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Published in:
Journal of Energy Storage

DOI (link to publication from Publisher):
10.1016/j.est.2022.104587

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Journal of Energy Storage 50 (2022) 104587

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Research Papers

Role of energy storage in energy and water security in Central Asia

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ARTICLE INFO

Keywords:
Energy storage
Seasonal pumped hydropower storage
Water management
Renewable energy systems
Energy policy
Electricity storage
Energy model

ABSTRACT

Central Asia has faced major energy and water security challenges. Technically, water from the Pamir and Tian Shan Mountain ranges could be sufficient to meet the needs of the countries in the region, if there was no temporal mismatch between the availability of water for irrigation and electricity generation. While water is required for agriculture in downstream countries during the summer, demand for hydro electricity generation is mainly in the wintertime in upstream countries. With the aid of the open-source MESSAGEix energy systems optimization modelling framework, we study a renewable energy transition in the region through to 2050, considering innovative long duration water and energy storage solutions for optimal management of water and energy resources in different seasons. The modelling approach demonstrates that the proposed "dual water and energy storage scheme", with two different hydrological cycles for up- and down-stream regions, can guarantee enough water for energy generation in upstream countries in winter while ensuring water availability for irrigation downstream in summer. This scheme is economically feasible and, with further detailed analyses and geopolitical considerations, it can serve to improve energy security and water resource management, towards achieving sustainable development goals in Central Asia.

1. Introduction

Water use for irrigation and electricity generation has long been subject to dispute between downstream and upstream countries in Central Asia [1]. The most remarkable impact of excessive water use for agriculture is the drying of the Aral Sea almost in its entirety, which has resulted in a large region with high salt concentrations causing soil degradation and desertification in the region [2,3]. The Aral Sea used to support fishing and a vibrant population surrounding the lake. Several controversial solutions have been proposed to solve this issue, such as the transposition of water from the Ob river to Central Asia [4–10] or reduction in water extraction from rivers in the region [11,12]. Progress has been seen in efforts to revive the Northern part of the Aral Sea with the construction of a dam to limit the surface area of the lake [13].

A large part of the water that flows from the Pamir and Tian Shan Mountains to the Aral Sea is used mainly for irrigation (primarily cotton), followed by industry and public supply [14]. A water management challenge in Central Asia is a conflict of interests between upstream and downstream countries. Upstream Kyrgyzstan and Tajikistan have abundant water resources that they want to release during winter to fulfil their energy needs through hydropower generation (Fig. 1 (a)). However, if the water is released in the winter, it would be underutilized as there is no need for water in agriculture in this season. Downstream Uzbekistan, Turkmenistan and Kazakhstan, in contrast, have far less internal renewable water resources and rely on the water from transboundary rivers to be released primarily in summer to meet their irrigation needs and avoid uncontrolled winter flooding [15]. This water management regime is presented in Fig. 1 (b), (c), where, in Kyrgyzstan, the share of discharge has doubled from about 20% in the Soviet period to around 40% after gaining independence in the early

Abbreviations: GIS, geographical information system; GLOBIOM, Global Biosphere Management Model; HPP, hydropower plant; MESSAGEix, Model for Energy Supply Systems Alternatives and their General Environmental Impact; PHS, pumped hydropower storage; SPHS, seasonal pumped hydropower storage; VRE, variable renewable energy.

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https://doi.org/10.1016/j.est.2022.104587
Received 7 September 2021; Received in revised form 15 March 2022; Accepted 30 March 2022
Available online 3 May 2022

Table 1
Additional information to support the technical approach presented in the paper.

Topic	Description
Low land requirement and evaporation	As the reservoir is parallel to the river and the water is pumped to the reservoir, the depth of the reservoir can vary up to 250 m. Thus, the flooded area to store water is considerably smaller than conventional reservoirs (10 to 100 times smaller) [28,76,77], resulting in less evaporation of water by 10 to 100 times. For example, the Nurek Dam is the second tallest dam in the world with 300 m in height [78]. This design decision involves the need to regulate the flow of the river, increase hydropower generation, store river sediments, have small land requirement and reduced evaporation.
SPHS in cascade	Another arrangement that could be used to reduce the water extraction from the river during the winter to store energy is to create two SPHS plants in parallel, similar to Kaprun in Austria [79]. In this case, the combined generation head of both systems could add up to 2400 m high, and less water will be required to store the same amount of energy.
Sedimentation	Another major challenge of the rivers in Central Asia is sedimentation. A sizeable amount of sediment is carried by the rivers, which considerably reduces the storage capacity of the reservoirs. For example, the storage capacity of the Nurek reservoir is estimated to reduce by 4 km^3 in 65 years [56]. SPHS plants have the advantage that the catchment is very small when compared to the main river. Thus, sedimentation in SPHS reservoirs is negligible. As the conventional reservoirs in the region are filled with sediments, SPHS can provide additional energy and water storage capacity.

1990s and onwards during the winter, i.e., October to March.[1] This trend verifies increasing reliance on hydropower generation to meet high energy demand in wintertime during the post-Soviet, independence period.

During the Soviet period, a regional water-energy sharing scheme was in place. The main idea behind the scheme was that downstream countries of Kazakhstan, Uzbekistan, and Turkmenistan would provide hydrocarbons as well as electricity generated from coal and gas-fired power plants to their upstream neighbours Kyrgyzstan and Tajikistan during the winter so that these upstream countries could displace the need to generate domestic hydropower. This way, Kyrgyzstan and Tajikistan would channel the excess electricity to the downstream countries during the summer and release the valuable water for agriculture. Under current conditions, the same scheme would entrench the dependency of the region on fossil fuels, and hinder the reduction of CO_2 emissions necessary for sustainable development in the region.

Existing watersheds that have several reservoirs with seasonal or pluriannual storage capacities, i.e., watersheds where the storage capacity is significantly higher than the annual river flow, usually use their upstream dams operation focused on hydropower generation, and the downstream dams focused on delivering water for irrigation and water supply needs. This is convenient because it allows both energy and water needs to be met in the region. An example of this happens in the Colorado river [18,19], where upstream dams (Glen Canyon and Hoover dams) generate most of its electricity during periods with high electricity demand in the year and the downstream dams (Davis and Parker dams) generate electricity according to the demand of water after the dams [20]. Other examples can be seen in the Snowy Hydro Scheme in Australia [21] and recently a similar scheme has been proposed for the Indus basin [22].

While energy and water conflict among Central Asian countries has been extensively discussed [23], few technical solutions have been explored to address the energy and water needs of the region [24,25]. We explore a technical approach based on renewable energy sources. Our approach integrates an innovative upstream and downstream, seasonal pumped hydropower storage and hydropower storage arrangement complemented by wind and solar power. To our knowledge, only one paper investigated the role of pumped hydropower storage along with wind and solar power in Uzbekistan [26]. Meanwhile, similar technical approaches have been extensively explored elsewhere in the world that has shown a notable potential to address energy and water needs [28–31]. The engineering-economic viability of our approach is investigated with the MESSAGEix systems optimization modelling framework.[2] The region has vast potential for hydropower in the Pamir and Tian Shan mountain ranges [32], solar power [33], wind power [34], and fossil fuel reserves, including natural gas, oil and coal [35], although deployment of renewables remains minuscule and associated policies and strategies are in early stages of development [36].

Seasonal pumped hydropower storage (SPHS) is an alternative to conventional hydropower, which allows large amounts of water and energy to be stored parallel to a major river with low land use requirements, social and environmental impacts [37,38]. During the summer, when energy is abundant, water is pumped to an upper reservoir, storing water and energy. During the winter, when energy is scarce, the stored water is used to generate electricity. Apart from storing water and energy seasonally, the SPHS plant can be used to store energy from intermittent electricity generation sources [39,40] such as wind and solar, generate electricity during peak hours, and provide ancillary services to the power grid.

The originality of this paper is to propose an innovative approach for water management in a basin with two complementary storage cycles using SPHS to fulfil both water and energy needs of Central Asia. The SPHS plant upstream the river basin can store energy from summer to winter, while the hydropower plants downstream the river basin store water during the winter coming from upstream dams to release it during the summer when water demand is the highest. This paper is divided into five sections. Section 2 shows the methodology implemented in the paper. Section 3 presents results. Section 4 discusses the results. Section 5 concludes the paper.

2. Methodology

The methodological framework applied in this paper is described in Fig. 2, divided into four main steps. Step 1 consists of gathering data from Central Asian countries to develop the MESSAGEix energy system and a generic river flow model. These include water availability and demand, energy availability from both renewable and fossil sources, electricity demand, techno-economic data of available technologies, and potential growth in water and energy demand through to 2050. Step 2 consists of presenting a novel storage formulation in MESSAGEix. This includes the conceptual representation of storage in the model, including the mathematical formulation for storage, and the way sub-annual time slices are structured and implemented in the model. Step 3 consists of adding the proposed energy and water solution to the model. The existing hydropower potential in the region is turned into the representative downstream reservoirs in the model, the existing potential for SPHS is explored and turned into the representative upstream reservoirs, and then they are consolidated into the proposed hydrological model for Central Asia.

[1] Data for Tajikistan prior to 1992 is unavailable; otherwise, it would have shown a similar trend as with Kyrgyzstan.

[2] The documentation and the scope of the modelling framework can be found at: https://docs.messageix.org/.

2.1. Central Asian energy-water model

Long-term energy investment and planning tools such as MESSAGEix [41], TIMES [42], OSeMoSYS [43], etc., can inform energy and climate policy by investigating the implications of different decisions over several decades [44]. The MESSAGEix modelling framework has been selected for this analysis because it is an open-source framework, with versatile and flexible features for modelling an energy system and its linkages with other sectors, such as water supply-demand as presented in this study. MESSAGEix has been applied for similar projects, e.g., for the evaluation of co-benefits of optimizing energy and water use in the cross-border Indus basin [45]. Moreover, MESSAGEix is one of the modelling tools widely used for the analysis of long-term energy and emissions pathways and their implications, e.g., investment needs [46]. MESSAGEix formulation has dedicated equations for assessing the flexibility requirements and reliability issues in the integration of variable renewable energy (VRE), which is an important aspect of low-carbon energy pathways [47]. More details on the MESSAGEix features, references and case studies, and mathematical formulation can be found on its website (see footnote 2).

Through the development of the model for this paper, we proposed a few improvements to the MESSAGEix core formulation, to represent storage technologies explicitly, a method that can be applied for modelling long-term storage, such as SPHS and other energy storage options. The proposed representationcan capture the main functionality of a wide range of storage solutions, including:

- A separate representation of power conversion system (PCS) and storage reservoir: this will allow the user to specify storage configurations flexibly by parametrizing PCS, e.g., pump and turbine in a pumped hydropower plant, independent from the reservoir, e.g., dams. Therefore, different values for costs, lifetime, efficiencies, etc. can be defined for these two sections. The user can specify different charging and discharging power capacity, if relevant, e.g., for some batteries.
- The main parameters of storage, including charge/discharge losses, self-discharge of the storage section (reservoir) over time (independent from charge/discharge regime), and the possibility of linking an input commodity to keep the storage media over the long term.
- Possibility of optimizing the initial content of storage, e.g., the most optimal filling level of a dam after the construction. This initial content of storage is required to be equal to the content of storage at the end of the last sub-annual time slice, to ensure a cyclic operation and commodity balance in a yearlong period.
- Other important features of storage technologies can be parameterized using MESSAGEix standard parameters, e.g., degradation of performance of storage over several vintages (as a function of time), modes of operation for storage, and vintage-based cost and efficiency specifications.

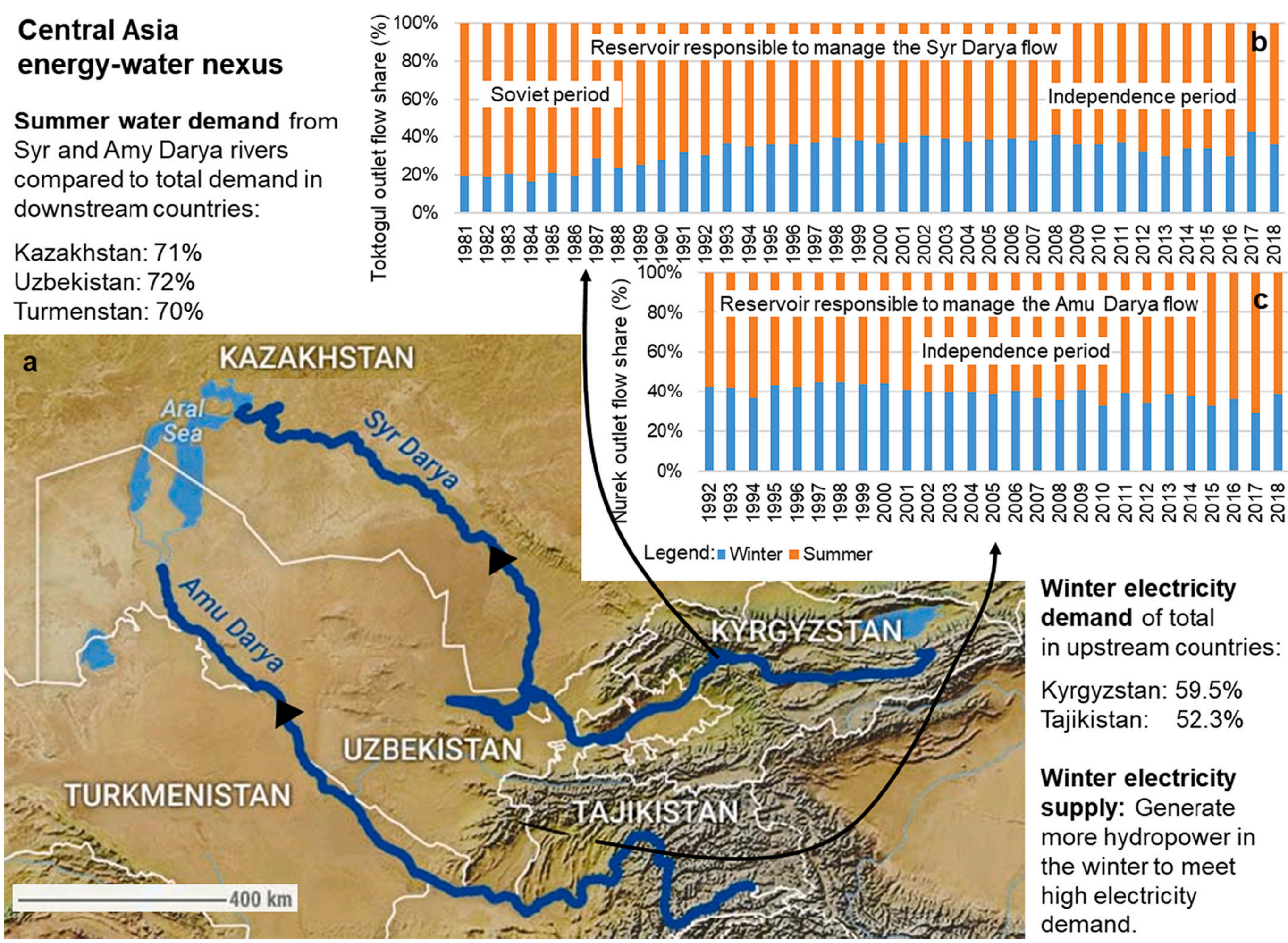


Fig. 1. Energy-water nexus in Central Asia [16,17]. (a) diagram of the Central Asia Syr and Amu Darya river basins, showing water flowing from the Pamir and Tian Shan Mountains to the Aral Sea and Central Asian countries: upstream Kyrgyzstan and Tajikistan, and downstream Kazakhstan, Uzbekistan and Turkmenistan, (b) seasonal water release from Toktogul reservoir in Kyrgyzstan, and (c) Nurek reservoir in Tajikistan.

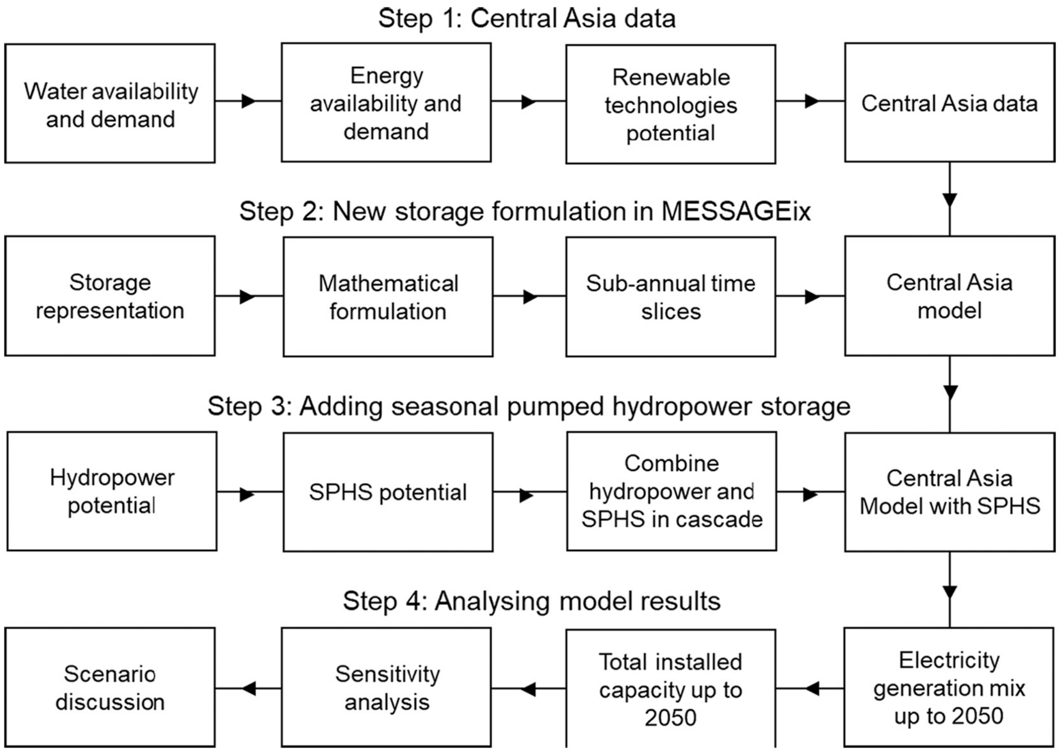


Fig. 2. Methodological framework applied in the paper.

In this study, twelve months as sub-annual time slices were modeled to capture the monthly variations in VRE sources and water-energy demand. We model Central Asian countries in MESSAGEix calibrated to the installed capacity in 2015 with scenarios spanning from 2020 to 2050. The electricity generation installed capacity of the region is based on the Platts database (2019) [49]. The model is multi-node, representing the five countries that constitute Central Asia, i.e., Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan.

Individual country data on electricity demand was extracted from [50]. The data for solar and wind power generation was extracted from [51]. This data is available hourly, and it is aggregated to monthly data. Fossil fuel-based generation is based on the existing natural resources of the region [52,53], their extraction costs and costs for electricity generation with gas and coal, obtained from [54,55]. To make sure that the water demand for Central Asian countries is met in different months, the model includes a hydrological model of the region applying the proposed scheme in Fig. 3. We assume each of the two main rivers in the region (Syr and Amu Darya) has one downstream reservoir and one upstream SPHS. An important restriction to the operation of the hydropower and SPHS plants in the model is the demand for water in the countries downstream, which is taken from [17]. The inflow to the upstream and downstream reservoirs for these rivers is based on [24,56,57]. The potential and cost for SPHS are from [58], while the costs for hydropower are from [59]. The increase in evaporation with the construction of the reservoirs is assumed to be negligible. For more information about the developed model, and open access to the underlying data and assumptions, please refer to the related project repository[3].

2.2. Adding seasonal pumped hydropower storage

The flow in the head of the river (inflow_up_amu) can be stored in the upstream reservoirs by pumped hydro with electricity consumption or spilled (spillage_amu) to the downstream reservoirs (reservoir hydro) (Fig. 3). The downstream reservoir has an additional river flow (inflow_up_amu2). If the downstream reservoir (reservoir hydro) is already full and the reservoir does not have enough electricity generation capacity for all river flow, some of the flow is spilled (spillage_amu2). The flow after the downstream reservoir (inflow_down_amu) should always be higher than the water demand of downstream countries (outflow_amu).

3. Results

3.1. Operation of upstream and downstream hydropower storage

We explore a hydropower scheme for the construction of new reservoirs located upstream from existing hydropower plants with conventional reservoirs, and the addition of SPHS plants, as shown in (Fig. 4 (a), (b)). The explored operational strategy for the new water management cascading system would be as follows. During the spring and summer seasons, water is released for agriculture and at the same time, electricity is produced by downstream, existing hydropower plants. Because produced electricity exceeds demand, this excess electricity is used to pump water from the upstream hydropower reservoirs to SPHS upper reservoirs. This is feasible because existing downstream reservoirs had already been filled to maximum capacity during the previous winter and will be releasing this accumulated water, i.e., not relying on new flow during the spring/summer period. The upstream reservoirs and SPHS upper reservoirs, meanwhile, store the new snow and glacier melt (as well as rain) water flow during the spring and summer periods. During the fall and winter seasons, the downstream reservoirs reduce hydropower generation and the release of water and start storing water. On the other hand, the upstream hydropower and SPHS plants start to generate electricity by releasing water from their reservoirs, which will flow into the downstream reservoirs to be stored for the next spring and summer seasons. Fig. 4 (c) presents the existing and proposed reservoirs in the Amu and Syr Darya basins [60–62]. The targeted hydropower and SPHS plants, river inflows and storage variations at different levels in the

[3] https://github.com/iiasa/central-asia-storage

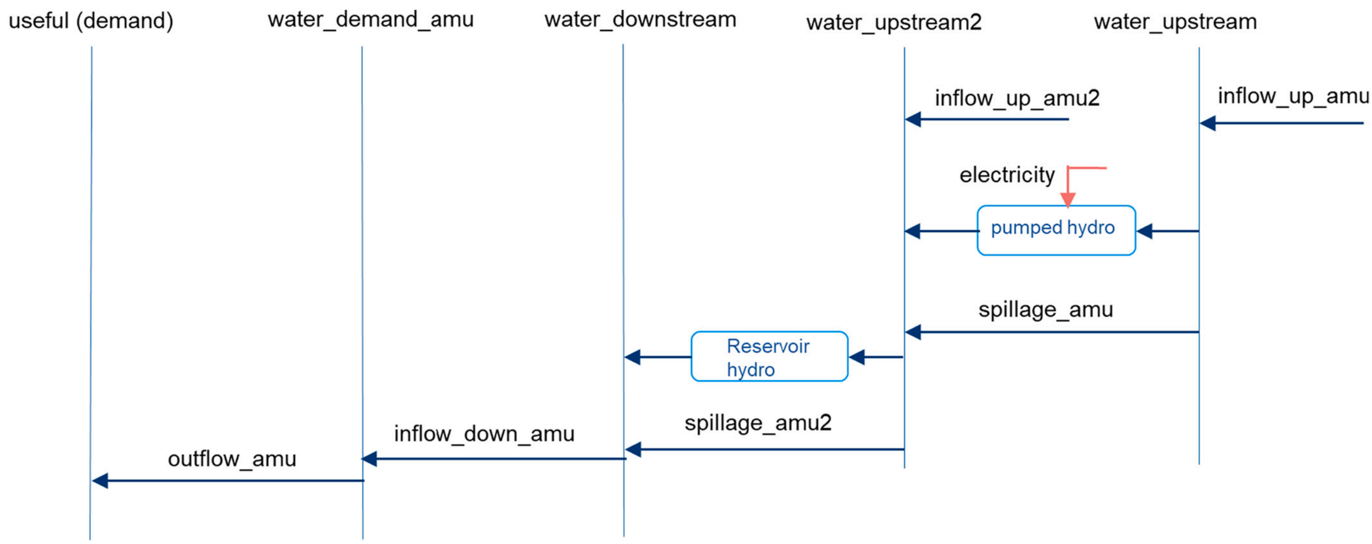


Fig. 3. Description of the hydrological model implemented in the Central Asia model.

basins are shown in Fig. 4 (d), (e), and (f).

To explore the feasibility of hydropower storage, we estimate regional SPHS potential and energy storage cost based on a GIS-based method presented in [58,63]. The projects can be seen in more detail with the interactive map [64]. By applying this method to Central Asia, we demonstrate that there are potential locations for SPHS projects with energy storage costs lower than 10 US$/MWh of storage, mainly in Tajikistan and Kyrgyzstan (Fig. 5 (a)). This low energy storage cost alternative could be used to store energy seasonally from hydropower, and excess wind and solar energy during the summer, and generate electricity during the winter, when electricity demand is at its peak. This is possible with a small share of the river flow, given the high-altitude difference between the SPHS lower and upper reservoirs. SPHS plants can also serve the power system to balance the intermittency of solar and wind electricity generation.

The two selected SPHS sites in Panj River, Tajikistan, and Naryn River, Kyrgyzstan, illustrated in Fig. 5 (c), (d), can store enough water for approximately an average of 3 GW of electricity generation capacity during six months in summer and provide 2.5 GW capacity during the six winter months. This capacity reduction in winter is due to system losses, assuming an SPHS system is 83% efficient [65]. This would result in a generation capacity difference of 5.5 GW between summer and winter. Apart from storing energy, the SPHS plants also store water, which increases the overall storage potential of the basin. If this energy storage potential is not enough to balance the water and energy supply needs of the region, more SPHS storage sites could be built, as shown in Fig. 5 (a). If the water available upstream is not enough to meet all energy storage needs of the region, closed-loop SPHS plants could be built as well, where all the water required to operate the system can be stored in the lower and upper reservoirs [66].

3.2. An integrated model for water-energy systems in Central Asia

To analyse the role of energy-water storage, we develop a high-renewable energy scenario (High-RE) with a target of two-third of electricity from renewable sources by 2050. Results show that the main sources of electricity supply in Central Asia in 2050 under High-RE will be solar photovoltaic (PV) (34%), coal (17%), natural gas (17%), wind (15%), hydro (13%), and pumped hydro (4%) (Fig. 6). Kazakhstan with the highest coal generation will reduce its reliance on coal to around 15% from 2020 to 2050. Gas generation reduces significantly in Uzbekistan and Turkmenistan, replaced mainly by wind and solar generation. Tajikistan and Kyrgyzstan would benefit from a rapid increase in solar generation and SPHS capacity. To increase the total solar-based electricity generation to 34% by 2050 in the whole region, the installed capacity of solar power has to increase to 74 GW, which is equivalent to 51% of the total installed capacity (141 GW) in 2050 (Fig. 7). Turkmenistan starts 2020 with almost 100% gas-fired electricity generation, and the transmission lines interconnection with Kyrgyzstan and Tajikistan is not in use, so it cannot rely on the seasonal energy storage provided by the SPHS plants. Thus, the reduction in gas generation is limited by 2040, as the gas power plants have to guarantee the generation during the winter when solar power is limited.

While 54% of the electricity demand occurs during the winter and 46% during the summer, 59% of solar power in the region is generated during the summer and 41% during the winter. The capacity factor of solar PV in different countries is presented in Fig. 8. This is the main reason why the SPHS capacity increases to 4 GW (Fig. 9). This generation capacity can reduce the seasonal supply and demand gap by around 7 GW, which is equivalent to 5% of the total generation capacity in 2050. The remaining supply-demand gap is bridged with the increase in gas and coal power generation during the winter. As shown in Fig. 9, the SPHS plant in Tajikistan stores solar energy seasonally from April to November and generates electricity with a higher capacity factor during February and March. The main objective of hydropower is to supply water downstream and reduce its generation substantially in January and February. The demand in Tajikistan is smaller than the generation. This is because the main part of the electricity is exported to other countries, mainly Uzbekistan (exports to Afghanistan are not considered in this study).

In 2050, Tajikistan is expected to produce most of its electricity from solar power (Fig. 9). The hydropower reservoir focuses on guaranteeing the supply of water to meet the demand in Uzbekistan and Turkmenistan.

3.2.1. System costs and CO_2 emissions

The construction of SPHS in Tajikistan and Kyrgyzstan offers economic benefits for the whole region. Countries downstream can import hydropower-based electricity and reduce their fossil-based generation in different seasons. On the other hand, the construction of SPHS requires additional investment costs, which diminishes the cost savings in the high-renewable scenario (High-RE), especially in Kyrgyzstan (see Fig. 10). Uzbekistan is the country with the highest benefits from the installation of the proposed SPHS in the region, saving 367 million $/year thanks to SPHS installed in upstream countries. Overall, if the proposed SPHS solution in this paper will be installed, the region will

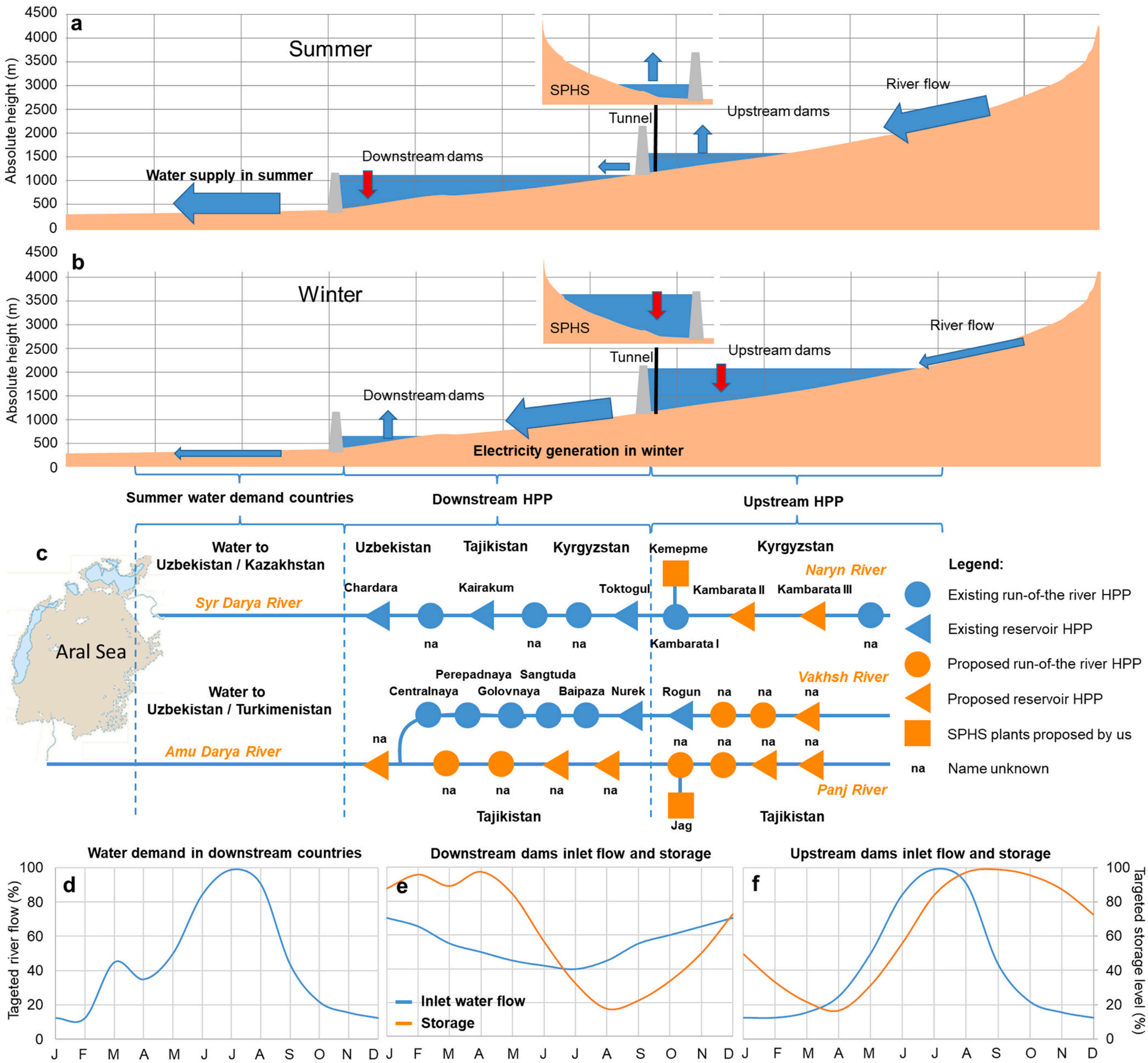


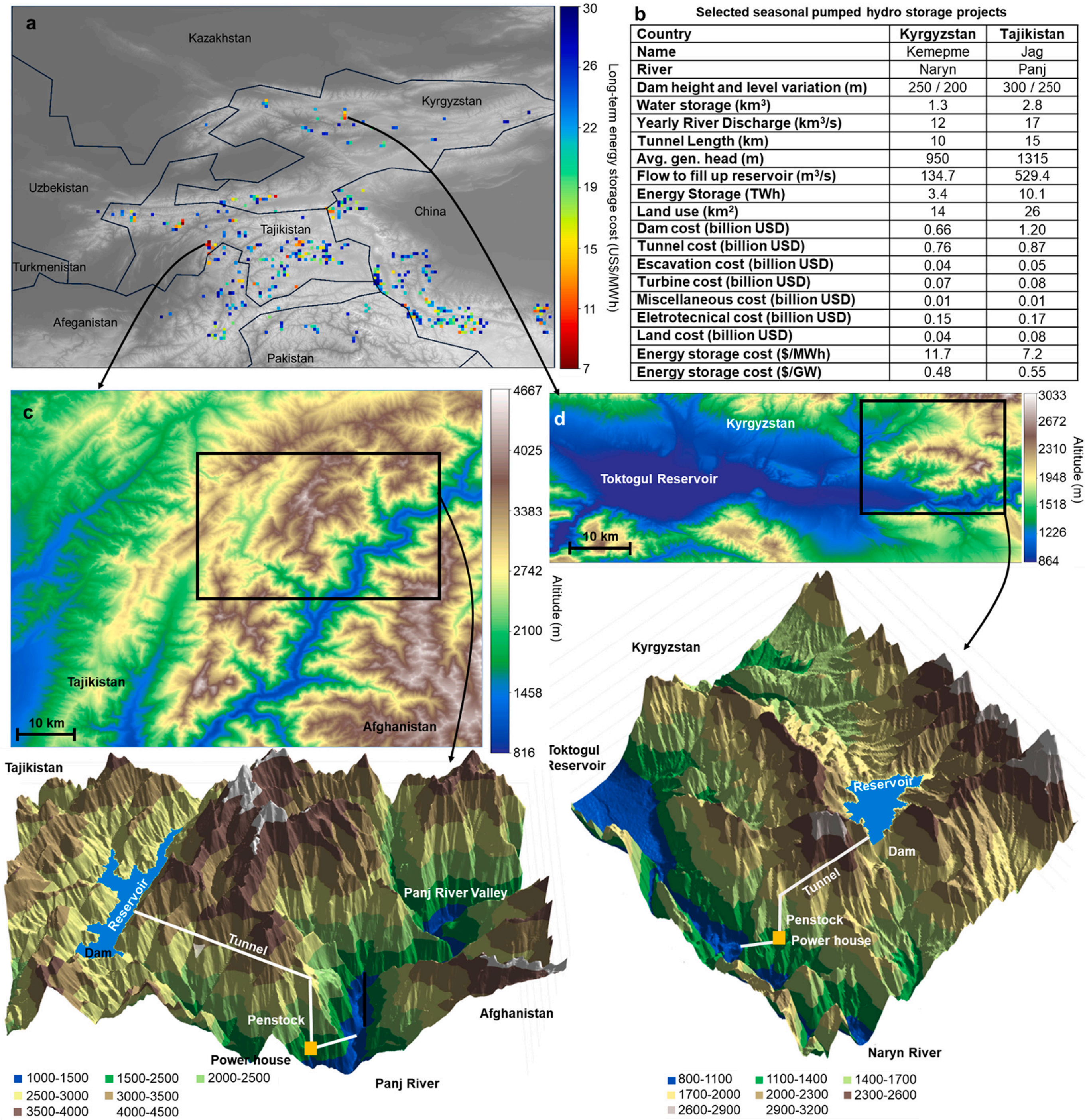
Fig. 4. Hydropower storage cascade in Central Asia and the proposed dual water-energy storage scheme. (a) summer operation: upstream reservoirs and seasonal pumped hydro storage (SPHS) plants store water and energy; water is released from downstream reservoirs for water supply and electricity generation. (b) winter operation: upstream hydropower plant (HPP) reservoirs and SPHS plants release water generating electricity; water is stored in the downstream reservoirs. (c) representation of the hydropower and SPHS developments, showing the upstream and downstream reservoirs. (d) desired river flow released by the downstream reservoirs. (e) inflow and water storage in downstream reservoirs. (f) inflow and water storage in upstream reservoirs.

save 184 million $ per year. This benefit will be materialized in cooperation and in an interconnected electricity and water system for the region. Greenhouse gas (GHG) emissions do not change significantly after the operation of SPHS in the region. This can be partly due to the efficiency losses of SPHS, and slightly higher generation of some cheap fossil fuel electricity that is stored in SPHS. This phenomenon has been observed in other regions and studies too [67].

3.3. Sensitivity analysis

In this Section, the sensitivity of the results is examined with respect to three main input parameters, namely, water demand, water supply upstream, and electricity demand. These input parameters are uncertain in long term, depending on different socio-economic developments, e.g., GDP and population growth and the impact of that on energy demand. Moreover, water availability is a critical issue in the region, with climate change, and after the glaciers in the Pamir and Tian Shan Mountains melt, the river flow will reduce significantly. This will impact water availability, and the potential for hydropower and SPHS. For the sensitivity analysis, we decrease and increase these three main parameters in steps of 10, 20, 30 and 50%, relative to the initial value used in the main high-renewable energy scenario (High-RE) examined in the previous section.

The results of the sensitivity analysis (see Fig. 11) show that the water supply-demand system cannot feasibly operate in scenarios with more than 20% increase in water demand or those with more than 20% reduction in water supply. This infeasibility is an indication that the level of water demand relative to water availability in the region is already high, and without measures for reducing the demand for water, the system may be challenged by water scarcity in the future. The results



Country	Kyrgyzstan	Tajikistan
Name	Kemepme	Jag
River	Naryn	Panj
Dam height and level variation (m)	250 / 200	300 / 250
Water storage (km³)	1.3	2.8
Yearly River Discharge (km³/s)	12	17
Tunnel Length (km)	10	15
Avg. gen. head (m)	950	1315
Flow to fill up reservoir (m³/s)	134.7	529.4
Energy Storage (TWh)	3.4	10.1
Land use (km²)	14	26
Dam cost (billion USD)	0.66	1.20
Tunnel cost (billion USD)	0.76	0.87
Escavation cost (billion USD)	0.04	0.05
Turbine cost (billion USD)	0.07	0.08
Miscellaneous cost (billion USD)	0.01	0.01
Eletrotecnical cost (billion USD)	0.15	0.17
Land cost (billion USD)	0.04	0.08
Energy storage cost ($/MWh)	11.7	7.2
Energy storage cost ($/GW)	0.48	0.55

Fig. 5. Selected sites for seasonal pumped hydropower storage (SPHS) in Central Asia. (a) SPHS potential in Central Asia showing the long-term energy storage cost of different sites (US$/MWh) [58]. (b) details of selected SPHS sites in the Naryn and Panj rivers [58]. (c) selected SPHS sites in Panj River, and (d) in Naryn River.

demonstrate a direct correlation between the total cost of the energy system and its emissions with the level of electricity demand. Reducing water demand or an increase in water supply would cut the costs of the energy system, as hydropower can provide flexibility to the grid, replacing more costly fuel-based electricity generation.

The installed capacity of SPHS is highly sensitive to water demand, much more than electricity demand. 10% additional water demand in the region, would justify building ~800 MW additional capacity of SPHS, compared to the capacity already estimated in the High-RE scenario. Also, if water availability in the region will decline by 10%, e.g., due to lack of glacier melt-down as a result of climate change, the need for SPHS will motivate an additional ~420 MW capacity to be installed. However, the need for SPHS has a slightly negative correlation with electricity demand.

4. Discussion

Energy transitions based on increasing the share of variable renewable energy (VRE) sources, such as wind and solar PV, have increased the challenges of matching the supply and demand of electricity [68–70]. We model long-term energy storage needs in a monthly resolution to capture seasonal variations of renewable electricity generation

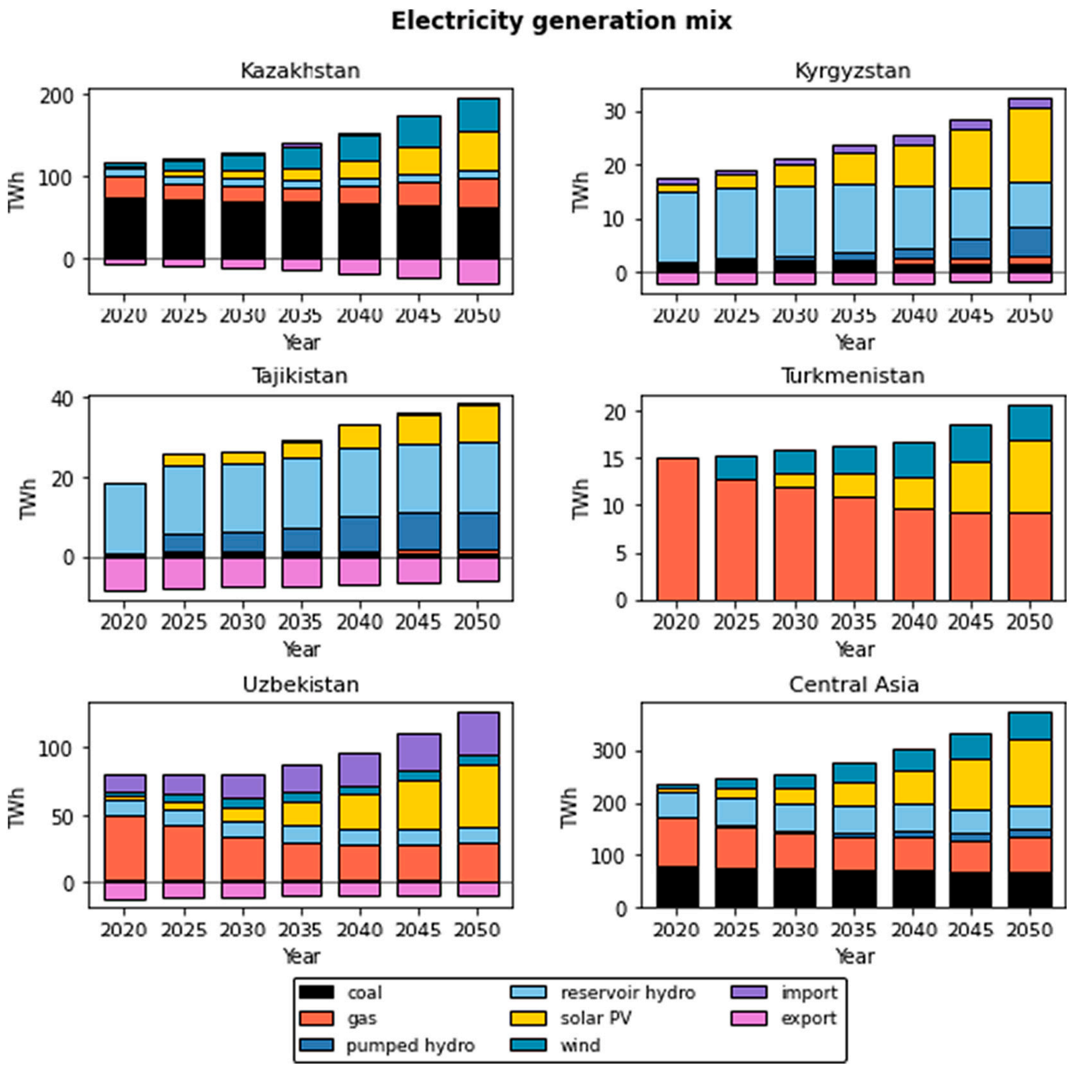


Fig. 6. Central Asia's electricity generation mix from 2020 to 2050. Assuming a high-renewable energy scenario with 66% of renewable electricity by 2050. The share of solar PV increases from 2% in 2020 to 34% of total electricity generation by 2050, and natural gas and coal generated electricity combined reduces from 73% in 2020 to 34% in 2050.

sources, mainly hydropower, solar and wind generation, as well as electricity demand. The Central Asia model in this paper consists of the energy system of five countries in the region, interlinked through electricity transmission lines and rivers, developed partly in a bottom-up approach using country-level data, and also based on downscaling some regional data from the MESSAGEix-GLOBIOM global model.[4] The developed model includes the demand for water for agriculture, as well as electricity, heating and fuel demand in industry, buildings and transport sectors, and the available transmission lines between the countries. The monthly data of wind and solar energy availability, the electricity demand of each country, and the monthly flows of the Syr and Amu Darya rivers are represented in the model. The main objective of the model is to meet the demand for electricity and water for each country in a cost-optimal manner, assuming that two-third (~66%) of the electricity generated in the region comes from renewable energy sources in 2050. The Government of Kazakhstan issued the "National Concept for Transition to a Green Economy up to 2050" that, among other things, aims to increase the share of renewable energy in electricity generation by 30% by 2030 and 50% by 2050 [74]. In the short- to medium-term transition period, fossil fuels will still play a role to support economic development, until sufficient renewable capacity is installed and operational [36].

The modeling results suggest that only 4 GW of pumped-hydro storage is needed to be installed due to the high potential for solar and wind power in the region and the low installation costs for solar and wind in 2050. If the cost for solar and wind does not reduce as much as proposed in the model, there are other potential sites to install other SPHS plants with higher costs, as shown in Fig. 12. Another aspect that would increase the costs for storage is if the amount of water required to store the energy is higher than the yearly water availability in the basin. In this case, closed-loop seasonal pumped storage plants would be required, which requires two large reservoirs and would increase the cost of the project. Apart from providing seasonal storage, SPHS systems also provide flexibility for short-term balancing of PV and wind, e.g., in seconds, minutes and day-night, and weekly energy arbitrage [75].

SPHS can be a viable solution for Turkmenistan to improve the management of water from the Amu Darya river (Fig. 13). The Zeid reservoir is used to regulate the flow of the Main Turkmen Canal, that flows to Ashgabat, the capital of Turkmenistan. It was built in 1963, and has an active storage capacity of 3.6 km^3, a surface area of 465 km^2 and an average level variation of 10 m. The Zeid dam has 17 m in height and 18 km in length. Annual evaporation losses can reach as much as 1.4 km^3, which is almost half of the entire reservoir volume [75]. This very

4 https://docs.messageix.org/projects/global/en/latest/.

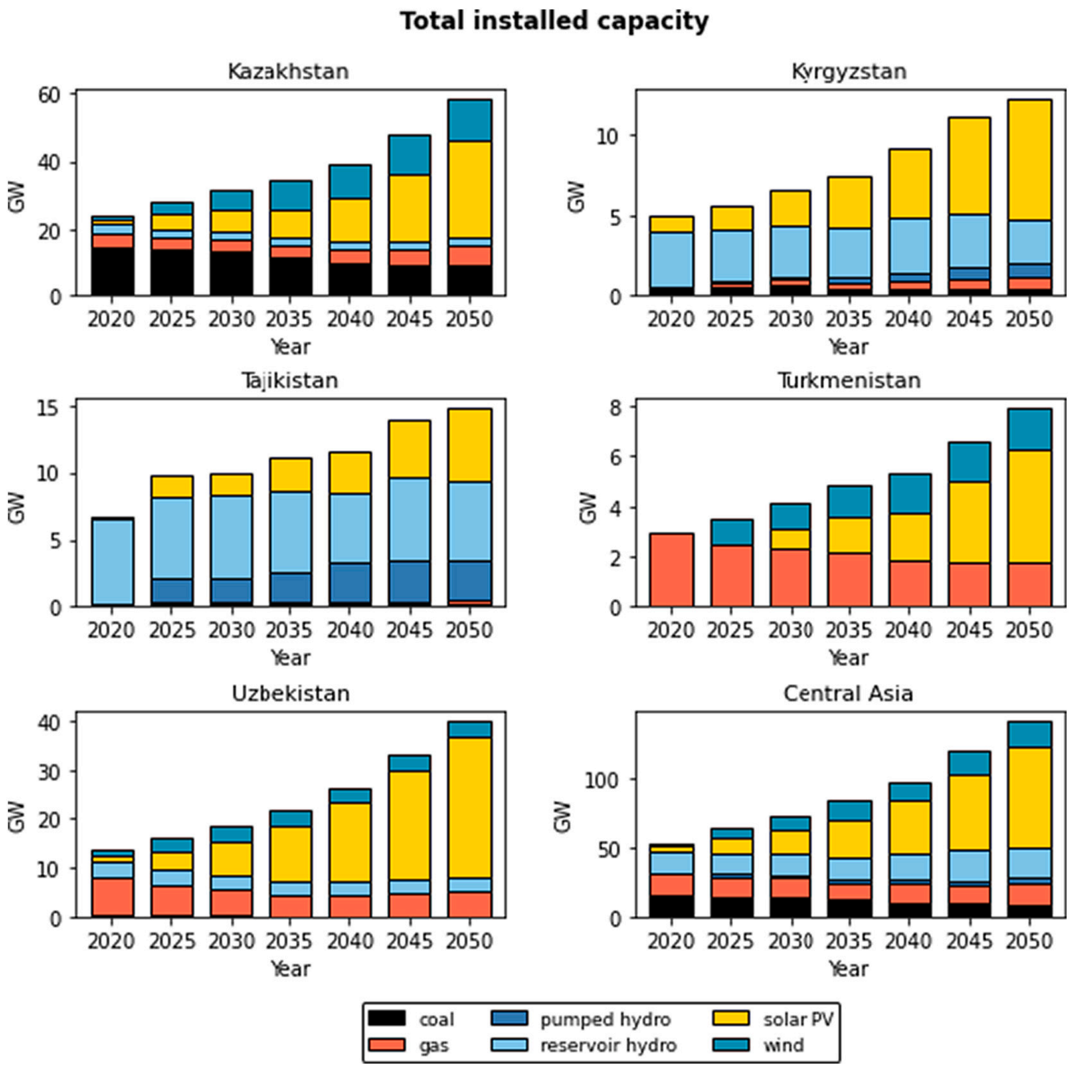


Fig. 7. Central Asia installed power capacity mix from 2020 to 2050 under a high-renewable energy scenario (66% of total generation). Solar PV installed power capacity increases in all countries substantially, wind power is mostly present in Kazakhstan, Turkmenistan and Uzbekistan, and SPHS is built in the mountains of Kyrgyzstan and Tajikistan.

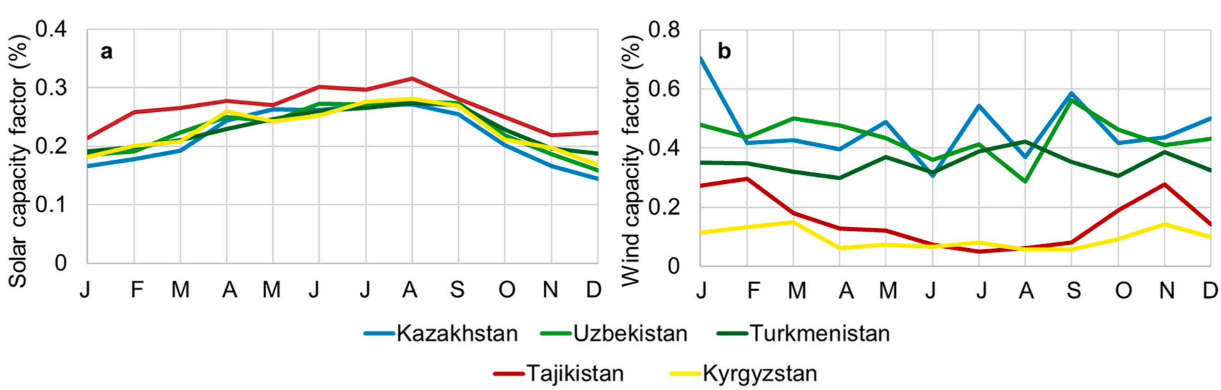


Fig. 8. Capacity factor for solar PV and wind power applied in the paper.

inefficient reservoir is not a good alternative for water management and should be replaced by a more efficient alternative, such as the proposed SPHS in Fig. 13. Apart from storing water, this reservoir could also be used to store energy and support the introduction of solar and wind sources in Turkmenistan. Other benefits of implementing SPHS in the region can be seen in the Table 1.

5. Conclusions and implications for policy making

The Central Asian region has faced challenges to maintain the supply of energy and water in a secure and sustainable way. There are several options to potentially resolve the conflicting interests in water and energy use between the upstream and downstream countries in the region.

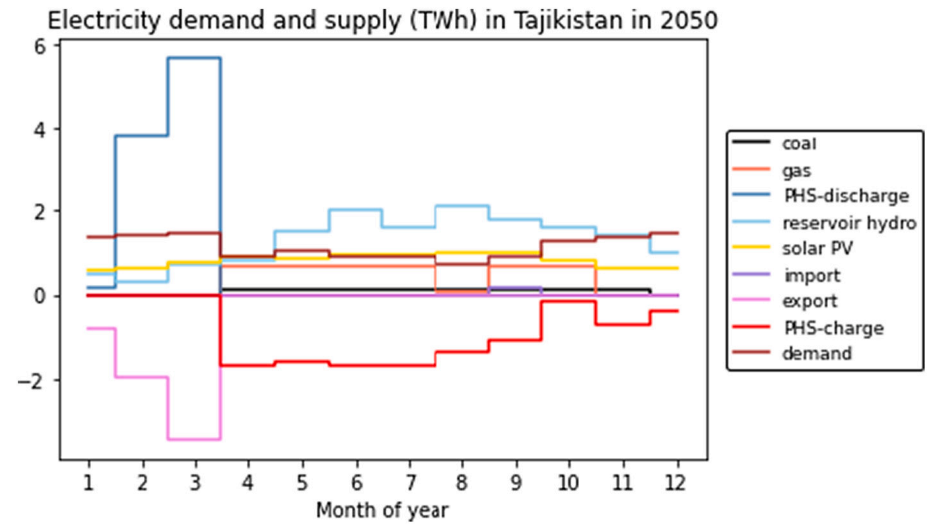


Fig. 9. Monthly electricity generation, demand, and pumped-storage electricity consumption in Tajikistan in 2050.

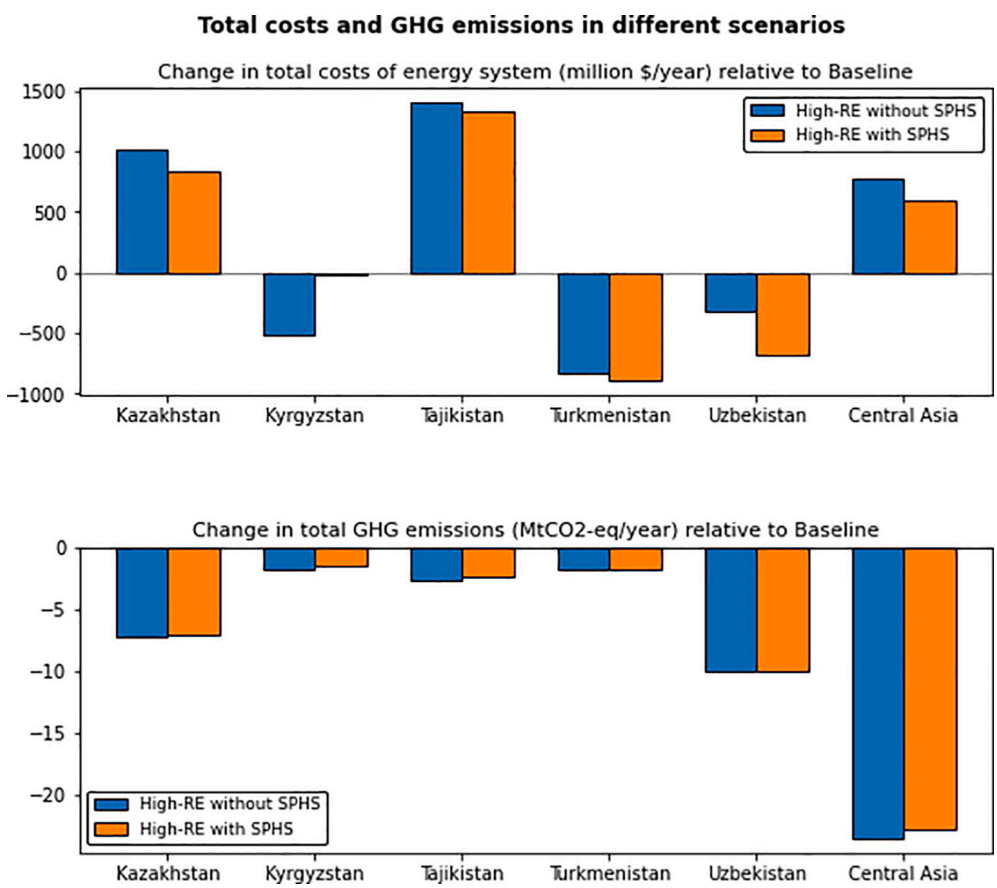


Fig. 10. Changes in the total cost of the energy system and GHG emissions in different countries and Central Asia in total. The results compare a high-renewable energy scenario (High-RE) with and without seeasonal pumped hydro storage (SPHS) relative to the Baseline scenario. The values are the average of 2020–2050. Negative values shows the reduction.

The business as usual, i.e., generating electricity from fossil fuel resources (natural gas and coal) during the winter and from hydropower during the summer so that the water can be used for irrigation downstream the rivers, does not capture the potential of hydropower resources in the region optimally and leaves upstream countries in need of electricity imports in winter. One solution could be to rely on renewable energy sources, such as solar PV and wind power, and curtail or export electricity during the summer when there is excess solar energy. However, such variable renewable energy sources require balancing and storage options in high shares, which can increase the cost of grid management.

The option proposed in this paper is a dual water and energy storage scheme, allowing two seasonal hydrological cycles for water and energy storage. A water cycle in downstream reservoirs to meet the water

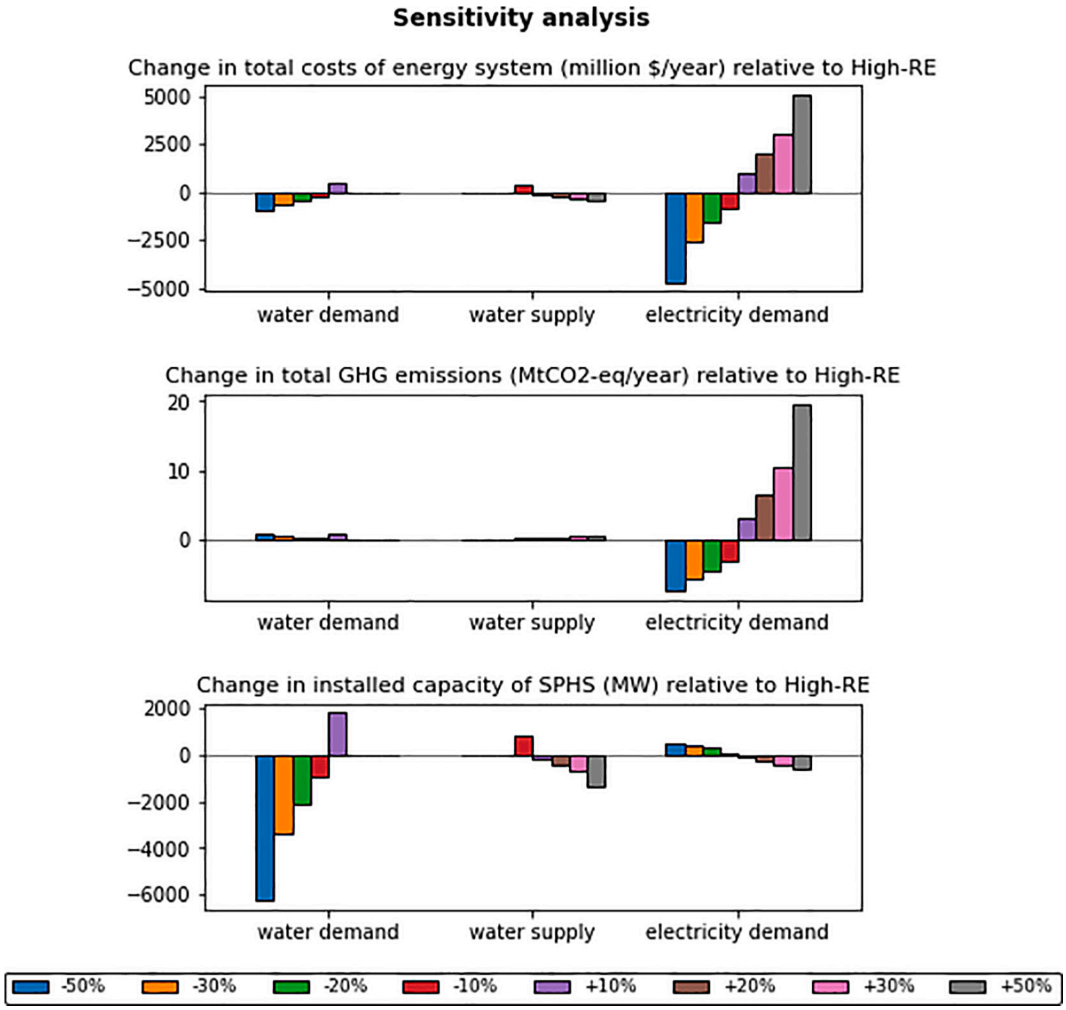


Fig. 11. Sensitivity analysis: The changes in total system costs, GHG emissions, and total installed capacity of seasonal pumped hydropower storage (SPHS) in Central Asia in 2050, relative to the high-renewable energy (High-RE) scenario analyzed in Section 2.1. Scenarios with more than 20% water demand in the region, or less than 20% reduction in water availability in upstream countries are technically infeasible.

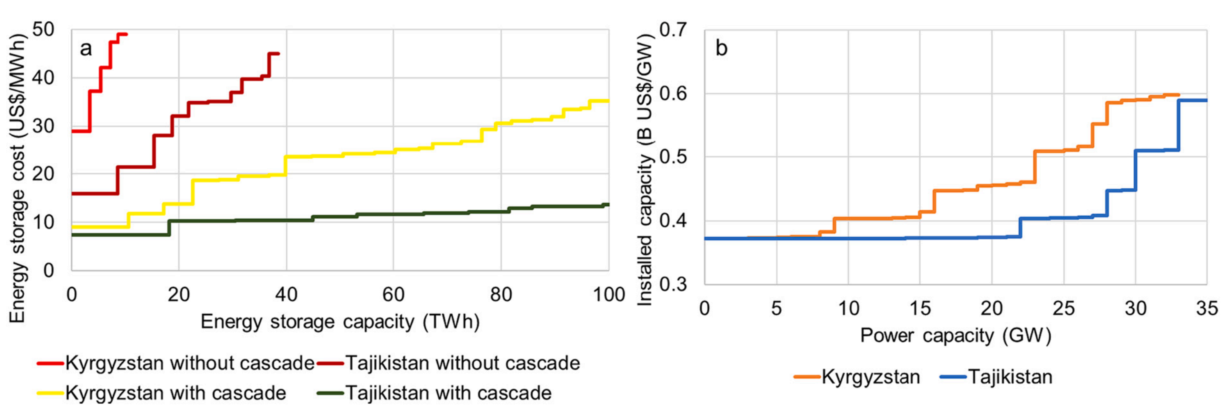


Fig. 12. Cost curve (a) for long-term energy storage costs, and (b) installed capacity in Kyrgyzstan and Tajikistan.

demand in Kazakhstan, Uzbekistan, and Turkmenistan in summer; and an energy cycle in upstream reservoirs (including seasonal pumped hydro) to store solar power during the summer and generate electricity during the winter. This option has shown to be economically viable if the region intends to increase the share of renewable electricity up to two-third of the total electricity generation. The proposed scheme would enhance water and energy security in all the countries in the region. This scheme would offer additional benefits if the countries accelerate the formation of regional electricity and ancillary services markets. For example, the proposed storage options could reduce the need for back-up capacity and flexibility in high-renewable energy scenarios in each country. This requires further political and economic cooperation between the Central Asian countries, and could serve the region in achieving planned sustainable development goals. This underpins the

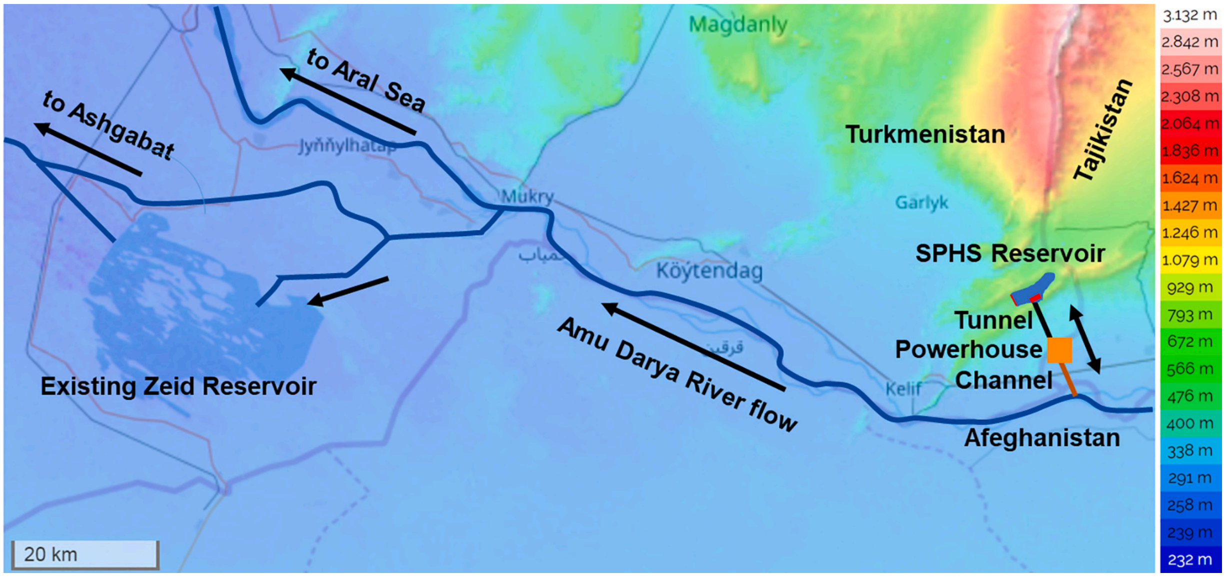


Fig. 13. Location of the proposed seasonal pumped hydro storage (SPHS) plant in Turkmenistan. The GIS mapping tool used to identify the most suitable place for the proposed scheme in this paper, which has a high depth to water surafce ratio to minimize the evaporation of stored water from the dam over long storage time.

role of transboundary cooperation and integrated management of water and energy resources in the region as identified elsewhere [80].

We recognize that further detailed analyses (e.g. of geology, financial resources, environmental and social impacts) are necessary to ascertain the suitability of the solution proposed in this analysis. However, as a technical approach, our analysis offers noteworthy potential to address water and energy security in the region, and can be complementary to other decision support tools that policymakers may use in efforts to resolve conflicts around sharing vital natural resources for mutual benefits of the nations in the Central Asian region. The model and data developed in this study is freely available for further refinement and more detailed analysis.

CRediT authorship contribution statement

Conceptualization, B.Z., J.H.; methodology, B.Z., J.H., V.K., A.V.,; formal analysis, B.Z., J.H.,; investigation, M.L., A.V.; data curation, B.Z., J.H., S.P.; writing—original draft preparation, B.Z, J.H., M.L.,; writing—review and editing, B.Z., J.H., M.L., V.K., A.V., S.P.; visualization, B.Z., J.H.; project administration, resources, and funding, V.K.., K.R.; software, B.Z., J.H., S.P. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

There is no conflict of interest involved in this publication.

Acknowledgements

This research was carried out at International Institute for Applied Systems Analysis (IIASA), and we appreciate the funding and support from IIASA. We appreciate the feedback and comments from Jihoon Min, Francesco Lovat, and Daniel Huppmann, and extensive support from Paul N. Kishimoto for setting up the storage section in the MESSAGEix modelling framework. We also appreciate comments and feedback from anonymous reviewers of the Journal.

Appendix A. Supplementary information

Supplementary information to this article can be found online at https://doi.org/10.1016/j.est.2022.104587. The project repository containing input data, code, and instructions for building the model used in this study and postprocessing some results can be found freely at https://github.com/iiasa/central-asia-storage.

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