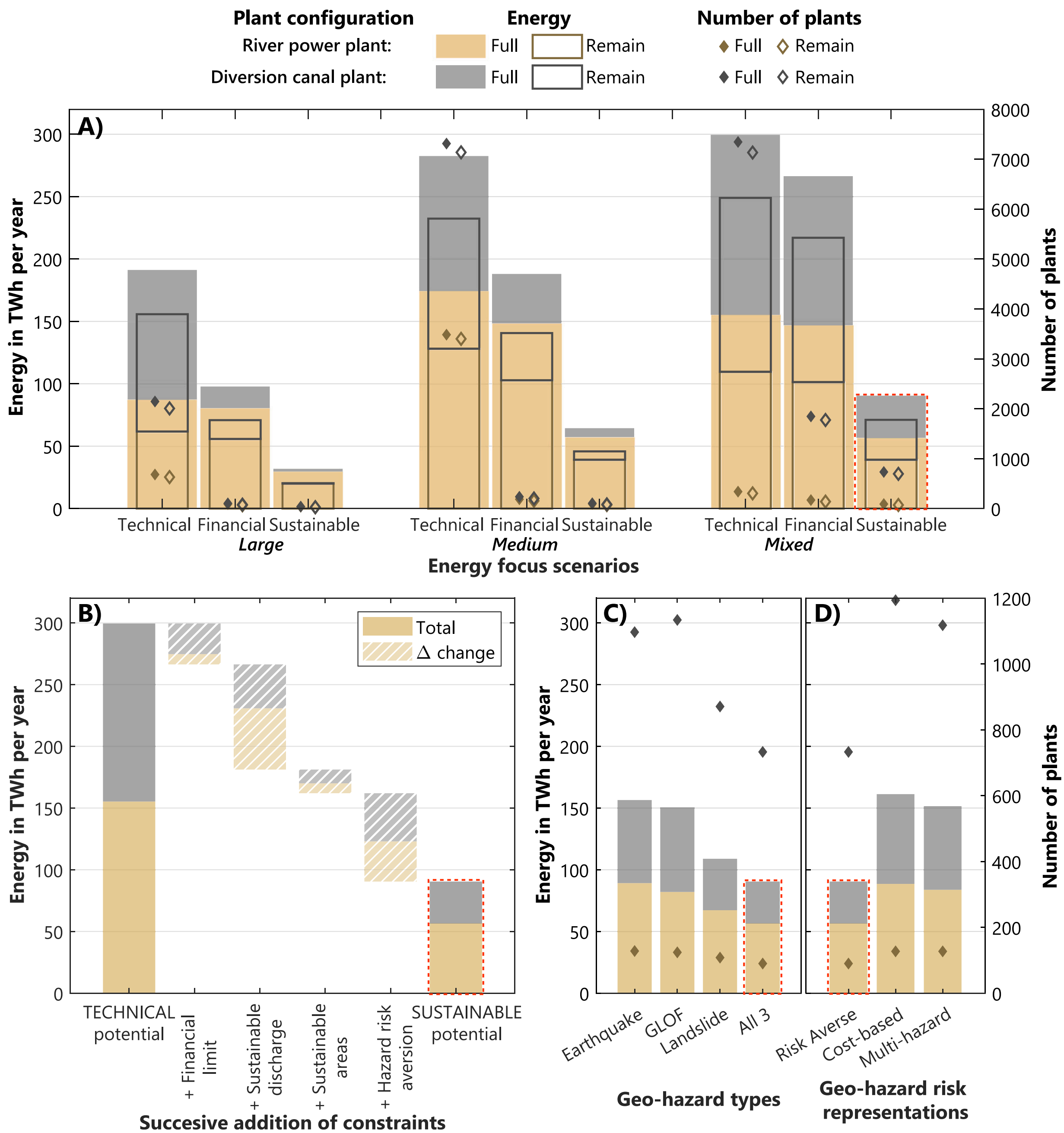


**Fig. 4.** Total energy (bars) and number of plants (⋄) for two RoR plant configurations under various scenarios. (A) The three energy focus scenarios considering full and remaining potential with risk-averse geo-hazard representation. (B) Drop in total potential with successive addition of constraints moving from technical to sustainable case. (C) Change in the mixed sustainable potential if considering the three geo-hazards separately and all together (D) Change in mixed sustainable potential for three hazard risk representations. The common denominator across (A)–(D) is the mixed sustainable potential with risk-averse representation highlighted by the red dotted line.

### *3.4. Sub-basin energy potential*

Although the magnitude of visualized potential (Fig. 5A) is nearly a fifth of the theoretical potential (Fig. 5B), the spatial distribution is similar across all sub-basins except Kabul. Among the sub-basins, the Indus main has the highest theoretical potential and visualized potential covering 39% (616 TWh/yr) and 52% (159 TWh/yr) of the potentials at the basin level and the lowest sustainable potential covering only 15% (13.2 TWh/yr). The visualized potential of the Indus main is 26% of its theoretical potential, far exceeding its technical (9%), financial (7%) and sustainable (2%) potentials (see Graphical Abstract). Many of the visualized storage plants in the UIB lie in the Indus main, so it is reasonable that visualized potential here exceeds the modelled RoR potentials. In all sub-basins except the Indus main and Beas, visualized potential remains within the extent of technical potential. Alongside, in all sub-basins except Kabul and Swat, the visualized potential exceeds the sustainable potential. This raises the concern that current plans are within technical limits but may not be adequately considering sustainability.

The Jhelum and Chenab sub-basins follow after the Indus main in the theoretical and visualized potential. Moreover, in Fig. 5C the Jhelum sub-basin dominates the technical, financial and sustainable potential covering 69, 64 and 24 TWh/yr, with some of the highest sub-basin RP potentials (Fig. 5B). These make Jhelum the most utilized sub-basins commensurate with its high sustainable potential. The Kabul sub-basin has the fourth-highest theoretical potential (191 TWh/yr)

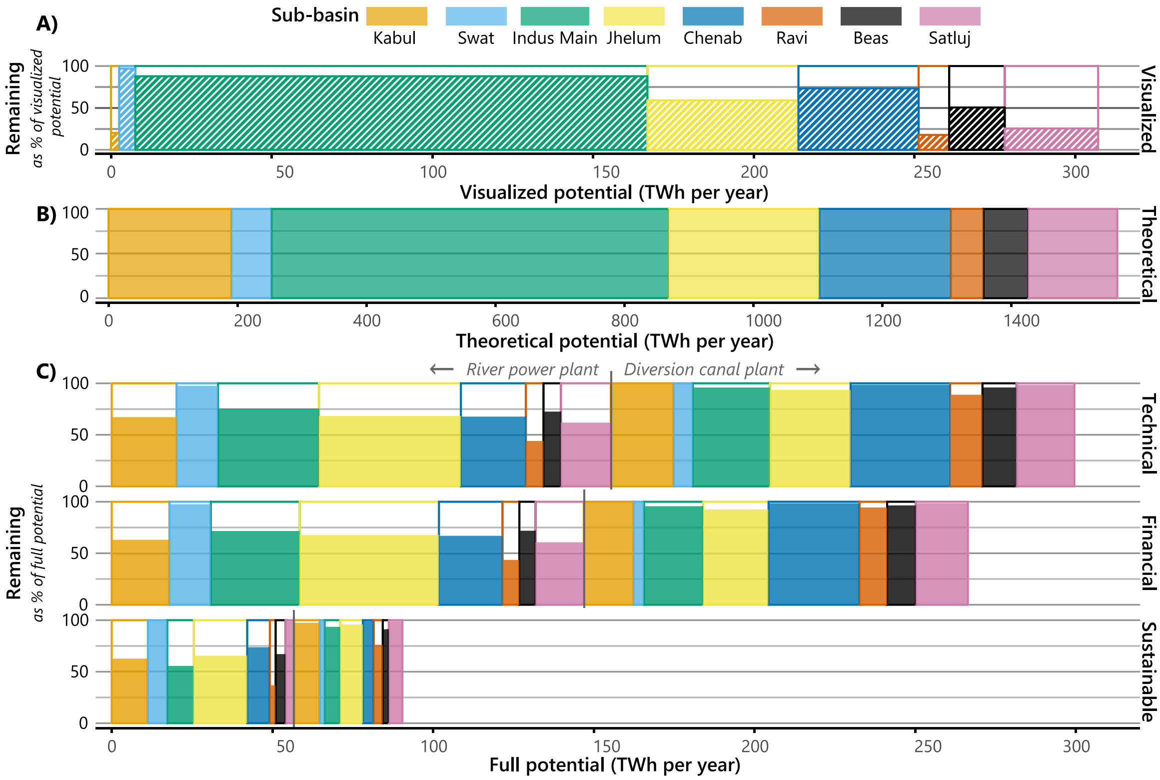


**Fig. 5. Full and remaining sub-basin hydropower potential under the five classes.** (A) Visualized potential from the hydropower inventory considering only plants which are geo-referenced. The magnitude of visualized potential is indicated along the *x*-axis while the remaining potential after excluding the existing plants is indicated as a percentage of the visualized along the *y*-axis. (B) The theoretical RoR potential estimated along 500-m river segments is indicated along the *x*-axis. (C) Technical, financial and sustainable RoR potential for the mixed scenario with risk-averse geo-hazard representation estimated by our cost-minimization model. The magnitude of full potential is indicated along the *x*-axis while the remaining potential is indicated as a percentage of the full potential in the *y*-axis. The hydropower potential estimated for river power and diversion canal plants are shown separately.

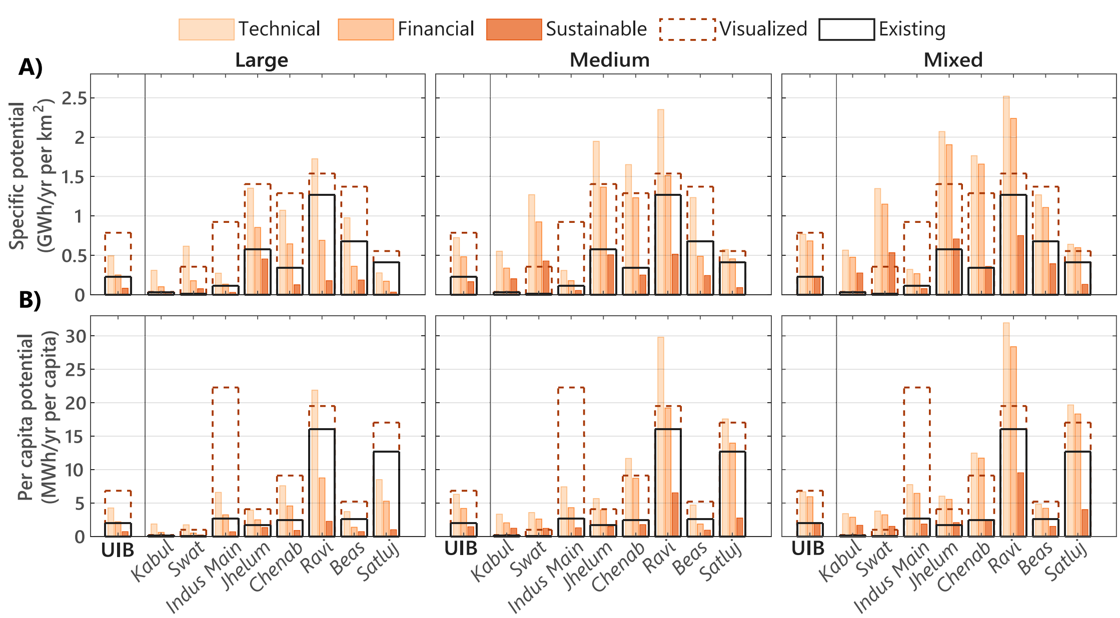


**Fig. 6. Per area and per capita energy potential**. Modelled technical, financial and sustainable potential for the three energy focus scenarios with risk-averse geo-hazard representation. The solid black line is the existing hydropower and the dotted brown line is the visualized potential.

and second-highest sustainable potential (19 TWh/yr) after Jhelum, but it has the lowest visualized potential. The existing potential (0.15 TWh/yr) in the Swat sub-basin also is very small compared to its sustainable potential (7.5 TWh/yr).

The difference between remaining and full RP/DP potential further illustrates the scope for hydropower expansion across the sub-basins. In Fig. 5A, excluding the Kabul sub-basin, the remaining visualized potential decreases as we move from west to east in the UIB. The majority of visualized potential in the Satluj and Ravi sub-basins is already utilized. In Fig. 5C, the full technical, financial and sustainable potential are higher for RP than DP for the western Kabul, Swat, Indus Main and Jhelum sub-basins. However, for remaining potential, DP is higher than RP for a majority of the sub-basins. Over 90% of technical, financial and sustainable potential is remaining in all sub-basins for DP, except for the Ravi sub-basin where 76% remains for the sustainable potential. In contrast, only about 37% of RP sustainable potential is remaining in the Ravi sub-basin. Meanwhile, in the Swat sub-basin, nearly 100% of both the RP and DP potential remains. The RP potential here is four times higher than the DP potential for the financial and sustainable case. The other basins have a remaining RP potential ranging from 56%–98%. Surprisingly, the relatively small 2 TWh/yr existing hydropower in the Kabul sub-basin lowers the remaining RP potential to over 60% for all three potential classes indicating that the existing plants in Kabul may be suitable for further expansion.

Fig. 6A and B show the per area and per capita energy potential under the three energy focus scenarios. The sub-basin patterns across the three scenarios are similar but values for the mixed-scenario is the largest. At the UIB scale, the energy availability ranges from 0.23–0.79 GWh/yr per $km^2$ and 1.98–6.84 MWh/yr per capita for the five potential classes under the mixed scenario. However, the per capita potential across the sub-basins has a wider range from 0.01–2.52 GWh/yr per $km^2$ and 0.03–31.94 MWh/yr per capita. The Ravi sub-basin is the smallest and the least populated, but has high elevation changes in the south. Hence, it has the highest per area and per capita values for the modelled technical, financial and sustainable potential as well as the visualized potential (Fig. 6A). The Jhelum sub-basin has the second-highest energy per area for the modelled potential. The Chenab sub-basin ranks third for both technical and financial potential, but it drops to the fifth rank for the sustainable potential after the Swat and Beas sub-basins. Due to high landslide and earthquake risks in Chenab, many areas within the sub-basin are constrained under geo-hazard risk aversion. The larger sub-basins (Satluj, Kabul and Indus main) have lower per area potential.

The Ravi, Satluj, Chenab and Indus main sub-basins have the highest per capita energy potential while the Kabul, Swat and Beas sub-basins have the lowest (Fig. 6B). For instance, the Satluj sub-basin is the third largest sub-basin but has some of the lowest population resulting in high per capita potential. The opposite applies to the populous Kabul basin. Not surprisingly, modelled per capita potential is markedly higher than visualized in Swat and Kabul. However, note that the visualized inventory has higher uncertainty for Kabul compared to other sub-basins due to the lack of publicly available data on hydropower in Afghanistan. Overall, the basin-level patterns for the energy potential and energy availability should not be generalized spatially as notable differences exists, also between the DPs and RPs. There is low utilization of potential in the Kabul and Swat sub-basins, high utilization in the Indus Main sub-basin and a reasonable balance in the other sub-basins.

### 3.5. Characterization of hydropower potential portfolios

Here, we explore the range of cost and energy potential of optimal plants under the technical and sustainable portfolios without any financial constraints. In Fig. 7, for both DP and RP plants the unit production cost declines exponentially with increasing size. The cheapest plants are large RPs while the most expensive ones are small DPs. Fig. 7B demonstrates the median cost of plants in all three scenarios lies above the financial limit of 0.10 USD/kWh. The mixed portfolio shows the smallest production costs with the lowest median and range for both DPs and RPs. Over 17% of plants in the mixed portfolio cost ≤0.10 USD/kWh, but the proportion drops below to 4% for the large and medium portfolios.

There is a visible shift in the mixed DP costs in Fig. 7A because we use separate cost functions for small and large plants which lowers the DP median cost. Without such differentiated cost functions, small DPs will have high costs similar to DPs in the medium scenario. The lowering of RP median cost is due to a reduction in the number of RP plants as the mixed scenario only allows large RPs to be built. In contrast, the medium scenario allows development of RP plants throughout the basin and hence identifies many small RPs with relatively high costs.

Fig. 7C demonstrates that the mixed scenario has more variability in plant size than the large and medium scenarios. The large scenario with 25-km segments results in larger DPs and RPs while the mixed scenario with 2- and 4-km segments results in the lowest median potential for DPs and highest median for RPs. Additionally, the whiskers for the mixed scenario for DPs cover the range for the large and medium scenarios. Thus, the use of variable river segmentation results in a balanced mix of small DPs, large DPs and large RPs.

### 3.6. Cost curves

Fig. 8A presents cost curves for the technical and sustainable potential. The threshold for financial potential is indicated by the 0.10 USD/kWh line. For all three energy scenarios, the sustainable cost curves reach their asymptotes faster with steeper slopes and lower cumulative energy than the technical cost curves. The addition of sustainability constraints results in a smaller number of plants that are more expensive than the corresponding technical portfolio. Between the scenarios, the large scenario cost curves are the steepest because of large expensive projects while the mixed scenario curves are shallow with smaller and cheaper plants. Here, as also seen in Fig. 7, the combination of smaller and cheaper plants in the mixed scenario allows for higher energy production at the same cost than the large and medium scenarios. For instance, if 50 TWh/yr of cumulative energy is to be developed, the cost curves indicate that the mixed technical scenario provides the cheapest options costing below 0.02 USD/kWh. Producing the same energy level sustainably, will cost below 0.05 USD/kWh under mixed case while the large case will cost over ten times more for the risk-averse representation. The shape of the cost curves for the three scenarios also provides an indication of the relative sensitivity of the portfolios to increases in the threshold for financial potential (Fig. 8). This sensitivity may be lower for large and medium scenario as the cost curve is steeper. In contrast, small changes in costs will bring bigger changes in the cumulative potential for the mixed scenario.

Between the three hazard representations, the risk-averse scenario is most expensive as many plants located in high single hazard risk areas are excluded from the portfolio. The cost-based scenario appears the cheapest indicating that plants remain financially feasible even after additional costs for hazard mitigation. In contrast, the multi-hazard representation results in a smaller area being excluded than in the risk-averse scenario, hence there is a left-ward shift in the curve indicating lowered total potential but limited changes in costs. This implies that high hazard risk areas are also cheaper hydropower potential areas highlighting the need for policy regulation to ensure these are not developed haphazardly. At minimum, the multi-hazard representation should be considered to ensure a better balance between geo-hazard risk minimization and hydropower development beyond cost consideration.

Fig. 8B presents the sub-basin wise cost curves under the mixed sustainable scenario. The Jhelum, Kabul and Indus main sub-basins have the lowest production costs with shallower slopes under 0.10 USD/kWh. These also have some of the bigger plants and the highest number of plants in their portfolio. However, the median plant size across the sub-basin is largest for the Ravi, Satluj and Indus main sub-basins. Meanwhile, the Ravi, Beas and Satluj sub-basins have steeper cost curves that already reach their asymptotes before 0.10 USD/kWh. Hence, sustainable and financial potential in these sub-basins will be less sensitive to cost changes while those in the larger basins will vary

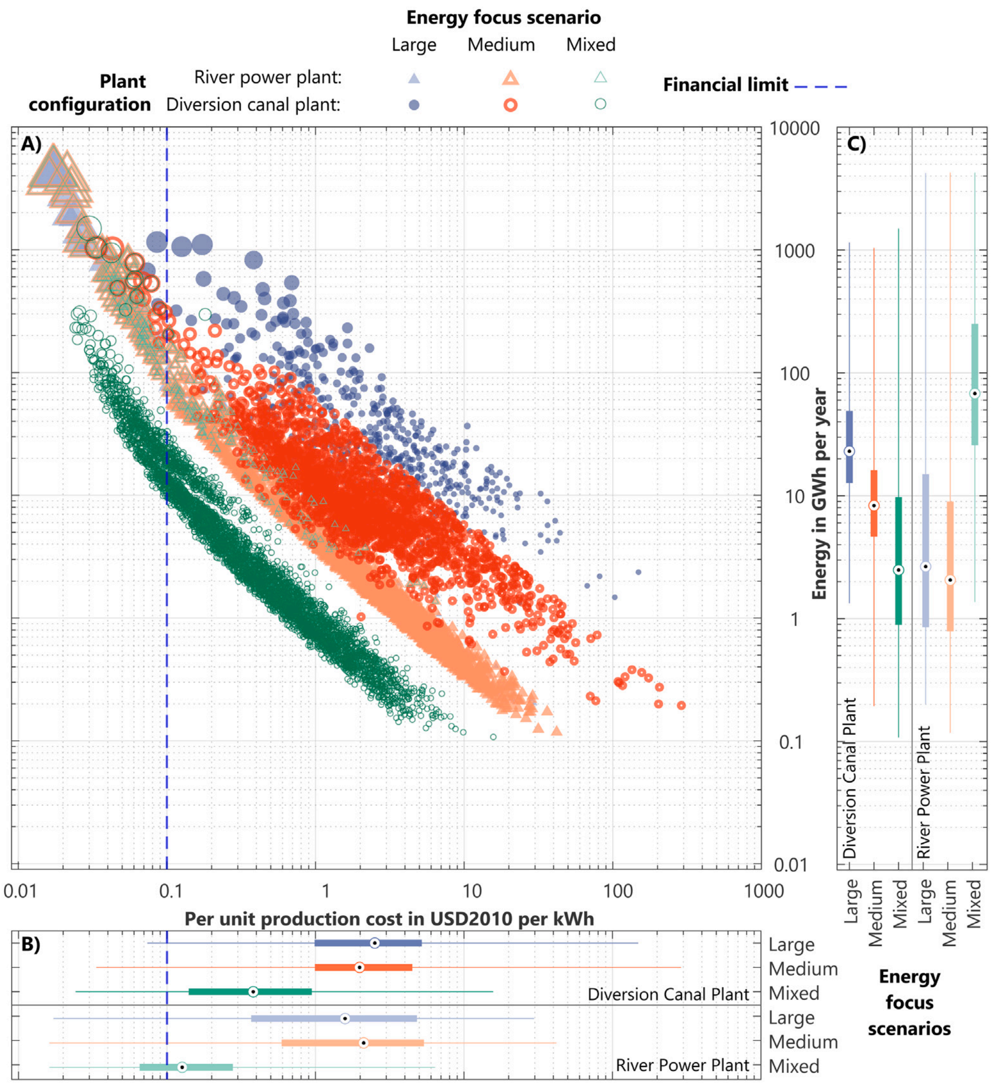


**Fig. 7. Distribution of production cost and energy potential for the sustainable potential portfolio for the three energy focus scenarios.** The colours distinguish the three energy focus scenarios while colour shades distinguish between RP plants (lighter) and DP (darker) configurations.

with change in the threshold. The Jhelum, Indus Main and Chenab sub-basins initially have ample scope for RP plant development followed by a jump in price after the initial large plants are built. In contrast, the cost curves for the Kabul and Swat sub-basins do not have such a large scope at the low-cost range, but this scope improves above a cost price > 0.05 USD/kWh. If we consider the sub-basin cost curves under the mixed technical scenario, the Jhelum sub-basin has the highest cost-effective potential followed by the Chenab, Indus main, Kabul and Satluj sub-basins. Possibly the visualized potential is high in the Jhelum, Chenab and Indus main (Fig. 5) as compared to the other sub-basins because of their cheaper technical potentials.

### 3.7. Sensitivity analysis

Changes to mixed sustainable potential under risk-averse geo-hazard representation ranged from −22 to +14% for changes in design discharge and from −15 to +13% for other parameter changes (Supplements A.1, A.2). Sustainable potential is most sensitive to design discharge, e-flow and interest rate. But, sensitivities vary for the different HP configurations. RP is most sensitive to decreases in design discharge, followed by any changes to e-flow requirement, RP efficiency and interest rate. DP has similar sensitivity to increase or decrease in design discharge, followed by interest rate, DP efficiency and e-flow requirement. The number of plants is most sensitive to interest rate while small DP efficiencies are more important than large DP. Both of these observations can be attributed to the many small plants whose unit costs are close to the financial potential cut-off (Fig. 7). However, the changes in mixed potential under these sensitivity analysis runs are much lower than the differences between the mixed potential across the energy (−65 to −29%) or the geo-hazard scenarios (+68 to +78%). Thus, policy assumptions are more significant than parameter assumptions. Full discussion of the sensitivity analysis is in Supplement A.

## 4. Discussion

### 4.1. Comparison with past assessments

In Table 7, we compare our hydropower potential estimates to the estimates from the few other hydropower potential studies that

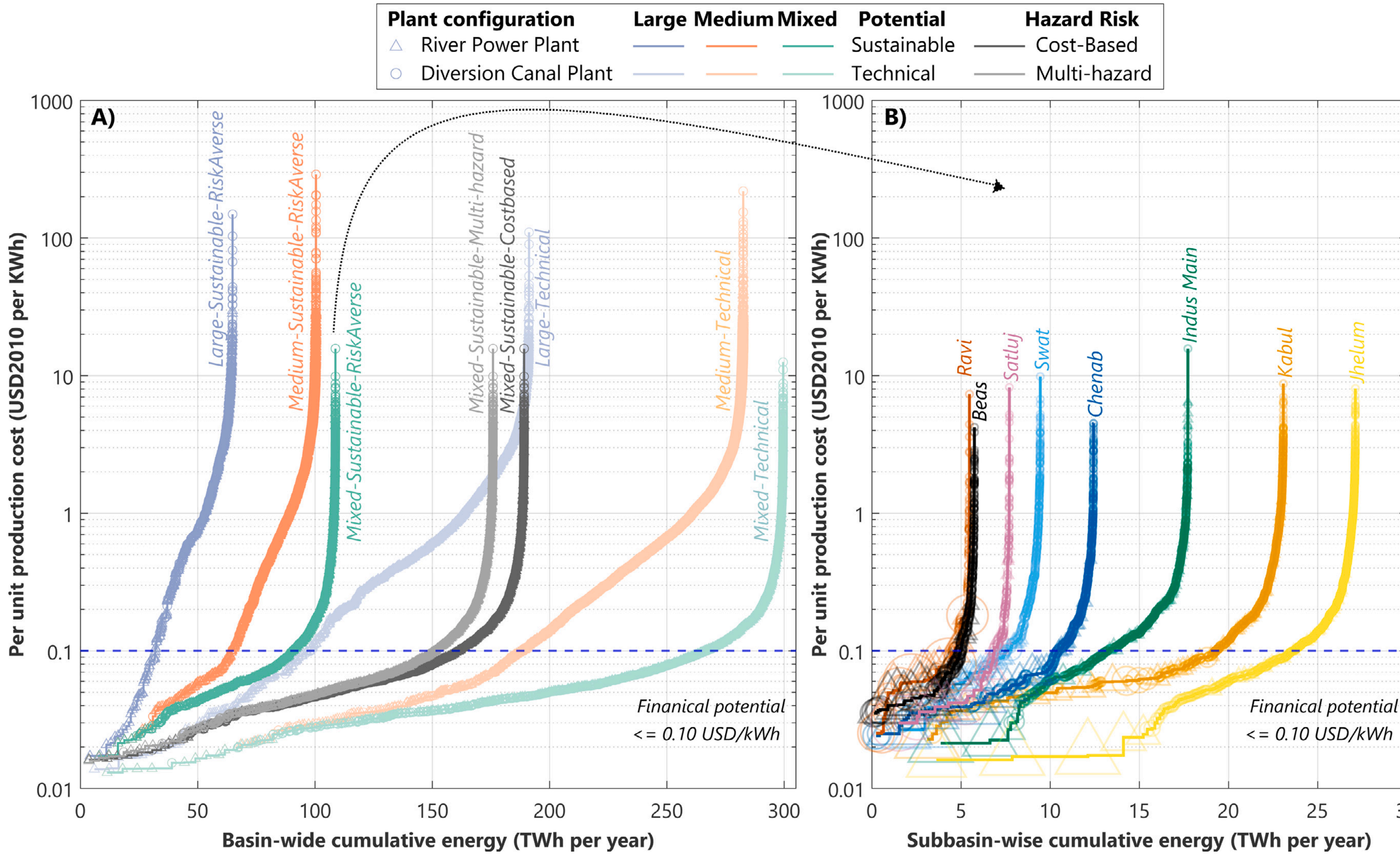


**Fig. 8. Cost curve for development of hydropower plants.** (A) Basin-wide cost curve for the UIB under the five main energy and hazard representation scenarios differentiated by colour. Lighter colours show the technical potential portfolios while darker colours show the sustainable portfolios. (B) Sub-basin wise cost curves for the eight sub-basins of the UIB Indus under the mixed sustainable potential portfolio. Symbol sizes indicate relative potential for each plant in the portfolio.

cover the Indus basin. Our theoretical potential is comparable to the theoretical potential estimates by Hoes et al. [14]'s global assessment at similar resolution. Naturally, our estimates are much higher than the crude estimates by Lieftinck et al. [116] based on average discharge and elevation for the entire Indus basin. Furthermore, our full technical potential under the large focus scenario is higher than that for a comparable scenario by Gernaat et al. [15], however our financial potential is lower (Table 7). The former is as expected and can be attributed to the improved discharge simulation by our higher resolution cryosphere-hydrology model and better representation of steep elevation gradients in our high-resolution analysis. The latter lower financial potential can be attributed to the increase in plant costs in our localized representation due to addition of locally relevant cost factors (e.g de-sanding basin, road access, community compensation, forest loss and distribution). Nonetheless, it remains challenging to compare estimates of resources assessment models like HyPE because potential assessments for the same study area using the same methods are rare. The lack of a standardized definition and assessment methods for hydropower potential classes as well as subjective choices on hydropower design parameters and spatio-temporal resolution can add considerable difference between studies even at global scale [117]. Given these factors, our estimates can be considered reasonable when compared to past studies. A comparison of our basin scale approach with on-site data collection would provide further validation to the results. However, on-site survey is beyond the scope of our study and infeasible at the basin scale.

### 4.2. Limitations

Hydropower is a flexible technology with many possible configurations [98,118]. The visualized hydropower inventory also includes a wide variety of plants with or without dams, reservoir or diversions and plants on irrigation canals. There are also plants with multipurpose, multi-stage or inter-basin transfer configurations. For example, Tarbela has five stages while Sherqilla and Misgar powerhouses have multiple small canals pooling water from different sides of the hill. However, our model only captures two RoR plant configurations underestimating potential achievable by other configurations. Hence, some sustainable potential estimates lie below the visualized potential value. Nonetheless, our approach already expands search algorithm complexity to go beyond past studies covering only one plant configuration for small or large plants [30–32,119]. The model could be further expanded by including search algorithms for other plant types [33,120–122].

Many parameters (Table 3) in the model are currently based on stakeholder inputs. Dis-aggregating the visualized potential inventory further by plant configuration can help improve technical and financial parameters. For instance, thresholds used for design discharges, plant efficiency and reservoir limits could be based on dominant characteristics in the existing portfolio. UIB specific cost functions could be developed based on representative RP and DP plant costs to replace those from US and Norwegian hydropower industry here. However, consistent categorization of plant configuration is missing with no standardized definition for the classification of hydropower plant configurations even at the global scale [98,118,123]. Standardized hydropower definitions will be a key starting point to enable consistent data collection in hydropower inventories and their subsequent use to inform local or global hydropower exploration models.

Higher spatio-temporal resolution data, especially discharge [49], will allow for better representations of even the RP and DP plants. Fixed river segments is a constraint imposed by the data resolution that we partly overcome by differentiating the segmentation across three river classes in the mixed scenario. Still, for RPs, only the outlets of the fixed segments are tested by the cost-minimization. Viable points may also exist in between segments, especially in the large scenario with 25-km segments. As finer discharge data becomes available, algorithms like that of Garegnani et al. [30] at 100-m can be applied to split rivers into optimal segments to maximize RoR hydropower production. Similarly, for DP, we consider the shortest Euclidean distance between the inlet and outlet to perform cost-based sizing of the penstock. Especially in mountainous regions like the UIB, small plants will combine a headrace canal tracing the hillside topography for long distances before feeding into a shorter and steeper penstock on the optimum hill-slope to maximize production as done by Müller et al. [124]'s algorithm at a finer 30-m resolution. Using daily instead of monthly discharge to assess design flows and capacity factor would improve turbine sizing, e-flow requirements and hydropower production. Furthermore, the use of an ensemble of hydrological models can allow for a quantification of the propagation of uncertainty from hydrological simulation to the estimation of hydropower potential.

Additionally, the use of long-term monthly average discharge data for plant sizing in the HyPE algorithm may not sufficiently capture the variability and trends in discharge over time. Past analysis of historical streamflow data from observation stations show that annual and seasonal trends vary between the glacier-fed and snow-fed sub-basins of the Indus. Reggiani and Rientjes [125], Liaqat et al. [126] find a statistically insignificant decrease in annual discharge at the UIB outlet station while a decreasing or stable trend is found in high-altitude glacier-fed catchments. For lower-altitude catchments in the southeast, studies agree on an increasing trend in discharges and decrease in the southern sub-basins [125–128]. Overall, these studies find increases in the annual discharge while the winter and spring discharges show slightly rises and the summer shows a declining trend through the magnitude and significance of trends vary across the stations. Such trends will alter the hydropower potential estimated in our study for average flow conditions. Furthermore, we only considered hydropower potential under historical hydro-climatology even though future projections for the UIB already show that these trends in discharge variability may exacerbate under future climate change [44,129]. Analysis of the impact of climate change on future discharge and hydropower potential is imperative for hydropower planning and is addressed in a concurrent study [130].

Our choice of datasets to represent geo-hazard risk also poses important limitations that should be improved in future work. We define geo-hazard risk based on susceptibility maps that classify the relative likelihood of geo-hazard occurrence based on geo-physical characteristics. For landslide and earthquake, these are derived from the reclassification of global landslide susceptibility and earthquake seismicity maps. However, these susceptibility maps do not consider the intensity, frequency and timing of these disasters. For instance, the comparison between the susceptibility maps and historical occurrences of landslides and earthquake in Supplement B.2 shows that the susceptibility maps capture areas of geo-hazard occurrence well. What is critical however is that the low-medium risk areas show a higher number of historical occurrence. As stakeholders have argued in our discussions [102], in a geo-hazard prone area like the Indus it is imperative to consider risk beyond susceptibility. It remains a larger scientific challenge to quantify the risk of geohazards to hydropower development also considering both the intensity and frequency of geo-hazards. On the other hand, for GLOFs we consider only potentially hazardous glacial lakes as high risk when recent GLOFs in South Asia have also occurred outside these lakes [47]. Hence, all glacial lakes should be considered to represent GLOF risk with different risk classes differentiating between glacial lakes that are considered potentially dangerous. New datasets now available on historical occurrences of GLOFs [131] and avalanches [132] in the high mountain Asia can also be included to improve the geo-hazard risk representation.

Dhaubanjar et al. [28] enlist other datasets that can be added to HyPE to expand the consideration for sustainability in trans-boundary context and application of our framework to other basins. Specially environmental sustainability is limited here to preserving e-flows and protected natural habitats. These help minimize environmental impacts

**Table 7**
Estimates of various classes of hydropower potential for the Indus basin in literature.

| Sources | Hydropower potential | | | Method |
|---|---|---|---|---|
| | Rated capacity (MW) | Energy (TWh/yr) | Type | |
| Lieftinck [116] | 10,000 | 87.6* | Theoretical for entire Indus | • Average annual basin discharge weighted by average elevation |
| Hoes et al. [14] | – | 1679 | Theoretical for upper Indus | • Discharge-weighted elevation difference method applied at 7.5” river segment length at global scale to identify sites with potential<br>• GMTED2010 7.5” DEM used with runoff data from the UNH-GRDC Composite Runoff Fields V1.0 dataset<br>• Uses plant capacity factor of 50%<br>• Considers head drop >=1 m, discharge>=0.1 $m^3/s$ and projects >= 1 KW |
| Gernaat et al. [15] | – | 158 | Technical for upper Indus | • Optimized design discharge-weighted elevation difference to minimize per unit cost of production for individual projects applied at 25 km river segment length at global scale |
| | – | 126 | Economical for upper Indus | • HydroSHEDs 15” x 15” DEM used with 0.5°× 0.5° monthly runoff data (30 yr average 1970–2000) from the hydrological LPJmL model |
| Vinca et al. [103] | – | Not reported | Technical | • Design discharge-weighted elevation difference applied at 5 km segment length<br>• Assumes penstock length < 3 km based on trends in the basin<br>• Only considers projects > 1 MW |
| This study | 1,78,600 | 1564 | Theoretical | • Discharge-weighted elevation difference method applied at 500 m river intervals |
| | – | 191–300 | Technical | • Optimized design discharge-weighted elevation difference to minimize per unit cost of production for individual projects |
| | – | 98–266 | Financial | • Considers major technical cost components alongside constraints on other usage of water and land as well as geo-hazard risk |
| | – | 32–90 | Sustainable | • Value ranges for three energy policy scenarios with varied river segment length and search radiuses |

* Energy is estimated from reported power levels assuming 24 hr runtime and 100% efficiency.

at individual plant level. The cumulative impact of multiple plants on river connectivity and sediment transfer disrupts biodiversity habitats as well as human livelihoods [20,23,133]. Grill et al. [134]'s riverine connectivity indices may provide a way forward to incorporate such impacts in basin-scale hydropower exploration. Ultimately, incorporating better datasets may provide higher trade-offs with added computational intensity than supporting more plant configurations for a reconnaissance assessment.

### *4.3. Standards for sustainability*

A larger question our analysis raises is what sustainability means in hydropower development. Even within our narrow technical representations of sustainability, stakeholder discussions revealed that thresholds for sustainability are subjective. Given the high probability of geo-hazards across the UIB, hydropower developers and even some locals consider acceptable risk levels higher than those set by global assessments or environmentalists. Similar negotiations occurred in our discussions on e-flow levels. In contrast, prevention of hydropower development within protected areas was less contested. This demonstrates that sustainable hydropower development will require setting some binary constraints to avoid irreversible impacts as done for e-flows here. Other constraints will have to be flexible allowing stakeholders to balance costs with ensuing benefits as done for geo-hazards in the case of multi-hazard risk representation. Given the observation that high hazard risk areas are also some of the most cost-effective hydropower potential areas (Fig. 8), it is imperative that regulations are stricter here and more relaxed elsewhere. But first, as Mayeda and Boyd [34] point out, there is a need to establish a common understanding of the social, political, technical, economical and ecological risk from hydropower and define acceptable indicators of sustainability. Thereafter, binary or non-binary thresholds should be set for each indicator based on negotiating locally or globally acceptable values. Else, status-quo hydropower development will continue under increasing pressures for green energy expansion.

To some extent, the Hydropower Sustainability Assessment Protocol (HSAP) provides indicators to assess sustainability of individual plants. But this differs from our basin-scale perspective evaluating the most sustainable sites for hydropower development considering spatial variation in site conditions such as geo-hazard risk or water availability.

For such strategic planning, sustainability needs to be defined more holistically to consider the trade-offs and synergies between our basin development priorities and subsequent land and water allocation for hydropower versus other usage. Moreover, as Ahlers [37] argue, sometimes sustainable solutions may be those that "produce benefits that are less impressive but more realistic, more reliable, faster, and possibly cheaper and result in fewer negative impacts". Hence, sustainability needs to look beyond just least-cost addition of hydropower capacity with technocratic models. Quantitative assessments like ours should be supplemented by emerging qualitative assessment of hydropower portfolios to also consider socio-political parameters such as affordability, intra-generational equity, transparency and accountability to promote equitable and sustainable hydropower development [11,35,36]. Ultimately, hydropower decisions affect geopolitics, power relations and subsequent resource allocation at the societal scale [21,35,36,135]. Thus, sustainability must be considered at the system-scale using quantitative models, qualitative assessments and regulatory frameworks to capture the multi-faceted implications of hydropower development across the basin.

### 4.4. Implications for hydropower development in the Indus

Despite many limitations, our high-resolution quantification of five classes of hydropower potential provides many insights for incorporating IRBM in sustainable hydropower expansion in the UIB. The technical, financial and sustainable potential portfolios identify ideal locations for hydropower plants of varying sizes, costs and configurations. Our approach demonstrates how emerging datasets can already be used to broaden the set of evaluation criteria for hydropower development. At the plant scale, while the optimization of cost and configuration comes with uncertainty, the identified sites provide definitive guidance on where future hydropower can be developed. How and when these sites should be developed needs further analysis considering the objectives for hydropower development and IRBM. For instance, DP plants that are expensive but in important locations could be developed cheaper under other plant configurations. Some RP sites lying outside the areas restricted by the IWT for storage hydropower plants may be justified for development as storage plants, especially under multipurpose usage. Cascading RPs and DPs may serve better than single large plants. Possibilities may also exist to develop RPs as storage plants with cascading DPs that further maximize the hydropower generation. Therefore, the spatial patterns revealed by the various scenarios at the basin scale show many possibilities for hydropower planning and the need for strategic policies to ensure sustainable and equitable development.

The mixed energy focus scenario demonstrates that the spatial variation in theoretical potential is best utilized by combining small and large plants with both RP and DP configurations. Moreover, a mix of RP and DP configurations can add robustness to the hydropower portfolio as the two configurations have different sensitivities to changes in cost, discharge, generation efficiency, e-flow requirements and interest rate. However, policy choices on scale of development and geo-hazard risks have a larger influence on potential than these parameters. National hydropower planning in South Asia is dominated by masculine and technocratic attitude promoting large plants in large rivers [2,35,36]. This is also demonstrated by the majority of visualized potential concentrating in the Indus main river (Fig. 2C). Our large focus scenario shows how such bias will lead to large RP plants emerging as cost-effective. In contrast, in the mixed scenario many rivers that have low visualized potential emerge with notable potential (Fig. 4) combining more small than large plants (Fig. 7). Also, adding sustainability constraints results in a decline in the average size of both RP and DP plants. A shift from current focus on larger plants with economic efficiency would consequently make room for smaller plants that allow non-technical and non-economic sustainability factors in plant design.

Though small plants may not be politically attractive, they cover more of the remote mountains in the UIB (Figure B.4) [29], where other sources of electricity are scarce, expensive, risky or time-consuming [4,136,137] and energy poverty is worse than in the LIB [5]. Even marginal increases in electricity here has a compound effect on quality of life, especially for women and children that are already disadvantaged [138]. Moreover, large plants provide limited benefits to local communities [35,135] with high probability of delays and cost escalation [4]. Hence, smaller projects have a higher likelihood of increasing immediate energy access of marginalized populations [32]. While riparian countries have dedicated organizations for small and large hydropower development, the latter hold decision-making power [135]. Large plants predominantly get first pick for sites in the basin. Though many competitive advantages of small plants are not explicitly accounted for in our model, the difference between the mixed and large scenario clearly shows that systematic comparison of small and large plants in a single framework can reveal smaller plants that are equally cost-competitive and potentially easier to materialize [4]. Thus, without explicit policies to evaluate small plants alongside large plants, small plants will be sidelined by current biases in hydropower decision-making that do not consider the non-technical and non-economic impacts of hydropower and its effects on equitable energy availability and access [35,39].

Further concerns of energy justice are raised by the uneven distribution of hydropower potential and its costs across the sub-basins of the UIB (Figs. 8B). Across the riparian countries, current per capita energy consumption ranges from 0.2–5.1 MWh/yr [7], which is lower than even the mixed sustainable per capita energy across the UIB sub-basins (Fig. 6). The Ravi and Satluj sub-basins have the highest per capita sustainable potential that is likely to be serving energy outside the sub-basins already. In contrast, despite having relatively high sustainable potential, the Kabul and Swat sub-basins have lowest per capita potentials. These also have some of the lowest existing and visualized potential (Fig. 5) suggesting that bottom-up initiatives focused on hydropower expansion for use within the sub-basin are suitable here. The sub-basins also vary in the opportunities available for DP vs RP plants and geo-hazard risk that will attract different types of hydropower developers. These sub-basin variations raise the question of who will develop the sub-basin potential and whose energy demands will they fulfil. It may seem encouraging that the theoretical potential in the UIB is over twelve times higher than the current annual electricity consumption across Pakistan alone (120 TWh/yr) IEA [7]. But, sustainable potential even under the best case is much lower at 90TWh/yr. With population rise and socio-economic development, electricity consumption in the Indus basin may double or triple, especially in large cities like Kabul and Islamabad [82]. Thus, hydropower in the UIB will be a key resource to be shared within the sub-basins and even downstream in the LIB in the future.

Our paper shows an analysis of the spatial limits to the supply-side of hydropower in the UIB. Actual energy self-sufficiently in sub-basins will depend on the realization of this supply potential. The construction of hydropower plants of varying size, cost and configuration is fundamentally dependent on the spatio-temporal nature of energy demand and other energy sources available throughout the Indus basin countries, now and in the future. Hydropower expansion planning models [8,9] used by riparian countries to inform such hydropower planning can already benefit from using our cost curves (Fig. 8) in such demand-based scheduling of hydropower plants. But such power systems model miss out on the dependency of hydropower on water availability. Already, current water consumption poses a major constraint to sustainable potential (Fig. 4B) while socioeconomic development is projected to increase water and energy demands in the future [100]. Future changes in climate will alter water availability [129] and geo-hazard risk [47]. Alongside, even RPs are raising concerns regarding their impact on seasonal water availability [27].

Under IRBM, hydropower planning should thus be broadened to also consider future energy as well as water demand to further assess the best usage of basin water under the WEFE nexus. Strategic planning is necessary to explore how the hydropower potential sites can be developed sustainably [139,140]. Water resources need to be allocated to fulfil not just SDG-7 for energy but also SDG-2 for food and SDG-6 for water [100]. Additionally, these technocratic planning exercises need to be updated to appreciate, value and support the benefits of diverse hydropower plants from the perspectives of equitable energy access to truly achieve SDG-7. Socio-political considerations are even more imperative in a trans-boundary basin like the Indus to ensure hydropower decisions promote equitable water and energy sharing between sub-basins, upstream–downstream regions and riparian countries.

## 5. Conclusion

The lack of a systematic assessment of hydropower potential in the Indus poses a formidable challenge for the identification of sustainable pathways for hydropower development. Our study presents a quantification of five classes of hydropower potential in the UIB. First, we developed an inventory for the basin's visualized hydropower potential. The inventory shows that the existing hydropower energy of 89 TWh/yr will double after under-construction plants are commissioned. The visualized RoR potential is 306 TWh/yr from 447 plants. In contrast, theoretical potential varies between 880–1564 TWh/yr as a function of river segmentation. Across the three energy focus and three geo-hazard risk representation scenarios, our cost-minimization based hydropower exploration model finds that technical (12%–19%), financial (6%–17%) and sustainable (2%–10%) potential are a small portion of the theoretical potential. River segment length changes the types of hydropower plants identified. Except sustainable discharge, other financial and sustainability constraints cause a higher decrease in DP potential (11–39 TWh/yr) than RP (8–33 TWh/yr) in the mixed sustainable scenario. Overall, non-energy water usage under the nexus and geo-hazard risk aversion emerge as major constrains causing over 20% reduction in technical potential.

Differential search under the mixed focus scenario identifies the highest technical, financial and sustainable potential covering a wider range of plant sizes and costs. Such variety allows for top-down as well as bottoms-up hydropower development accommodating the diverse needs of hydropower developers in the Indus while adding robustness to the system. Landslide risk is the most constraining to hydropower. High geo-hazard risk areas are also some of the most cost-effective hydropower potential areas highlighting the need for at least the multi-hazard representation to balance geo-hazard risk mitigation and hydropower development. Opportunities for hydropower expansion vary across the sub-basins of the UIB because potential is unevenly distributed. Kabul and Swat sub-basins emerge as under-utilized hotspots for hydropower development where visualized potential is smaller than modelled potentials. Jhelum and Chenab have cheaper potential, most of which has been utilized. Much DP potential remains to be utilized in all sub-basins and RPs in Swat.

Decisions regarding the location, scale and configurations of hydropower plants will impact the availability and access of energy across the UIB. Especially for the mountain communities of the UIB, cost curves generated by our mixed scenario with small and large plants in a single framework can help alleviate the biases propagated by current hydropower planning promoting large plants. Though discharge, efficiencies and e-flows are some of the most sensitive parameters, policy assumptions regarding development scale, geo-hazard risk and sustainability factors cause a bigger change in sustainable potential than these parameters. Consensus must thus be established on acceptable levels of geo-hazard risks and addition of further social, ecological and political criteria towards defining "sustainable" hydropower incorporating IRBM. Nonetheless, the hydropower potential portfolios and cost curves we developed provide a superior starting point for strategic hydropower planning in the riparian countries. These cost optimal hydropower potential sites that have been identified as technically, financially and/or sustainably viable with our desktop analysis should be further evaluated for their ability to fulfil local and national aspirations for equitable hydropower development. Desirable sites should then be investigated further using on-site feasibility studies and detailed design analysis to confirm their suitability. The sites should also be ranked further considering water and energy demand as well as cost of other energy sources, now and in the future, to strategically schedule if, when and how these plants should be developed. Hydropower is a highly flexible technology. Our HyPE model shows how hydropower portfolios can be identified to suit both the physical conditions and the anthropogenic needs for sustainable development. Further research is necessary with an interdisciplinary lens to strengthen the definition and quantification of "sustainable" hydropower in HyPE as one that promotes water and energy justice alongside cost-efficient energy expansion in the Indus and beyond.

## CRediT authorship contribution statement

**Sanita Dhaubanjar:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Arthur F Lutz:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **Saurav Pradhananga:** Formal analysis, Methodology, Validation, Visualization, Writing – review & editing. **Wouter Smolenaars:** Formal analysis, Visualization, Writing – review & editing. **Sonu Khanal:** Methodology, Software. **Hester Biemans:** Formal analysis, Funding acquisition, Project administration, Writing – review & editing. **Santosh Nepal:** Conceptualization, Methodology, Project administration. **Fulco Ludwig:** Formal analysis, Funding acquisition, Project administration. **Arun Bhakta Shrestha:** Conceptualization, Funding acquisition, Methodology, Project administration, Validation. **Walter W Immerzeel:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing.

## Data and code availability

Input and output data as well as model source code are available for download at links below:

Preprocessed input data: 10.5281/zenodo.10234264

Model Github: 10.5281/zenodo.10204323

Output inventory of visualized hydropower potential: 10.26066/rds.1973705

Output historical hydropower potential portfolios: 10.26066/rds.1973690

Additionally, hydropower potential portfolios are available for interactive viewing at our story map and the ICIMOD Indus Knowledge Partnership Platform.

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## Disclaimer

The views and interpretations in this publication are those of the authors, and they are not necessarily attributable to their organizations.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sanita Dhaubanjar reports financial support was provided by Netherlands Organization for Scientific Research.

## Appendix A. Supplements

A 3-part supplement with details on sensitivity analysis, extra figures and documentation of hydropower inventory can be found online at: https://doi.org/10.1016/j.apenergy.2023.122372.

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