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Complementing hydroelectric power with floating solar PV for daytime peak electricity demand

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ABSTRACT

Renewable energy is the cornerstone of our future energy needs. In particular, solar energy is being utilized at a faster pace than ever. Floating Solar Photovoltaics (FSPV) has recently gained traction as a suitable alternative of land-based large scale PV installation. It is a promising technology to utilize water surfaces for placing solar plants. Not only it utilizes the water as real estate but it has several other advantages as well. For example, FSPV can use the existing transmission and distribution infrastructure that is the part of hydroelectric power plants. In this paper, we evaluate an FSPV plant and its integration with the existing hydroelectric power station of a small reservoir in Pakistan. We have investigated the 500 kV, 132 kV and 11 kV voltage levels for the integration of FSPV plant. Moreover, we have devised a hydro-solar optimization model for the efficient utilization of energy. The combined system consisting of hydroelectric and 200 MWp FSPV produces more than 3.5% additional power overall when compared with production of only hydroelectric power. More importantly the FSPV generation coincides with the daily mid-day peak load thus works as a peaker plant for the national grid.

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1. Introduction

The demand for energy is bound to increase due to rising global population and rapid industrialization. Being a dominant contributor to climate change, energy generation accounts for almost 60% of the global greenhouse gas emissions [1]. Global interest and investments in renewable energy sources (RES) have increased considerably owing to the environmental consequences of greenhouse gas emissions along with increasing prices of fossil fuels. Many countries have initiated the installation of facilities that use RES for power generation. The importance of RES comes together with climate change challenges associated with the excessive use of fossil fuels [2]. The harvesting of energy from renewable resources like solar, wind and water using technological advancements are the core factors that define the future of renewable energy systems [3]. Playing as a crucial element in the economy, energy forms the focal component for a country's success while keeping the country's development on track. As a developing country, Pakistan requires a large amount of energy to fulfill its residential and industrial needs [4]. Pakistan is going through a bleak period in terms of energy crisis due to rising mismatch between power supply and demand scenarios and vast financial deficit due to this mismatch. Such a situation is having an adverse effect on the overall economy of the country. Moreover, the energy crisis and high cost associated with it has resulted in the capacity utilization in some key industries to fall to nearly 50% [5,6]. Therefore, Pakistan urgently needs to come up with alternate energy generation strategies to inflict a change in its national energy mix. Reliable provision of electrical power at an affordable cost has long been acknowledged as one of the key hurdles to the industrial and economic growth in Pakistan. The demand for electricity is growing and requires a substantial increase in the rate at which new generating capacity is introduced. Most of the demand is met through an amalgam of power from thermal and hydroelectric plants. While there has been a prominent increase in the thermal power generation in recent years, it has also resulted in a perceptible impact on the unit cost of generation. The current economy of Pakistan, like many any other countries, is carbon locked-in and quite susceptible to energy prices. During summers in Pakistan, the temperature in plains rises up to 50 °C at daytime causing maximum demand to occur during this

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period. This extreme weather along with the climatic change implies that the country has a power demand that is to be met primarily during the daytime peak hours [7]. Previously, Pakistan's power trend has been oscillating between the two extremes of under-supply and the oversupply. From mid-nineties up to end the end of the twentieth century, Pakistan experienced a shortfall in the power supply. From early 2000s till 2006 the country had surplus power. Following the year 2007 till 2014 the trends again shifted, and the power shortfall dominated the energy profile of the country [8]. The trends from 2017 till the present day have again relocated towards the oversupply side [9:10]. This imbalance accompanied with the uncertainty in demand forecasting is making it difficult to rely on the present resources to cater the growing needs of the economy and the population. Pakistan's electricity mix is heavily tilted towards thermal resources and the country is generating 61% of the total electricity from these resources [11]. According to the Asian Development Bank report [12], the projected total green house gas emissions of Pakistan, in accordance with the government's economic growth strategy, are expected to be more than double by 2020 and increase by almost 14 times by 2050. In this scenario, the country needs a cost effective solution in the form of a demand dependent source that is modular, can be added quickly and provide power based on the requirements. PV panel arrays mounted on floating structures, or commonly known as floating solar PV (FSPV), have emerged as an effective candidate to address the aforementioned challenges. The FSPV can cater the required energy demand and at the same time offer additional benefits both in terms of the cost and application. Pakistan's demand profile is completely coincidental with the solar provision peak at the daytime which can prove to be a major application of FSPV in Pakistan's electrical power provision infrastructure. FSPV, when used in conjunction with other power generation sources, especially with hydropower, is a viable alternative to cater the peak demand during daytime using RES. The hydro-solar combination can also result in the reduction of the basket price of electricity which Pakistan needs to overcome its current energy crisis and economic down slide.

Our research hypothesis for this study is that a combination of hydroelectric and FSPV provides a valuable addition to the power generation. We introduce an optimization methodology of combining hydro and FSPV to offer substantial advantages alongside meeting the daytime peak demand of the national grid. The hydroelectric power generation and FSPV will use the same transmission infrastructure, thus cutting down installation and transmission costs. The installation of the solar PV panel arrays on water bodies allows cooling of the solar cells in a natural manner, not owing to any additional requirements. The presence of a water body for FSPV allows the solar cells to alleviate the temperature and at the same time be cleaned and dusted off to ensure maximum efficiency. Additionally, by covering the water surface with these panel arrays, the rate of evaporation can also be reduced [13]. In this paper, we analyze and establish an integration, implementation and optimization framework to carry out FSPV installation on one of the hydropower reservoirs of Pakistan i.e. Ghazi Barotha Hydroelectric power plant, to evaluate the feasibility of installing large scale FSPV system. Our main contributions in this paper are as follow: (*i*) investigating the FSPV installation and utilization concept in the scenario of Pakistan; (*ii*) Analyzing installation of FSPV on dam reservoirs to utilize the existing power transmission and distribution infrastructure of hydroelectric plant; (*iii*) developing integration and implementation framework for FSPV deployment on the dam reservoir using a case study of Ghazi Barotha hydroelectric plant that includes the estimation of reservoir's feasible area and ground elevations, the power generation potential of FSPV and different techniques for FSPV integration with the main electrical infrastructure (*iv*) identification of linear optimization framework for optimal power dispatch of the FSPV-hydro integrated system to meet the peak demand occurring at a specific time period. The above mentioned contributions are divided into three comprehensive sections. The first section extends over Pakistan's solar energy and the overall peak demand profile, and further highlights the FSPV potential and its installation in Pakistan. The second section analyzes the implementation and integration technologies for a FSPV plant on the Ghazi Barotha hydropower project. The third section, elaborates the electrical power integration techniques and optimization of the Ghazi Barotha hydroelectric plant with FSPV facility, followed by the discussion on strengths and positive impacts of FSPV plant.

2. Literature review

Pakistan has a huge potential for electricity generation from a variety of RES. The identification and quantification of this potential is necessary to make the country self-dependent in meeting its energy requirements [14]. The urgency of reducing large scale carbon emissions in an environment-friendly and sustainable manner has paved the way for the deployment of renewable energy systems and technologies in Pakistan. Pakistan has millions of MWs of renewable energy generation potential [14:15]. The total renewable energy potential in Pakistan is almost 167.7 GW, which is eight times more than the total electricity demand in the country (21 GW) [16].

2.1. Solar energy and hydropower potential in Pakistan

Pakistan has a remarkable solar and hydroelectric power generation potential. Sufficient solar irradiance is widely dispersed and abundantly available in the country. On average solar global insulation of 5–7 kWh $m^{-2}d^{-1}$ exists in most regions of the country. The average solar energy available is nearly 5.5 kWh $m^{-2}d^{-1}$ having annual mean sunshine duration between 8 and 10 h d^{-1} and 300 days (1500–3000 h) per year [17]. A study conducted by National Renewable Energy Laboratory (NREL), USA, in collaboration with USAID reported that solar energy potential of 2.9 million MW exists in Pakistan [14]. The average solar irradiance in Pakistan is 5.5 kWh/m^2/day [18]. Pakistan can make use of this abundant and extensively distributed solar energy potential for the improvement of its socio-economic conditions.

Hydropower is currently the largest renewable energy source of power generation in Pakistan, but it is utilizing only 11% of its total hydropower potential of 60,000 MW. The share of hydropower can become more than 40% and indigenous energy resources as a whole can contribute up to 80% in the supply mix for electricity production in Pakistan by the year 2030. At the same time the share of oil and gas based generation resources, which is currently more than 60%, can be reduced to 12% percent [14:19].

2.1.1. Major hydroelectric and solar power plants

There are major hydroelectric power plants in operation at Tarbela (3478 MW), Ghazi Barotha (1450 MW), Mangla (1000 MW) and at other locations which account for almost 30% of Pakistan's total electricity generation [20]. Diamer Basha and Dasu Dams are also under construction; when completed these projects will significantly increase the share of hydropower in Pakistan's total electricity mix. Similarly, Pakistan has also made advancements in solar energy utilization by installing its first large scale solar power plant, Quaid-e-Azam Solar Power Park (QASPP), which has a maximum generation capacity of 1000 MW [21].

2.2. Hydro-PV system

Hybrid Energy Systems (HESs) can play an important role in providing greater balance in the energy supply as well as boosting the system's overall efficiency [22]. The Hydro–PV system is amongst the most widely used HES, since hydropower can be generated at a large scale while solar energy is the largest available RES [23:24]. Regions of Pakistan that are rich in both hydro and solar energy generation potential, such as central and northwest Pakistan, are particularly suitable for the development of large hydro–PV systems. Research pertaining to the hydro–PV systems mainly focuses on exploration of time complementarity between hydropower and PV power [25], optimization of the system configuration [26:27] and plant operations management [28:29]. For the first aspect, a research study found that a better temporal complementarity between hydro and solar energy of a hydro–PV plant can help stabilize the energy supply [30]. In another analysis, it is found that the complementarity between small hydropower plants and solar PV systems could be improved by optimization [25]. These findings verified the advantages of the hydro–PV system in meeting the energy demand, which can be further enhanced through integration and optimization techniques for the hybrid system.

2.3. Floating solar PV system

Established on the above background, FSPV systems offers an effective solution for energy generation, without having a substantial demand for water and land resources. Installation of FSPV is a coherent substitute to the land-based PV systems for harnessing solar energy. FSPV system is a new form of solar PV electricity generation technology which involves the installation of PV panels on water surface using the floating structures as shown in Fig. 1 (31: 32). Following the first pilot FSPV plant that was installed in California in 2008, several such plants have been installed across the world with capacity ranging from 0.5 kW to 1150 kW, including Europe's largest FSPV system installed recently [33:34]. Since 2011, the cumulative installed FSPV capacity around the globe has reached 1100 MW [35].

In a research study, the authors propose a general outline of the FSPV as an emerging technology in the domain of renewable energy [32]. The paper discusses the need for FSPV and its design requirements along with the specifications and various advantages it has over the conventional ground mounted PV systems. It also compares the installed capacity of FSPV plants across the world and highlights its infrastructure requirements to be taken into account when transmitting the electricity to the load. Another research study focuses on the design perspective and improvements in the efficiency of the FSPV by modifying its design parameters. The study then enlists experiments performed by varying the design parameters to see the effects imposed on the efficiency and operating cost of the FSPV system [36]. The evaluation of FSPV and its role in water management has also been presented in a study which focuses specifically on the installation of a pilot FSPV plant on a water body in Arizona which highlights the potential of its installation and future implications [13]. In another study, the authors propose the prospects of combining the FSPV with hydropower reservoirs [37]. This approach is tested through a number of simulations, but the study does not represent any practical implementation of the idea. A practical implementation of this idea is explored in a study where the authors propose to combine the FSPV with Pumped Hydro Energy Storage (PHES) to produce uninterrupted 'Green' energy. The paper highlights the potential of this combination and at the same time, discusses the limitations and the future demand catered using this amalgamation [38].

While the research work carried out so far in the literature tends to manifest the resourcefulness of the FSPV, our approach on the topic mainly differs in terms of the fact that it involves a comprehensive and pragmatic implementation and integration techniques. The techniques not only utilize the inventiveness of FSPV but also tend to maximize the potential offered via the optimization methodology mentioned in this paper.

2.3.1. Benefits of FSPV system

The aforementioned literature also summarizes some of the obvious advantages that FSPV has over land-based solar PV installations, which include economic viability due to reduced real-estate costs, cooling effect of water which enhances energy yield of a given installed PV capacity, shading provided by the FSPV panels which consequently reduces rate of water evaporation and improves water quality by reducing algae growth, lesser accumulation of dust on the panel arrays as the surrounding environment of water surfaces contains less dust as compared to land, ease of cleaning of PV panels by readily available water using sprinklers and pumps (35: 36: 13).

Moreover, in our study, we have explored some technical and economical benefits of installation of FSPV system, particularly on the hydroelectric dam reservoirs. The benefits comprise: (a) Utilization of the existing transmission infrastructure which resultantly reduces the associated cost and complexities due to the negligible cost of laying out ancillary transmission network; (b) Complementary operation of hydro and solar to leverage more solar during the daytime and hydropower at night hours; (c) Reduction of stress on power generating turbines, thus increasing equipment life, and; (d) Conservation of water as hydroelectric plant caters only one peak demand instead of two, hence strengthens the hydropower generation company economically in its operations and maintenance.

In the context of Pakistan's FSPV potential, country possesses one of the largest canal irrigation systems in the world. It also has some of the largest dam reservoirs (Tarbela Dam, Mangla Dam etc) and river systems (Indus River) [39]. Deployment of FSPV on such water bodies can harvest a large amount of electrical energy, which in turn can have positive outcomes in the form of reduced

Fig. 1. Floating Solar PV installed on a water body ([31:32]).

dependency on carbon-based fuels for power generation. Also, the recent installations of FSPV plants delineate the fact that countries like Pakistan, that possess water resources in the form of large water reservoirs, have a reasonable potential to install FSPV plants [40].

3. Pakistan's solar and load demand profile

With a swift increase in population and rate of urbanization, Pakistan is facing severe electricity crisis as the country's energy mismatch in consumption and generation is increasing. Previously, the strategy was to focus on the installation of more thermal power plants to reduce the gap between consumption and generation but these power plants come at a very critical cost for the environment. Renewable energy sources are sustainable and environment friendly, while at the same time have the potential to fill the energy gap between the supply and demand. These sustainable sources, solar in particular, have a large potential and can play a vital role in overcoming the energy crisis, reducing harmful carbon emissions and providing sustainable energy [16].

Apart from its vast potential for energy generation, solar energy profile of Pakistan resembles the country's load demand curve. Typically, two major peaks occur in the load demand curve of Pakistan - one during the day and the other during the evening hours, which is shown in Fig. 2 as the normalized seasonal distribution of one of Pakistan's province average electricity demand verses it's matching with the solar profile [7]. The peak that appears during the daytime is coincidental with the solar energy profile of the country. However, to serve the second peak load, we can use hydro as well as thermal resources. The matching profiles of peak load demand and solar energy are the key aspects that encourage the integration of solar energy systems with the national grid to meet the peak load demands in an eco-friendly and sustainable way.

3.1. Floating PV system in Pakistan: a new technology

Despite having a vast potential for electricity generation, the installed capacity of solar and hydropower plants is limited in Pakistan mainly due to two reasons. First of all, the hydroelectric power potential of Pakistan lies in the north of the country, whereas most of the energy requirement is in the central region. Therefore, it requires massive investments to lay down transmission lines. Secondly, although the central region is rich in solar energy but at the same time it acts as the vital food basket for the country. Large utility-scale power plants are not desirable since they can compromise the precious acreage that is used for agricultural purposes. In this situation, integration of solar energy system and hydropower plant at the same site for the utilization of optimal energy mix is quite feasible option. Installation of solar PV system on water bodies like lakes, canals, reservoirs, and rivers is a crucial aspect of new paths for solar energy utilization. FSPV is a new and unique solar PV system technology that has a wide range of applications and has numerous advantages over the land-based solar PV systems. FSPV system is economically viable due to the absence of any land requirements and costs. It operates at lower temperatures due to the presence of water underneath, the panels can be cleaned and cooled by already available water reserves and conserve the water by reducing water evaporation which adds to the extra utility provided by these systems (36: 13). In Pakistan, FSPV has an outstanding potential for energy generation owing to the presence of one of the largest rivers, irrigation canals and dam reservoir systems of the world [39]. The installation of FSPV technology in Pakistan can have a significant impact in minimizing the

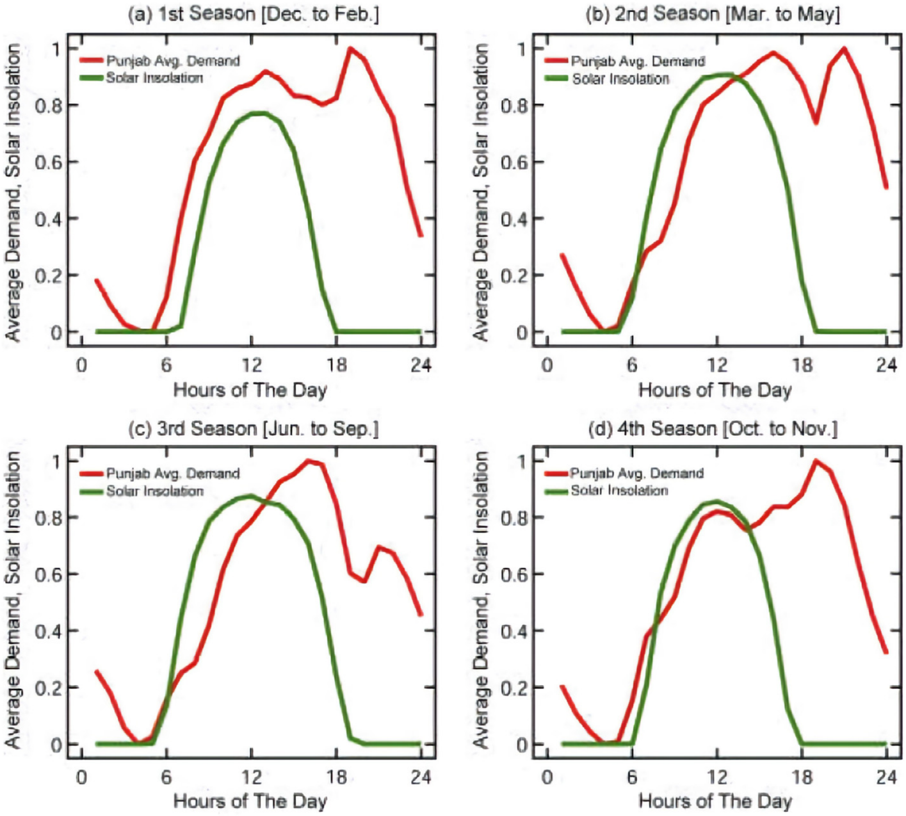


Fig. 2. Normalized seasonal distribution of Pakistan's average electricity demand vs it's matching with the solar profile [7].

gap between supply and demand of electricity. Fig. 3 depicts the classification of solar PV installation in Pakistan where FSPV is represented as a new technology that can be deployed in Pakistan ([21:41]).

3.1.1. *Installation of floating solar PV on reservoir*

The reservoir of the dam is used to reduce the spatio-temporal variability of natural water supply. Dam reservoir regulates the water flow and acts as a reliable source of water for a wide variety of applications [42]. Additionally, the reservoir assures water security and economic development. It has a long life span but its potential to handle vast water reserves and surface infrastructure remain unexplored [43]. Utilization of reservoir's enormous water surface by the installation of FSPV plants is an eco-friendly and a sustainable way of harvesting electrical energy. The reservoir of a dam generally has a massive water surface, which has the potential of producing hundreds of Megawatts (MW) of electrical power. Water reservoirs usually have optimal conditions for the installation of FSPV, which include stable water inflow and outflow, optimal temperatures and water availability for cleaning of panels.

Most dams constitute hydroelectric power stations, which have a complex electrical infrastructure and can provide thousands of MW of electrical power to the national grid. There is an important aspect explored and discussed in this paper for the implementation of FSPV on reservoir of the dam. It focuses on utilizing the pre-existing electrical infrastructure of a hydroelectric power plant. The basis of this assumption is our previous work which indicates that the existing electrical generation and transmission infrastructure of a hydroelectric plant makes the integration of the FSPV plant technically and economically more feasible than implementing it on any other water bodies such as like natural lakes, ponds or canals [44]. Pakistan has a large potential for FSPV plants that can be installed on reservoirs of the dams like Tarbela dam, Ghazi Barotha dam, Mangla dam, and many others. The electrical infrastructure of these dams has the capability to support an additional power generation unit like a FSPV plant. FSPV is modular and when combined with a hydroelectric power generation facility, it can minimize the transmission cost. Its modular nature allows easy installation, thereby facilitating both in terms of generation and transmission infrastructure [35].

4. Implementation of FSPV with Ghazi Barotha Hydroelectric plant

4.1. *Ghazi Barotha Hydroelectric power plant*

Ghazi Barotha Hydropower Project, with a generation capacity of 1450 MW and an average energy output of 6600 GWh, is located on the Indus River downstream of Tarbela dam in district Attock (Punjab). This is a major, run of river and an environmentally sustainable project designed to meet the acute shortage of peak power demand in the country. The hydroelectric power from Ghazi Barotha dam plays a major part in the country's total generation with a maximum contribution of 1450 MW at peak demand. Fig. 4 shows the complete geographical view of Ghazi Barotha Hydropower Project. Diversion of Indus River water takes place through a 100-m-wide and 9-m deep canal, and spreads over 52 km down to the village of Barotha. Generation of electric power takes place in the power complex that comprises of a fore bay, a siphon spillway, two head structures, a penstock, a powerhouse with five 290MW turbo generators and a tailrace channel. The two head ponds with a combined live storage capacity of approximately 25.5 million cubic meters are sufficient for daily requirement of 4 h peak generation. Each of the five generating units is fed by a 10.6 m diameter steel lined penstock. On average three out of five generating units operate for normal load conditions and according to records, on average an individual unit produces around 150 MW of power [45].

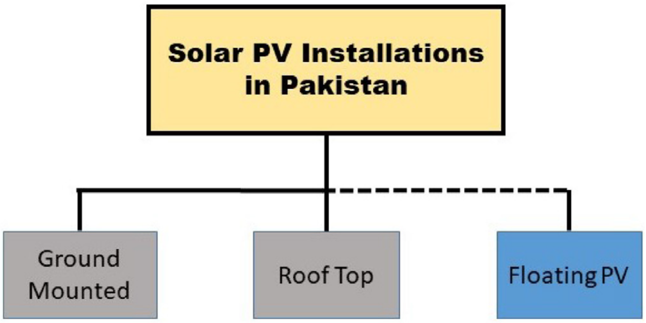


Fig. 3. Types of Solar PV installation in Pakistan (Floating as a new technology).

4.2. *FSPV on Ghazi Barotha reservoirs*

Introducing a FSPV plant on a huge hydroelectric dam reservoir can be a revolutionary step in the domain of renewable energy systems. FSPV, having a reasonable power generation potential, if implemented on Ghazi Barotha dam reservoir can play a vital role in sufficing the peak demand. According to reports of Water and Power Development Authority (WAPDA) of Pakistan, Ghazi Barotha dam has two heads with a storage capacity sufficient for daily requirement of 4 h peak demand. On average three out of five generating units operate for normal load conditions, while one additional generating unit operates only when there is a requirement to meet peak demand [45]. The storage capacity is utilized when demand is at its peak, and generally the plant has to cater two peaks in a day. The first peak occurs around 10:00–15:00 and the second peak takes place around 19:00–22:00. In some cases the peak demand cannot be fulfilled because the storage has already been used in the previous peak hours. There exists a solution, if one of the generating units can be replaced during daytime by a floating photovoltaic power source of 200 MW_p (which is the amount of power required to partially replace one of the generating units), then this ensures that the peak demand can be met at all times. FSPV system can provide the additional energy during the daytime peak, that cannot only be utilized to meet the demand but also to conserve the water in the reservoir storage for the provision of power during the evening peak. It is assumed that the overall transmitted power for both the peaks remains the same, but the hydropower generation is complemented by FSPV. Moreover, no new infrastructure is required in terms of the transmission lines as the FSPV system and of the hydroelectric generating unit is operating alternatively, therefore same transmission lines can be used for the peak demand. If for a case the FSPV system and hydroelectric are to be operated simultaneously, the available transmission networks will have to be upgraded adding enormous cost of laying out new transmission network, whereas for our study, the actual gain of the proposed structure is to use the existing infrastructure to minimize the transmission cost while adding 200 MW_p of solar energy in the system. Addition of a 200 MW_p FSPV plant at this site can fulfill the energy requirements of the peak demand during the daytime and save the additional costs associated with installing solar power plant at some other location. For the study on Ghazi Barotha, it is assumed that the base load demand is always catered by the power from the hydroelectric plant while FSPV plant only plays the role in meeting the peak demand during the daytime [44].

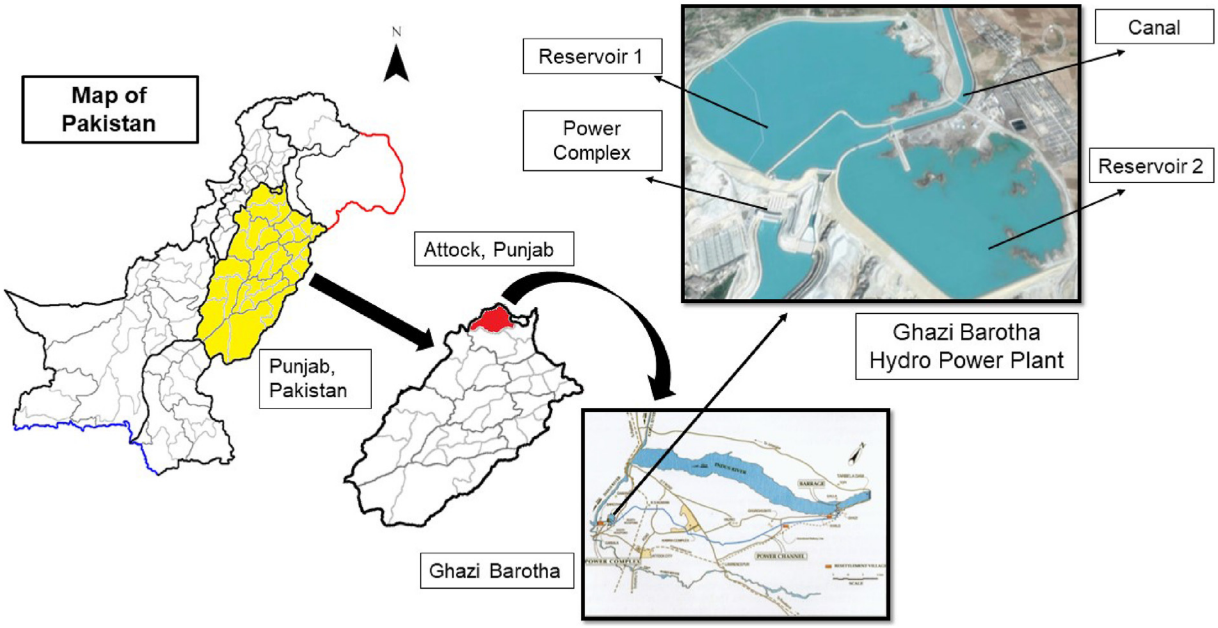


Fig. 4. Study area - Ghazi Barotha Hydro power plant.

4.3. *Solar module orientation and size considerations*

For the implementation of the 200 MW FSPV system, we have referred to the 260 W solar panel module recently installed at Quaid-e-Azam Solar Power Plant (QASPP 1000 MW phase-III expected output). The given solar modules implemented in QASPP have efficiency in between 15% and 20%, and have no rotation or tracking mechanism [21,46]. The same fixed array structure and efficiency range is considered for viability and feasibility of the FSPV system i.e. the proposed FSPV system has an overall efficiency in the range of 15%–20% and have a fixed array structure. However, the overall efficiency and power output of the system, unlike land based systems, is significantly enhanced during the system operation because of the additional benefits associated with FSPV as suggested in the literature (36; 32). A generic solar panel with a power rating of 260–290 W is used in QASPP like the one shown in Fig. 5 with the specifications mentioned in Table 1.

Four of these 260 W solar panels are joined together to produce 1000 W of solar power. We have also incorporated an additional free space of 1.4 ft between these four panels, which can be utilized in several ways as shown in Fig. 6. We now have a 1000 W or 1 kW solar module with definite dimensions and merge ten of these modules to produce a module of 10 kW with dimensions 230 ft × 3.25 ft, as shown in Fig. 7.

Table 1
Solar module specifications.

Number of solar panel modules	Power rating (kW)	Size (L X W)
1	0.260	5.4 ft × 3.25 ft
4	1.0	23 ft × 3.25 ft
40	10	230 ft × 3.25 ft

The 10 kW module is used in the configuration, implementation, and integration of FSPV system. The orientation selected to solar array modules is done by taking into account the width which can allow us to have multiple rows. Multiple rows and columns of 10 kW module are connected and arranged in a fashion so that the desired output is achieved. The problem related to cable length can be minimized by using small modules up to 500 kW i.e. 50 modules of 10 kW each having a dimension of $11,500$ ft. × 3.25 ft.

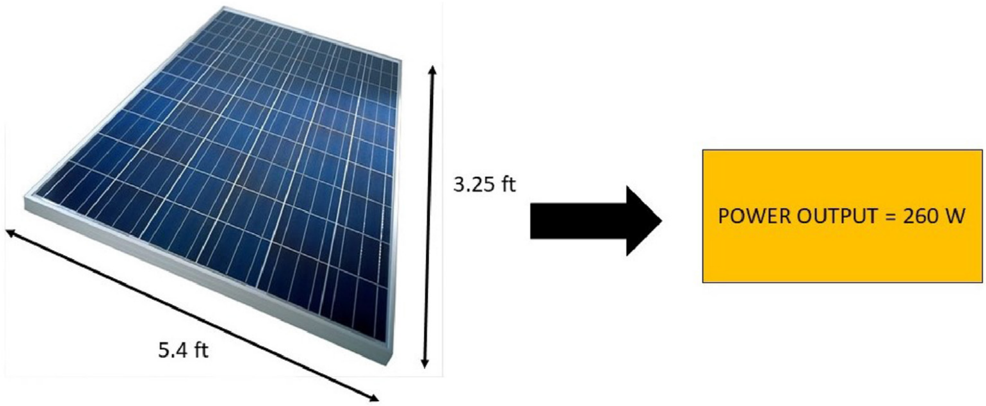


Fig. 5. 260W solar panel (5.4 ft × 3.25 ft).

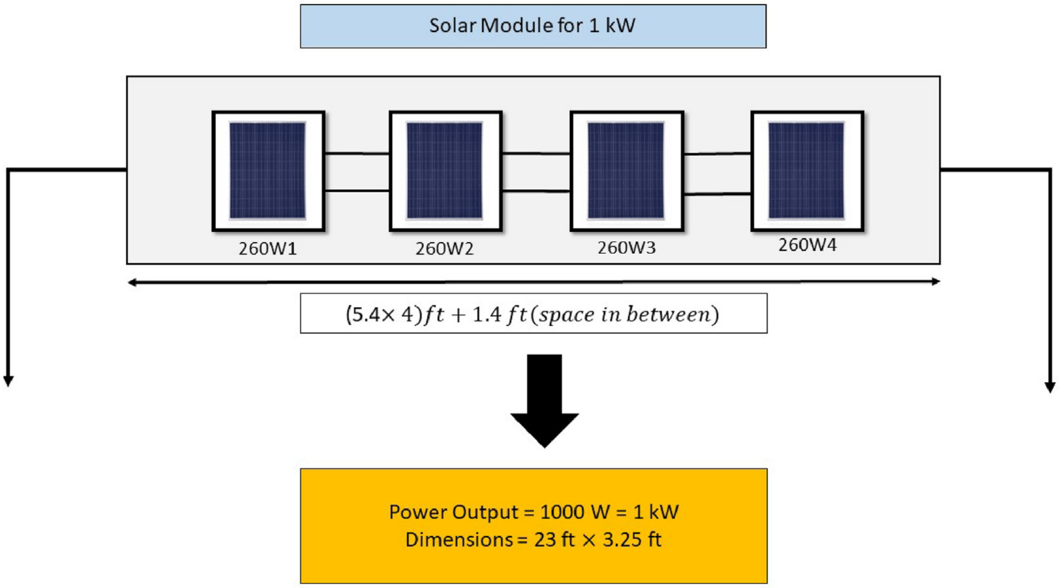


Fig. 6. Solar Module for 1 kW.

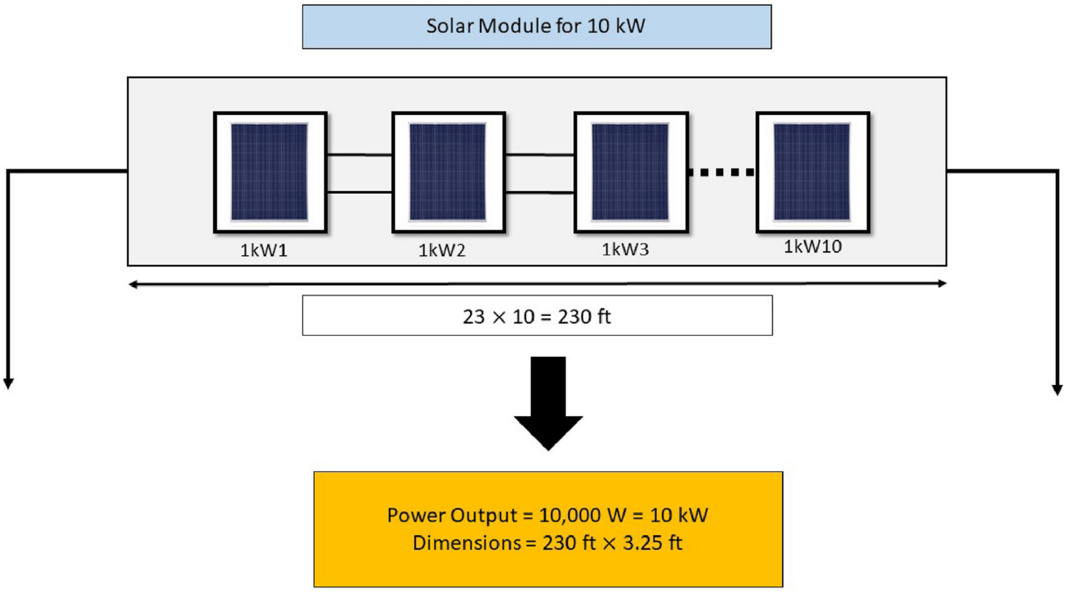


Fig. 7. Solar Module for 10 kW.

4.4. Ground elevations and area estimates

Installation of the FSPV plant requires some water body, unlike any land area. In our previous study, factors such as the ground/seabed of the water body, the land elevation and the depth of water were analyzed [44]. For this study, a FSPV plant has been proposed to be implemented on the reservoirs that will collectively produce 200 MW_p of power, thereby replacing one the generating units of the hydropower plant for daytime operation. We have explored this potential of 200 MW_p along with the ground elevation impact and the balancing of FSPV due to the rise and fall in the water level of reservoir. An important aspect in this set up is the reservoir bed which considers the unbalancing of FSPV system due to rise and fall of water level, and the feasible locations and areas for the installation of FSPV considering the topography of reservoir bed.

Firstly, the water inflow and outflow causing rise and fall in the water level of reservoir can result in structural unbalancing of FSPV system. Such unbalancing is generally overcome by the floating structures and platforms used in FSPV to maintain its balance during rough weather. Typically, the floating structure are made of self-buoyant floats that are combined with metal structures on which PV panels are mounted (34; 40). The floating platform are usually held in place by an anchoring and mooring system which keeps FSPV system firmly balanced on the water reservoir of a hydroelectric plant [35].

Secondly, the concern related to the feasible areas of reservoir outlines an important fact that when the water drops below a certain level in the reservoir, there is a significant possibility that the FSPV structure can hit the uneven terrain underwater and may results in damaging of the panels and the floating structure. In order to explore feasible locations and areas of reservoir where the FSPV system can be installed without the danger of damaging the panels and floating structures, we have used a tool called Google Earth which has a special feature that we used to gauge the underwater ground elevation of both the reservoirs. The Figs. 8 and 9 of reservoir 1 and reservoir 2 respectively show the area, highlighted in white, where we have sufficient depth and can install the solar panels without damaging them when the water level drops below a certain level in the reservoirs. The underlying reservoir bed is not a level surface unlike the surface of the water, which prevents uniform placement of the FSPV system over the whole reservoir. For our study, we have considered an area feasible if after drainage the water is more than 25% above the reservoir bed using Google Earth. The analysis undertaken depicts that FSPV panels cannot be fully installed on these reservoirs and comparatively less area is available for them. In order to optimize the approach, the best path technique is used in which the longest and the widest paths are selected to find out the potential along and across these pathways. Following sections discuss how we use the best path technique to determine the potential for both reservoirs.

Fig. 9. Feasible (Blue area) and Infeasible (black lines) areas of Reservoir 2 of Ghazi Barotha. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.5. *Reservoirs of Ghazi Barotha*

4.5.1. *Best possible path and potential of FSPV on reservoir 1*

The 10 kW solar module covers an area of 230 ft × 3.25 ft. The best feasible path in reservoir 1 is 5865 ft long and 2400 ft wide as depicted in Fig. 10. We have used a 10 kW solar module created by stacking smaller solar modules in series with dimension 230 ft × 3.25 ft (explained in section 4.3). Around 10 ($\frac{2400}{230}$) such units can be placed in the specified area and each of this 10 kW solar module (each unit module has output of 10 kW), results in 10× 10 = 100 kW power out of a single array with dimensions = 2300 ft × 3.25 ft. To lay out the 10 kW module along the length of reservoir 1 which is 5865 ft, is divided by 4 ft i.e. 3.25 ft module width with a margin of 0.75 ft. The calculation results in 1466, which indicates that 1466 arrays of such 10 kW solar module can be placed along the width of the reservoir 1. These 1466 arrays produce 100 kW × 1466 = 146600 kW or 146.6 MW of power.

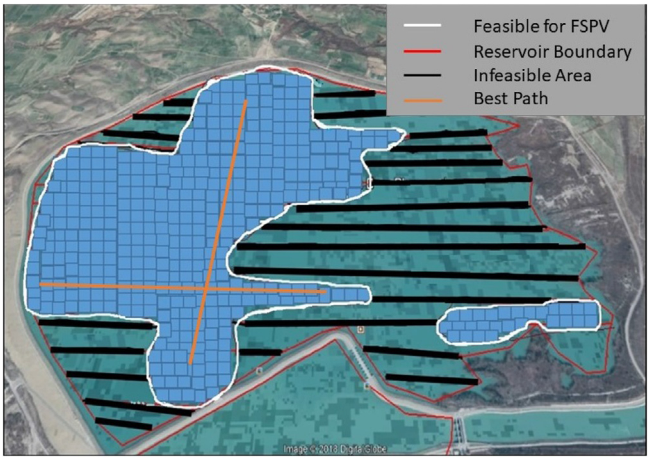


Fig. 10. Best path potential representation for reservoir 1.

4.5.2. *Best possible path and potential of FSPV on reservoir 2*

The best feasible path in reservoir 2 is 5641 ft long and 1200 ft wide as shown in Fig. 11. Making use of the 230 ft × 3.25 ft - 10 kW solar module (refer to section 4.3), placement of $\frac{1200}{230} = 5$ (approx.) such modules of 10 kW, results in 10 × 5 = 50 kW of a single array with dimensions 1200 ft × 3.25 ft and to lay out the 10 kW module along the length of reservoir 2 i.e. 5641 ft, it is divided by 4 ft i.e. 3.25 ft module width with a margin of 0.75 ft. The calculation results in 1410, which indicates that 1410 arrays of such 10 kW solar modules can be placed along the width of the reservoir 2. These

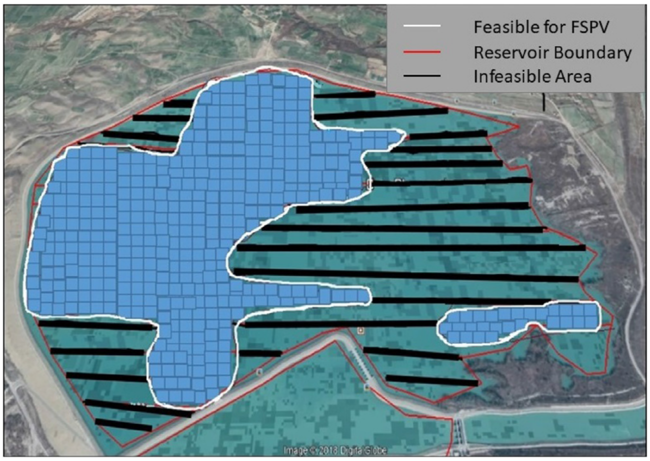


Fig. 8. Feasible (Blue area) and Infeasible (black lines) areas of Reservoir 1 of Ghazi Barotha. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

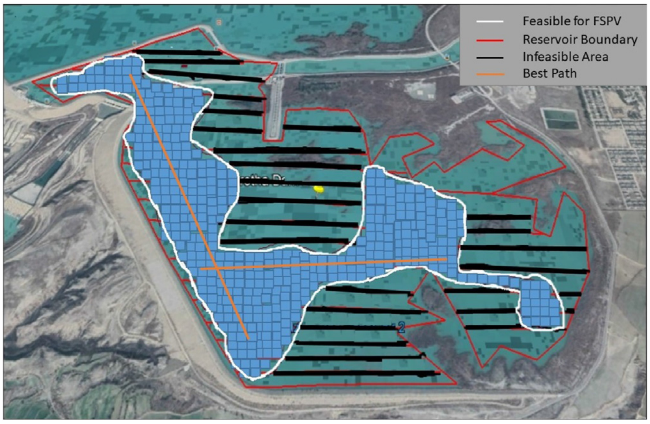


Fig. 11. Best path potential representation for reservoir 2.

1410 arrays produce 50 kW ×1410 = 70500 kW or 70.5 MW of power. This is a huge number and these values are mere approximates and only consider the best possible path in Ghazi Barotha's reservoir 2.

4.6. *Estimated potential of reservoir 1 and 2*

The best path analysis shows that if we only utilize the best path for FSPV plant, we can generate 217.1 MW of energy as shown in the Table 2 given below.

4.7. *Limitations*

The recently installed QASPP in Pakistan has a planned capacity of almost 1000 MW with no tracking or rotation mechanism. Additionally, its location being in the same province under study has presented us with a suitable solar model for our geographical location. The land-based solar plant setup allows us to have excess land at our hands to experiment with. At the same time according to layout and orientations, it gives each module, connected to the 500 kW inverter, an optimal cable length and almost same/radial cable with respect to the inverter. However, a FSPV plant enforces certain restrictions which limit us in applying the same land-like placement/orientation methodology. For a water body (assume a long channel of canal), we have a longitudinal direction and can only install panels in one direction. This implementation in a single direction indirectly implies the usage of long cables, especially for the first panel in the array to the inverter, (which is after the last panel). However, such an approach increases line losses. Another limitation states that sin contrary to the some structural differences between land based and floating PV systems, there are certain aspects that are applicable to both types of systems i.e. tracking/rotation mechanism. Many of the previous studies have considered the large scale FSPV system without any rotation mechanism which are deployed using special types of floats. In such systems the PV panels are mounted at fixed tilt angle or using some metal structures to support fixed array PV panels in a manner similar to fixed array land-based systems (32; 36; 44). We assume to use FSPV without any rotation or tracking system.

5. Integration of FSPV with Ghazi Barotha Hydroelectric plant

5.1. *Pre-grid integration*

A 10 kW solar module is considered for implementation. Fifty 10 kW solar modules produce 500 kW$_p$, feeding it through a DC cabinet and a 500 kW inverter. The 500 kW inverter converts this DC input into low voltage AC power. Two of such 500 kW PV power generating units connected with inverters will combine the low voltage AC output from the inverters to 33 kV through a 1000 kVA or 1 MVA double split winding step-up transformer as shown in Fig. 12. Instead of trying to combine the entire 200 MW output of the plant, we use four modules of 50 MW each. There are multiple techniques for collecting circuits, but we assume only two; either we transmit 50 MW to switching station by 10 collecting circuits, with each circuit of 5 MW capacity, or we transmit it by 5 collecting circuits with each circuit having 10 MW capacity. The first approach requires more circuits thus high initial cost, but reliability is also high as in case of any fault on one circuit only 10% of the system will be affected. The second approach requires less number of circuits thus less initial cost, but in case of any fault on one circuit, 20% of the system will be affected. Both techniques have their pros and cons and selection is based on the given objective. Thus for the case of minimum cost second approach, i.e. five circuits of 10 MW capacity can be used. Before integrating the setup with the national grid (500 kV Grid Station Ghazi Barotha), we have considered a scenario that if five circuits of 10 MW capacity for a 50 MW module are used and four of these modules need to be implemented, then 20 circuits (10 MW capacity each) have to be considered. The approach to integrate 20 circuits with the national grid cannot be used due to the associated complexity; at most two of them can be accounted for. To resolve this problem, a 33 kV bus bar is introduced and all the circuits terminate on this bus bar. Instead of utilizing a single bus for 20 circuits, two buses for 10 circuits each are used. As every circuit is giving its output on a single bus, a step-up transformer can be connected for integration with the national grid as shown in the Fig. 13.

5.2. *Integration techniques*

Integration of this FSPV system is quite important since we need to have maximum and optimal utilization of our existing infrastructure to avoid any extra cost associated with transmitting the power from the FSPV arrays to the grid or to the consumer. There are multiple options to transmit this power:

- Using a connection of 500 kV transmission line to transmit the power to 500 kV grid-tied system.
- Installing a 132-kV grid station with import/export energy feature for maximum utilization of power matter.

Currently, the hydroelectric power produced by Ghazi Barotha power plant is generated at a low voltage level of 18 kV, which is stepped up to 500 kV and connected to the bus bar of 500 kV grid station at Ghazi Barotha. This 500 kV grid station dispatches the power for transmission at different voltages i.e. 500 kV, 220 kV, 132 kV, and 11 kV [45].

5.2.1. *500 kV grid-tied solution*

The 33 kV low voltage output from 33 kV bus bar is passed through a step-up transformer. The rating of the transformer for this case is 33/500 kV; thus the output of the entire FSPV system is 500 kV. The nearest national grid station is 500 kV Ghazi Barotha grid station, which lies near the Ghazi Barotha power production facility. As the reservoirs of the dam are used for generation, the power is transmitted at low voltages due to short distance. For simplicity, it is assumed that the power is transmitted at 33 kV from FSPV source to the national grid while installation of a 33/500 kV transformer takes place in grid premises. The 500 kV transformer is then connected to the main bus bar of 500 kV at Ghazi Barotha grid station. Currently, Ghazi Barotha grid station has five transformers (one for each generating unit) as it serves a 290 MW source of

Table 2
Estimated potential of reservoir 1 & 2.

Reservoir path	Best possible path for Reservoir 1	Best possible path for Reservoir 2
Approximate dimension of best possible path	5865 ft × 2400 ft	5641 ft × 1200 ft
Estimated Power Generation Potential	146.6 MW	70.5 MW
Total estimated generation	217.1 MW	

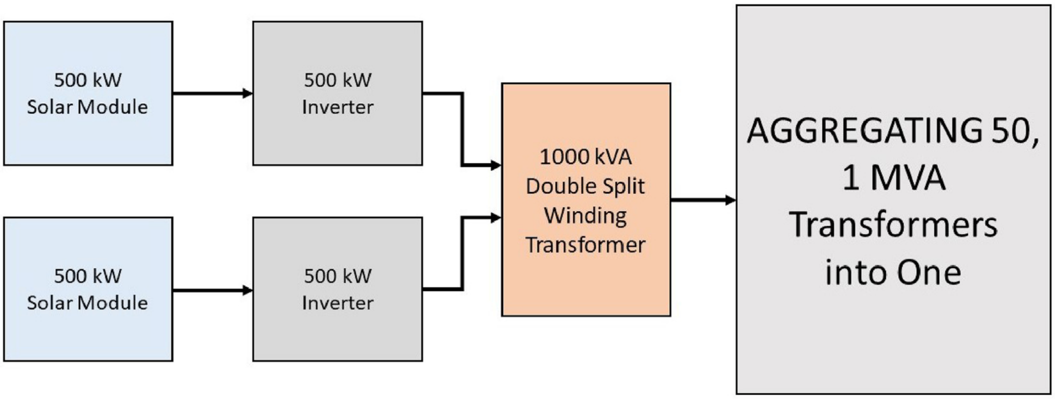


Fig. 12. DC to Inverter and 1 MVA transformer.

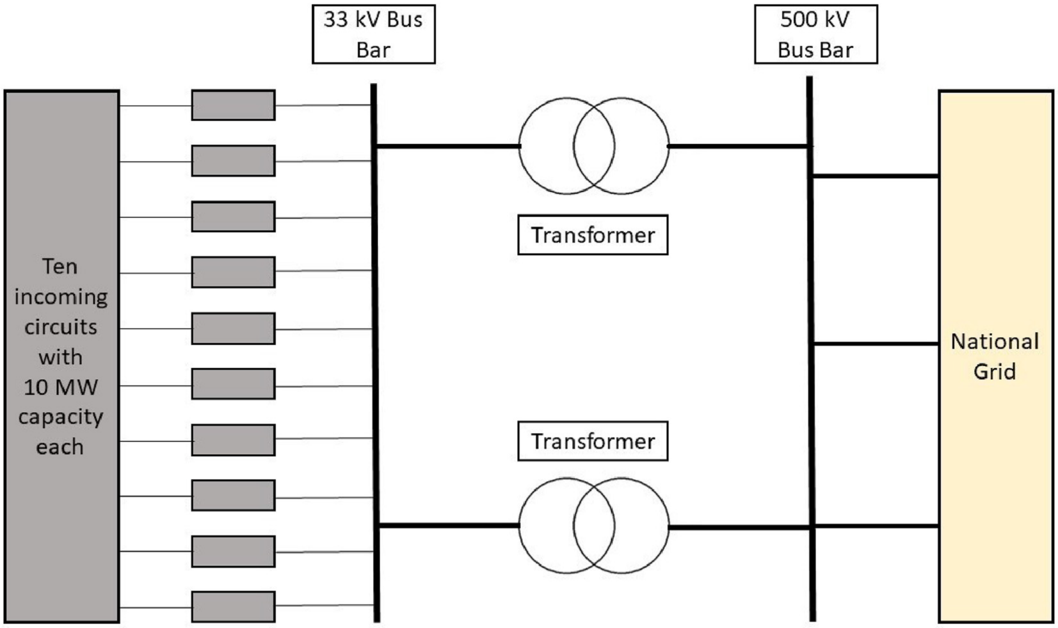


Fig. 13. 33 kV bus bar with incoming circuits and outgoing to National Grid.

electricity coming from hydroelectric power. There is a possibility for the extension of a sixth transformer that can hold the source of power which is 200 MW coming from our proposed FSPV plant. As peak demand has to be met during daytime with the FSPV source and evening peak demand with the hydropower source, additional infrastructure is not required as the total power output and demand remains the same on the grid station. The proposed architecture along with little investment in infrastructure such as electric conductors, use the existing transmission network to transmit the power. In typical electrical power systems, transmision cost is around 25% of the total cost that may reduce to just 5% or less through FSPV [47]. Accounting for these cost savings, the 500 kV grid-tied solution for integration of 200 MWp FSPV plant is quite cost-effective.

5.2.2. Installation of new 132 kV grid station

Another approach is the installation of a new 132 kV grid station, a few miles away from the hydroelectric plant. Installation of this new grid station will completely isolate the FSPV plant and represent it as an independent source of power unlike in 500 kV grid-tied solution. The 33 kV low voltage bus bar explained in the previous section now uses a step-up transformer of rating 33/132 kV which has 132 kV circuits all connected to a 132 kV bus bar. With the national 500 kV grid station of Ghazi Barotha, the 132 kV newly commissioned grid station is connected in energy import/export method. The significance of this approach is to get the maximum utilization of the new infrastructure when the FSPV plant is generating power during the day. During the night, when power production is low or zero, energy can be imported from a huge source and exported to some other grid station that is demanding power i.e ring main system. Although, the cost of 132 kV grid station is slightly higher than a 500 kV grid-tied solution because transformers, circuit breakers, switches, current and voltage transformers are required for a newly installed grid station However, this integration may allow more utilization compared to the 500 kV. The additional benefits associated with 132 kV offset its higher cost. In the context of Pakistan's transmission infrastructure, there are some other integration plans at 11 kV, 33 kV, 66 kV and 220 kV, but the cost and utilization are no better than 132 kV and 500 kV.

6. Linear optimization model of the FSPV-Hydro hybrid power system

In Pakistan, as mentioned in section 2 and shown in Fig. 14, there are two peak demands; one during the daytime and other during the night time. FSPV, like other solar PV plants, is capable of generating power only during daytime when the solar radiance is largely available. During the occurrence of the peak load demand in the daytime, FSPV can provide substantial power to meet this demand to the national grid. Instead of using water reserves from dam reservoir to run additional power-generating turbines at Ghazi Barotha hydroelectric power plant for meeting the peak demand, FSPV plant can be used to produce the desired amount of power. It is assumed that the base dispatch power set by grid operator is always catered by the power from hydroelectric plant. Floating Solar PV plant only acts to play a critical role in meeting the peak demand during the daytime. Maximum utilization of solar energy is, therefore necessary for optimizing the operation of a hydroelectric power plant and FSPV plant. Using the following block diagram, mathematical operations and techniques are performed to get the optimized results for the integration of hydroelectric and FSPV plants.

6.1. Block diagram

The block diagram for the proposed optimized FSPV and Hydro system is shown in Fig. 14.

6.2. Objective function

In this paper, the purpose of integrating hydro and PV power is to conserve water to generate power through turbines for the evening peak hours and release stress on one of the power generating machines of the hydropower plant during the daytime peak period. The integration is also consequential for FSPV because the hydropower can complement in case of the discontinuity and instability in solar radiance. The total power output of the hydro/PV hybrid system is expected to be reliable with variations quite small and utilization as optimal and maximum as possible. The objective of the optimization framework is to maximize the total generated energy of the hydro/FSPV hybrid system while meeting all the relevant constraints. Maximizing power generation of the whole system in the entire time period is an important operational objective for any power generation system. The objective function can be written as:

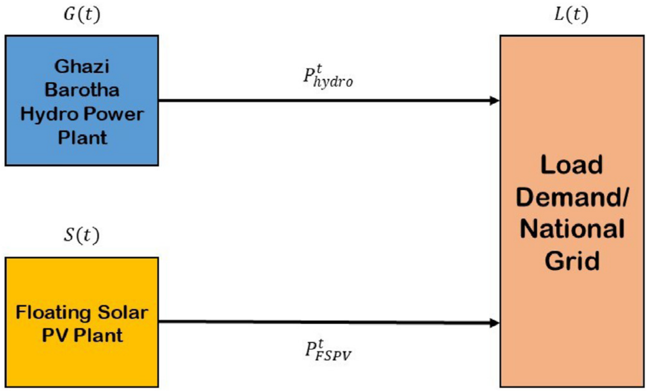


Fig. 14. Block diagram of optimization problem.

$$Z = Max\sum_{t=1}^{T}\left(P^t_{hydro} + P^t_{FSPV}\right) \times \Delta t \tag{1}$$

6.3. Decision variables

The decision variables in this problem are P^t_{hydro} and P^t_{FSPV} which are adjustable to optimize the objective. The objective function is linear in the power P^t_{hydro} delivered to load by a hydroelectric power plant and linear in power P^t_{FSPV} that is delivered to load by FSPV plant.

6.4. Constraints

The main operational constraints of the hybrid system include the constraints of power delivered by hydro and FSPV plant to the power grid, as well as the capacity of the power grid, as shown below:

1. The decision variables must be non-negative i.e. the amount of power delivered to load by the hydroelectric and FSPV plant must always be positive as shown in the equations below

$$P^t_{hydro} \geq 0 \tag{2}$$

$$P^t_{FSPV} \geq 0 \tag{3}$$

2. The amount of energy delivered by FSPV plant and hydroelectric power plant at any time 't' is always less than or equal to the maximum power the respective plants can generate as shown in equations

$$P^t_{hydro} \leq G_{max} \tag{4}$$

$$P^t_{FSPV} \leq S_{max} \tag{5}$$

where S_{max} and G_{max} are the maximum power that FSPV plant and hydroelectric power plant can generate

3. The total power produced by hydroelectric power and floating solar PV plant at any time 't' must always be less than or equal to the load demand L(t)

$$P^t_{FSPV} + P^t_{hydro} \leq L(t) \tag{6}$$

7. Results and discussions

7.1. Power generation by Ghazi Barotha hydropower

We have taken an hourly real-time power generation data of Ghazi Barotha hydroelectric power plant from WAPDA and Central Power Purchasing Agency (CPPA) as mentioned in Table 3. There are two load peaks appearing in 24 h of the day; one appears in the daytime and the other during night [45]. It is assumed here that load demand that Ghazi Barotha hydropower has to cater is exactly equal to its real-time power generation. Ghazi Barotha does not have control over the water inflow and outflow beyond 24 h window. The water authority of Pakistan controls the water inflow and outflow for each day. Therefore, any optimization, control, analysis,

Table 3
Optimized power output data.

Time (Hours)	Load Demand (MW)	GB Hydropower output (without FSPV) (MW)	Output profile of 200 MW Solar System at GB (MW)	Optimized GB Hydropower Output (with FSPV) (MW)	Optimized FSPV Power Output (MW)
1	1190	1190	0	1190	0
2	1190	1190	0	1190	0
3	960	960	0	960	0
4	680	680	0	680	0
5	680	680	0	680	0
6	680	680	0	680	0
7	680	680	2.862	677.137	2.862
8	680	680	47.273	632.726	47.273
9	1160	1160	82.660	1077.339	82.660
10	1420	1420	90.900	1329.09	90.900
11	1450	1450	110.307	1339.69	110.307
12	1450	1450	115.652	1334.34	115.652
13	1420	1420	116.363	1303.63	116.363
14	990	990	116.170	873.829	116.170
15	990	990	114.928	875.071	114.928
16	990	990	69.601	920.398	69.601
17	990	990	27.057	962.942	27.057
18	990	990	13.640	976.359	13.640
19	1190	1190	3.456	1186.543	3.456
20	1420	1420	0	1420	0
21	1450	1450	0	1450	0
22	1450	1450	0	1450	0
23	1420	1420	0	1420	0
24	1190	1190	0	1190	0

forecast and informatics can only be performed in the next 24-h window for power generation at Ghazi Barotha [48]. The power generation data of hydroelectric plant i.e. power dispatch point as set by the grid operator is mapped in the form of a graph which is shown in Fig. 15.

There are two categories of power generation taking place at Ghazi Barotha hydropower plant.

(*i*) base generation (*ii*) peak generation. The base power generation is the minimum amount of power that the hydropower plant has to generate all the time to meet the dispatch power set by grid operator which is shown in Fig. 16. According to records, at least two generating units are always kept in operational mode at Ghazi Barotha hydropower plant to generate a minimum amount of power, which in our case is assumed it to be the base power generation [45].

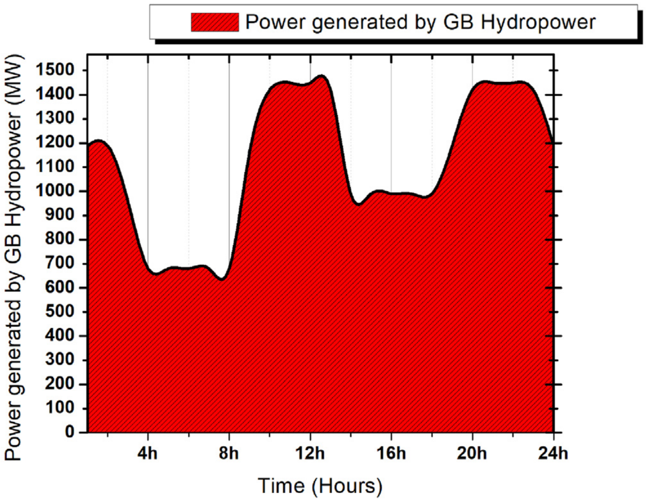


Fig. 15. Power generated by Ghazi Barotha dam.

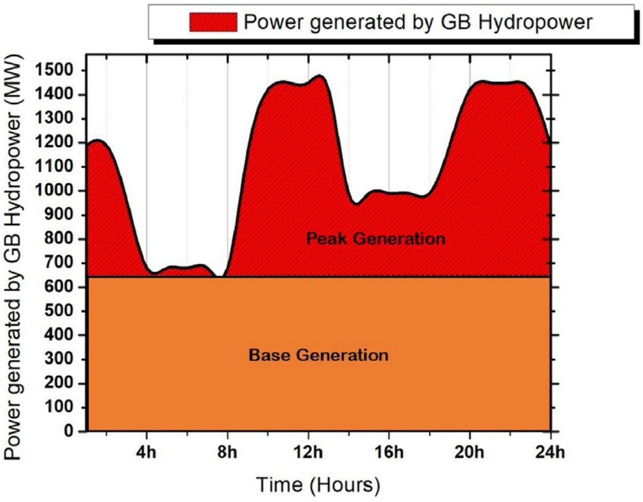


Fig. 16. Base and Peak generation distribution.

7.2. *Solar output data of Ghazi Barotha*

We have assumed the solar PV system size of 200 MW to be implemented as FSPV, which is of course less than the power generation potential of FSPV we have already found in the implementation part. The solar output data for a random day at Ghazi Barotha (coordinates Latitude 33 47′ 35.62″N & Longitude 72 15′ 44.82″E) is taken from NREL [49] as shown in the Fig. 17.

7.3. *Simulation results*

7.3.1. *Optimization software*

The optimization problem is assumed to be linear, therefore linear programming technique is considered suitable for the problem. Linear optimization technique has been developed in MATLAB environment. This approach is selected because the solution's search space is confined and an optimal solution can be detected in short computation time.

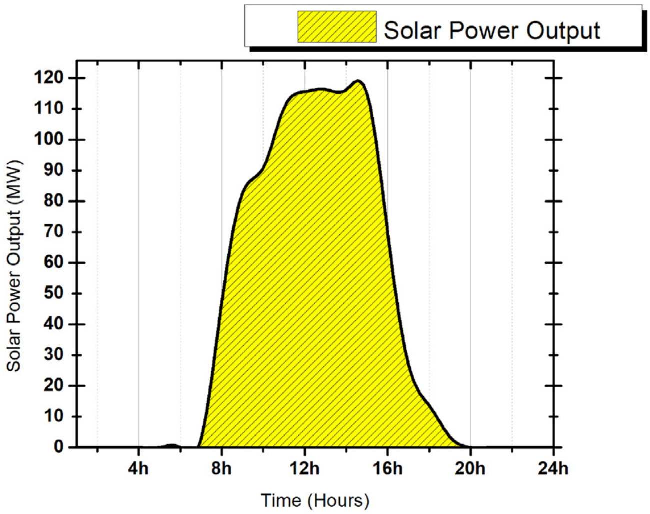


Fig. 17. Solar energy profile at Ghazi Barotha.

7.3.2. *Non optimized power delivered to national power grid*

It can be observed that there are two peak demands that appear on a specific day. The first peak occurs during the day and the other occurs during night time. It is assumed that power dispatch set by grid operator that Ghazi Barotha hydropower plant has to cater to or power delivered to the national grid is the same as the power generated by hydropower plant.

7.3.3. *Optimized power from hydroelectric dam*

The hydroelectric dam has to suffice the full demand set by grid operator including the peak and base demand, when there is no solar power available. In the optimized case as shown in Fig. 18, when 200 MW capacity of FSPV is available, the hydropower plant generates less power during the time when there is sufficient solar radiance, given the fact that power dispatch point is same and the FSPV has to be utilized to its maximum capacity. While hydroelectric power continues to suffice base demand for the whole day, it now only caters to the peak power dispatch point that occurs during the night. The optimal dispatch of power from FSPV results in the fact that a portion of the daytime peak is sufficed by the FSPV plant; the mathematical results of which are given in the Table 3. The results show that the energy generated by the addition of FSPV corresponds to additional 3.5% power. Theoretically, the results for the optimized power dispatch are interpreted as the following advantages:

7.3.3.1. *Water conservation.*

Massive water flow through turbines generates electric power in normal conditions for base power generation. A surplus amount of water is used when hydroelectric power plants have to meet the peak demand. In case of Ghazi Barotha hydropower, generators have to produce additional electric power to serve the peak demand that occurs twice a day. This results in the supplemental usage of the water reserves. By integrating the FSPV with Ghazi Barotha hydropower, the additional amount of water that previously has to be utilized for the daytime peak generation, can now be conserved.

7.3.3.2. *Reduced stress on power generators.*

Originally, four power generation machines each with a capacity of 290 MW, have to be operated for the peak power generation; the power from the two generator machines results in the base generation, while the other two are operated along with the first two machines only when the peak generation is required. The operation setup changes when a FSPV plant is introduced; now only for the daytime peak generation, FSPV plant along with other alternate power generators are operated. The addition of FSPV plant and its optimal operation in conjunction with hydropower reduces the power generation stress on the turbines and generators of the hydropower plant.

7.3.4. *Power from floating solar PV plant*

It is assumed that power output of the FSPV is same as that of solar power output at the given site which is shown in Fig. 19 [49]. This assumption actually depicts the maximum power utilization behavior of the floating solar PV plant. The power output curve of FSPV in Figs. 19–21 and its respective mathematical results mentioned in Table 3 show that the energy generated by the FSPV in a day examined for our study is approximately 911 kWh. The results also depict that when the peak power dispatch point is to be met during the daytime, FSPV plant responds to suffice it. The system operation, thus reduces the power output from the hydroelectric dam and conserves the water in the reservoir. The conserved water can now be used to generate power from turbines during the night time. The mechanism of catering the daytime peak by FSPV plant not only conserves water but also reduces stress on

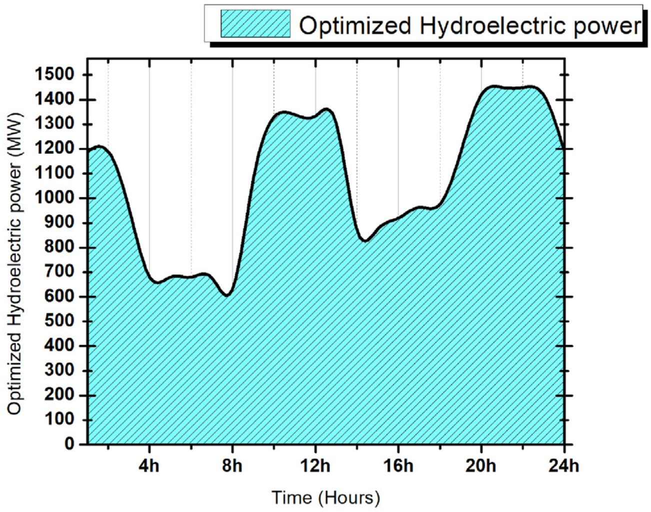


Fig. 18. Optimized hydroelectric power.

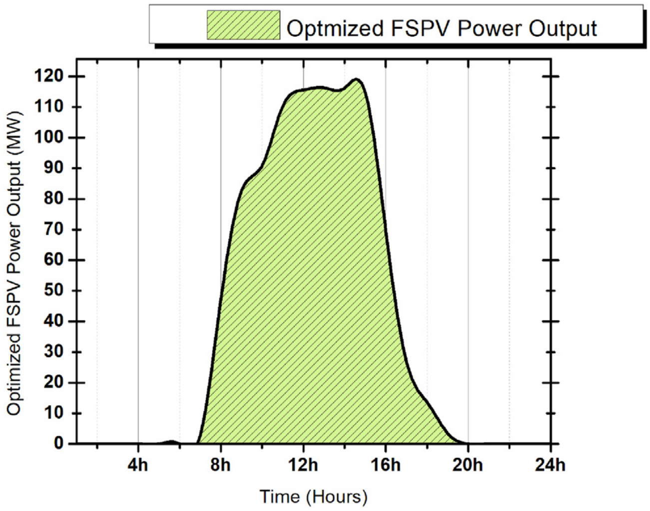


Fig. 19. Optimized FSPV plant power.

the power generators at Ghazi Barotha hydroelectric plant. The power from the FSPV plant is only available when there is sufficient solar radiance which is used to cater the peak load occurring during the daytime, while the hydropower plant is used for serving the base as well as the peak power dispatch set by the grid operator during the evening.

7.3.5. Combined power operation of FSPV and hydroelectric plant

The study aims to utilize the FSPV power and reduce the hydropower output simultaneously during selected hours. The overall generation capacity of the whole system remains the same for the proportion of the power need to meet the peak dispatch. It is alternatively generated and transmitted by the FSPV and hydroelectric to the national grid using the existing electrical infrastructure of the hydroelectric plant. The proposed framework outlines the results as the reduction of hydropower output and utilization of FSPV for the corresponding curtailed hydropower. The Fig. 20 gives information about the power generation data and optimized power output of hydro and FSPV plants, whereas the Fig. 21 shows the combined results for an un-optimized hydropower output and optimized hydropower and FSPV output. The data set and the corresponding output results are mentioned in Table 3. The output results shown in the table are hourly power generation values which correspond to energy generated by FSPV

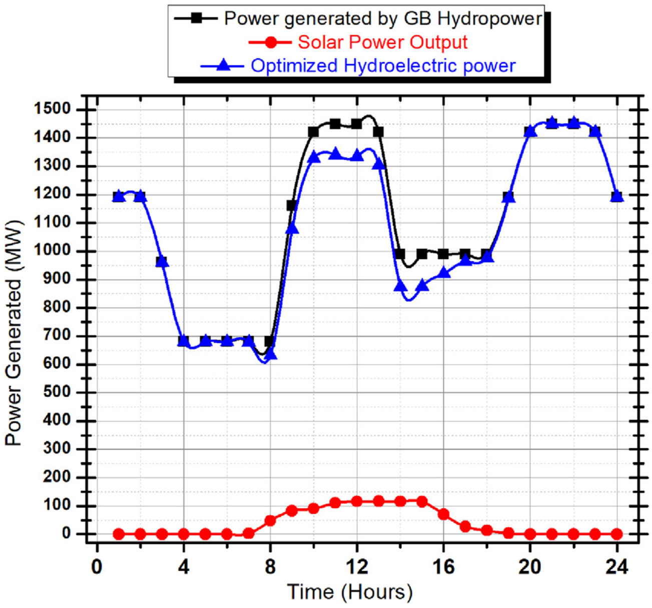
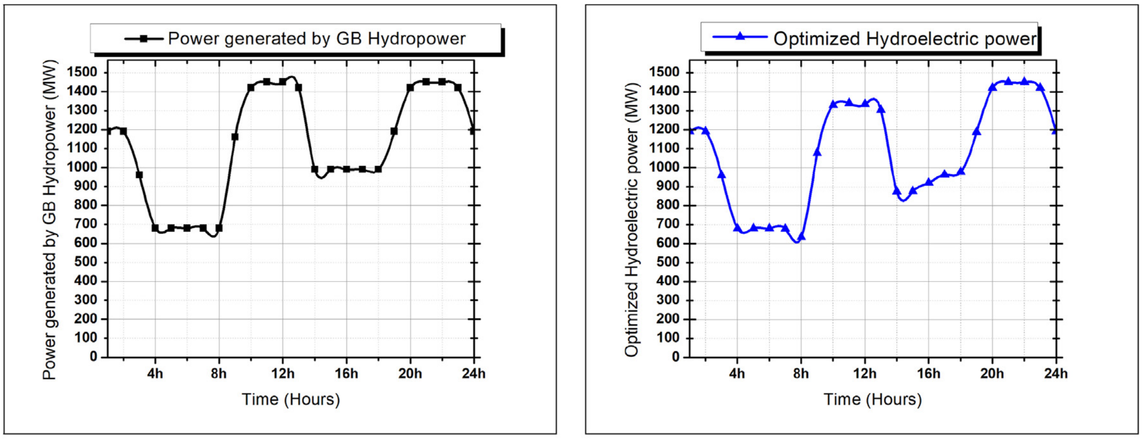
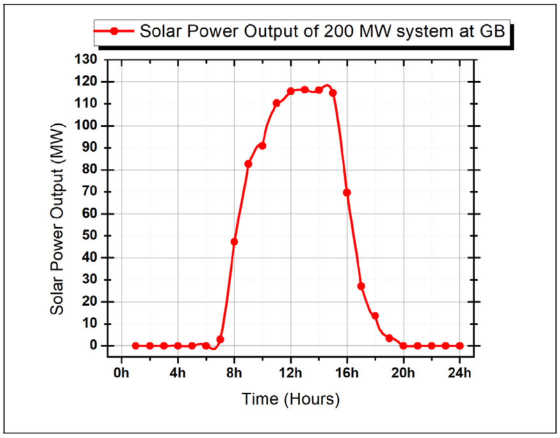


Fig. 21. Optimized power production (combined).



(a) Power generated by Ghazi Barotha Hydropower Project

(b) Optimized Hydroelectric power output



(c) Optimized FSPV power output

Fig. 20. Hydroelectric and FSPV power output.

and hydroelectric plant. The energy generated by the FSPV in a day examined for our study is approximately 911 kWh, which corresponds to more than 3.5% additional power generation output of the overall system during the daytime peak. The results clearly suggest the effectiveness of the proposed 200 MW_p FSPV plant in terms of power distribution and management on Ghazi Barotha hydroelectric plant. The power generation/load demand curve and optimized power output of FSPV and hydro plants are separately shown in Fig. 20a, b and 20c. The Fig. 20c, which is the optimized power output of GB hydropower plant, represents that the additional power produced for sufficing peak demand during daytime has significantly reduced due to the inclusion of FSPV. The power generation required to meet the peak demand has reduced by an amount which is equal to the power produced by the FSPV plant at the given time.

In Fig. 21, the simulation results given in Table 3 for the unoptimized and optimized power outputs, are mapped on the same graph to comprehend the outcomes of integrating FSPV with the hydropower plant. It can be discerned that original power generated by Ghazi Barotha hydroelectric plant (black line) during daytime peak period has now reduced due to the inclusion of 200 MW capacity of FSPV plant (red line) and now imparts a modified power generation output (blue line) for the hydropower plant. The daytime peak generation output of hydropower has reduced equally in the magnitude of the output power produced by the FSPV plant at a specific time interval. The hydropower output for evening peak remained undisturbed, while the perturbations only transpired for the daytime peak period. The objective to achieve maximum utilization of the hydro PV system power can be clearly seen in Fig. 21. The simulation results for our proposed optimization theory suggests that after the PV plant is added, the grid operator can issue a higher power dispatch set point during the day. On a typical day, the output from the hydroelectric plant is now reduced and energy is conserved in the form of water storage, especially during the daytime hours, when FSPV generation is high. The saved energy (in the form of water storage) is then requested by the operator to be used during evening or late-night hours. Although the daily generation pattern of the hydroelectric plant is modified, the daily reservoir water balance can be maintained as to also meet the night hours peak demand. All the power generated by the hydroelectric and FSPV system is fully dispatched to the grid, without any retrenchment. The system shows that hydroelectric plants can provide adequate response as demand and PV output varies. Moreover, the results also clarify that the solar capacity can be used to maintain the energy yield of the hydroelectric plant and can help to manage periods of low water availability by allowing the hydropower plant to not only operate in base load mode but to also operate in peaking mode. The benefits of optimized operation can be taken other way around as well i.e. hydropower can smooth variable solar output by operating in a “load-following” mode. In summary, our results show an additional power generation output of more than 3.5% on a 1450 MW hydroelectric plant when combined with a 200 MW_p FSPV system. More importantly the FSPV generation coincides with the daily peak load thus works as a peaker plant for the whole national grid, and also allows the hydroelectric plant to be used as a spinning reserve during peak hours. The complementary operation of hydro and floating solar combination, is therefore of a particular interest for the developing country like Pakistan where grids are weak.

7.4. Discussion

In this section we will evaluate our hypothesis of integrating hydroelectric power with FSPV. The solar and hydro complementary operation allows the utilization of water reserves for enhancing the peaking capability of hydroelectric plant and to cater the peaks occurring during day and night hours. Moreover, solar and hydro integration reduces the stress on the generating turbines of hydroelectric plant for power production, and eliminates the need of new infrastructure to support the solar generation as existing electrical transmission infrastructure is being utilized. Conservation of overall water resources is another vital aspect of the solar hydro complementary operation. Evaporation rates are also minimized upon installation of the FSPV thus increasing water availability. Furthermore, the cleaning of solar PV module can be carried out by utilizing the readily available water in the reservoir. In a nutshell, the implementation of hydroelectric with solar for complementary power operation across the various hydropower reservoirs in the country can eventually reduce the cost of electricity production along with other ancillary benefits.

Nevertheless, while these outcomes seem compulsive, there are certain limitations and areas left unexplored. The cost and the financial plan to implement the system is an area left unexplored in the case study. At the same time, the hardware specification, type and design of the FSPV has not been shed light upon. These aspects including the structural component of the design (poles, floating structure) are left for further exploration in the future.

8. Conclusion

In recent years, a drastic shift from traditional resources of energy generation to renewable energy has played a significant role in imparting sustainable and environmental friendly energy solutions in Pakistan. Consequently, the approach towards renewable energy has imposed a positive impact on the economy of the country. As the energy generation trends are moving toward solar PV technology for the generation of electricity, the large scale ground-mount and rooftop solar PV installations in Pakistan are an explicit depiction of the PV technology taking over the power generation sector. Pakistan’s hourly solar profile complements its daytime peak demand has led to the exploration of evolutionary solar PV technologies that can aid in maintaining energy balance between supply and demand. Floating Solar PV is one of the outcomes of those evolutionary paths of solar PV technology which is widely known for its utilization in the conservation of water resources, the integration and the implementation with the existing infrastructure of a hydroelectric plant, and its vast potential and capability to meet the peak load demand. In this paper, a case study has been discoursed which discusses the methods of integration and implementation of FSPV at Ghazi Barotha hydroelectric power plant in Pakistan and its reservoirs’ potential analysis to produce 200 MW power. The analysis exhibits the significance of the FSPV plant for meeting the peak demand requirements during the sunlight hours and aims to explore a linear optimization model for an integrated Hydro-FSPV system. Firstly, the PV power output and the typical hydroelectric output are taken as hourly solar radiance and power generation, respectively, and maximization of the hourly Solar power generation is then set as an objective to be optimized. Owing to its high efficiency and lower operating temperature, there are several other constructive impacts of the FSPV system on the electrical infrastructure. Therefore, the deployment of the innovative renewable technologies like FSPV can fairly supplement the long-term energy requirements and act as a reasonable step towards the attainment of 100% renewable energy production goal of Pakistan by 2050.

CRediT authorship contribution statement

Huzaifa Rauf: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft,

Visualization, editing. **Muhammad Shuzub Gull:** Conceptualization, Methodology, Validation, Formal analysis, Writing - review & editing, integration. **Naveed Arshad:** Conceptualization, Resources, Supervision, Project administration, Funding acquisition.

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.

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