Renewable and Sustainable Energy Reviews 167 (2022) 112726

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Sustainable small-scale hydropower solutions in Central Asian countries for local and cross-border energy/water supply

Ulugbek Azimov [a,*], Nilufar Avezova [b]

[a] Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne, NE1 8ST, UK
[b] National Research Institute of Renewable Energy Sources, 2B, Ch.Aitmatov Str., 100084, Tashkent, Uzbekistan

ARTICLE INFO

Keywords:
Central Asia
Hydropower
Small-hydro
Micro-hydro
Modular hydropower design
Cross-border challenges
Water management
Irrigation canal
Levelized cost of energy
Coupled energy systems

ABSTRACT

The Central Asian area is confronted with a number of acute obstacles as it attempts to transition to a long-term electrical power supply. Small-scale hydropower systems may be a viable answer to these problems. Central Asian nations' hydropower resources are allocated unevenly. Regardless, it remains the most exploitable renewable energy source in the area, with both Kyrgyzstan and Tajikistan possessing some of the world's highest hydropower potential. Nonetheless, for fossil-fuel-rich nations like Uzbekistan, Turkmenistan, and Kazakhstan, hydropower will play a significant role in the future energy balance. Furthermore, because rivers often run across many boundaries, water security plays an important role in cross-border relations between Central Asian countries. To achieve effective exploitation of small hydropower potential, technological and financial expenditures are needed to improve the levelised cost of energy (LCOE) of diverse hydroelectric equipment by increasing lifetime, improving efficiency, and increasing yearly power output. Several of these issues can be resolved by installing small and micro hydropower plants in the many minor rivers and irrigation canals. A pumped hydro energy storage system should also be tested and certified for better usability. A hydrological digital twin of relevant river system and irrigation network should be constructed to increase the understanding for performance and enable system-level improvement. Furthermore, optimal performance necessitates constant monitoring of the network, necessitating the development of intelligent monitoring employing sensors in conjunction with control systems and smart grid interactions. This review focuses on the broad and efficient use of these existing resources, which are still underutilized.

1. Introduction

Central Asia (CA) includes Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. The present population of CA makes over 70 million people and is predicted to increase to 90 million by 2050. The landscape of the region is diverse, with high passes and mountains such as Tian Shan and Pamir, large deserts such as Kara Kum and Kyzyl Kum, and multiple steppes. Since CA countries are connected by several transboundary rivers, which connect all five nations, the countries of CA are highly interdependent in terms of water, energy, and the environment. However, energy and water resources of CA countries are not uniformly dispersed. For instance, the Kyrgyz Republic and Tajikistan, the countries located the upstream of Amu Darya and Syr Darya rivers, have the most hydropower resources, whereas Kazakhstan, Uzbekistan and Turkmenistan, have the most hydrocarbon resources. The Kyrgyz Republic and Tajikistan's present hydropower generating capability is limited by an agreed-upon summer water flow schedule for downstream irrigation. Growing conflicting demands for water amongst CA states, compounded by massive water loss in irrigation infrastructure, producing drainage difficulties and rising environmental degradation of aquatic and terrestrial eco-systems, are the most significant concerns for Central Asia.

For science-based management, Karthe et al. [1] undertook an integrated evaluation of water in Central Asia. Demands from industries in agricultural, energy, and raw material sectors, and due to population expansion, have led to increasing water scarcity, as well as a diversified and significant pollution imprint on rivers, lakes, and groundwater bodies, according to the researchers. Changes associated with water quantity and quality were reasons that have not only harmed aquatic and riparian ecosystems, but they have also jeopardised the region's socioeconomic growth. The complexity of Central Asia's water challenges necessitates comprehensive evaluation and management

* Corresponding author.
E-mail addresses: ulugbek.azimov@northumbria.ac.uk (U. Azimov), avezovanr@gmail.com (N. Avezova).

https://doi.org/10.1016/j.rser.2022.112726
Received 4 April 2022; Accepted 17 June 2022
Available online 29 June 2022
1364-0321/

techniques. They stressed that adoption on a broader scale of integrated water resource management and the Water–Food–Energy nexus techniques might be critical to a more sustainable future.

Another issue is a lack of collaboration among CA nations in the way they manage water resources, which are usually shared. This can have serious economic effects, particularly in light of the growing dangers posed by growing concerns related to climate change. Recent Adelphi (2017) [2] analysis shows that the consequences of ineffective or sometimes even lack of action on water cooperation might cost Central Asia more than US$ 4.5 billion per year. Policy adjustments in the water sector, compared to a 'business as usual' scenario under the conditions and growing concerns related to climate change, may result in 20% difference in positive vs negative growth of GDP, according to World Bank statistics (2017) [3].

This diverse set of climate and political concerns necessitates the development of innovative solutions to secure the region's energy and water security. One of these is the untapped potential of small-scale hydropower. In Central Asia's electric power sectors, hydroelectric electricity plays a significant role. These nations formed their own interstate power pools after the disintegration of the Soviet Union [4]. This allowed all of the benefits of energy integration that had been gained inside the Soviet Union's centralized administration to be preserved. This made it feasible to utilise these nations' reasonably diversified energy resources. For instance, coal utilization in Kazakhstan, oil and natural gas utilization in Turkmenistan, and hydropower utilization in Tajikistan and Kyrgyzstan. The joint centre in Uzbekistan was in charge of managing the joint network for water and energy, which guaranteed that seasonal changes in power supply and water demand for agricultural irrigation were balanced. With Turkmenistan's withdrawal in 2003, however, political and commercial problems culminated in the disintegration of centralized coordination. The disintegration intensified disputes between energy generation and agricultural demands, affecting Tajikistan's and Kyrgyzstan's capacity to maintain electricity balances. The discrepancy in water and energy distribution, on the other hand, continues to motivate cross-border cooperation [5].

This review covers the objectives to identify extensive and efficient use of existing resources in Central Asian region to develop small-and micro-scale hydropower solutions, which are currently either inefficiently used due to aging network and equipment or still unexploited. We have taken more synergetic approach and analysed the current status and potential for small- and micro-scale hydropower in Central Asia looking at: 1) cross-border energy and water challenges in the region; 2) design and integration of hydropower generation systems; 3) development prospects in Central Asia; and 4) potential hydropower sites selection and comparisons. The review emphasized that the approach in implementing small- and micro-scale hydropower should not only consider engineering and technological advancements but also environmental, socio-economic, and business models. The value of this review is that it provides overall outlook on the small-scale hydropower development in Central Asian region, including the developments related to energy/water nexus in the region, current situation and initiatives, future prospects and potential, and an example of levelized cost of energy (LCOE) estimation for hydropower location sites with different power ratings. The structure of this review is shown in Fig. 1.

1.1. Potential and advantages of small-scale hydropower

Small- and micro-scale hydro power makes minimum negative impact on the environment and local flora and fauna and causes no social problems associated with a construction of big power plants. Aside from providing energy, small-scale hydropower infrastructure may help manage water resources for vital public services like irrigation, flood protection, and water delivery. Recognizing these benefits and assigning a fiscal value to these benefits would considerably improve the case for hydropower business. Expanding the access to finance with concessional orders and adoption of novel and progressive business models would allow emerging and developing countries to grow quicker.

Also, small scale hydropower has much smaller areas of flooding, very small size dams can be used, and the construction of long and expensive power lines is not required. However, the challenge for small- and micro-scale hydropower is that the development cost turns out to be higher than that of larger hydropower. Nevertheless, the benefit of using small- and micro-scale hydropower stations is that they can be installed in remote areas where centralized power supply is not available, and there is no other possibility to supply electricity. Therefore, small hydropower can make significant impact on the development and prosperity of rural and remote areas.

Between 2021 and 2030, small-scale hydropower projects, usually those which include plants with power generation less than 10 MW [6] are expected to contribute for 5% of further worldwide hydropower growth. When compared to major projects, the expansion patterns by region/country are slightly different since the possible untapped potential differs and is more broadly dispersed. Furthermore, small

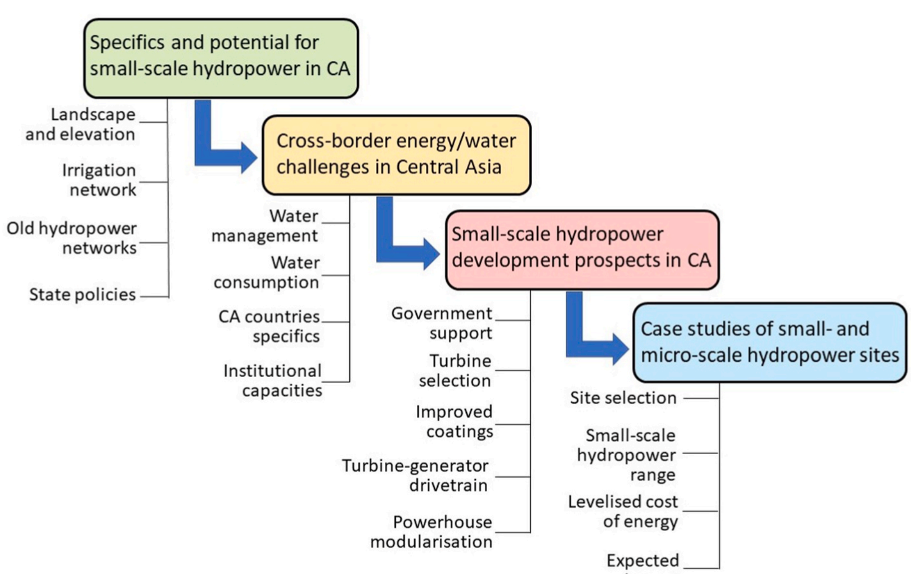

Fig. 1. Structure of this review paper.

hydropower has a number of support measures in place, including faster licensing in some circumstances compared to larger scale projects and a greater ratio of private ownerships, as well as local ownerships. Fig. 2 shows forecast for small hydropower capacity addition in the world during 2021–2030.

1.2. Potential of small-scale hydropower in Central Asia

Central Asia has a great potential for small- and micro-scale hydropower. The governments of Central Asia have established targets for renewable energy generation, and the Central Asia Regional Economic Cooperation program under the Asian Development bank have provided both a cohesive and sustainable cross-border energy strategy and development funding towards achieving its goals. Small-scale hydropower schemes provide a good compromise, allowing Central Asian countries to take advantage of the hydropower generation potential without disturbing the political balance [8]. However, the type of installed small-scale hydropower technology will depend on the geographic landscape, as both Kazakhstan and Turkmenistan have flat fertile valleys, Kyrgyzstan and Tajikistan have mountainous areas with peaks of about 4500 m above sea level, and Uzbekistan has extended flat irrigation network with about 25% mountainous territory, as shown in Fig. 3. Table 1 shows the hydropower resources and generation by CA countries.

Small- and micro-scale hydropower should take advantage of existing structures in irrigation channels to recover energy by hydropower production, wherever feasible. Small- and micro-sized hydropower plants could be a very effective solution to organize a supply of electricity to remote areas. This is especially important for countries with relatively large areas and sparsely distributed populations in mountain ranges, such as Uzbekistan and Kyrgyzstan, respectively, where the construction of large electricity supply networks is economically unfeasible. Within the landscape of Central Asia there are many small rivers and irrigation canals, which could accommodate small- and micro-scale hydropower sites to generate local electricity. As examples, Figs. 4–6 show the typical landscapes and potential hydropower resources in some Central Asian countries.

For example, in Uzbekistan, there are 27,868 km of inter-farm and 154,957 km of on-farm irrigation channels. Pumps irrigate almost 2.2 million hectares, consuming 7.5 billion kWh of power every year. A cascade of pumping stations along the Amu-Bukhara Canal, for example, lifts 200 m^3/s of water up to 157 m, essentially for irrigation of 335,000 ha in the Karshi Steppe; a cascade of pumping stations along the Amu-Bukhara Canal lifts 216.4 m^3/sec of water up to 115 m, essentially for irrigation of 315,000 ha in the Amu-Bukhara Canal. There are 1687 pumping stations with 5284 pump units, totaling 59.6 billion m^3 of water capacity per year.

It would be also important to emphasize that the old and existing network and hydropower facilities built during Soviet era are aging and becoming expensive to maintain. One example is the construction of a small hydropower station in Shakhimardan Uzbekistan that was started in 2002 but has never been completed. There have been several attempts to resume the construction, but it has never reached the stage of tryout. Fig. 7 shows the current condition of Shakhimardan hydropower station.

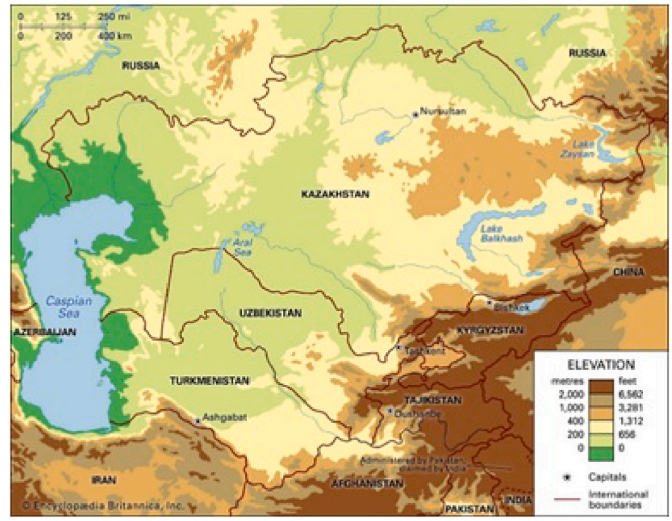

Fig. 3. Geographic landscape of Central Asia.

Small- and micro-scale hydropower can be integrated with other local renewable energy systems, such as solar, wind, and geothermal. Alternative renewable energy sources have a lot of promise in Central Asia. According to experts, the potential is three times that of organic nonrenewable fuel. There are more than 300 sunny days each year in the region, as well as adequate terrain and mountain rivers that may be used to generate power. Such abundant natural resources should be put to good use, and the technique of producing power from renewable energy sources should be extensively adopted.

For example, the Uzbekistan government has initiated the development of 5 GW of solar energy production by 2030 [9], which can be used more effectively if accompanied by pumped hydro energy storage (PHES). PHES is by far the most common and economic means of storing energy [10]. Rich natural opportunities must be exploited to improve food, water, and energy security for the people of Central Asia. However, such exploitation also carries the burden of care for the natural and socio-economic environments, and for consideration of a future under threatening climate change. As demands for water, energy, and food increase due to growth and standards of living, so will the interconnectedness between the sectors; this is the Water/Food/Energy/Climate nexus. Understanding the interrelationships and burden of care requires a framework for complex decision-making processes. In terms of management scheme simplicity (i.e. at the expense of ballast loading) and operation without service employees, current small and micro hydroelectric power stations can become economical. Their efficiency

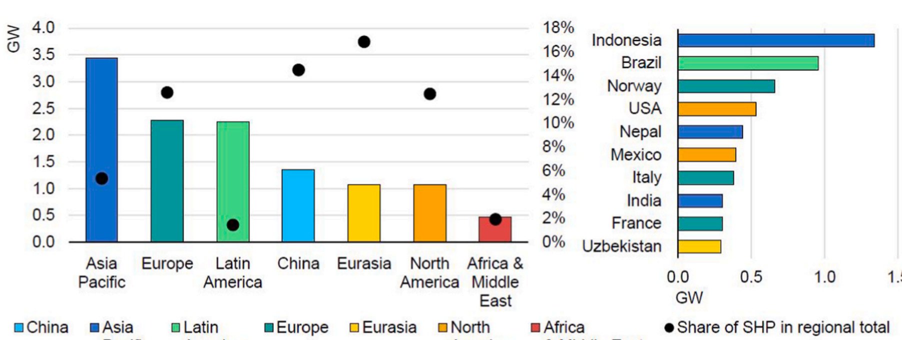

Fig. 2. Small scale hydropower increase by region (left) and leading countries (right) for 2021–2030 [7]. The data excludes China.

Table 1
Hydropower resources in Central Asia [8].

CA country	Installed capacity (this also includes pumped storage) in 2016, GW	Generation in 2016, TWh	Gross theoretical generation, TWh/year	Technically exploitable generation, TWh/year	Present utilization
Uzbekistan	1.889	10.59	88.5	27.4	39%
Kyrgyzstan	3.091	13.32	163	99	13%
Kazakhstan	2.372	9.27	198.6	61.9	15%
Tajikistan	5.19	16.9	527	317	5%
Turkmenistan	0.001	0.003	23.9	4.8	0%

Fig. 4. Typical irrigation canal and small dam in Uzbekistan.

Fig. 5. Natural mountain reservoir and small canal in Kyrgyzstan.

Fig. 6. Small river and irrigation system in Kazakhstan.

improves as a result of their multi-purpose use and electricity transmission to the grid.

2. Cross-border challenges

The removal of Turkmenistan (2003) and later Uzbekistan (2009) from the coordination of the energy supply system was due to political and trade conflicts between individual Central Asian nations [11]. On

Fig. 7. Current condition of incompleted Shakhimardan hydropower station in Uzbekistan. (A) Sluice gates, (B) Weir, (C) Trash rack, (D) Penstock.

the one hand, this circumstance made it impossible to satisfy the irrigation needs in Uzbekistan from released water by hydropower plants in Tajikistan and Kyrgyzstan, while on the other hand, it made it difficult to maintain Tajikistan's and Kyrgyzstan's electrical balances. The issue is that the significant reduction in hydro energy produced by higher water release during the summer season due to low electrical demand leads to a shortfall during the winter season. The annual hydropower losses are estimated to be around 6 TWh [11].

In Central Asia, there are considerable inefficiencies in the administration of water resources as well as associated industries (agricultural, energy). Water, energy, and food security, as well as human and environmental health, economic progress, and political stability, are all at danger as a result of the status quo. Water politics continue to stymie cooperation in Central Asia, despite the fact that long-term water and energy management would benefit the region's economies significantly. For example, storing downstream summer water demands in upstream reservoirs in return for winter energy trades to provide winter energy security upstream; optimized cascade management paired with an integrated power grid and trades to reduce energy loss through spillage. A major source of conflict is a lack of regional cooperation, which is exacerbated by increased demand for water and energy resources. [12], as well as a substantial hindrance to long-term development and security.

Kuehnast et al. [13] did considerable research on the possibility for war in Central Asia, focusing largely on developing ethnic tensions over scarce natural resources, notably land and water. They emphasized the causes that drive local-level disputes in the area using qualitative evidence obtained from 52 case studies in Kazakhstan, the Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan. Access to drinking and irrigation water, as well as the rising demand for water and other resources, accounted for a significant share of the local disputes recorded for their study.

Stewart [14] looked at the differing perspectives on whether shortage of water in the region would result in cooperation among the CA states or it would bring them into a conflict. He came to the conclusion that water shortage will only lead to conflict if it poses an existential danger to people or state. In response to the notion of virtual water, his work recognises the need for a new definition of the most extreme level of water shortage and provides a new description of absolute water shortage and scarcity considering the probability of arising an existential danger for people. He looked at two Central Asian case studies to assess the possibility of conflict using the criteria derived from a study of the water conflict debate. It was concluded that water shortages, demography, and geopolitics are likely to produce insecurity along Kazakhstan's Ili and Irtysh Rivers.

Table 2 shows the predicted water consumption in Uzbekistan by each sector of country's economy by 2030. The largest weightage of water volume will be spent for irrigation. Based on the forecast of Uzbek government, in 10–15 years the population may reach 40 million and water requirements will far exceed those available in the country. Thus, the effective utilization of water and energy resources is paramount not only for Uzbekistan but also for the entire Central Asian region.

Many communities that rely on agriculture for survival are experiencing lower earnings, damaged irrigation infrastructure, inadequate water management, and declining water quantity and quality as a result of the region's complicated changes in water management. These factors contribute to and worsen cross-border water conflicts, as well as a

Table 2
Predicted water consumption in Uzbekistan by a sector in 2030 [15].

Water consumption by sector	Total volume of water consumption (mln.m^3/year)	Water sources (mln.m^3/year)		
		Surface	Ground	Recirculated
Municipal	6200	2450	3750	0
Industry	3500	1580	1920	0
Agriculture	950	810	140	0
Fisheries	640	460	0	180
Energy	780	780	0	0
Irrigation	48,000	46,800	700	500
Total	**60,070**	**52,880**	**65,10**	**680**

general mistrust of government authorities on the ground [16]. Increasing environmental risks and climate change are exacerbating the need for water to be used in agriculture and power generation in order to fulfil demands for rapidly rising populations and demands for economic growth. Climate change is predicted to have a detrimental influence on Central Asian countries' water supplies, putting economic and sociological hardship on the region. At both the national and regional levels, Central Asian governments are aware of the problems posed by environmental, climate, water, and energy issues. All Central Asian countries stand to benefit greatly from transboundary cooperation on water and energy. By promoting incremental, bottom-up approaches while guaranteeing consistency across a plan that builds on national strategies to launch interstate collaboration initiatives, this possibility may become a tangible reality in the area.

Another issue is insufficient consideration of transforming policy into funding in order to repair ageing infrastructure. Technical competence has been lost due to insufficient regular technical maintenance and low financing in infrastructure, applied science, and engineering education. It is critical for Central Asian governments' economic growth and political stability to enhance infrastructure and manage water resources on the regional level to fulfil needs for human consumption, agriculture needs, industrial usage, and energy production. This void can be partially addressed by investments that are both cost-effective and ecologically friendly. In addition, to address these challenges, any new projects on hydropower to be implemented in Central Asia should develop not only technological innovations but also a framework that will help to resolve local issues associated with water/energy/environment in Central Asia.

3. Small-scale hydropower development prospects in Central Asia

3.1. Government support

There is considerable unexploited small-scale hydropower potential in Central Asia. The benefit of using small- and micro-scale hydropower stations is that they can be installed in remote areas where centralized power supply is not available. Therefore, solving this problem will make significant impact on the development and prosperity of rural and remote areas. In 2017, Kyrgyzstan government published a law on "Renewable electricity supply" [17] where renewable electricity tariffs were set, as shown in Table 3, with hydropower being the cheapest. However, the growth in small-scale hydropower sector has been very slow as shown in the same table, where the total amount of power generated by small-scale hydropower plants was negligible. This underlines massive potential as there is serious need for Kyrgyzstan to accelerate the implementation of small-scale hydropower projects to meet the demand of continuously growing population and businesses.

The development of small and micro hydropower systems in Uzbekistan is fully supported by the Uzbek government, which is implementing design and construction programmes as well as investment projects aimed at developing innovative solutions for Central Asia's underutilized small-scale hydropower potential, which will help to address the region's specific cross-border water and energy management challenges. In 2017, the President of Uzbekistan signed a decree establishing the JSC Uzbekgidroenergo [18], with the goal of developing new regulatory standards for effective utilization of Uzbekistan's hydropower potential, forming a unified water and energy resources management system, and consistently increasing the country's share of renewable hydropower resources. The main responsibilities of JCS Uzbekgidroenergo are to critically analyse the technical capability of local industries and develop new solutions for the implementation of innovative hydropower technologies in the region as reflected in the government-approved plan called "Concept and development of hydropower for 2020–2024" [18]. This paper also lays out the mission of fostering public-private partnerships in order to connect with corporate structures and encourage private investment in hydropower plant building.

In the Central Asian area, 45 large-scale hydropower plants with a gross capacity of 36.7 GWh/year are located on huge water reservoirs. Uzbekistan produces just 11% of the hydropower, whereas Tajikistan produces over 90%. Kyrgyzstan and Tajikistan contain around 78% of the region's total hydroelectric capacity, but barely use 10% of it. Future hydropower projects should aim to scale up renewable energy in Uzbekistan and introduce innovative hydropower components to Kyrgyzstan and Kazakhstan. It will embed resilience and sustainability provisions in CA countries' hydropower planning landscape. Project benefits can be classified under (i) incremental benefits, (ii) non-incremental benefits, and (iii) benefits from CO_2 reductions. Since the electrification rate is almost 100% in Uzbekistan, 85% of project outputs should be considered incremental supply to meet future demand, and the rest are non-incremental supply that will displace diesel generators during blackouts.

Government strategies to reduce project risks, such as guarantees provided by local authorities, long-lasting contracts, and other steps, which may increase certainty for compensation might be helpful. Reduced finance costs through policy measures are critical for ensuring hydropower generation's competitiveness, particularly in Central Asian nations where significant macroeconomic instabilities and risks may result in high costs.

The development of underlying concepts for small- and micro-scale modular hydropower solutions can potentially be achieved through the demonstration of the following underpinning concepts: a) Turbine selection and efficiency; b) Optimisation of turbine-generator drivetrain design; c) Coupling of small- and micro-scale hydropower with other renewable energy systems. These are explained in the following sections.

3.2. Turbine efficiency and optimisation of turbine-generator drivetrain design

There is a number of different turbines with different innovations. The turbine selection for small- and micro-scale hydropower in Central Asian countries is driven primarily by the available sites, by the social and cross-border issues, and by the challenges presented by high suspended solid content (SSC, also known as suspended sediment, silt content, etc.), which is present in many Central Asian waters. Using the common approach to determining theoretical power available, $P = \rho qgh$ where ρ is density (~1000 kg/m^3 for water), q is the flow in m^3/s, g is the acceleration due to gravity (9.81 m/s^2), and h is head in m, and a turbine selection guide, such as that shown in Fig. 8, one can determine the suitable types of turbines for each application [19]. However, turbine selection needs to match the efficiency profile to the flow duration curve as well as head. The reason for this can be seen from the graph in Fig. 9 [19], which shows efficiency by percentage of load (flow). This matching is best accomplished by means of modelling and simulation.

Table 3
Renewable electricity tariffs in Kyrgyzstan and electricity generation by small-scale hydropower [17].

Maximum electricity tariff, T_{MAX} (Kyrgyz Som) - 2.24		$T_{RES} = T_{MAX} \cdot A$	Conversion rate $1 = 102 Soms	
Renewable energy source	Coefficient (A)	Kyrgyz Som	$ cent	
Hydropower	2.1	4.7	4.6	
Solar	6.0	14.44	14.2	
Wind	2.5	5.6	5.5	
Geothermal	3.35	7.5	7.3	
Biomass	2.75	6.16	6.0	
	2013	2014	2015	2016	2017
Electricity generation by small-scale hydropower (MWh)	43.5	43.5	43.5	46.75	46.75

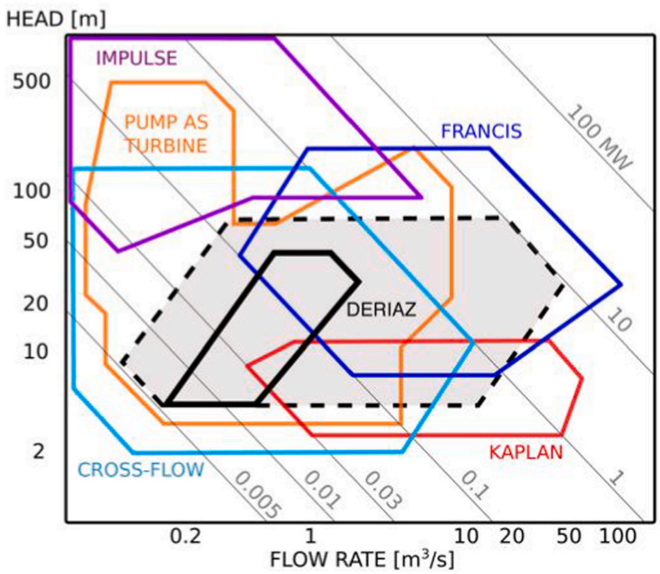

Fig. 8. Hydropower turbine selection chart. Adapted from Ref. [19] with permission.

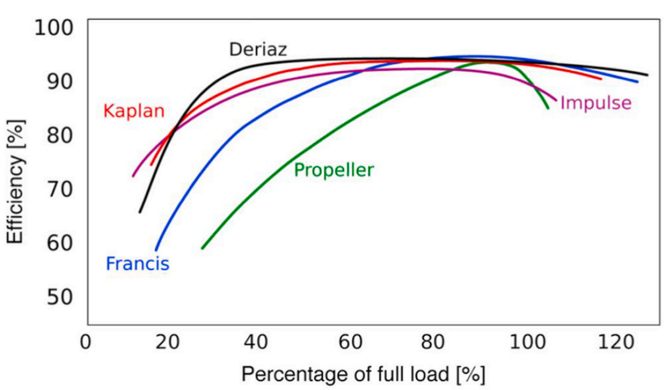

Fig. 9. Turbine efficiency vs load. Adapted from Ref. [19] with permission.

Advanced shape optimisation of turbine components can be performed using Computational Fluid Dynamics (CFD) to further optimise the chosen turbines. Using CFD, Zhou et al. [20] created an ultra-low head syphon hydro turbine. At the Gaoliangjian power station, they investigated the hydraulic performance of an axial turbine. They constructed a new syphon turbine based on the original distributor and turbine runner equipment using the same numerical approach. They also looked at how different syphon outlet passage geometry parameters, runner blade shapes, and distributors affected the syphon turbine's hydraulic performance. At the lowest head, the bell-shaped distributor with four guiding vanes produced the maximum power output. As a result, they came to the conclusion that the syphon turbine is a viable choice for energy conversion at ultra-low water heads.

Minimising equipment cost, and maximising amount of energy produced is key to reduce overall Levelised Cost of Energy (LCOE). To realise this, an optimized turbine – generator drivetrain must be developed with the highest level of efficiency in both turbines and generators. CAPEX and OPEX must be reduced, and the component lifetime maximized, to achieve higher competitiveness. To reduce LCOE, Permanent Magnet Synchronous Generators (PMSG) could be chosen due to its superior efficiency [21,22] curve at around medium speed as compared to Doubly Fed Induction Generator (DFIG) – which is less efficient at all speeds and a gearing drivetrain is preferred [23]. PMSGs are also more reliable, easier to maintain, great with reactive power compensation and minimal cogging and torque ripples [24]. All these characteristics can contribute to excellent power quality and grid compliance.

Furthermore, Direct Drive Technology (DDT) can be utilized for its advantages in lowered construction costs and COE [25]. It is clear that the energy yield of the DD machine is the lowest of all due to large copper losses. This can be addressed with system optimisations on the field-current levels to maximise efficiency of both generator and convertor during partial loads. Furthermore, rotor optimisation can be carried out to reduce loss from eddy currents in the permanent magnet. An ironless rotor core will be adapted to eliminate iron losses as well as cogging torque, thus simplifying design & construction cost and weight reduction [26]. To manage the difference in river flowrates, Variable Speed Operation (VSO) can be applied for the system to remain efficient over a larger range of flow speeds. A converter will be needed to allow the synchronous generator to vary in operating speed.

3.3. Powerhouse modularisation & component digitalisation

Ensuring system flexibility is essential to reduce LCOE as well as minimising impact to regional ecology. Most of the costs in hydro arises from civil works in the construction of dam, intake, pipes and powerhouse [27]. To address this, a containerization of hydro components in an open frame standard shipping container is a potential solution. This allows the avoidance of erecting of a permanent concrete powerhouse. Concrete production releases large amount of carbon dioxide – up to 8% of world-wide man-made emission of the gas [28]. It also causes damage to topsoil – the most fertile layers of earth, as well as soil erosion and water pollution due to surface runoff. Thus, implementing innovative flexible powerhouse design allows for cheap and fast system deployment and by fitting all components with completed control system into a container and shipping it to destination. Installation is as simple as connection to penstock and distribution network.

For small- and micro-scale hydropower plant modularisation new design methodologies should be developed and applied where individual components of a hydropower plant could be integrated as separate blocks like in a LEGO construction set [29]. This approach would allow maintaining standard sizes of individual components but at the same time being able to scale up and down hydropower plants based on the specific requirements. Using comprehensive geographic/hydrologic database, knowledge-based system (KBS) and decision support system (DSS) could be jointly used to identify the segments and locations with hydropower potential. Micro-hydropower plants, according to Gómez-Llanos et al. [30], where pump-*as*-turbine location is required, especially in areas with an excess of energy, result in an additional cost in terms of infrastructure conservation and maintenance or necessitates the installation of dissipation devices. Because the topographical and hydrological circumstances substantially impact the positions of these sites, a Geographic Information System (GIS) is an extremely important tool for implementing small- and micro-scale hydropower projects.

Through matching modular design and environmental requirements, individual blocks of hydropower system such as *Generation* (Turbine/Generator/Transformer), *Passage* (Intake/Sluice/Penstock/Trash rack), *Foundation* (Powerhouse/Dam/Outflow/Fish passage/Recreational watercraft passage/Sediment passage) can be optimized, manufactured using 3D printing technology, and assembled onsite. *Generation* module produces hydroelectric power, *Passage* module controls the flow, *Foundation* module provides structural stability. The same modules can be installed in similar streams or optimized for the specific sites. For this approach, however, regional (inter-country) standards and codes will have to be developed and adopted by Central Asian countries. This is explained in more details in section 3.7.

To address operational inflexibility and enhance small hydro utility through digitalisation of components, a health monitoring system with novel low-cost microchip-based sensors should be developed. For thermal effect simulation, Kang et al. [31] developed a dam health monitoring model based on long-term air temperature. To replicate the influence of temperature on dam reaction, harmonic sinusoidal functions are substituted with long-term air temperature in the model. They found that employing long-term air temperature in a nonlinear radial basis function network (RBFN) model produces better results than using harmonic sinusoidal functions. Dudhani et al. [32] examined minor hydropower potential using remote sensing data. They illustrated how remote sensing data may be used to identify and choose potential hydropower project sites, demonstrating that remote sensing data can be used to identify and assess hydropower projects in a scientific manner.

Bukenya et al. [33] conducted a literature study on the issue of concrete dam health monitoring using static and dynamic testing. They looked at case studies of concrete dam health monitoring and concluded that, despite extensive study into monitoring the structural integrity of infrastructure, such as bridges and buildings, dam health monitoring is still trailing behind. Despite the fact that dam monitoring has been practised for longer than other civil engineering disciplines like as bridges, it has not kept up with recent improvements in sensing technology and data analysis approaches. The investment in this study will be beneficial if particular approaches can be adopted to evaluate the structural health of concrete dams and increase the life of these structures. In a Bayesian environment, Sevieri et al. [34] provided a system for the dynamic structural health monitoring of concrete gravity dams. The researchers demonstrated that this technique has a minimal processing load and can identify damage and decrease uncertainty in forecasting dam structural behaviour, thereby increasing the structural health monitoring system's overall dependability. The suggested approach was tested on an Italian concrete gravity dam, demonstrating its viability in real-world situations.

3.4. Coupling of small-scale hydropower with other renewable energy systems

A feasible solution would be to take advantage of existing structures in irrigation channels to recover energy by small-scale hydropower production. The hydroelectric energy recovery in irrigation networks was studied by Chacon et al. [35]. They spoke about how to validate a statistical approach for estimating network flow and head fluctuation, as well as how to choose the pump-*as*-turbine with the shortest payback period. They also compared the predicted and actual occurrence probability for various flow rates at nine possible locations for micro-hydro power installations found inside a real network in Southwestern Spain. Butera et al. [36] calculated the hydropower potential of irrigation networks. They discussed several approaches for calculating hydropower potential and offered a strategy for analysing irrigation networks in order to determine their hydropower production potential.

Mollinga et al. [37] looked at the governance and system-level design characteristics of large-scale irrigation infrastructure in Uzbekistan. They looked at the relationship between technological structures and management and governance systems at the irrigation system level from a 'social construction of technology' approach. They discovered qualitative disparities in the infrastructural layout of the three irrigation systems, characteristics that matter for management and usage, as well as their consequences and implications. Djumaboev et al. [38] looked at the influence of institutional reform on irrigation management in Southern Uzbekistan as a case study. They discovered that obsolete infrastructure, weak administration, and farmers' failure to pay irrigation service fees are all obstacles to long-term water management.

At the present, there is no large solar power plants operating in Central Asia. Uzbekistan government has initiated development of 5 GW of solar energy production by 2030, and have already awarded a 100 MW project, and tendered an additional 800–900 MW, for which the process is in various stages. This could be used more effectively if accompanied by pumped hydro energy storage (PHES), which is by far the most common and economic means of storing energy [39,40]. The three states (Kazakhstan, Uzbekistan, and Turkmenistan) are continued to be highly dependent on fossil fuels, although they have some small percentage of hydro generation, and two states (Kyrgyzstan and Tajikistan) produce greater amount of electricity with hydropower but are still highly dependent on fossil fuel. Nevertheless, developing solar energy production plants is a very important priority in Central Asia. Development of such solar power plants would add value to CA countries energy sustainability, save national natural gas to be used for other higher value-added products, and lower GHG and toxic emissions.

Central Asia has a huge solar irradiation potential. For example, the solar irradiation capacity in Uzbekistan is presented in Fig. 10A as the Direct Normal Irradiation (DNI) and in Fig. 10B as the Global Horizontal Irradiation (GHI). The DNI was correlated with concentrated solar power (CSP) potential and the GHI was correlated with photovoltaic (PV) potential. For future small-scale hydropower projects to be integrated with the potential solar energy systems a selection process should be carried out to identify feasible sites for the hybrid mini/micro hydro + photovoltaic systems installation. The sites for such hybrid systems should be carefully chosen in the areas with preferred available infrastructure and convenient location.

The long-term solar resource in the selected areas was estimated using data collected over six months in ground meteorological stations and 13-year satellite data as shown in Fig. 11. This data shows that there are areas ideal for solar energy generating plants, including CSP and PV, with GHI greater than 1.800 kWh/m^2 per year and DNI greater than 2.000 kWh/m^2 per year.

For the integration of small-scale hydropower with solar PV, it will be required to make a comparison of system design parameters and expand the analysis to different PV plant locations in Central Asia. Some

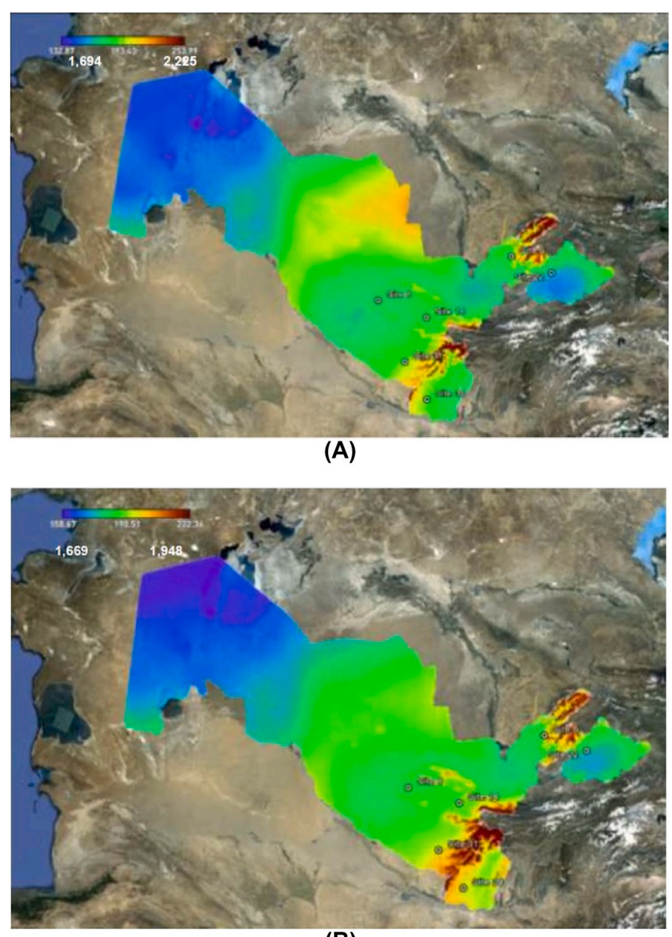

Fig. 10. (A) Representation of direct normal irradiation (DNI) and (B) global horizontal irradiation (GHI). (W/m^2/year kWh/m^2 year).

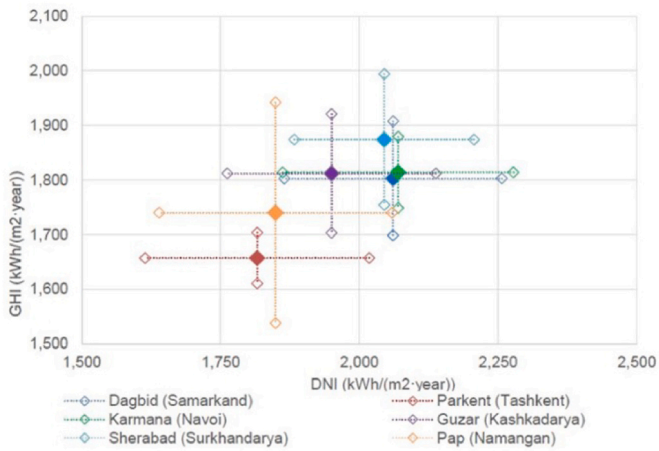

Fig. 11. Annual irradiation collected from six meteorological stations located at different areas in Uzbekistan.

research on integrating hydropower with solar plants was presented. Apichonnabutr et al. [41] looked at the trade-offs between economic and environmental performance of a micro hydro hybrid energy system. They demonstrated a strong benefit in establishing an integrated hybrid renewable energy system based on micro hydro power to boost off-grid energy infrastructure capability, particularly in environmentally sensitive areas in developing nations. Stiubiener et al. [42] looked into PV power generation on hydro dam reservoirs. They looked at a huge number of flooded regions caused by hydroelectric power plant reservoirs to see if PV floating power plants may be installed near the dams. They discovered that hydropower plant reservoirs in Brazil can accommodate PV floating power plants by using less than 10% of their surface area, supplying electricity demand with solar energy during peak irradiation hours while balancing grids with hydropower during low/no irradiation hours, improving operational flexibility.

Cazzaniga et al. [43] looked at combining PV floating plants with hydroelectric power plants as well. They studied the hydropower plant potential of the world's 20 greatest hydropower plants and discovered that by covering 10% of the hydropower plant basin surfaces, hydropower energy production may rise by 65%. Syahputra et al. [44] proposed hybrid micro-hydro and solar photovoltaic system planning for rural regions in central Java, Indonesia. They demonstrated that hybrid power plants may fulfil the electrical energy demands of the communities surrounding the facility while also selling the extra energy to national electricity suppliers.

The capital cost, cost of selling to the grid, energy expenses, and net present costs will all be compared in the hydropower and PV solar plant integration study. The total capital cost is the sum of all expenditures associated with the hybrid power plant building project. The initial cost of constructing a hybrid micro-hydro and PV power plant will be the total cost. The cost of electricity will be the subject of further investigation (COE). The average cost of electricity per kWh of electrical energy produced by the system is referred to as COE.

3.5. Development of regional standards on small-scale hydropower modularisation

To successfully apply flexible and modular hydropower solutions in Central Asian countries, inter-governmental regional normative standards and codes need to be developed and accepted. Clauses in local standards which conflict with novel practices and environmental regulations may create obstacles in implementing uniform and modern hydro power solutions in the region. Additionally, local labour laws, and occupational health and safety regulations should be adhered to. Recommendations for policies and standards that support the instalment and continued optimal use of small and micro-scale modular hydropower stations should be developed. Because the water bodies flow across-borders, policy development requires the involvement of governments of the relevant Central Asian countries. Such collaboration will ensure inter-government policy coherence on geographic, hydrologic, topographic, flood risk & mitigation for small-scale hydropower potential of rivers and irrigation canals in selected Central Asian countries. Access to and control over small-scale modular hydropower plants with transboundary significance will also be addressed in the recommendations. Given the significance that certain reservoirs are located on the territory of Kyrgyzstan and Tajikistan, and hydropower stations and irrigation canals are located on the territory of Uzbekistan, Kazakhstan, or Turkmenistan, such access is essential for maintenance and repairs. Therefore, to ensure efficient regional implementation of novel modular and flexible hydropower solutions and address energy/water challenges in the Central Asian region the following should be carefully considered:

1. Mapping of geographic, hydrologic, topographic, flood risk & mitigation for small-scale hydropower potential of rivers and irrigation canals in selected Central Asian countries;
2. Mapping of seasonal water supply intermittency during irrigation, high and low demand periods.
3. Mapping of infrastructure and supply of water and electricity in rural and remote areas of selected Central Asian countries;
4. Mapping of seismic activity in selected Central Asian countries;
5. Development of small-scale modular and innovative technology of hydropower plants and equipment (turbines, generators, inverters, pumps, control system, etc.);
6. Development of manufacturing processes for key system components
7. Development of auxiliary modular systems (pumped hydro energy storage, water purification, agricultural pumping system, bespoke installation components, gateways, and interface with the grid and other renewable electricity generation systems);
8. Development of new standards for small- and micro-scale hydropower in selected Central Asian countries;
9. Development of regulations on resource, techno-economic, environmental and social indicators for the design, construction and maintenance of small- and micro-scale hydropower stations in selected Central Asian countries;
10. Development of integration scheme to connect small- and micro-scale hydropower stations to the grid and other available renewable electricity generating systems (solar, wind, geothermal) in order to ensure the stable electricity generation and supply.
11. Analysis of the project sustainability at the juncture of the Water/Food/Energy/Climate nexus.

The future innovative projects should be focused on developing unexploited small and micro-scale hydropower in Central Asia. They should demonstrate a range of 10 kW to 2 MW hydropower generation systems. Innovative turbines, generators, controls, materials, and software will provide solutions for Central Asian businesses whilst fulfilling high standards for levelized cost of energy, local engagement, and social and environmental sustainability.

The potential projects should enhance competitiveness among potential technology suppliers, create new synergies between foreign and Central Asian businesses, and provide opportunities for ongoing and future business relationships. Innovative knowledge-based system (KBS) and decision support system (DSS) to support the complex decision-making required to achieve sustainability at the cross-border should be developed and implemented to achieve Water/Food/Energy/Climate nexus. Projects should also modularise the elements of the hydropower systems, which, along with the KBS and DSS will significantly reduce time to market and present an innovative way to faster commercialisation. This can be achieved through creating a smart online platform based on DSS facilitated by a KBS. The smart online platform would provide a streamlined approach to opportunities for embedded auxiliary services. A unified concept will reduce both capital expenditures (CAPEX) and operational expenditures (OPEX). The platform will serve as a public online platform to distribute DSS for potential hydropower projects. The DSS will be built on a decision-making module that includes Multi-Criteria-Analysis tools for comparing and rating options [45]. This can provide the opportunity for efficient hydro equipment matching to hydropower potential in specific location, which means utilising all relevant small hydro infrastructure and reduce Levelised Cost of Energy (LCOE) on all fronts.

3.6. Private and/or community ownership of small size hydropower sites

High growth in energy consumption, combined with a scarcity of money for power plant construction, has prompted several emerging countries to pursue private power generating. This enables governments to generate new power plant capacity without having to make significant financial investments [46]. Electricity consumption is increasing at a rate of 10%–15% or more per year in emerging countries due to industrial expansion.

Nearly 70% of new hydropower plants, that makes more than 10,000 of plants, which have been commissioned worldwide since the year of 2000, have been controlled and owned by a private sector [46]. Despite this, more than 70% of installed capacity (nearly 340 GW) belongs to the government. The size and ownership profile of a plant are inextricably linked. Usually, the greater a project's capacity, there is a higher chance that it is constructed or supported by any government-related utility. Usually, larger-scale hydropower projects demand huge investments, which may be counted by millions or even billions of dollars' worth investment, not to mention the lengthy development times that may not match private sector return expectations. Local resistance and societal acceptability issues, as well as regulatory hurdles including lengthy and complex approval processes, can significantly increase project risk.

The private sector owns roughly 75% of small plants with a capacity of less than 10 MW [46]. Small plants have lower investment needs than bigger facilities, allowing a broader number of enterprises to invest in hydropower projects. Auctions and feed-in tariffs are examples of policy instruments that stimulate investment in small-scale plants by ensuring steady income channels and reducing risks for investors. To enhance energy availability and electrification, developing-country governments are supporting private sector investment in small and micro plants. Due to enhanced economic feasibility, implementation of economic models that allow community-ownership would instigate wider and faster application of renewable energy assets compared to those with individual-ownership. Boosted deployment of renewable energy resources focusing on decentralised approach can help to achieve local decarbonization targets while also providing socioeconomic advantages such as job creation and energy availability. Some nations that have adopted community-ownership plans have good methods and expertise to share. Eigg Electric, for example, was founded on Eigg Island in Scotland as a corporation that is owned, operated, and maintained by a community. This offers renewable energy to all island residents. Such community-owned system comprises of three 110 kW hydropower generators, four 24 kW tiny wind generators, and a 50 kW array of solar electric panels, all of which are distributed over the island based on the best resource availability. The system's overall producing capacity is roughly 184 kW, and it has delivered around 95% of the electricity required since it was initially turned on in 2008. Two 80 kW diesel generators provide the remaining 5% of power when renewable resources are in short supply or when maintenance is required. The Eigg plant is decoupled from the mainland's energy supply, thus it is supplied by Eigg Electric, a community-owned company [47].

Because community energy projects have lower upfront costs, they can help local communities build renewable energy projects in areas where power is scarce. In addition to supplying energy to communities, this approach would also enhance neighborhoods by enabling profitable applications in agricultural processing, effective utilization of cold storage, cost-effective planning of irrigation and desalination, or other micro-enterprises. In these areas, community-owned models can be combined with flexible payment mechanisms, like pay-*as*-you-go models [48], to provide power to disadvantaged populations.

Projects with community ownership can also result in much cheaper energy costs for the community. For starters, electricity generated by locally deployed small- or micro-scale hydropower plants may be less expensive than electricity provided by other retailers. Demand (sometimes known as "peak") costs are a significant part of power bills, and they are typically calculated using the greatest electricity use demand (in kW) [47]. Peak load management and demand charges might be managed with on-site pumped hydro energy storage devices. In addition, community-owned projects would be compensated for power pumped into the main grid in accordance with current regulations.

3.7. Investments and partnerships

The International Energy Agency (IEA) released the first thorough predictions for three different types of hydropower, which include 1) reservoir, 2) run-of-river, and 3) pumped storage facilities, for the year 2030. Reservoir hydropower plants, which include dams that allow for long-term water storage, usually may account for almost half of total hydropower additions until 2030 [46]. The key drivers of reservoir project expansion are cost-effective power access, cross-border export prospects, and multifunctional dam usage. Facilities for pumped storage can store electricity by pumping water from a reservoir located at lower level to a reservoir located at higher level and then at peak hours, when electricity is required, can release the water through turbines. In that prediction, they account for 30% of net hydro-power additions until 2030. It is expected that between 2021 and 2030, the growing demand in many markets to ensure the system flexibility and storage to support the integration of bigger proportions of variable renewables will drive record development of pumped storage facilities [46]. Because it contains numerous small-scale projects under 10 MW, run-of-river hydropower, that can generate energy through natural water flow with little storage capacity, will continue to grow. As a result, run-of-river technology imbedded into small- or micro-scale hydropower is predicted to be cost-effective enough to attract private investment and partnership finance.

The development of a business case for pumped hydro energy storage systems is still a difficult task. Future power systems will increasingly combine pumped storage and battery technology. Each provides cost-effective storage options for a variety of timeframes. However, because pumped storage plants are larger and require more money, they are considered riskier than battery projects and are not usually appropriately compensated. Insufficiently developed long-term payment schemes and plans, low pricing for flexibility schemes, and lack of assurance over power prices and conditions of the market all reduce the economic appeal of new pumped storage investments [46].

Because hydropower installation costs are dictated by the conditions of local hydrological, geographical, and geological specifications, as well as ecosystems, and infrastructure, and also the purpose of the plant and its expected performance, they are very project specific. Civil works are the most expensive part of most large-scale hydro projects, as illustrated in Fig. 12, but because of the economies of scale that may be realised, usually large-scale projects also may have lower overall cost per unit of power of added capacity. Electromechanical equipment often accounts for the largest portion of total expenses for smaller run-of-river projects. Low labour and construction material prices can help Central Asian countries cut their civil works budgets, but other key aspects may include the existence of economically feasible sites located in desirable and easily accessible areas, and also the availability of efficient approval processes.

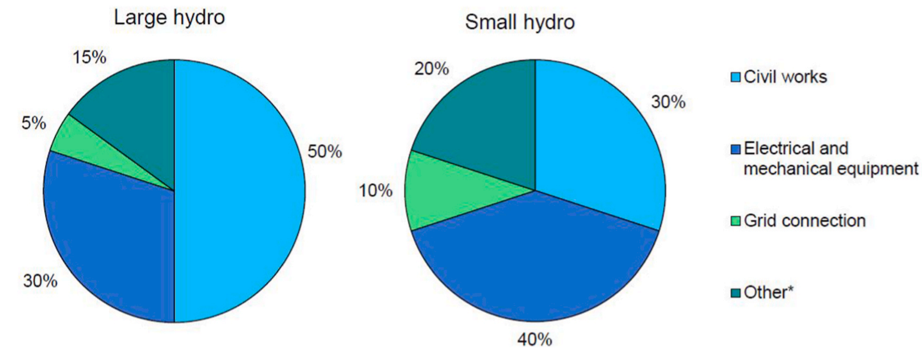

Fig. 12. Large and small hydropower plants typical investment cost distribution [46].

4. Case study: site selection

As a case study, five potential sites were considered with different landscapes and potential for electricity generation in a range of 10 kW - 2 MW. These sites have considerable variation in flow throughout the year [49–52].

Case 1: Shakhimardan, Uzbekistan with potential installation of 1 MW Franics & 1 MW Deriaz turbines.

Case 2: Naiman, Kyrgyzstan with potential installation of 209 kW Kaplan turbine.

Case 3: Gisaar, Uzbekistan with potential installation of 125 kW Pelton turbine.

Case 4: Namangan, Uzbekistan with potential installation of 50 kW Bulb turbine with pumped hydro energy storage.

Case 5: Andijan, Uzbekistan with potential installation of 10 kW Siphon turbine.

The site for Case 1 is in location called Shakhimardan, in the Uzbekistan exclave, within the borders of the Kyrgyz Republic, has wide seasonal variation in flow, with monthly averages between 1.68 m^3/s and 3.55 m^3/s, of which it can divert between 0.8 m^3/s and 3.2 m^3/s. With a minimum working head of 80.2 m, and accounting for head losses, we it can produce approximately between 550 kW and 2 MW power. Two turbines would have an overall higher annual production than one turbine. This is due to efficiency at low flow. Because the runner blades are adjustable, a Deriaz turbine may have high efficiency at a much lower percentage of the flow of its best efficiency point (BEP). Therefore, if at least one is a Deriaz turbine, the annual production capability could be better. The other can be a Francis turbine with advanced coatings.

The site for Case 2 is in location called Naiman, in the Kyrgyz Republic, that has 23.3 m head and 1.25 m^3/s, so can be used to install the Kaplan turbine.

The site for Case 3 is in location called Gisaar on the Aksu river in the Shakhrisabz district of the Kashkadarya region, that has approximately 80 m head and 0.32 m^3/s and can be a site suitable for installation of Pelton turbine.

The site for Case 4 is in location called Pap, Namangan, where the hydro power station can be installed on a branch of the Fergana canal where approximately 2.5 m head and 3 m^3/s flow are available. This site is suitable for installation of 50 kW bulb turbine with pumped hydro energy storage. The site is situated near a 130 kW experimental solar PV power production site and can be further coupled with PV solar station.

The site for Case 5 is in location called Andijan, Marhamat district, that will make use of infrastructure on irrigation canal with available flow of 2 m^3/s and existing drop of 1 m where a siphon turbine can be installed. The theoretically available power then would be between 17 and 22 kW, enough to supply power for a few local homes or farms. In this site, a 10 kW siphon turbine can be installed to provide a solution that is useful to the local community and takes advantage of existing infrastructure.

Levelized Cost of Energy (LCOE) and Return on Investment (ROI) were calculated for the most optimal scenario. Currently, LCOE of high performing hydropower sites can reach as low as 0.017 EUR/kWh [53]. In comparison, average large-scale hydro projects added in the last decade range from 0.034 EUR/kWh in China and Brazil, to 0.1 EUR/kWh in Europe. Similar trends can be observed for small hydro, where LCOE rises from 0.034 EUR/kWh in China and Brazil, to 0.11 EUR/kWh in Europe. The data were collected by IRENA and it is clear that cost of Hydro is significantly higher in Europe – with a 102% difference to China. Therefore, the potential technology investors and businesses will develop competitiveness on a cost front by reducing overall LCOE, maximising energy generated by small-scale hydropower equipment, and minimising related costs – including social economical, and environmental costs & impact.

With referral to Table 4, water-to-wire efficiency is calculated as the product of generator efficiency (97%), turbine and power electronics efficiencies (96%) with all components operating at most optimal scenarios. These figures are conservative estimates as medium speed of Permanent Magnet Synchronous Generators can easily achieve 97%+ in efficiencies. But it may be difficult to maintain these efficiencies due to variation in flowrate and other factors due to operating conditions. Since

Table 4
LCOE estimation for hydropower location sites with different power ratings.

Case 1		Case 2	Case 3	Case 4[b]	Case 5
Power rating	2 MW	209 kW	125 kW	50 kW	10 kW
Head (m)	82.5	23.3	80	4	1.5
Water to wire efficiency[a]	~87%	~86%	~88%	~88%	~81%
Estimated Operating Days annually	200	200	200	300	350
Expected Project Lifetime (years)	40	40	40	40	40
Estimated Annual Output [55]	9.16 GWh	946 MWh	579 MWh	347 MWh	74.6 MWh
Estimated CAPEX[a]	€1,255,852	€408,091	€267,202	€178,782	€51,011
Estimated OPEX, % of CAPEX/yr	1%	1%	1%	1%	1%
LCOE	€0.005/kWh	€0.015/kWh	€0.016/kWh	€0.018/kWh	€0.024/kWh
LCOE of small hydro projects by IRENA [56] (refurbishment cost)			€0.01 - €0.05/kWh – inflation adjusted		
Annualised ROI	5.06%	2.12%	2.35%	1.21%	1.11%

[a] Estimated from calculations and with the assistance of North West Hydro Resource Model [57].

[b] Only turbine mode is considered.

all systems can be installed with variable speed operation, the real water to wire efficiency should be closer to claimed figures. Furthermore, Variable Speed Operations can also boost annual output as nominal efficiency can be increased. The annual output is adjusted to the water to wire efficiency. LCOE and ROI can be calculated via the following equations [54]:

$$LCOE = \frac{CAPEX + OPEX \times Project\ lifetime}{Project\ lifetime \times Annual\ output} = \frac{CAPEX + 0.01 \times CAPEX \times 40}{40 \times Annual\ output}$$

ROI and annualised ROI is calculated as

$$ROI = \frac{Gain\ from\ investment - Cost}{Cost}\ ;\ ROI_{Annualised} = (1 + ROI)^{\frac{1}{N}} - 1$$

where, N is the project lifetime.

From the calculated LCOE, all test cases reside below LCOE of small hydro refurbishment projects (no civil works cost, includes all other relevant costs as published by North West Hydro Resource Model). It is observed that as the system power output decreases, LCOE increases, and annualised ROI decreases. This diminishing return matches expectations as demonstrated by IRENA. A contributing factor to this trend is the increased cost of equipment to maximise efficiency in low head settings. Overall, comparing the lowest LCOE figure to safe operating area (SOA) industry LCOE (€0.01/kWh), a 66.7% improvement can be observed.

5. Impact of small-scale hydropower

5.1. Social, industrial, agricultural & environmental sustainability impacts

In order to estimate the influence of micro and small hydro energy production classes, it is vital to remember that the number of possible plants, not the production of each plant, is what matters. Micro and small hydro plants do not usually necessitate the construction of large works across a large area, such as dams or water storage systems [58,59]. The installation of small plants serves a dual purpose: on the one hand, the costs of installation and operation are lower than for bigger hydroelectric plants, and on the other hand, electricity is supplied, at least locally and to the grid where infrastructure is available.

At the transboundary basin scale, hydropower projects' implications on the water-food-energy nexus were modelled by Amjath-Babu et al. [60]. It was shown that electricity generation, higher agricultural production, and flood damage mitigation may all provide large potential economic advantages. Jalilov et al. [61] looked at how to manage the water–energy–food nexus in the Amu Darya River Basin in Tajikistan, taking into account the benefits and drawbacks of new water development. They looked at two possible dam operation modes: Energy Mode (which would meet hydropower demands) and Irrigation Mode (which would meet the irrigation needs) (ensuring water for agriculture downstream). According to the findings, the Energy Mode may more than quadruple country's energy capacity while reducing water availability during the growing season, resulting in a 37% reduction in agricultural advantages in downstream countries. Irrigation networks must be included in this situation to create a considerable quantity of hydropower [62]. Small hydropower facilities may be simply fitted into existing irrigation canals, as old mills were in the past. When water is used for irrigation and hydroelectric power, it is put to many uses: this benefits society by highlighting the significance of implementing cost- and resource-effective irrigated agriculture, which is sometimes attacked by urban people as an inefficient use of water [62].

Kim [63] investigated the long-term viability of irrigation in Uzbekistan, as well as the consequences for female farmers. Using empirical data collected in post-Soviet Uzbekistan, the author shed light on the unintended consequences of an apparently well-intentioned irrigation project on farmers with poor ties to the state's agricultural trade apparatus. Using fieldwork data from a village largely affected by Aral Sea desiccation, the author described the daily struggles of these people, who are mostly women, to make a living and provide subsistence for their families in a situation of economic hardship, environmental disaster, and mass out-migration of male population. These findings will be very important to consider when integrating small- and micro-scale hydropower with irrigation networks. It is hoped that this would assist policy developers in formulating combined power production so that the irrigation schemes are designed in such a way that they are environmentally and socially sustainable.

5.2. Impact of small-scale hydropower integration with pumped hydro energy storage via hybridisation

With reference to Case study 4 in the Namangan region of Uzbekistan, it can be demonstrated a hybrid system through a pumped hydro energy storage (PHES) with a bulb turbine/pump coupled to a solar station with the capacity of 130 kW at the Fergana canal. It should be noted that the canal also a major irrigation canal spanning 350 km through Uzbekistan, Kyrgyzstan and Tajikistan. As shown in Table 5, PHES is preferable over large scale stationary Li-ion batteries. Currently, renewable energy combined with PHES is set to becoming a dominant factor in ensuring energy balance in Uzbekistan. The concepts of exploiting small hydropower plant in the context of sustainable development was reported [64]. Also, the concepts of exploiting renewable energy systems based on micro-hydro and solar photovoltaic for rural areas were reviewed [65,66]. The concepts of exploiting PHES with intermittent renewable energy generation were also reported, as an option for bringing power to rural communities [67] and as a UK government's plan to set out the shared approach to unlock UK's renewable energy potential [68].

However, inefficient regulation/use of pumped hydro energy storage in an irrigation network can present issues with pressure drops downstream, causing conflict of usage with agriculture purposes and being a nuance to nearby farming communities. Thus, monitoring for pressure drops downstream of the PHES and assigning critical thresholds to how much pressure can be safely lost is essential to avoid negative social-economic and agricultural impacts. This can be addressed via the impact assessment gained from the hydrological simulation and the creation of a hydrological digital twin of the Fergana canal. The results of the simulation can be fed to the SCADA control system to enable intelligent monitoring of the canal system, and only proceed to enter pump mode when it is safe to do so without negative impact to the surrounding.

Table 5
Specification of planned pumped hydro energy storage at Namangan, and performance vs SOA Li-ion battery.

Width, Length, Depth (in m)	10, 1000, 6
Head (m)	4
Volume (m^3)	40,000
Energy (kWh)	436
Discharge Time (h)	8
Flowrate (m^3/s)	1.39
Pumped Hydro Energy Storage (PHES) Estimated Cost (€)	54,500
Comparable Li-ion battery cost (€)	209,280
% diff between PES & Li-ion	117.4%
Total Irrigation Canal (IC) length, volume in Uzbekistan	27,620 km, 1,104,800,000 m^3 (est)
Estimated % of total IC useable for PHES	60%
Estimated energy potential of IC (GWh)	7.23
PHES cost vs Li-ion equivalent (€ billion)	0.9 vs 3.47

6. Conclusions

Small- and micro-scale hydropower is a feasible solution for Central Asian region to concurrently tackle local and cross-border energy and water challenges. By applying systematic knowledge-based and decision-support system approach, it will be possible to integrate, geographical, hydrological, environmental, and socio-economic data of the region to design high-performance and cost-effective small- and micro-scale hydropower plants. This can also include hybrid systems through combining hydropower with other renewable energy systems such as solar, wind, or geothermal. Such cost-effective solutions would allow creating new paradigms for renewable energy implementation not only for the development of engineering and technology, but also business models. With initiatives and support from the Central Asian local governments, new private and combined business ownership models could be adopted. Also, adopting regional standards for micro-scale hydropower integrated within irrigation network would allow utilization of the untapped potential of these vast resources. Small hydropower projects should be developed using new methodologies that focus on standardisation, system modularity, and acceptable environmental compatibility as being critical parts of a low-cost, high-impact facility. The strategy may be formalised through an environmental design methodology that prioritises the preservation of critical water-energy-environment nexus processes. These include water continuity, sustainable and continuous electricity production, aquatic life pathways, natural resource service, and sediment connection. These approaches would also instigate the development of local new pumped hydro energy storage systems, run-of-the-river solutions, and local manufacturing.

Due to the inter-connectivity and inter-dependence of Central Asian states on the energy and water resources in the region, these challenges should be collectively addressed with proposed new engineering, business, and social solutions. Implementing innovative and cost-effective small-and micro-scale hydropower may truly become a solution for supplying low-cost renewable electricity to remote and rural areas in Central Asia.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112726.

References

[1] Karthe D, Abdullaev I, Boldgiv B, Borchardt D, Chalov S, Jarsjo J, Li L, Nittrouer JA. Water in Central Asia: an integrated assessment for science-based management. Environ Earth Sci 2017;76:690. https://doi.org/10.1007/s12665-017-6994-x.
[2] Adelphi. Rethinking Water in Central Asia - The costs of inaction and benefits of water cooperation. https://www.adelphi.de/en/system/files/mediathek/bilder/Rethinking%20Water%20in%20Central%20Asia%20-%20adelphi%20carec%20ENG.pdf; 2017.
[3] World Bank data. Water resources management. 2017. https://www.worldbank.org/en/topic/waterresourcesmanagement#1.
[4] Belyaev LS, Chudinova L, Khamisov OV, Kovalev GF, Lebedeva LM, Podkovalnikov SV, Savelyev VA. Studies of interstate electric ties in Northeast Asia. Int J Global Energy Issues 2002;17(3). https://doi.org/10.1504/IJGEI.2002.000942.
[5] CAREC. Energy strategy 2030: common borders. Common solutions. Common energy future. In: Central Asia regional economic cooperation program. Asian Development Bank; 2019. https://doi.org/10.22617/TCS190515-2. November.
[6] World Small Hydropower Development Report. Small hydropower plants are defined as having less than 10 MW of capacity. In: Accordance with UNIDO (2019); 2019.
[7] Hydropower special market report analysis and forecast to 2030. International Energy Agency. [www.iea.org].
[8] International Fund for the Aral Sea. Ministry of water resources of the republic of Uzbekistan national committee on irrigation and drainage (UzNCID) irrigation and drainage in REPUBLIC of Uzbekistan, history and modern state, towards the 70th anniversary of the international commission on irrigation and drainage tashkent. 2020.
[9] Ministry of Energy of the Republic of Uzbekistan. Uzbekistan's ministry of energy plans to increase its 2030 renewables targets. https://minenergy.uz/en/news/view/1389.
[10] International Hydropower Association. The world's water battery: pumped hydropower storage and the clean energy transition. December 2018. IHA working paper.
[11] Belyaev L, Savelyev V, Chudinova L. The role of hydropower in electric power integration of Asian countries. In: 10th International Conference on Asian Energy Cooperation (AEC 2017), E3S Web of Conferences. 27; 2018, 01005. https://doi.org/10.1051/e3sconf/20182701005.
[12] GRID-Arendal center report. Water management in Central Asia: state and impact. https://www.grida.no/resources/7385.
[13] Kuehnast K, Dudwick N, Clarke M, O'Donnell A, Rana S. Whose rules rule? Everyday border and water conflicts in central Asia. The World Bank Group, Social Development Department; 2008.
[14] Wing Commander David I. Stewart raf. Water conflict in central Asia – is there potential for the desiccation of the Aral Sea or competition for the waters of Kazakhstan's cross-border Ili and Irtysh rivers to bring about conflict; and should the UK be concerned? Defence Stud 2014;14(1):76–109. https://doi.org/10.1080/14702436.2014.890336.
[15] Source: Ministry of water resourced of Uzbekistan.
[16] Waśkiel T. The water resources management in central Asia - the political and economic contradictions as a source of inefficiency. Nowa Polityka Wschodnia 2018;16(1). https://doi.org/10.15804/npw20181605.
[17] Renewable energy snapshot: Kyrgyzstan. United Nations Development Programme; 2017.
[18] Water power and dam construction magazine. Hydro development in Uzbekistan 1 October 2019.
[19] Morabito Alessandro, Guilherme de Oliveira e Silva, Patrick Hendrick. Deriaz pump-turbine for pumped hydro energy storage and micro applications. J Energy Storage 2019;24:100788.
[20] Zhou Daqing, Jia Gui, Deng Zhiqun Daniel, Chen Huixiang, Yu Yunyun, An Yu, Yang Chunxia. Development of an ultra-low head siphon hydro turbine using computational fluid dynamics. Energy 2019;181:43–50. https://doi.org/10.1016/j.energy.2019.05.060.
[21] Gieras JF, Wang RJ, Kamper MJ. Axial flux permanent Magnet brushless machines. Springer; 2008, ISBN 978-1-4020-6993-2.
[22] Wirtayasa K, Irasari P, Kasim M, Widiyanto P, Hikmawan M. Design of an axial–flux permanent-magnet generator (AFPMG) 1 kW, 220 volt, 300 rpm, 1 phase for pico hydro power plants. Int Conf Sustain Energy Eng Appl (ICSEEA) 2017.
[23] Thirumalai S, Chenniappan S. Performance analysis of wind driven generators supplying an isolated load. J Comput Theor Nanosci 2017;14. https://doi.org/10.1166/jctn.2017.7050. 2017.
[24] Gu Nnachi, Mosetlhe CT, Hamam Y. A comparative power quality study of DFIG and PMSG renewable energy conversion systems. In: 2020 5th international conference on renewable energies for developing countries (REDEC); 2020. p. 1–6. https://doi.org/10.1109/REDEC49234.2020.9163892.
[25] Hart K, McDonald A, Polinder H, Corr E, Carroll J. Improved cost of energy comparison of permanent Magnet generators for large offshore wind turbines. EWEA; 2014.
[26] Zhang Z. Ironless permanent Magnet generator for direct-driven offshore wind turbines. NTNU Trondheim; 2015.
[27] Renewable energy technologies: cost analysis series. Volume 1: power sector. Issue 3/5 – International Renewable Energy Agency (IRENA).
[28] The cement sustainability initiative: our agenda for action. World Business Council for Sustainable Development; 1 June 2002. p. 20. https://www.dcement.com/UploadFiles/CSI_UploadFiles_7000/201108/2011083116344603.pdf.
[29] Witt AM, Deneale S, Papanicolaou T, Athanasios N, Abban B, Bishop N. Standard modular hydropower: case study on modular facility design. United States: N. p.. 2018. https://doi.org/10.2172/1484123. Web
[30] Gómez-Llanos E, Durán-Barroso P, Arias-Trujillo J, Ceballos-Martínez JM, Torrecilla-Pinero JA, Candel-Pérez M. Small and micro-hydropower plants location by using geographic information system. Proceedings 2018;2:1300. https://doi.org/10.3390/proceedings2201300.
[31] Kang F, Liu X, Li J. Temperature effect modeling in structural health monitoring of concrete dams using kernel extreme learning machines. Struct Health Monit 2020;19(4):987–1002. https://doi.org/10.1177/1475921719872939.
[32] Dudhani S, Sinha AK, Inamdar SS. Assessment of small hydropower potential using remote sensing data for sustainable development in India. Energy Pol 2006;34:3195–205.
[33] Bukenya P, Moyo P, Beushausen H, Oosthuizen C. Health monitoring of concrete dams: a literature review. J Civil Struct Health Monit 2014;4:235–44. https://doi.org/10.1007/s13349-014-0079-2.
[34] Sevieri G, De Falco A. Dynamic structural health monitoring for concrete gravity dams based on the Bayesian inference. J Civil Struct Health Monitor 2020;10:235–50. https://doi.org/10.1007/s13349-020-00380-w.
[35] Chacon MC, Rodríguez Díaz JA, Morillo JG, McNabola A. Hydropower energy recovery in irrigation networks: validation of a methodology for flow prediction

and pump as turbine selection. Renew Energy 2020;147:1728–38. https://doi.org/10.1016/j.renene.2019.09.119.
[36] Butera I, Balestra R. Estimation of the hydropower potential of irrigation networks. Renew Sustain Energy Rev 2015;48:140–51. https://doi.org/10.1016/j.rser.2015.03.046.
[37] Mollinga PP, Veldwisch GJ. Ruling by canal: governance and system-level design characteristics of large-scale irrigation infrastructure in India and Uzbekistan. Water Altern (WaA) 2016;9(2):222–49.
[38] Djumaboev K, Hamidov A, Anarbekov O, Gafurov Z, Tussupova K. Impact of institutional change on irrigation management: a case study from Southern Uzbekistan. Water 2017;9:419. https://doi.org/10.3390/w9060419.
[39] Ibrahim H, Ilinca A, Perron J. Energy storage systems—characteristics and comparisons. Renew Sustain Energy Rev 2008;12:1221–50. https://doi.org/10.1016/j.rser.2007.01.023.
[40] Environmental and Energy Study Institute. Fact sheet - energy storage. 2019. https://www.eesi.org/files/FactSheet_Energy_Storage_0219.pdf.
[41] Apichonnabutr W, Tiwary A. Trade-offs between economic and environmental performance of an autonomous hybrid energy system using micro hydro. Appl Energy 2018;226:891–904. https://doi.org/10.1016/j.apenergy.2018.06.012.
[42] Stiubiener U, da Silva CT, Morante Trigoso FB, da Silva Benedito R, Teixeira JC. PV power generation on hydro dam's reservoirs in Brazil: a way to improve operational flexibility. Renew Energy 2020;150:765–76. https://doi.org/10.1016/j.renene.2020.01.003.
[43] Cazzaniga R, Rosa-Clot M, Rosa-Clot P, Tina GM. Integration of PV floating with hydroelectric power plants. Heliyon 2019;5:e01918. https://doi.org/10.1016/j.heliyon.2019.e01918.
[44] Syahputra R, Soesanti I. Planning of hybrid micro-hydro and solar photovoltaic systems for rural areas of central Java, Indonesia. Journal of Electrical and Computer Engineering 2020. https://doi.org/10.1155/2020/5972342. Article ID 5972342.
[45] Mateo JRSC. Multi-criteria analysis. In: Multi criteria analysis in the renewable energy industry. Green energy and technology. London: Springer; 2012. https://doi.org/10.1007/978-1-4471-2346-0_2.
[46] Environmental Energy Agency. Hydropower Special Market Report 2020-Analysis and Forecast to 2030. https://iea.blob.core.windows.net/assets/83ff8935-62dd-4150-80a8-c5001b740e21/HydropowerSpecialMarketReport.pdf.
[47] IRENA. Innovation landscape brief: community-ownership models. Abu Dhabi: International Renewable Energy Agency; 2020.
[48] IRENA. Innovation landscape brief: pay-as-you-go models. Abu Dhabi: International Renewable Energy Agency; 2020.
[49] Uzbekenergo. Environmental impact assessment, UZB: sustainable hydropower project EIA Vol. 11 _Technical appendices cumulative impact on fishes project number: 50130-002. May 2019.
[50] Ministry of Innovative Development. Data for Pap, Namangan and the Fergana canal. March 2020.
[51] JSC Uzbekgidroenergo. Request for tender documentation, for Shakhimardan hydropower facility. 2019.
[52] Economic feasibility study for shakhimardan hydropower 1994, Republic of Uzbekistan.
[53] IRENA Hydropower. https://www.irena.org/costs/Power-Generation-Costs/Hydropower.
[54] Aldersey-Williamsa J, Rubertb T. Levelised cost of energy – a theoretical justification and critical assessment. Energy Pol 2019;124:169–79. https://doi.org/10.1016/j.enpol.2018.10.004.
[55] Vougioukli AZ, Didaskalou E, Georgakellos D. Financial appraisal of small hydro-power considering the cradle-to-grave environmental cost: a case from Greece. Energies 2017;10(4):430. https://doi.org/10.3390/en10040430.
[56] IRENA Renewable Energy Cost Analysis – Hydropower. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/RE_Technologies_Cost_Analysis-HYDROPOWER.pdf; 2012.
[57] North West Hydro resource model. Lancaster University. [http://www.engineering.lancs.ac.uk/lureg/nwhrm/economics/emcosts.php].
[58] Adhau SP, Moharil RM, Adhau PG. Reassessment of irrigation potential for micro-hydro power generation. In: Proceedings of the international conference on sustainable energy Technologies. ICSET; 2010.
[59] Adhau SP, Moharil RM, Adhau PG. Mini-hydro power generation on existing irrigation projects: case study of Indian sites. Renew Sustain Energy Rev 2012;16:4785–95.
[60] Amjath-Babu TS, Sharma B, Brouwer R, Rasul G, Wahid SM, Neupane N, Bhattarai U, Sieber S. Integrated modelling of the impacts of hydropower projects on the water-food-energy nexus in a transboundary Himalayan river basin. Appl Energy 2019;239:494–503. https://doi.org/10.1016/j.apenergy.2019.01.147.
[61] Jalilov S, Keskinen M, Varis O, Amer S, Ward FA. Managing the water–energy–food nexus: gains and losses from new water development in Amu Darya River Basin. J Hydrol 2016;539:648–61. https://doi.org/10.1016/j.jhydrol.2016.05.071.
[62] Gensle D, Kinzii KD. Examining the feasibility of hydropower generation in irrigation canals: middle Rio grande conservancy district. J Irrigat Drain Eng 2013;139(5):405–13.
[63] Kim E. Book chapter: sustainability of irrigation in Uzbekistan: implications for women farmers. In Water and sustainability 2019. IntechOpen, DOI: 10.5772/intechopen.73414.
[64] Walczak N. Operational evaluation of a small hydropower plant in the context of sustainable development. Water 2018;10(9):1114. https://doi.org/10.3390/w10091114.
[65] Syahputra R, Soesanti I. Renewable energy systems based on micro-hydro and solar photovoltaic for rural areas: a case study in Yogyakarta, Indonesia. Energy Rep 2021;7:472–90. https://doi.org/10.1016/j.egyr.2021.01.015.
[66] Come Zebra EI, van der Windt HJ, Nhumaio G, Faaij APC. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. Renew Sustain Energy Rev 2021;144:111036. https://doi.org/10.1016/j.rser.2021.111036.
[67] Jurasz J, Canales FA, Kies A, Guezgouz M, Beluco A. A review on the complementarity of renewable energy sources: concept, metrics, application and future research directions. Sol Energy 2020;195:703–24. https://doi.org/10.1016/j.solener.2019.11.087.
[68] UK Renewable Energy Roadmap. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48128/2167-uk-renewable-energy-roadmap.pdf; 2011.