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Wind-Hydro Pumped Storage Power Stations to Meet the Energy Demands of Irrigation: Feasibility, Optimal Design and Simulation of a System

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Keywords：pumped, hydro, wind, storage, irrigation, energy

ABSTRACT

The present study focuses on design and use of a grid connected optimal hybrid wind-hydro power station to supply energy for irrigation. To select the optimal system components, an optimization program that selects the cost-optimal wind-hydro pumped storage system components is developed and the energy flow in the system is simulated for the optimal system. Economic analysis was performed for the optimal option by calculating the key financial figures such as basic payback period (BPP), net present value (NPV) and internal rate of return (IRR). The optimal system is found to be feasible having a basic payback period of approximately eight years. Although the hybrid system has an energy storage component, still grid connection was necessary to ensure cheaper energy flow in some time periods. According the simulation results, all the components of the hybrid system are actively used and a great part of the electricity is supplied from the wind – pumped hydro hybrid system. One more observation of this work is that the pumped hydro storage systems are very suitable to be used together with wind energy.

INTRODUCTION

Renewable energy sources are applicable for a wide variety of applications including water pumping, and therefore using those to more effectively supply a constant amount of power is one of the recent popular topics. The dependence of renewable energy sources on the weather conditions and the climate pointed researchers to design hybrid systems that include a renewable energy generation facility and an energy storage system. Due to the high efficiency and relatively higher storage capacity, pumped hydro energy storage (PHES) systems are more preferable among the other bulk energy storage systems. PHES systems consist of four main components: upper reservoir, lower reservoir, hydro turbines, and hydro pumps. Under low energy demand, when excess electrical energy is available, water is pumped from the lower reservoir to upper reservoir, and when there is high energy demand, water is driven from the upper reservoir to lower reservoir to generate electricity in these systems (Dursun et al. 2011).

The studies of wind-hydro pumped storage power plants mostly involve the design, operation and economic viability of these systems. Kapsali and Kaldellis (2010) evaluated the techno-economic viability of a system that incorporates the simultaneous operation of existing and new wind farms (WFs) with pumped storage and hydro turbines for a remote island. They determined an increase in the contribution of renewable energy by almost 15% compared to current conditions. Similarly, Castronuovo and Lopes (2004) considered the optimal operation and hydro storage sizing of a wind and hydro hybrid power plant and determined that a yearly profit of 11.91% can be obtained by purchasing energy during the low demand periods and selling during the high demand periods in Portugal. Optimization of operational planning for wind and hydro hybrid water supply systems is studied by Vieira and Ramos (2009) and authors 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. Jaramillo et al. (2004) provided a conceptual framework for a hybrid wind-hydro power station that produces constant power output and specified that it is possible to guarantee the continuous availability feature of firm power by using hydropower to compensate for wind fluctuations. In addition to these studies, feasibility of pumped-hydro hybrid systems is evaluated by Deane et al. (2010), Padron et al. (2011), Malakar et al. (2014),

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Katsaprakakis and Christakis (2014) and Kapsali et al. (2012) while optimal design and operation are investigated by Papaefthymiou and Papathanassiou (2014), Duque et al. (2011) and Ding and Song (2013). On the other hand, numerous studies about usage of RESs for water pumping can be found in the literature (Ramos and Ramos, 2009; Kelley et al., 2010; Parikh and Bhattacharya, 1984; Fachina, 2016; Kose and Kaya, 2013). Possible application of solar energy to deep well water pumps for water supply in rural or isolated zones is discussed by Ramos and Ramos (2009). Authors stated in this study that the water cost obtained is believed to be a competitive value. The feasibility of solar powered irrigation is examined by Kelley et al. (2010) where authors found out that PVP irrigation is technically and economically feasible. Parikh and Bhattacharya (1984) studied the feasibility of wind powered water pumping systems for irrigation applications in India and reported that wind energy based water pumping systems are best suited for irrigation applications for Indian meteorological conditions. Fachina (2016) has studied supplying freshwater from oceans using hybrid renewable energy systems and calculated the minimum levelized cost for freshwater supply as 0.43 USD/m^3. A detailed review about RES powered water pumping systems can be found in the study by Gopal et al. (2013).

In this paper, a power system consisting of a renewable energy source and an energy storage facility is designed to cover the power demand for irrigation and analyzed. In this context, an operational concept that provides maximum daily monetary income and savings is developed. According to this operational plan, the optimum wind-hydro pumped storage system parameters that are wind turbine, pumped hydro turbine and hydro pump powers and the capacity of storage, are selected by simulating the system for various installation options using wind speed measurements in the region. Finally, the optimal system is simulated and an economic analysis of the optimal system is performed. Hourly wind speed and electricity consumption data used in this study are based on long-term measurements.

DESCRIPTION OF THE REGION

Cumra is a small town that is 41 km distant from Konya, Turkey. The region's economy relies mostly on agriculture and stockbreeding. Corn crops and different types of vegetables are primarily planted in the region. In the region, irrigation is supplied through submerged irrigation pumps that have input powers changing between 45 kW and 110 kW. Irrigation pumps have huge energy consumption, which is annually nearly 6000 MWh 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. 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 Figure 1 (ABH, 2010).

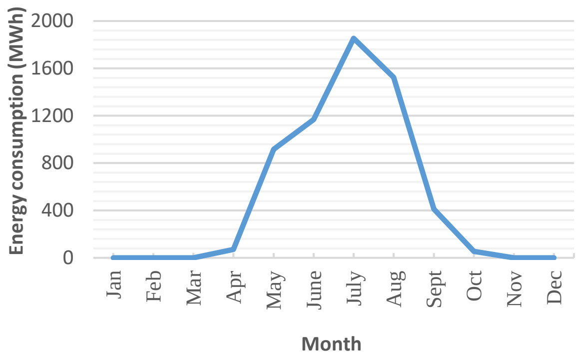

Fig. 1. Monthly mean energy consumption of irrigation pumps (ABH, 2010).

As seen in Fig. 1, larger values are obtained in the months June, July and August with 1168 MWh, 1853 MWh and 1523 MWh of electricity consumptions, respectively. The monthly, daily, and hourly mean energy consumptions are nearly 857 MWh, 28 MWh, and 1.16 MWh, respectively, during the irrigation period.

Wind Characteristics of the Region

The wind speed data were measured over several years with the help of a wind pole in the region. The wind pole is equipped with three Thies 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 Figure 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 Cumra, 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. The wind speed frequencies and the Weibull and Rayleigh curves are presented in Figure 3, plotted using the ALWIN software (Alwin, 2007).

Fig. 2. Monthly mean wind speeds in the region

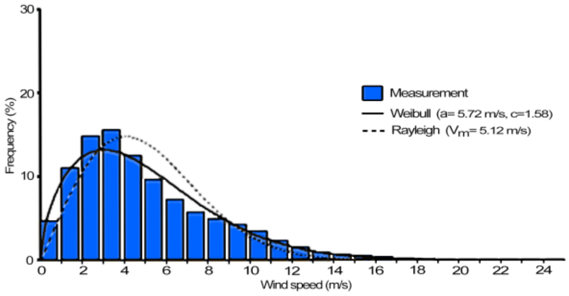

Fig. 3. Wind speed frequencies and the Weibull and Rayleigh curves

PROPOSED MODEL

Schematic presentation of the proposed system is given in Figure 4. The hybrid system includes a wind power station (WPS), pumped hydro power plant, and irrigation pumps, all of which are connected to the grid. The energy generated by the wind turbines will be used to meet the energy demand of the irrigation pumps and the hydro pump used for storage, and it will be sold to grid if both do not require energy.

Selected wind turbines to be studied

In this study, six different commercial wind turbines are considered. The characteristics of selected wind turbines are presented in Table 1.

Table 1. Characteristics of the selected wind turbines

Wind turbines	Cut-in WS (m/s)	Cut-out WS (m/s)	Rated Power (kW)	Hub Height (m)	Rotor diameter (m)
WT - 1	2.5	25	500	75	54
WT - 2	3	22	850	75	52
WT - 3	3	22	1500	100	87
WT - 4	4	25	1500	100	82
WT - 5	3	25	1500	100	77
WT - 6	3	25	3000	99	101

Since the mean wind speed is low in the region, the wind turbines with lower cut-in wind speed, high hub heights, and larger rotor diameters are appropriate for the region (Kaya and Köse, 2016).

Calculation methodology of the electrical output of wind turbines

Wind speeds are usually measured at a height different from the hub height. For this reason, the wind speeds must be extrapolated to the wind turbine hub height. Wind speeds are extrapolated by using Equation (1), where v is the wind speed at the required height, v_o is the wind speed measured at reference height h_o and α is the surface roughness parameter. The surface roughness parameter is calculated by using the average wind speeds at 10 m and 35 m heights for the region (Kose and Kaya, 2013; Stefano et al., 2012; Diaf and Notton, 2013).

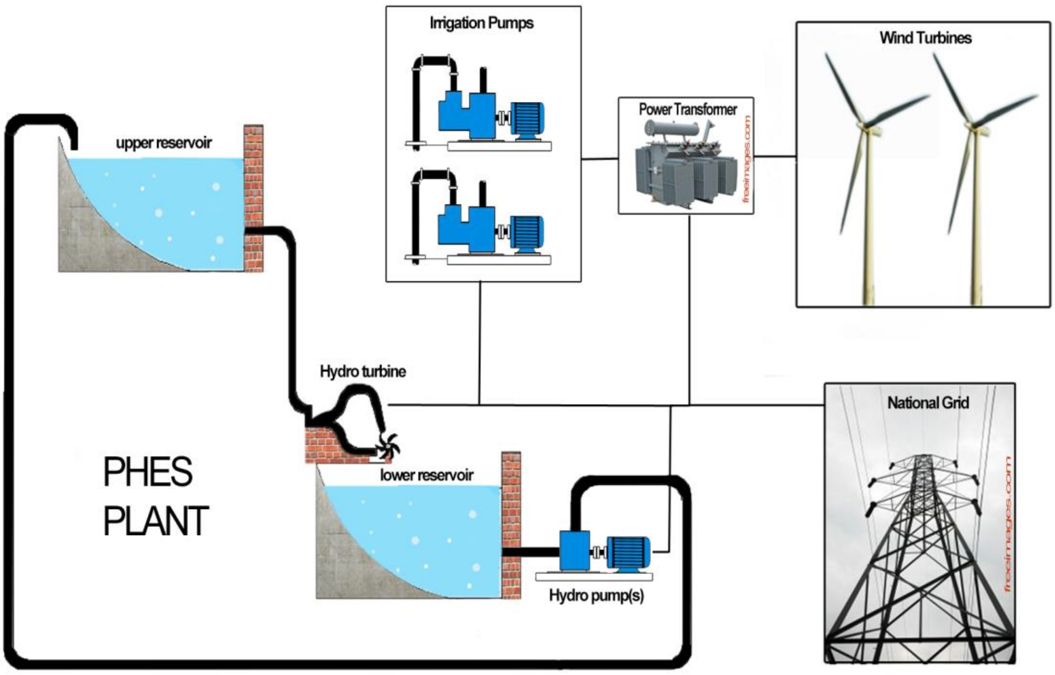

Fig. 4. Schematic presentation of the proposed system

$$\frac{v}{v_o} = \left(\frac{h}{h_o}\right)^{\alpha} \quad (1)$$

The energy outputs from the wind turbines can be calculated by Equation (2) using the hourly mean wind speed values (Kose and Kaya, 2013; Stefano et al., 2012; Diaf and Notton, 2013).

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

where k is the number of hours, which is 8760 for a year; $Pw(v)$ is the wind turbine power output at wind speed v,; and t is a 1 h time duration. The capacity factor C_f can be calculated using Equation (3), where E_p is the annual energy production (kWh/year), and E_{rated} is the annual energy production at the rated power (Kose and Kaya, 2013; Stefano et al., 2012; Diaf and Notton, 2013).

$$C_f = \frac{E_p}{E_{rated}} \quad (3)$$

Operation Strategy of the System

The operation strategy is planned to provide the user the maximum daily income/savings. While implementing this strategy, the daily energy tariff, which is divided into three periods, is considered. According to this tariff, the electricity purchasing price is the most expensive during the evening hours from 17:00 to 22:00, and it takes its lowest value during the night hours (between 22:00 and 06:00). The unit prices of electricity in Turkey are presented in Table 2.

Table 2. Unit prices of electricity (EMRA, 2012)

	Selling	**Purchasing**		
Time Period	24 hours	6:00-17:00	17:00-22:00	22:00-06:00
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 Table 3 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, are considered. It is assumed that the PHES system operates only during the irrigation period.

To implement the operational strategy, a set of Equations are defined. The amount of stored electricity power, $S_{se}(t)$ is calculated by Equation (4), where $S_{se}(t\text{-}1)$ is the amount of stored electricity in the previous hour, P_p is the storage pump power (kW), P_t is the storage turbine power (kW), and η_p and η_t are the storage pump and the turbine efficiencies, respectively.

$$S_{se}(t) = S_{se}(t\text{-}1) + P_p \cdot \eta_p - P_t / \eta_t \quad (4)$$

Table 3. Simplified decision rules of the system

Time period	**Task***
06:00 – 17:00	$P_g > P_d$→ 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 – 22:00	$P_g > P_d$→ 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 – 06:00	P_g→ Electricity production will be sold to the grid. (0.065 dollar cents/kWh)
	P_d→ Electricity demand will be bought from the grid. (0.058 dollar cents /kWh)
	If the storage is not full, then it will be filled.

*Pg = Electricity generation from wind energy, Pd= electricity demand.

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.

$$P_{ph,max} = \Delta S_{se\text{-}rej,max}(t) = P_t / \eta_t \quad (5)$$

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

$$\Delta S_{se\text{-}fill,max}(t) = P_p \cdot \eta_p \quad (6)$$

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 using Equation (7).

$$C_{wt} = C_{spe} \cdot P_r \quad (7)$$

where C_{spe} is the specific cost, and P_r is 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 are chosen using a band interval, as given in Table 4 (Stefano et. al. 2012; Gokcek and Genc, 2009; Sathyajith, 2006). Because there are three wind turbines with the same rated powers (1500 kW), the specific costs are selected by considering the rotor diameters for these turbines. Moreover, the fewer specific costs that are selected, the more the rated power increases. Specific costs of WT-1, WT-2, WT-3, WT-4, WT-5 and WT-6 are selected as 1400, 1300, 1200, 1150, 1100 and 1000 $/kW, respectively. Other initial costs are assumed to be 30% of the wind turbine cost for the WPS.

Table 4. Cost of wind turbines based on the rated power

Wind turbine size (kW)	Specific cost ($/kW)
10-20	2200-2900
20-200	1500-2300
> 200	700-1600

The specific costs of the PHES system components are chosen from Table 5, which was created by performing a small market survey in Turkey. In addition to the costs specified in Table 5, other initial costs to construct the PHES facility are assumed to be 10% of the total component costs. The hydraulic head is assumed to be 55 m in the calculations.

Table 5. Specific costs of the PHES components

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

Operation and maintenance costs for the wind power station and the PHES system are assumed to be a fraction of the facility cost. In this paper, such costs are assumed to be 20% of the annual cost of the WPS and PHES systems (facility cost/life time).

OPTIMIZATION PROBLEM

The objective function to be minimized is defined as the ratio of the total investment cost (C) to the monetary amount of the annual primary energy savings/incomes (PES). It is also assumed that 10% of the upper reservoir capacity is always kept full to ensure secure operation.

$$OBJ.\ Func. = \frac{C}{annual\ PES} \quad (8)$$

The total investment cost C includes the investment cost of the wind power station (E_{wps}), storage turbine and pump (obtained by multiplying the power of the turbine and pump with the specific costs (c_p and c_t)), the upper reservoir construction cost (obtained by multiplying the volume of the reservoir with the construction cost per volume (c_{up}) of the reservoir), and the cost of the pipe line (obtained by multiplying the length of the pipe with its price per meter). In addition, 10% of the total investment cost is added by considering other costs, such as permits, land cost, and licenses. All of the specific costs are presented in Table 5 in the previous section.

$$C = E_{wps} + ((P_p \cdot c_{sp}) + (P_t \cdot c_{st}) + (V_{up} \cdot c_{up}) + (L_{pl} \cdot c_{pl})) \cdot E_{dm} \quad (9)$$

where E_{wps} is the investment cost of the WPS ($), P_p is the storage pump power (kW), c_{sp} is the specific cost of the storage pump ($/kW), P_t is the power of the storage turbine (kW), c_{st} is the specific cost of the hydro turbine ($/kW), V_{up} is the upper reservoir volume (m^3), c_{up} is the specific construction cost of the upper reservoir ($/m^3), L_{pl} is the total length of the pipe line (m),c_{pl} is the specific cost of the pipe line ($/m), and E_{dm} is the ratio to add other expenses for the PHES system construction (additional costs = 10%).

The annual primary energy savings of the wind-hydro hybrid system E_{pes} is calculated using Equation (10), where E_{exp} is the annual expenses of the irrigation company before the hybrid system (when all of the electricity demand is purchased from the grid), E_{gs} and E_{gp} are the monetary amounts of the annual sold and the purchased electricity, respectively, and E_{om} is the annual operation and maintenance cost of the system. E_{gs} and E_{gp} are calculated using Equation (11) and Equation (12), respectively.

$$E_{pes} = E_{exp} - (E_{gp} - E_{gs} + E_{om}) \quad (10)$$

$$E_{gs} = \sum_{t=1}^{t=8160} P_{gs}(\mathrm{t}) \cdot c_s(\mathrm{t}) \quad (11)$$

$$E_{gp} = \sum_{t=1}^{t=8160} P_{gp}(\mathrm{t}) \bullet c_p(\mathrm{t}) \quad (12)$$

In Eqs. (11) and (12), P_{gs}(t) is the amount of sold electricity at the hour t (kWh), c_s(t) is the unit price of electricity at the hour t ($/kWh), P_{gp}(t) is the amount of electricity purchased at the hour t (kWh), and c_p(t) is the price of purchased electricity at the hour t ($/kWh). Some other boundary conditions are defined from Equations (13) to (15) to solve the optimization problem. Eqs. (13) and (14) define the specific ranges that the hydro pump and the turbine powers must be within. In this study, the minimum hydro pump and hydro turbine powers – $P_{p,min}$ and $P_{t,min}$ – are both defined to be 1000 kW, and the maximum powers ($P_{p,max}$ and $P_{t,max}$) are both 3000 kW. The reason for defining the minimum capacity to be 1000 kW is that the electricity demand of irrigation pumps is hourly approximately 1000 kW on average during the irrigation period. Eq. (15) defines the storage capacity to be within a band that is selected to be between 5 MWh and 15 MWh for this study.

$$P_{p,min} < P_p < P_{p,max} \quad (13)$$

$$P_{t,min} < P_t < P_{t,max} \quad (14)$$

$$S_{se,min} < S_{se} < S_{se,max} \quad (15)$$

An optimization program that gives simulation results of various system options is developed based on the Delphi program. This program changes the three main PHES parameters, which are hydro pump power, hydro turbine power and storage capacity, in a given order. The program calculated all the possible results (eight million) to find the optimal solution.

Methodology of the economic analysis

In addition to optimization and simulation, a brief economic analysis was performed. The basic payback period (BPB) is the value in years that indicates the amount of the minimum time to recover the total investment, which is calculated using Equation (16) (Ozerdem and Ozer, 2006).

$$BPB=(C/AS) \quad (16)$$

where, C is the total investment cost and AS is the net annual saving. NPV is calculated by discounting all future income and expenditure flows to the present using Equation (17) (Ozerdem and Ozer, 2006).

$$NPV=\sum [(B-C)/(1+r)^n] \quad (17)$$

where, B is the benefit, C is the cost, r is the discount rate and n is 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. The internal rate of return (IRR) is the rate that would make the NPV value zero, which can be calculated using Equation (18), where the parameters are same as the ones of the NPV (Ozerdem and Ozer, 2006).

$$\sum[B/(1+r)^n]=\sum[C/(1+r)^n] \quad (18)$$

RESULTS

For the selected wind turbines, the capacity factors are determined to be between 0.19 and 0.30%. The annual electricity generation amounts and capacity factors of each turbine are listed in Table 6.

Table 6. Power outputs and capacity factors of the selected wind turbines

	WT–1	WT–2	WT–3	WT – 4	WT–5	WT–6
Rated Power (kW)	500	850	1500	1500	1500	3000
Annual gener. (MWh)	921	1438	3462	3245	2843	5946
Capacity factor (%)	0.21	0.19	0.26	0.25	0.22	0.23

I. Optimization Results

The optimum system parameters obtained are presented in Table 7. The optimal system components are two of the WT – 3 units coupled with a hydro turbine and a hydro pump, each of which have 1000 kW capacities. Moreover, the optimum storage size is found to be 6500 kWh, which is nearly 48,000 m^3 of reservoir capacity. It may appear to be illogical that the hydro pump and turbine have the same rated powers; however, note that these operate for different numbers of hours in total to fill and empty the upper reservoir (8.1 hours to fill, 7.64 hours to empty) because they have different efficiencies.

Table 7. Optimum wind-hydro hybrid system parameters

Type	Optimum component/power
Wind Turbine	Two of the WT – 3 units (total 3000 kW)
Storage size	6500 kWh (≈ 48,000 m^3)
PHES hydro pump power	1000 kW
Hydro turbine power	1000 kW

II. Simulation Results

The simulation results are graphically presented for two months, May and September, as examples of the other months. The share of energy suppliers to meet the energy demand and the storage variation in May are presented in Figures 5 and 6, respectively. In Fig. 5, P_d represents the total energy demand, and P_{ph}, P_{wt}, and P_{gr} represent the share of PHES, WPS and grid, respectively, to cover the energy demand.

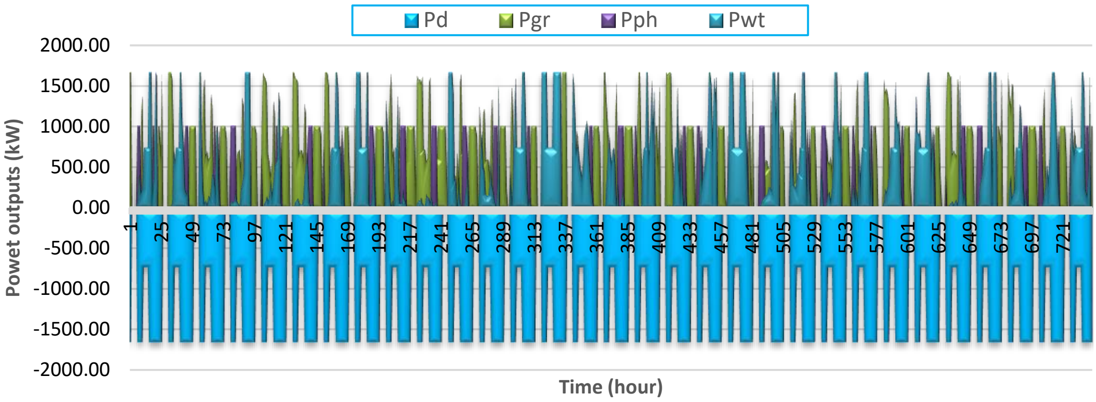

Fig. 5. Share of the energy suppliers to meet the energy demand in May

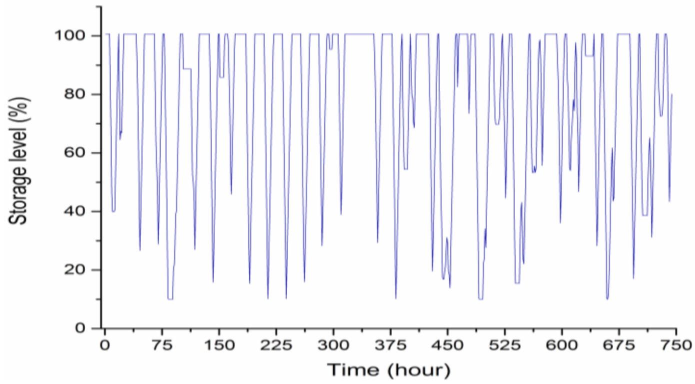

Fig. 6. Storage level variation in May

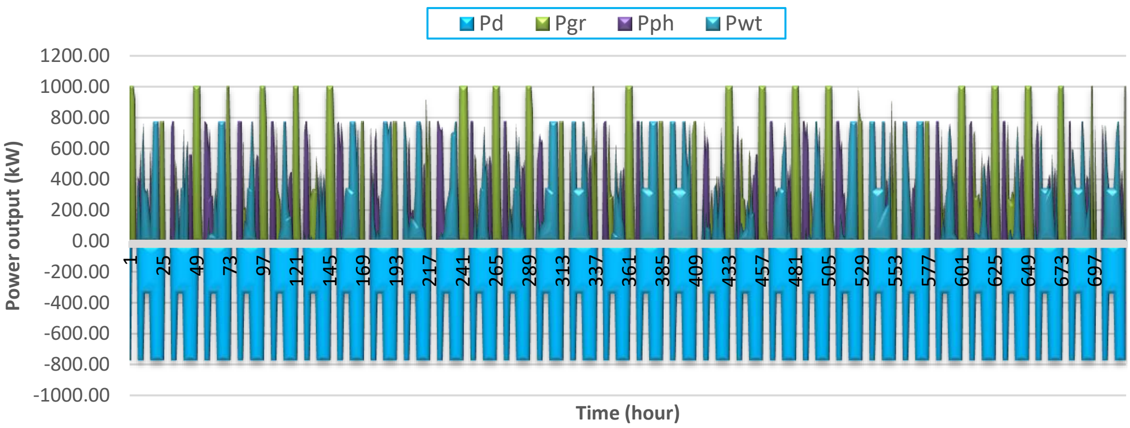

Fig. 7. Share of the energy suppliers to meet the energy demand in September

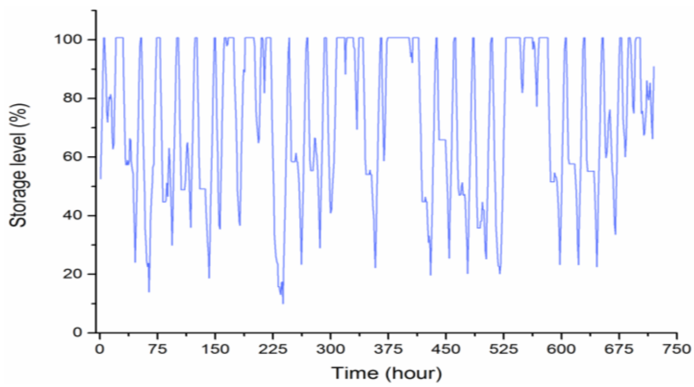

Fig. 8. Storage level variation in September

Table 8. Summary of the simulation results of the optimal system

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

The total energy demand is determined as 916 MWh in May, with 35.9% (329 MWh), 15.2% (139 MWh) and 48.9% (448 MWh) being covered from the WPS, PHES and grid, respectively.

The share of energy suppliers to meet the energy demand and the storage variation in September are presented in Figure 7 and Figure 8, respectively. The total energy demand is determined as 412 MWh in September, with 40.1% (165 MWh), 27.6% (114 MWh) and %32.3% (133 MWh) being covered from the WPS, PHES and grid, respectively.

The economic analysis results of the optimal system are presented in Table 9. NPV, IRR, and BPP are determined as $4,670,710, 9.1%, and 9.04 years, respectively. These values are obtained by only 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 is calculated to be approximately 8 years.

Table 9. Economic analysis results

Method	Result
Investment cost ($)	6,447,118
Sum of annual cost savings and income ($)	777,676
Annual O&M costs ($)	64,471
NPV ($)	4,670,710
IRR (%)	9.1
BPP (years)	9.04

CONCLUSION

In the present work, an optimal hybrid wind-hydro power station was designed, simulated, and analyzed to meet the energy demand of irrigation pumps. The results indicated that wind and hydro power can complement each other very well. The optimization results indicated that the larger the PHES components becomes, the more unfeasible the project becomes for the small-scale systems because the incentives for renewable energy are not very sufficient in Turkey. The optimal system is found to be feasible having a basic payback period of approximately nine years if the system is considered to operate just during the irrigation period, and around eight years if the PHES system is operated during the non-irrigation months as well to make a profit. Although the hybrid system has an energy storage component, still grid connection was necessary to provide cheaper energy flow during some periods such as nights to fill the storage and use the energy during expensive periods. Simulation results show that the hybrid system is operated according to the daily energy tariff that is divided to three periods, and a great part of the electricity is supplied from the wind – pumped hydro hybrid system. The storage is filled by the wind and grid during the night hours when electricity purchasing price takes it lowest value and stored energy is mostly used during the evening hours when the electricity purchasing price is the most expensive.

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NOMENCLATURE

AS	annual savings ($)
B	benefit ($)
BPB	basic payback period (year)
C	total investment cost ($)
c_f	capacity factor
$c_p(t)$	price of purchased electricity at the hour t ($/kWh)
c_{pl}	specific cost of the pipe line ($/m)
$c_s(t)$	unit price of electricity at the hour t ($/kWh)
c_{sp}	specific cost of the storage pump ($/kW)
c_{st}	specific cost of the hydro turbine ($/kW)
C_{wt}	wind turbine cost
C_{spe}	specific cost of the wind turbine
c_{up}	specific construction cost of the upper

	reservoir ($/m^3)
E_{dm}	additional costs (10%)
E_{exp}	annual expenses
E_{gp}	cost of the annual sold electricity ($/year)
E_{gs}	cost of annual sold electricity ($/year)
E_{om}	annual operation and maintenance cost ($/year)
E_{pes}	annual primary energy savings of the wind-hydro hybrid system
E_p	annual energy production (kWh/year)
E_{rated}	annual energy production at the rated power (kWh/year)
E_{wps}	investment cost of the wind power station ($)
h	height (m)
IRR	internal rate of return
k	number of hours (8760 for a year)
L_{pl}	total length of the pipe line (m)
n	lifecycle (year)
η_p	storage pump efficiency
η_t	storage turbine efficiency
NPV	net present value
PES	primary energy savings/incomes
P_d	electricity demand (kWh)
P_{eR}	Rated output Power (kW)
P_g	Electricity generation from wind energy (kWh)
$P_{gp}(t)$	amount of electricity purchased at the hour t (kWh)
P_{gr}	share of grid
$P_{gs}(t)$	amount of sold electricity at the hour t (kWh)
P_p	storage pump power (kW),
P_{ph}	share of PHES
P_r	rated power of the wind turbine (kW)
P_t	storage turbine power (kW)
PHES	Pumped hydro energy storage
$Pw(v)$	wind turbine power output at wind speed v (kWh)
P_{wg}	total generated electricity from the WPS (kWh)
P_{wt}	share of WPS
r	discount rate
$S_{se}(t)$	stored electricity power (kW)
v	wind speed (m/s)
V_{up}	upper reservoir volume (m^3)
WT	Wind turbine
WPS	Wind power station