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Assessment of On-Grid Hybrid Renewable Power Generation Potential at Khanpur Dam in Pakistan

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Abstract

In this article an on-grid hybrid renewable power plant model has been proposed at Khanpur Dam to feed power to Khanpur village and national grid. The irregular nature of renewable energy sources can be compensated through Pumped Hydro Storage (PHS) scheme, as Khanpur Dam is a large reservoir of stored hydro energy. Three operation schemes of the hybrid system have been proposed and simulation results have been calculated on HOMER using physical data of Khanpur Dam. The decision of selection of energy sources from hydro, solar and wind is made on the basis of optimum cost, generated output, capacity factor and maintenance of the sources by using Analytical Hierarchy Process (AHP). The results demonstrate that cheap, reliable and environmental friendly power solution with 90% to 95% power autonomy can be achieved, with a significant decrease in the CO_2 *emission.*

Key Words: Hybrid Energy, Renewable Energy, Analytical Hierarchy Process

1. Introduction

The rapid depletion of conventional energy sources and environmental concerns has added to the significance of exploring sustainable and renewable pollution free power generation sources. The distributed power generation from hydro, wind, solar and other renewable energy sources can serve as a remedy. But the irregular fluctuating nature of these sources, due to varying climatic and atmospheric conditions, is the main hindrance in their use for on-grid distributed power generation. For the compensation of this inherent fluctuating nature, methods such as hybridization of more than one renewable energy sources, pumped hydro storage etc. have emerged as a solution.

In the literature many practically implemented hybrid systems have been reported which are producing power successfully. An example of such a power system comprised of solar photovoltaic, wind, and hydro energy source has already been successfully implemented at Thingan in Nepal [1]. Similarly, an off grid system based on solar, wind with pumped hydro storage has been proposed for a remote island in Hong Kong [2]. An on grid solar-hydro system was proposed in [3], which operates seasonally i.e. solar system during summer and hydro during rainfall season. In Brazil, for a rural area, a system comprising of solar and wind generation, with batteries as backup has been proposed with sizing of modules and unit cost analysis [4]. A feasibility and mathematical modelling of hybrid system consisting of solar and hydropower system has been carried out for Europe and other regions with similar climatic conditions [5].

Pakistan is energy deficient and a developing country with an average load shedding of 6-8 hours. It had an installed capacity of 22797 MW with average demand of 17000 MW and a short fall of 4000 to 6000MW in 2014-2015 and gradually increasing as shown in figure 1 below [6]. This shortage is mainly due to the insufficient indigenous conventional resources, rapidly growing population and expensive imported fossil fuel. This demand of energy is rising very rapidly with the increasing electrification of more and more villages of Pakistan. It has been estimated that Pakistan has eight times unexplored renewable energy resources than that of its present total energy demand.

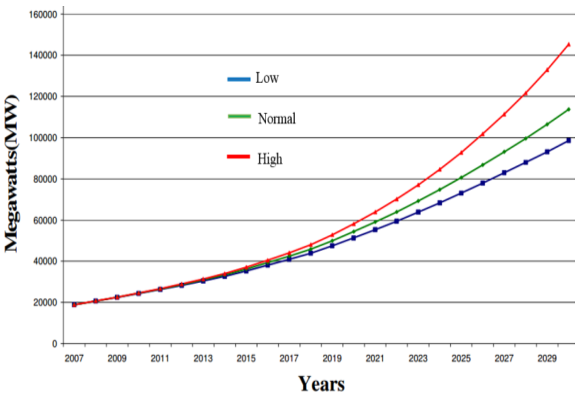


Figure 1: Summary of Load forecast of Pakistan [6].

Due to costly power generation from fossil fuel and environmental concerns, Pakistan Alternative Energy Board and other organizations are taking initiatives to extend the electricity generation from renewable and sustainable energy sources mostly in the province of Sindh through wind power. However, there is a great renewable energy potential in northern areas, which has not been explored yet. Khanpur is an example of such an area, whose energy generation potential through the use of hybrid renewable energy sources is explored in this paper.

In the following paragraphs the geographical location of Khanpur site and its solar, wind, pumped hydro storage and hydel potential shall be discussed briefly. Then the simulation of proposed hybrid renewable power generation scheme at Khanpur dam, carried out in HOMER will be represented. Decision analysis based upon cost, annual average energy generated, capacity factor and maintenance of the source using Analytical Hierarchy Process (AHP) shall be discussed also. And finally a discussion on the results obtained will be carried.

1.1 Geograhical Location of Khanpur Dam

Khanpur Dam is a multipurpose project located at Khanpur, eight miles from Taxila, behind Margalla Hills on Haripur road, and was constructed on Haro River in the north of Pakistan. The location on the map is as shown in figure 2. This reservoir is used for irrigation purposes as well as for providing drinking water to Islamabad and Taxila. The project was completed in 1983 at a cost of 1352 million and the life of this project is almost 75 years [7]. This dam has a large catchment area of 308 square miles as well as a live storage of 81,650 Acre-Feet. The average annual rainfall in the catchment area of Khanpur Dam is 1245 mm [8]. Through the proper management of inflows and outflows, the purpose of agricultural irrigation as well as power generation on the dam site can be achieved. In addition, the developmental reforms, proper water management and availability of funds is required for better management of this project.

1.2 Solar and Wind Potential of Khanpur

For the design of solar power generation at any site monthly average solar irradiance is an important parameter to be considered, and the database for Khanpur Dam was obtained from the online system [9]. From the table 1, it can be seen that the average annual solar irradiance is 5.64 kW/m^2/day. This is an optimum irradiance value throughout the year and is suitable for trapping solar energy through solar panels. But the monthly average wind speed here as shown in table 2, is quite low and annual average is less than 5 m/s, so the annual energy generated will also be quite low and the levelized cost of electricity (LCOE) will also be quite high.

Figure 2: Location of Khanpur Dam on Google maps.

Table 1: Khanpur/ Taxila - Average Solar Insolation Measured in kWh/m2/day onto a solar panel set at a 41° angle.

Month	kWh/m^2/day	Month	kWh/m^2/day
Jan	5.15	**Jul**	5.02
Feb	5.21	**Aug**	5.00
Mar	5.58	**Sep**	6.00
Apr	5.88	**Oct**	6.94
May	5.79	**Nov**	6.33
June	5.58	**Dec**	5.20

Table 2: Khanpur/ Taxila- Average Wind Speed measured in m/s.

Month	Speed (m/s)	Month	Speed (m/s)
Jan	4.2	**Jul**	3.7
Feb	4.3	**Aug**	3.6
Mar	5.0	**Sep**	4.1
Apr	5.5	**Oct**	5.3
May	4.7	**Nov**	5.2
June	4.2	**Dec**	4.4

1.3 Hydel Potential of Khanpur Dam

As the basic purpose of Khanpur Dam is irrigation and to provide water for domestic use, however, by the proper management of outflows a considerable amount of power can also be generated. From the flood management data of Khanpur Dam it can be seen that there is average outflow of 6000 cusec for almost 7 months of the year during January to April and July to September [10]. If only average 30000 liter/sec of this outflow is utilized, several MW of electrical power can be generated. As upper and lower reservoir is already constructed, so initial cost of hydro system will be quite low, as only electrical power system components like hydro turbine, generator, transmission line and transformers are to be installed.

1.4 Pumped Hydro Storage Scheme

Table 3: Khanpur Dam Salient Features:[7,8].

Catchment Area	308 sq. miles
Gross reservoir capacity	89,653 Acre-Ft (Initial: 107,076 Acre-Ft)
Live Storage	81,650 Acre-Ft (Initial: 87,012 Acre-Ft)
Mean Annual run off	280, 000 acre feet (345374914.5 m^3)
Type	Earth and Rock-fill
Height	167 ft.
Max. water level	1982 ft.
River bed level	1825 ft.
Spillway capacity	166000 cusec (4700.6 m^3/s)
Canals Outlets	650 cusec (18.4 m^3/s)

For load balancing in electrical power systems, a very practical approach for hydro electric energy storage used nowadays is pumped storage hydroelectricity [11]. The method stores energy in the form of gravitational potential energy of water, pumped from a lower elevation reservoir to a higher elevation. Low-cost off-peak electric power is used to run the pumps. During periods of high electrical demand, the stored water is released through turbines to produce electric power [12]. Although the losses of the pumping process makes the plant a net consumer of energy overall, the system increases revenue by selling more electricity during periods of peak demand, when electricity prices are highest. In Khanpur Dam, luckily both the lower and upper large capacity reservoirs are already available (See details in Table: 3). The reversible turbine/generator assemblies e.g. Francis turbine design, that can act as a pump and turbine are a feasible solution for this scenario. A 1.25 MW reversible turbine/generator assembly shall be for the proposed hybrid generation scheme.

2. Simulation of the Proposed Hybrid Electricity Generation Scheme

For an optimized hybrid electricity generation scheme, power generation from wind, solar panels and water, collectively is proposed.

In the proposed schematic model, there are 2000 kW solar panels, one hundred and fifty 10 kW wind turbines and a 1.25MW hydro turbine to estimate the generated power from the hybrid-plant on HOMER software, for both technical and economic feasibility. The Hydro turbine is connected to AC bus and wind turbines and solar panels are connected to the DC bus, due to lack of frequency regulating mechanism. The DC bus is coupled to the AC bus through an on-grid converter.

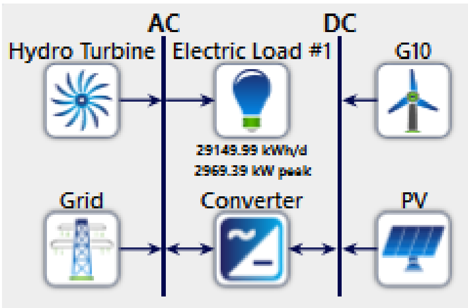


Figure 3(a): Schematic Diagram of hybrid system.

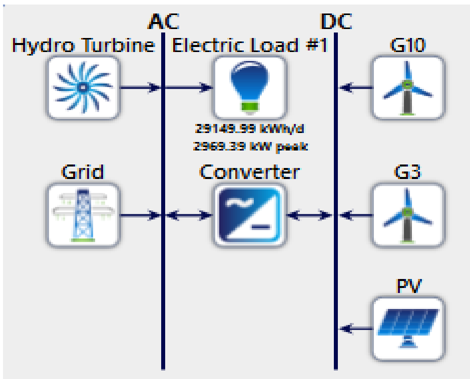


Figure 3(b): Schematic Diagram with 10kW and 3kW wind turbines.

Following are the sequences generated by HOMER that satisfy the technical constraints at the lowest

Architecture						Cost				System
PV (kW)	G10 (qty)	Grid (kW)	Hydro Turbine (kW)	Converter (kW)	Dispatch	COE ($/kWh)	NPC ($)	Operating Cost ($)	Initial Capital ($)	Ren Frac (%)
		3,000	1,243		CC	$0.036	$1,487,224	($3,760)	$1,500,000	86.9
2,000.0		3,000	1,243	1,500	CC	$0.063	$3,233,890	($549,222)	$5,100,000	95.2
		3,000			CC	$0.100	$3,615,106	$1,063,976	$0	0
	150	3,000	1,243	800	CC	$0.090	$3,884,114	($716,915)	$6,320,000	90
2,000.0		3,000		1,800	CC	$0.133	$5,000,487	$376,865	$3,720,000	36.3
2,000.0	150	3,000	1,243	1,800	CC	$0.102	$5,540,953	($1,229,952)	$9,720,000	96.2
	150	3,000		800	CC	$0.165	$5,959,015	$335,228	$4,820,000	7.1
2,000.0	150	3,000		1,800	CC	$0.190	$7,233,643	($290,298)	$8,220,000	41.8

Figure 4: Optimization cases in HOMER.

life-cycle cost [13]. For various optimization schemes/cases, different sequences of hybrid energy sources are generated, each having different renewable energy fractions and grid shares to feed the load.

The most important factors for decision analysis of any renewable energy are cost, annual average energy generated, capacity factor and maintenance of the source. From the simulations of the proposed system generated by HOMER, it can be seen that the cost of 10 kW wind turbines is much higher than the cost of solar panels. As the annual average wind speed is less than 5 m/s, so annual energy generated by wind turbines is much less as compared to the energy generated by the solar panels, as shown in figure 4 and 5. The system was also simulated using solar panels with three hundred 3 kW wind turbines but the result was almost the same.

The generated output power by wind turbine greatly depends on the wind speed and is directly proportional to cube of wind speed. Here, the mean output of the wind turbine is only 134.6 kW with a capacity factor of 6.7% while that of panels is 514.7 kW and 25.7%.

By only using the solar panel with hydro turbines the cost of energy per unit is $0.063. But by using wind turbines along with solar panels and hydro turbine, the cost of energy per unit rises to $0.102 and renewable energy and renewable energy fraction rises by only one percent. The solar output decreases in the summer season as shown in the graph. This is due to the rise in temperature as well as due to the cloudy/rainy season of Monsoons. The output voltage of solar panels reduces with the rise of temperature [9]. Due to the decrease of output voltage generated, power also decreases. As solar panels are static devices, so their operation and maintenance cost is also less as compared to wind turbines.

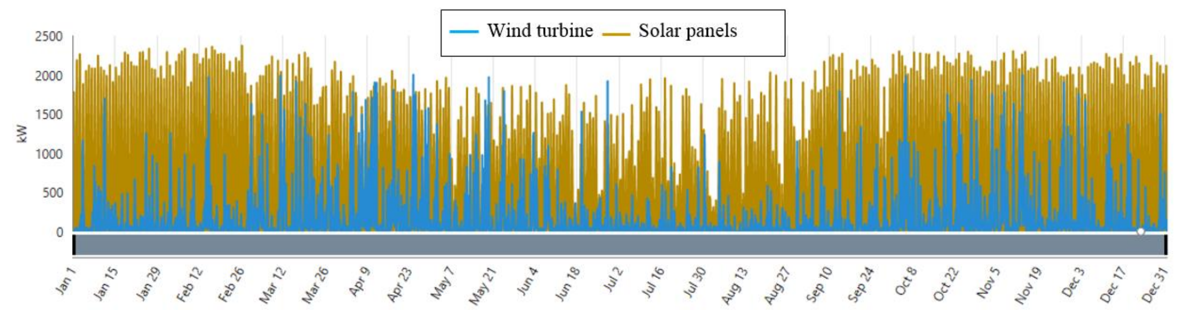


Figure 5: Annual monthly average outputs of solar panels and wind turbines.

2.1 Analytical Hierarchy Process (AHP)

AHP is a Multi Criteria Decision Analysis (MCDA) technique developed by Thomas Saaty, which is a widely used in the energy sector. A detailed discussion on AHP can be found in [14]. AHP decomposes a complex problem into hierarchy of criteria, sub-criteria and alternatives for pair wise comparison and prioritize the available alternatives by assigning numerical values. On the basis of pair wise ranking, comparison matrix are developed. To obtain priority weights of alternatives, the maximum Eigen values, consistency index (CI), consistency ratio (CR) and normalized Eigen vectors are calculated for each comparison matrix and this process is applied to the whole hierarchy to get the overall ranking of each alternative.

$$CI = \frac{(\lambda_{max} - n)}{(n-1)}$$

$$CR = \frac{CI}{RI}$$

Table 4: Random Consistency Index.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Where λ_{max} is the maximum Eigen value and n is the number of comparisons, while RI is the random consistency index. The n-RI pairs are shown in Table 4. Consistency evaluates the correction of pair wise comparison and CR should be less than 0.1, otherwise pair wise comparisons are made again.

2.2 AHP for the Energy Source Selector

For each comparison of the two alternatives, the quantitative importance is transformed into numerical information from 1 to 9 and a comparison matrix is developed. Then a normalized principal Eigen vector calculated which is also called priority vector. In the end, a consistency test is performed for each comparison matrix. If its CR is greater than 0.1, the comparison matrix is adjusted again.

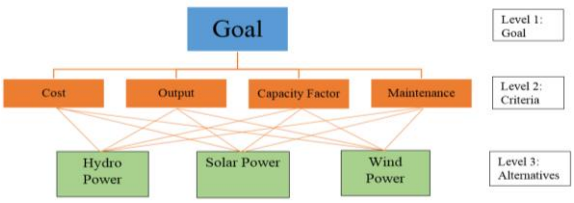
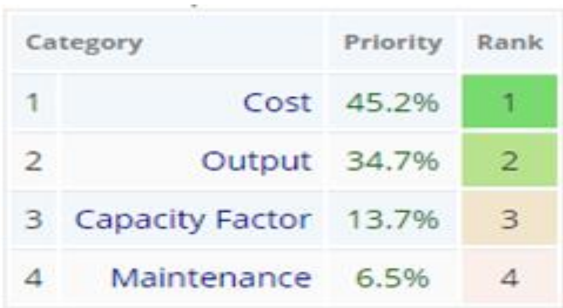


Figure 6: Flow Diagram of Analytical Hierarchy Process.

In the proposed hybrid system the most influencing factors for decision analysis of renewable energy are the cost, annual average energy generated, capacity factor and maintenance of the source. So the AHP model has level hierarchy, in which the first level is the goal, second level comprises of the four criteria and the third level consists of three alternatives as shown in the figure 6. Each alternative will be ranked on the basis of these four criteria as explained above. As Pakistan is developing country, so the most important criterion will be the cost that should be reduced in each case as shown in figure 7. Second most important criterion is the generated output of the energy source, third one is the capacity factor and fourth and least important criterion is the maintenance, as mentioned in the priorities.



Category		Priority	Rank
1	Cost	45.2%	1
2	Output	34.7%	2
3	Capacity Factor	13.7%	3
4	Maintenance	6.5%	4

Figure 7: Priorities of Criteria

2.3 Results and Discussion

The decision matrix and priorities are computed first, to further calculate the Priority weight of the alternatives with respect to the criteria by 3x3 decision matrices, and at the end, the priority weight of alternatives is multiplied with the respective priority weight of criteria with respect to goal and cumulated to get the composite weights [16]. The decision matrix of criteria is given in Table 5.

Table 5: Decision Matrix of Criteria.

Criteria	Cost	Output	Capacity factor	Maintenance
Cost	1	2.00	3.00	5.00
Output	0.5	1	4.00	5.00
Capacity factor	0.5	0.25	1	3.00
Maintenance	0.20	0.20	0.33	1

[Priority weight of alternatives with respect to criteria] * [Priority weight of criteria with respect to goal] = [Hydro Solar Wind]

After performing this process for the whole hierarchy, combined ranking is calculated by multiplying priority weights with criteria weight with respect to goal. This assessment model shows that hydro power is most suitable with a relative weight of 0.673, followed by solar power which weighs 0.258 and wind power with a weight of 0.0658. The details of overall composite weight of the alternatives are shown in Table 6. Therefore by using the solar and hydro power hybridization,

Table 6: Overall composite weight of the alternatives						
	Cost	**Output**	**Capacity Factor**	**Maintenance**	**Composite Weight**	**Rank**
Light(Adjusted)	0.449	0.356	0.134	0.06	1	
Hydro	0.669	0.73	0.65	0.16	0.673	1
Solar	0.237	0.19	0.28	0.76	0.258	2
Wind	0.064	0.068	0.062	0.077	0.0658	3

gives the most optimized results with respect to the cost as well as the generated output.

2.4 Power Shares and Electric Load

The estimated average monthly load demand of Khanpur village and other surrounding villages is 1215 kW with a peak of 2969 kW, and is shown in figure 8. Due to hot summer season in Pakistan, peak demand is during July and August. Hydel power will mostly meet the load demand and any remaining demand will be met by solar power and a small fraction by the grid as shown in the figure 9. Khanpur is a rural area with minimal air conditioning load. During day times, when the generation of hybrid system will be greater than the demand, the excessive power generated will be sold to the grid throughout the year as shown in the figure 10. During evening peak demand hours, power will be purchased from the grid as shown in figure 11. The black color signifies lowest power and red color signifies largest power purchased or sold.

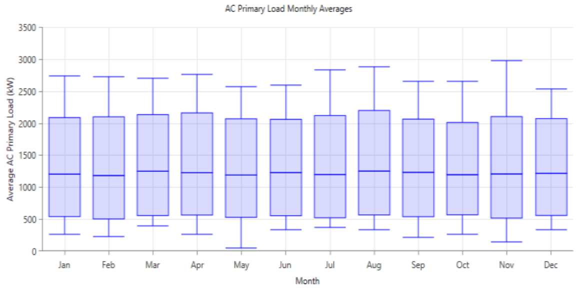


Figure: 8: Total Monthly AC Load served.

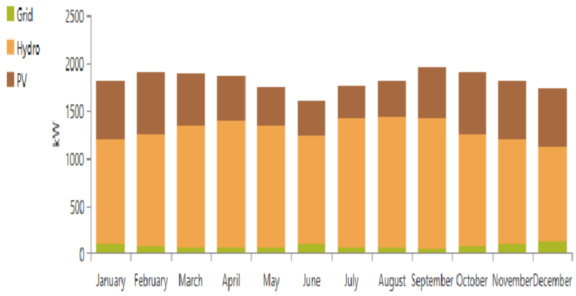


Figure 9: Electrical Power shares.

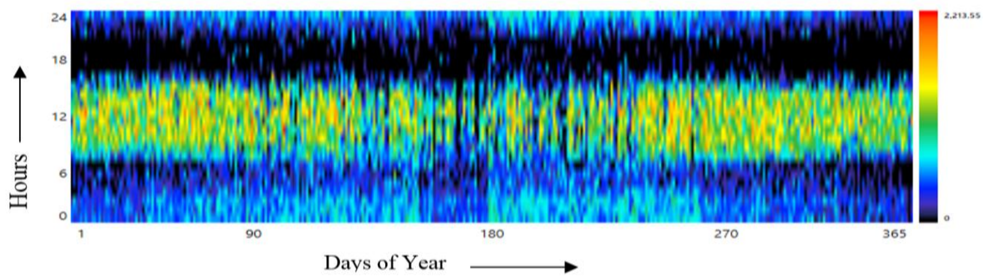


Figure 10: The data map of power sold to grid

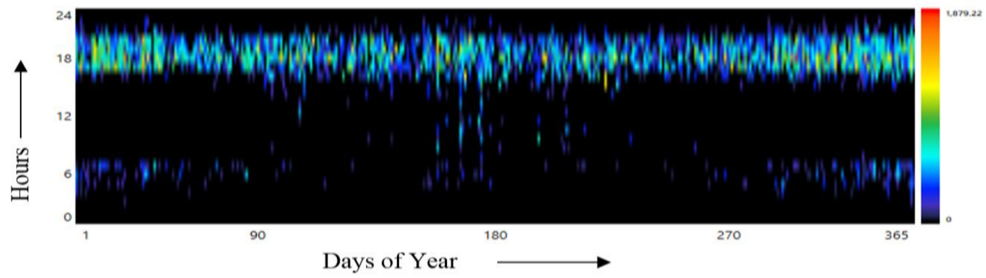


Figure 11: The data map of power purchased from grid.

2.5 Grid Connection

The connection and synchronization of mini hybrid system to national grid is very sensitive because national grid has a standard frequency and voltage level. The proposed mini hybrid system has to synchronize its frequency and voltage with the national grid. In the hybrid system, frequency regulation of hydro turbine can be easily done through the intelligent electronic load controller that can respond to quick load variations more efficiently as compared to speed governor which is a mechanical system.

The generated power can be easily supplied to the village at medium voltage level. A medium voltage transmission line has to be constructed from power house to the village and the national grid. A step-up power transformer will transform voltage to 11 kV. Then it can be easily supplied to villages and injected to national grid. Finally the step down transformers will step-down the voltage and electrical power will be distributed to the consumers.

3. Hybridization Schemes of Renewable Sources

Due to inherent fluctuating nature of solar sources, the concept of hybrid renewable energy systems is emerging throughout the world. By hybridizing one renewable energy source with other sources, they can backup each other and can result in a continuous power source. Pumped hydro storage provides a good solution for energy storage on a large scale, instead of batteries, which are environmentally unfriendly and suffer from other drawbacks. Depending upon the available reservoir, plant can be operated according to following operation schemes.

3.1 Scheme-1

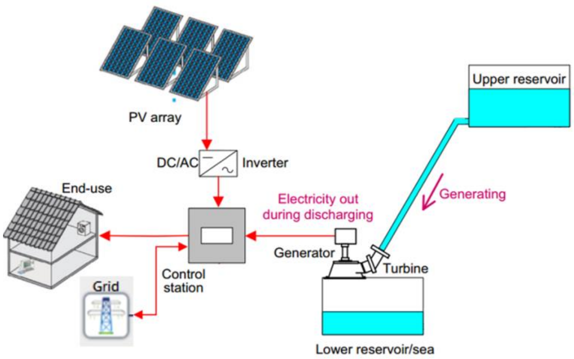


Figure 12: Schematic Diagram of Hybrid Scheme 1.

During spring season from January to April there is 50% of annual inflow and during Monsoon season from July to September due to precipitation there is 30% of annual inflow to the dam. During this period there is excess water in the dam which is extracted out through spillways with an average of above 6000 cusec in the last few years. This excess outflow from the dam the can be utilized to generate power for almost seven peak load months of a year [9]. While generation from solar sources will be excess power, it will be directly fed to grid. The schematic diagram is shown in Figure 12.

3.2 Scheme-2

During 2-3 months when there is relatively low inflow but there is full solar irradiance so day time inflow can be stored and release in the night time to compensate the solar power at night. In the day time, solar power will feed the load with hydro power and grid as backup. The schematic diagram is shown in Figure 13.

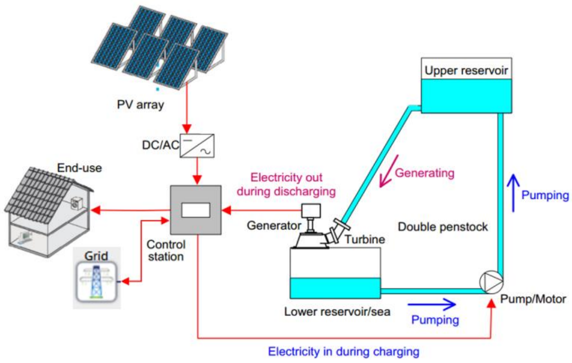


Figure 13: Schematic Diagram of Hybrid Scheme 2.

3.3 Scheme-3

For the remaining time period when there is very low live storage level in the dam, first water will be pumped up to the upper reservoir, using two options. Either through solar power at low demand hours in the day or through grid electricity at night when electricity is cheap and then released only during the peak hours, when cost of purchased electricity from the grid is high. So totally pumped up water through solar is used for power generation. The schematic diagram is as follows.

4. Economic Survey

As Pakistan is a developing country and investment is limited, so extra care should be taken to estimate whether the project will benefit the society or not. If any private sector organization invests in such a profitable project, a large amount of revenue can be generated. For the feasibility of any energy project the initial cost, levelized cost of energy, the project interest rate and inflation rate are important economic factors.

4.1 Initial Cost of Project

Initial cost of a project is a onetime expenditure for the design, purchase of equipment, installation, and construction. The initial cost of per watt solar panels in Pakistan ranges from $1 to $1.25 and it is gradually decreasing due to technological revolution in the solar technologies, while the initial cost of wind turbines is three times more than that of the solar panels. Although hydro power projects are quite expensive but the upper and lower reservoir are already available, so only penstocks and the hydro power station have to be installed. From the results shown in the table 7, the solar system will cost twice as much, as compared to the hydel system.

4.2 Levelized Cost of Energy

Levelized cost of energy (COE) is the average cost per kWh of useful electrical energy produced by the system. Although the initial cost of renewable energy system is greater than the conventional systems but for the future sustainability, these hybrid systems are most suitable solutions. The levelized cost of energy of proposed system will be $ 0.063 to $0.065 only. The cost of energy of the hybrid system is much lower as compared to the cost of unit estimated to $0.2 per kWh in the solar tariff report of Pakistan [15].

$$COE = \frac{C_{anu} - c_{boiler} H_{served}}{E_{served}}$$

C_{anu} = total annualized cost of system ($/kWh)

C_{boiler} = boiler marginal ($/kWh)

H_{served}= total thermal load served (kWh/Yr)

E_{served}= total electric load served (kWh/Yr)

4.3 Payback Time Period

The payback period of system is almost 4 to 5 years with in which the capital cost of the system can be recovered, while the life of all the system components including solar panels, hydro turbines and inverters is greater than 20 years. After payback period this system will produce energy at very low cost due to only operational and maintenance cost.

4.4 Interest Rate

The interest rate is the rate at which interest is charged by the lenders to borrower. According to State Bank of Pakistan, the interest rate in Pakistan was 10 % in 2014 and while now its cut down to only 8% [16]. These steps are taken by Government to subsidize the foreign investments in the energy sector. By such low interest rates and subsidies by the Government, high initial cost renewable energy projects become more feasible.

4.5 Inflation Rate

Inflation rate is the continuous increase in prices of services and goods and measured as annual percentage increase. In Pakistan the average inflation rate from 2010 to 2015 reported by State Bank of Pakistan is 8.87 % [17], and from recent trends, it is falling down gradually again between 4 to 5 %.

Conclusion

To summarize the whole assessment process it can be said that a hybrid renewable energy generation system at Khanpur dam, having catchment area of 308 sq. Miles, and a live storage of 81,650 Acre-Ft was proposed. It was observed that by the proper management of outflows, a considerable amount of power can be generated. In the site area, the annual average solar irradiance is greater than 5.5 kW/m^2, while due to low annual average wind speed, wind turbines are not included in the system. By this hybrid system (2000 kW solar panels with hydro turbine having 13000 liter/sec flow from 130 ft. head) an average load of 1215 kW load will be fed with 95% fraction from renewable hybrid system. During sunlight, surplus power will be sold to the grid. This power is greater in amount than the power purchased from grid, during peak hours. To gain the purpose of power generation from the dam, three operation schemes for this hybrid system are proposed. Any scheme can be operated depending upon the reservoir level of dam.

On the other hand the Government charges Pakistani Rs 11.50 per unit on average, to the consumers [18], while unit generated by the proposed hybrid system costs only Rs 6.30 on average. Although it's initial cost is a bit high, but there is a minute running cost and within four to six years, the capital cost as well as replacement cost can be recovered back, through the power generated from renewable sources. This also leads to reduction in the CO_2 production significantly. By this renewable energy system almost 245.5 tons of carbon dioxide and other polluting gases can be reduced each year.

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