USE OF PUMPED HYDRO ENERGY STORAGE TO COMPLEMENT WIND ENERGY
A Case Study

by

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The dependency of RES on the weather and climate increased the interest on bulk energy storage methods to supply firm power. Pumped-hydro energy storage systems are a step ahead among other bulk energy storage methods because these are more efficient and they have higher storage capacities. The present study focuses on the use of grid connected wind-pumped hydro power station to supply energy. A hybrid wind-pumped hydro storage system was designed and simulated using real data, and economic analysis was performed by calculating the basic pay-back period, the net present value and the internal rate of return. According to the results, it is found that the hybrid system is actively used and a part of the electricity is supplied from the wind-pumped hydro system. In addition, it was obtained that the pumped hydro storage systems are very suitable to be used together with wind power plants.

Key words: *wind, pumped hydro, energy storage, hybrid, power, simulation*

Introduction

Using RES as much as possible is a goal for many countries in the world, however, using those to more effectively and supply a constant amount of power is a problem to deal with [1]. Hybrid systems that include a renewable energy generation facility and an energy storage system are proposed by researchers to overcome the dependency problem of RES on the weather conditions and the climate. Pumped-hydro energy storage (PHES) systems are more preferable among the other bulk energy storage systems due to the relatively higher efficiency and storage capacity. The four main components of PHES systems are upper reservoir, lower reservoir, hydro turbines, and hydro pumps. When the energy demand is low and excess electrical energy is available, water is pumped from the lower reservoir to upper reservoir, in contrast, when there is high energy demand, water is driven from the upper reservoir to lower reservoir to generate electricity in these systems [2, 3].

Renewables are used in a variety of applications including water pumping and also numerous studies about it can be found in the literature [4-10]. Application of solar energy to cover the energy demand of deep well water pumps for water supply in rural or isolated zones was discussed by Ramos and Ramos [4]. They claimed in the study that a competitive water cost

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value is obtained. The feasibility of wind powered water pumping systems for irrigation applications in India was studied by Parikh and Bhattacharya and the authors reported that the wind energy based water pumping systems are best suited for irrigation [5]. A detailed review about RES powered water pumping systems can be found in the study in [6]. Considering the studies on wind-hydro pumped storage power plants, they mostly involve the design, operation and economic viability of these systems. Kapsali and Kaldellis [11] evaluated the techno-economic viability of a system that incorporates the simultaneous operation wind farms with pumped storage and hydro turbines for a remote island and determined an increase in the contribution of renewable energy by almost 15%. Castronuovo *et al*. [12] worked on the optimal operation and hydro storage sizing of a wind and hydro hybrid power plant and calculated a yearly profit of 11.91% by purchasing energy during the low demand periods and selling during the high demand periods in Portugal. Vieira *et al*. [13] studied optimization and operational planning for wind and hydro hybrid water supply systems and concluded that with the optimization mode, it is possible to save up to 47% of the energy costs when compared to the normal operation mode. More detailed information about feasibility, optimal design and operation of pumped-hydro hybrid systems can be found in references [14-18].

In this paper, a hybrid power system consisting of a RES, wind energy, and an energy storage facility, pumped-hydro power storage station, was designed to cover the power demand for irrigation and analysed. In this context, the hybrid system was simulated using an operational concept that provides maximum daily monetary income and savings, and economic feasibility of the system was calculated. Hourly wind speed and electricity consumption data used in this study are based on long-term measurements.

Combining bulk energy storage and wind power

Wind energy is one of the RES that rely on the weather conditions. When there is electricity demand on a system covering the electricity needs from the wind turbines while there is no wind blowing, there will be an energy deficit. Furthermore, when the energy production from the wind is higher than the instantaneous energy need of a system, not used energy will be wasted. Therefore, it is necessary to combine wind power plants with a storage system. When the stored power amount is high, bulk energy storage systems should be considered. Bulk energy storage has some significantly important advantages and these are listed in tab. 1 [2, 19].

Table 1. Advantages of bulk energy storage

Advantage	Explanation
Efficiency	All power plants have an optimum operation in which they run at specific outputs. These can be operated optimally by using energy storage plants
Intermittent power source balancing	Energy storage methods can be used to cope with the unreliability of intermittent power sources.
Peak shaving	Fast-responding energy storage plants can be used to match relatively small increases in demand more flexibility when managing their power grid
Faster lead-in times	Some energy storage methods allow for much faster lead-in times that are useful to match the rapid changes in demand.
Reduction in energy import	Efficient operation of power plants by using energy stage power plants can help to reduce energy import.

Wind-pumped hydro power plants are an example of combination of a renewable energy system with a bulk energy storage system and it can be used for reliable energy production. Combining wind power plants with PHES plants gives the flexibility to user when to store or use the wind power. In these systems, surplus energy is stored as potential energy in the hydro-pump storage system by pumping the water from a lower reservoir to a higher reservoir. If there is higher demand, the stored energy is used to cover the need. Briefly, combined wind and energy storage systems can be regarded as a reasonable way of both storing the energy and keeping the energy continuity of the system. Wind energy can be used efficiently in this way [2].

Selected region and the proposed model

The selected region is Alibeyhuyugu, a small town that is 41 km distant from Konya, Turkey. The region's economy relies mostly on agriculture and stockbreeding and the irrigation is supplied through submerged irrigation pumps that have input powers changing between 45 kW and 110 kW. The irrigation pumps have huge energy consumption, nearly 6000 MWh per year in total. In this study, the real energy consumption data saved between 2004 and 2012 were used to obtain the electricity demand curve. The irrigation pumps are in operation only in seven months of the year and this period is called the irrigation period that begins in April and ends in October. The monthly mean energy consumption of irrigation pumps is shown in fig. 1 [20].

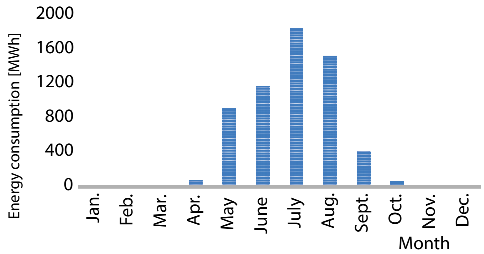

Figure 1. Monthly mean energy consumption of irrigation pumps

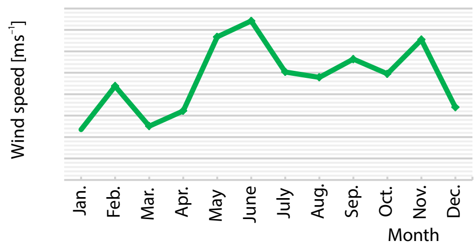

Figure 2. Monthly mean wind speeds in the region

With the help of a wind pole, the wind speed data were measured over several years in this region. The wind pole is equipped with three first class anemometers that have less than 1% measurement instability under 50 m/s wind speed. The monthly mean wind speed values at 35 m height are presented in fig. 2. The mean wind speeds were approximately 4.9 m/s and 5.12 m/s at 10 m and 35 m heights, respectively, in the region. In regions such as Alibeyhuyugu, where the average wind speeds are rated as low, wind turbines that have higher tower heights and larger rotor diameters are required to have a reasonable capacity factor [21].

The proposed hybrid system includes a wind power station (WPS), pumped hydro power plant, and irrigation pumps, all of which are connected to the grid. Schematic presentation of the system is given in fig. 3. Briefly, the energy generated by the wind turbines will be used to meet the energy demand of the

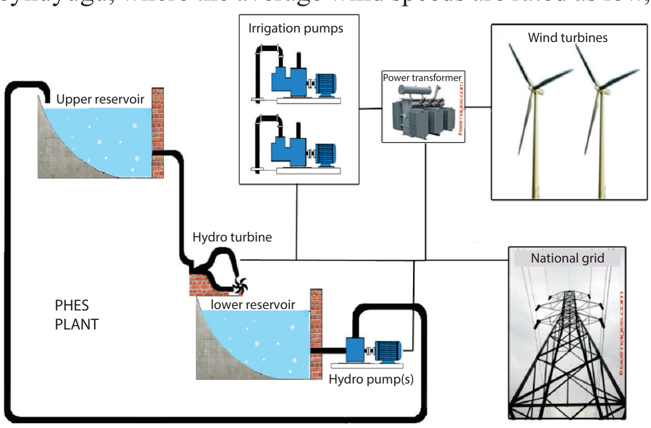

Figure 3. Schematic presentation of the proposed system

irrigation pumps and the hydro pump used for storage, and it will be sold to grid if both do not require energy.

Selected system components

As mentioned before the mean wind speed is low in the region, so, wind turbines with lower cut-in wind speed, high hub heights, and larger rotor diameters are appropriate for the region [21]. The energy consumption of the irrigation pumps is nearly 6000 MWh per year. By considering this value, two of a commercial wind turbine which has 1500 kW of capacity is 3000 kW in total – was selected. The wind turbine has a cut-in wind speed of 3 m/s, cut-out wind speed of 22 m/s, a rotor diameter of 87 m and the hub height is 100 m.

Luckily, a proper location exist near irrigation pumps and selected wind power plant site. The dam called May is thought to be lower reservoir and the top of the hill next to dam that has nearly 55 m hydraulic head was planned to be used as upper reservoir of the PHES plant. For the wind power plant, another hill near PHES and irrigation pumps was selected where wind speed measurements have been performed for several years. Selected hydro pump and hydro turbine and their specifications are given in tab. 2. Finally, upper reservoir size was selected as 62500 m^3 which is equal to nearly 8800 kWh storage capacity.

Table 2. Characteristics of selected hydro turbine and pump

	Number	Power [kW]	Flowrate [m^{3}s^{-1}]	Height [m]	Efficiency [%]
Hydro turbine	1	1250	3	52.5	82
Hydro pump	3	1890 (630 × 3)	2.75 (0.917 × 3)	57.5 (max – 65m)	74

Calculation methodology of the electrical output of wind turbines

Wind speeds are usually measured at a height different from the hub height to reduce the cost for measurements and they can be extrapolated by using eq. (1), where v is the wind speed at the required height, v_0 – the wind speed measured at reference height h_0, and α – the surface roughness parameter. The surface roughness parameter was calculated by using the average wind speeds at 10 m and 35 m heights for the region [21-23]:

$$\frac{v}{v_0} = \left(\frac{h}{h_0}\right)^{\alpha} \tag{1}$$

Using the hourly mean wind speed values, the energy outputs from the wind turbines can be calculated [21-23]:

$$E_p = \sum_{i=1}^{k} P_w(v)t \tag{2}$$

where k is the number of hours, which is 8760 for a year, $P_w(v)$ – the wind turbine power output at wind speed v, and t – the 1 hour time duration. The capacity factor can be calculated using eq. (3), where is the annual energy production (kWh/year), and is the annual energy production at the rated power [21-23]:

$$C_f = \frac{E_p}{E_{\text{rated}}} \tag{3}$$

Operation strategy of the system

The goal was to provide the user the maximum daily income/savings when planning the operation strategy. The daily energy tariff, which is divided into three periods, was considered while implementing this strategy. According to this tariff, the electricity purchasing price is the most expensive during the evening hours from 17:00 p. m. – 22:00 p. m., and it takes its lowest value during the night hours (between 22:00 p. m. and 06:00 a. m.). Table 3 shows the approximate unit prices of electricity in Turkey [24].

Table 3. Unit prices of electricity

	Selling	Purchasing		
Time Period	24 hours	6:00 a. m.-17:00 p. m.	17:00 a. m.-22:00 p. m.	22:00 p. m.-06:00 a. m.
Unit price (US Dollars/MWh)	73	98	153.5	58

The main principles to obtain the daily maximum savings and/or income are summarized in tab. 4 where $P_g(t)$ and $P_d(t)$ are the power generation and the power demand, respectively, at a specific hour, t. In addition, the hourly maximum storage filling rate, which depends on the storage pump power, and the maximum electricity supply rate from the PHES, which depends on the hydraulic turbine power, were considered. It is assumed that the PHES system operates only during the irrigation period.

Table 4. Simplified decision rules of the system

Time period	Task*
06:00 a. m. – 17:00 p. m.	$P_g > P_d$ → Electricity demand will be covered from production, and the rest will be used to fill the upper reservoir; if the reservoir is full, then the excess energy will be sold to the grid.
	$P_g < P_d$ → Determination of the electricity amount that will be used in the next period when the electricity price is at its highest rate; this amount will be kept in the PHES, and the rest of the energy stored will be used. If the amount of stored energy available for use is not sufficient, then the missing amount will be purchased from the grid.
17:00 p. m. – 22:00 p. m.	$P_g > P_d$ → Electricity demand will be covered from the production, and the rest will be stored; if the storage is full, the excess will be sold to the grid.
	$P_g < P_d$ → All of the production will be used to cover the demand, and the deficit will be covered from the storage; if the storage is also not sufficient, then the remaining deficit will be purchased from the grid.
22:00 p. m. – 06:00 a. m.	P_g → Electricity production will be sold to the grid.
	P_d → Electricity demand will be bought from the grid.
	If the storage is not full, then it will be filled.

*P_g = electricity generation from wind energy, P_d = electricity demand.

To implement the operational strategy, a set of equations were defined. The amount of stored electricity power, $S_{se}(t)$ is calculated by eq. (4), where $S_{se}(t – 1)$ is the amount of stored electricity in the previous hour, P_p [kW] – the storage pump power, P_t [kW] – the storage turbine power , and η_p and η_t are the storage pump and the turbine efficiencies, respectively:

$$S_{se}(t) = S_{se}(t-1) + P_p\eta_p - \frac{P_t}{\eta_t} \tag{4}$$

The maximum energy amount provided from the PHES system, which is also equal to the value of maximum energy rejection from the storage, is limited by the hydro turbine capacity:

$$P_{\mathrm{ph,max}} = \Delta S_{\mathrm{se\text{-}rej,rmax}}(t) = \frac{P_{\mathrm{t}}}{\eta_{\mathrm{t}}} \tag{5}$$

The maximum energy amount to fill the upper storage is limited by the capacity of the pump:

$$\Delta S_{\mathrm{se\text{-}fill,max}}(t) = P_{\mathrm{p}}\eta_{\mathrm{p}} \tag{6}$$

Initial investment cost of the components

The initial investment cost of the WPS includes the wind turbine cost and all other initial costs, *e. g.*, the cost of transportation, installation, civil work and connections. The cost of a wind turbine is calculated:

$$C_{\mathrm{wt}} = C_{\mathrm{spe}} P_{\mathrm{r}} \tag{7}$$

where C_{spe} is the specific cost and P_{r} – the rated power of the wind turbine. The specific cost of wind turbines varies according to the rated power and the manufacturer of the wind turbine. The specific costs of wind turbines were chosen using a band interval, as given in tab. 5 [22, 25, 26]. The specific costs of the wind turbine was selected as 1000 \$/kW considering the recent reductions in wind turbine costs. Other initial costs are assumed to be 30% of the wind turbine cost for the WPS.

Table 5. Cost of wind turbines based on the rated power

Wind turbine size [kW]	Specific cost [$\$\mathrm{k}^{-1}\mathrm{W}^{-1}$]
10-20	2200-2900
20-200	1500-2300
> 200	700-1600

Table 6. Specific costs of the PHES components

Component type	Specific cost
Hydro turbine	300-500 \$/kW
Hydro pump	200-400 \$/kW
Upper reservoir	2-6 $\$/\mathrm{m}^3$
Pipe-line	300-700 \$/m

The specific costs of the PHES system components were chosen from tab. 6, which was created by performing a small market survey in Turkey. In addition the costs specified in tab. 6, other initial costs to construct the PHES facility are assumed to be 10% of the total component costs.

Operation and maintenance costs for the WPS and the PHES system are assumed to be a fraction of the facility cost. In this paper, such costs are assumed to be 10% of the annual cost of the WPS and PHES systems (facility cost/lifetime).

Methodology of the economic analysis

Brief economic analysis was performed and key financial figures such as basic payback period (BPB), net present value (NPV), and internal rate of return (IRR) were calculated using eqs. (8)-(10), respectively. Briefly defined, BPB is the value in years that indicates the amount of the minimum time to recover the total investment, NPV is the presented value of all future income, and expenditure flows and the IRR is the rate that would make the NPV value zero [27, 28]. In eqs. (8)-(10), C is the total investment cost and AS – the net annual saving, B – the benefit, C – the cost, r – the discount rate (annual interest rate), and n – the lifecycle year of the project. In this study, the project lifespan was taken as 20 years for the analysis, as suggested by many turbine manufacturer companies, and the overall annual interest rate, r, is assumed to be 2.5%. The salvage cost was not taken into account, which is estimated to be equal to the disassembly cost of the wind power system components at the end of the project lifespan.

$$BPB = \frac{C}{AS} \tag{8}$$

$$NPV = \sum \frac{B - C}{(1+r)^n} \tag{9}$$

$$IRR = \sum \frac{B}{(1+r)^n} = \sum \frac{C}{(1+r)^n} \tag{10}$$

Results and discussion

The hourly mean (a) and monthly mean (b) power productions of the WPS are presented in fig. 4. As it can be seen, power production reaches its peak value at the evening times and during the summer months. Because of the fact that the power is mostly required in the summer months, use of the wind energy to supply is suitable for the studied region. Annual power generation and capacity factor of the WPS is calculated as 6924 MWh and 0.26%, respectively using the measured wind speed data. This is great value considering the low-rated average wind speed in the region.

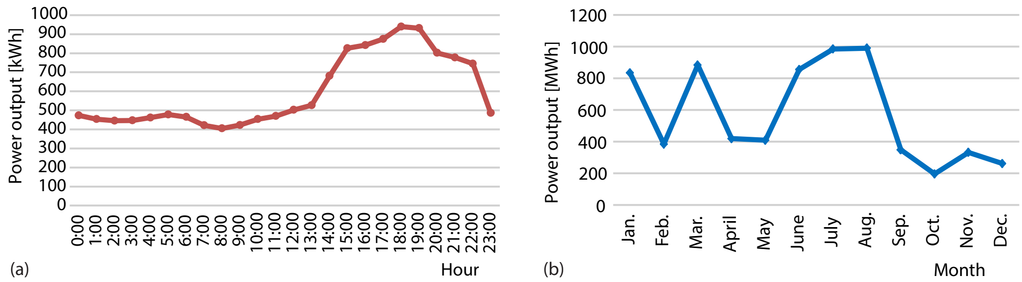

Figure 4. Hourly mean (a) and monthly mean (b) power production of the WPS

The simulation of the hybrid system are graphically presented for June as examples of the other months. The share of energy suppliers to meet the energy demand and storage variation in June are presented in figs. 5 and 6. In fig. 5, P_{demand} represents the total energy demand, P_{ph}, P_{wt}, and P_{grid} represent share of PHES, WPS, and grid, respectively to cover the energy demand. Total energy demand was determined as 1168181 kWh in June and 33.8% (395208 kWh), 14.2% (165316 kWh), and 52% (607657 kWh) of it was covered from the WPS, PHES and grid, respectively.

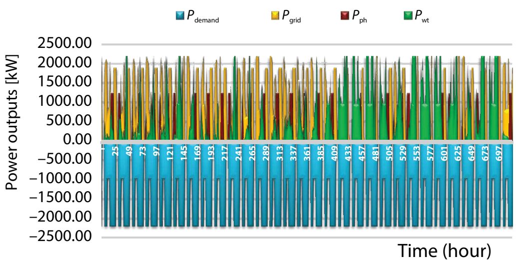

Figure 5. Share of energy suppliers to meet the energy demand in June

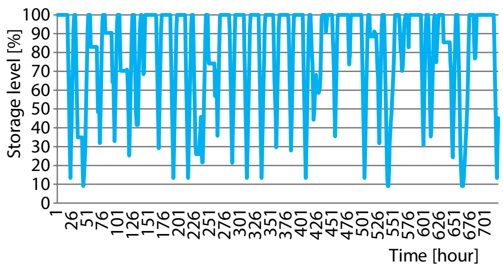

Figure 6. Storage level variation in June

Table 7. Summary of the simulation results of the optimal system

	P_{demand} [MWh]	Share of P_{wt} [%]	Share of P_{ph} [%]	Share of P_{grid} [%]
April	70.64	49.9	25	25
May	916.28	35.9	15.2	48.9
June	1168.18	33.8	11.2	54.9
July	1853.85	24.9	7.8	67.3
August	1523.89	26.5	9.3	64.3
September	412.43	40.1	27.5	32.4
October	54.73	61.4	15	23.6
Average	5999.8	30.4	11.6	58

Summary of simulation results are presented in tab. 7. It can be seen that the share of WPS and PHES system varies between 24.9-61.4% and 7.8-27.5%, respectively. Although an energy storage facility is used, grid connection was necessary to ensure continuous energy flow. The PHES system increased the contribution of the wind energy by nearly %12 which is close to the value of the study by Kapsali and Kaldellis [11].

Table 8. Economic analysis results

Method	Result
Investment cost [$]	5830901
Sum of annual cost savings and income [$]	644284
Annual O&M costs [$]	29,154
NPV [$]	3758460
IRR [%]	8.47
BPP [years]	9.48

The economic analysis results of the hybrid system are presented in tab. 8. The NPV, IRR, and BPP are determined as $3758460, 8.47%, and 9.48 years, respectively. These values were obtained by considering that the PHES system operates only in irrigation period (7 months). If the PHES system is operated during the non-irrigation months as well to make a profit by purchasing electricity in during inexpensive periods and selling back power during other periods, then the BPP was calculated to be around 8.5 years.

Conclusion

In this study, a hybrid wind-hydro power station was designed and simulated to meet the energy demand of irrigation pumps. According to the results, wind and hydro power complement each other very well in terms of power supply. The hybrid system has a relatively feasible basic pay-back period of approximately 9.5 years if the system is operated just during the irrigation period, and around 8.5 years if the PHES system is operated during the non-irrigation months as well to make a profit. According the simulation results of the hybrid system which was operated according to the daily energy tariff, a part of the electricity was supplied from the wind-pumped hydro hybrid system. The storage was filled by the wind and grid during the night hours when electricity purchasing price takes it lowest value and stored energy was mostly used during the evening hours when the electricity purchasing price is the most expensive. Finally, results show that pumped hydro storage systems are very suitable to be used together with wind power plants.

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