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Analysis on meeting the electric energy demand of an active plant with a wind-hydro hybrid power station in Konya, Turkey: Konya water treatment plant

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ABSTRACT

Hydroelectric plants play an important role in electricity production in Turkey as well as all over the world. However, the increase in the irregularity of flow regimes and the decrease in water ranges of the rivers due to global warming in recent years have revealed that supporter systems are necessary. One alternative solution that could be applied is an integrated system with both hydropower and wind energy. In this study, a system consisting of a hydroelectric power plant (HEPP) and/or wind power plant(s) (WPP) is designed to resolve the energy demand for the Konya water treatment plant, and the results were analyzed. The wind power calculator program and local wind energy measurement data were used to design the WPP. In addition, the water flow rate due to the mean of the elevation difference between the bend of the dam and plant was used to design the HEPP. The electrical energy consumption of the Konya water treatment plant was considered in the design of the WPP and HEPP. The energy production of the WPP and HEPP, the energy demand of the water treatment plant, the monthly and yearly affordability of the energy production were calculated. Additionally, an economic analysis was performed, where the basic payback period was calculated. All the data used in this study are based on long-term measurements.

1. Introduction

According to information from the International Energy Agency in 2009, a total of 194.8 billion kWh of electrical energy was produced in Turkey, where 49.3% of this energy was produced from natural gas, 28.5% from coal, 18.45% from hydraulic, 2.46% from liquid fuel and 1.16% from renewable resources [1]. The majority of the natural gas and coal used for electricity production was purchased from neighboring countries, which means Turkey pays much more for the energy compared with what Turkey would pay if the energy was not imported. However, Turkey has a great hydroelectric potential, yet only 20% percent of its hydroelectric potential, which is 140 GWh/year, is used [2]. Developed countries use approximately 60% of their hydroelectric potential. By the end of 2009, 50,000 GWh of electricity has been generated from 213 active HEPPs with an installed capacity of 14,300 MW in Turkey. Currently, 145 HEPPs have a 16.98% capacity of the total potential with 7200 MW installed, and 23,770 GWh/year generation capacities are still under construction. There will be 1418 HEPPs constructed in the upcoming years, and the number of HEPPs will be 1738 with an additional capacity of 22,700 MW installed. The installed hydroelectric power capacity will be 44,200 MW once the new HEPPs are constructed in Turkey by 2023 [3].

The total world WPP capacity was 238,351 MW at the end of 2011. The amount installed in Turkey was 803 MW, where the total amount has increased in the last ten years. The China has the largest installed capacity with 62,733 MW, USA is in the second place with 46,919 MW and Germany is in the third place with 29,060 MW. However, the amount installed in Turkey was only 1799 MW, where the total amount has increased in the last ten years [4]. According to potential determination study by the Electrical Power Resources and Development Administration, there is 130 billion kWh of electricity from a potential of 48,000 MW generated in areas where the wind velocity is greater than 7 m/s at an elevation of 50 m. In the same study, the wind power potential was determined to be 1860 MW for the Konya region [5]. There are two ways to generate electricity with wind energy in Turkey; first is to sell the electricity generated under a license to power distribution units and/or to use

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the electricity for its own consumption. The second way is to design a system with less than 500 kW of capacity to generate electricity for one's own needs without a license and with permission from the local distribution company. The second way is an attractive option to encourage investments in wind energy because wind power generation systems that have less than 500 kW of capacity do not require governmental license.

There have been numerous studies on the optimization, increasing penetration, complementation and contribution to the electricity production of wind/hydro hybrid systems [6–10]. Dursun and Alboyacı [6] stated that wind/hydro solutions not only guarantee the continuous capability to cover the electricity demand of the local grid but also minimize the dependency on imported fuel and reduce the negative consequences of using fossil fuels. In addition, using these systems and increasing the electrical efficiency are good solutions to help remain below the CO_2 emission amount specified by Kyoto Agreement [7]. Jaramillo et al. studied the potential of using hydropower to complement wind energy and concluded that it is possible to guarantee continuously available power using hydropower to compensate for wind fluctuations [8]. Papaefthymiou et al. pointed out operating policies for wind-hydro hybrid power stations in autonomous on-island grids and concluded that with hybrid power stations, wind energy penetration can significantly increase in saturated autonomous grids and can also provide reliable capacity to the systems, substituting expensive peak units [9]. Denault and his colleagues stated that any proportion of wind up to 30% improves the production deficit risk profile of an all-hydro system [10].

In this study, a system consisting of wind power plant(s) (WPP) and/or a hydroelectric power plant (HEPP) is designed to meet the energy demand of the Konya water treatment plant, and the results were analyzed. Local wind energy measurement data were used to design the WPP. The electrical energy consumption of the Konya water treatment plant was considered in the design of the WPP and HEPP. An economic analysis was performed, and the basic payback period was calculated.

2. Materials and methods

In this paper, the HEPP is designed in place of the pressure reduction valve that is constructed 5158 m away from the dam on the transmission line, as observed in Fig. 1.

After measuring the real operational values, such as the flow rate of the water in the transmission line, water level and the energy consumption of the water treatment plant, the HEPP is designed using these real conditions. The flow rate and water level values at the point where the pressure reduction valve is located on the transmission line are given as monthly mean values. Although the plant was activated in April 1995, the data measured after January 1996 were used to assess with accurate yearly values. The total flow rate values of the water entering the WTP, which were recorded between 1995 and 2009 for 15 years, were used in the study and shown in Fig. 2. These data were taken from Konya Bus, Water and Sewage Management (KOSKI) [11]. Although the flow rate of the water entering the WTP could be determined by measuring the water level of the dam, this method was not used because this measurement would not be as sensitive. Instead, the measurements were obtained with a sensitive flow meter.

There were dry periods with a minimum flow rate of 3 million m^3/year and very productive periods with a maximum of 32 million m^3/year flow rate during the 15-year period. If the flow rate reported in 2001, which is when the minimum flow rate occurred, is not considered, the mean flow rate would be 20 million m^3/year (0.634 m^3/s), and if the flow rates reported in the years 2000, 2005 and 2006, which are low flow rate values, are not considered, the mean flow rate is 22.88 million m^3/year (0.725 m^3/s). The monthly mean flow rate values measured between the years 1995 and 2009 of the HEPP are shown in Fig. 3. The monthly mean flow rates fluctuate between 0.35 m^3/s and 0.8 m^3/s. A sensitive flow meter placed at the entrance of the treatment plant was used to measure and record the flow rate through the transmission line. The flow rate of the water in the transmission line is a monthly constant because a constant water flow rate is required in several processes during the water treatment. Additionally, it was required that it has a smooth workout. The geometric elevation radius between the pressure reduction valve (PRV) and the water level of the dam was used to determine the gross water level. Pipe friction losses and 50% of the pipe friction losses taken as elbow losses were subtracted from the gross water level, and the net water level was then obtained.

The monthly water level change is calculated and shown for several years in Fig. 4. The net water supply network changed between 48 and 58 m, and the mean net water level was 50.77 m between 1996 and 2009. In this case, to construct an HEPP pool, the

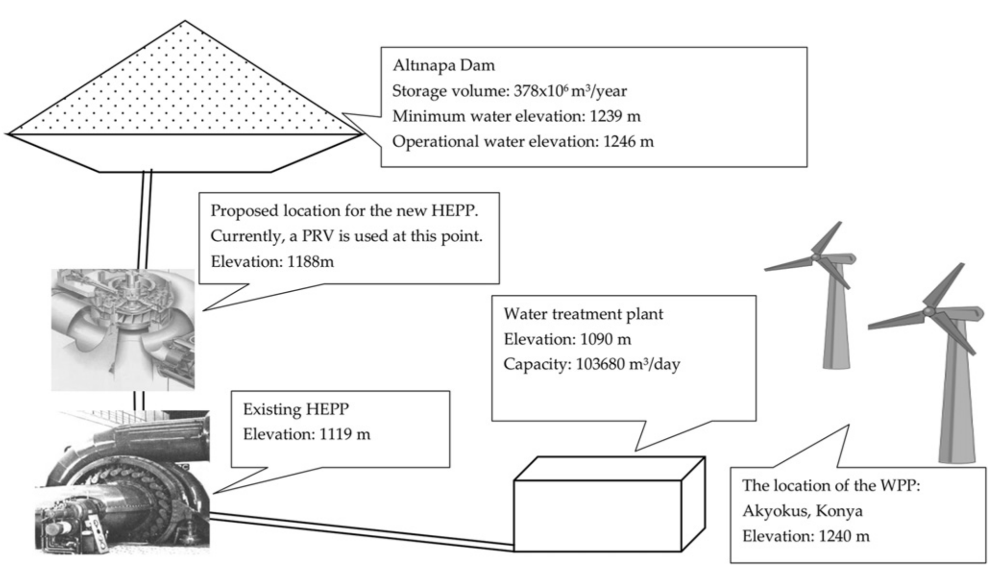

Fig. 1. Graphical illustration of the system.

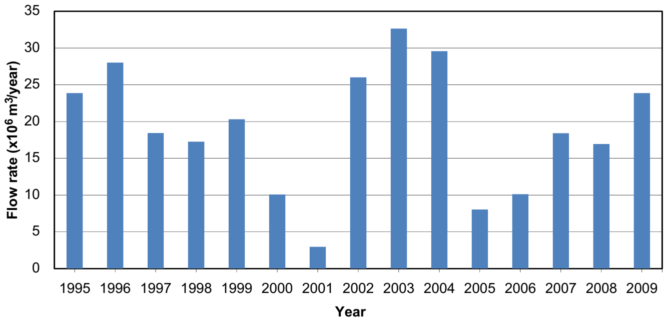

Fig. 2. The mean flow rates of the water coming from Altınapa Dam to the water treatment plant.

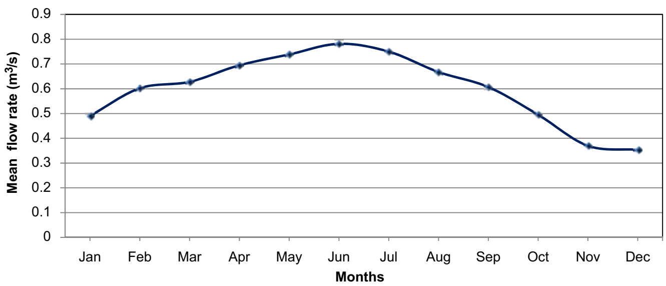

Fig. 3. The monthly mean flow rates of the water entering the treatment plant between the years 1995 and 2009.

net water level must be 40 m, and if it is constructed without loading room and with a balance chimney, it will be more productive with a balance chimney that has a height between 30 and 40 m and a pressure control valve. The monthly power consumption of the water treatment plant was measured with an electric meter supplied by the electric distribution company. Plans to install one or two wind turbines with 250- and 500-kW capacities on the Akyokus hill are being made to provide additional power when the energy amount required for the Konya water treatment plant cannot be supplied from the HEPP or if more capacity is desired.

The measurement results obtained in Selcuk University through the Campus Wind Investigation Station (taken between December 2004 and March 2007), which is at the same elevation as Akyokus hill and is 15 km away from there, were used. The WPP is approximately 750 m away from Akyokus hill. The data are saved every 10 min, which are the averages of the measured data taken at 10-s intervals using standard measurement devices (three anemometers, one for direction, pressure, temperature and humidity meters) at the wind investigation station. In this area, the mean wind velocity is 6.0 m/s and the mean unit power is 294–308 W/m^2 at an elevation of 40 m [12,13]. The mean wind speed values recorded for 2 years, shown in Fig. 5, are taken at the Selcuk University campus, and these data will likely represent that at Akyokus hill because it is essentially at the same elevation. The mean velocity can be taken as 6 m/s at 40 m in this area.

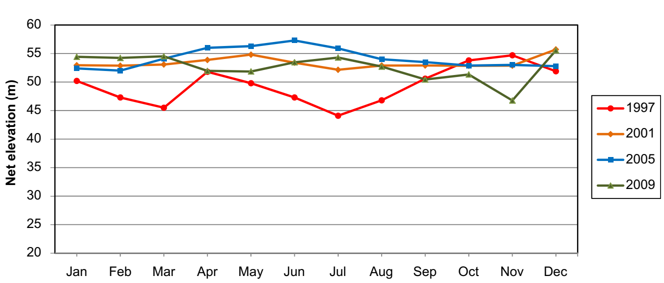

Fig. 4. The monthly mean elevation values at the PRV for different years.

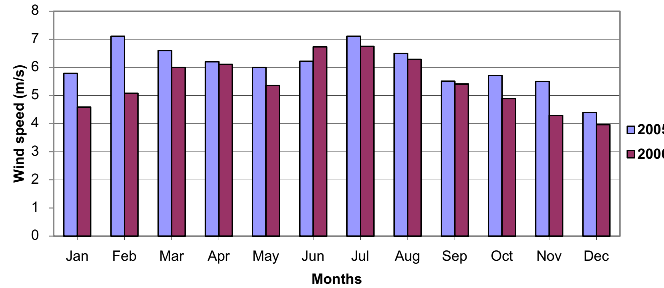

Fig. 5. Monthly mean wind speeds of the area where the WPP is designed for the years 2005 and 2006.

The mean energy production amount of the water turbine is calculated by using Eq. (1), where ρ is the water density, which is approximately 1000 kg/m^3, g is the gravitational acceleration (9.81, m/s^2), Q is the flow rate (m^3/s), H is the net water level (mSS), which is obtained by subtracting total hydraulic loss from the water level, η_j is turbine generator efficiency and η_g is the general efficiency taken from the water turbine efficiency graphic according to the value obtained by dividing the working flow rate to the nominal flow as observed in Fig. 6 [14–17].

$$P_T = \rho \cdot g \cdot Q \cdot H \cdot \eta_g \cdot \eta_j \cdot 10^{-3} [\text{kW}] \quad (1)$$

The energy production amount of the wind turbine is calculated according to Eq. (2) using the air density (ρ_a), turbine capacity factor (Cp), sweeping area of the turbines rotor (A) and the mean wind velocity (v), generator efficiency (η_j) values [2,12,13,15].

$$P_w = 0.5 \cdot Cp \cdot \rho_a \cdot A \cdot v^3 \cdot \eta_j \quad (2)$$

The selection of the hydraulic turbine type is chosen according to the specific speed (n_q) given by Eq. (4) [17].

$$n_q = n \cdot Q^{0.5} \cdot H^{-0.75} \quad (3)$$

In Eq. (3), Q is the flow rate (m^3/s), H is the net water head (m) and n is the revolution per minute (rpm) of the turbine.

The specific speeds calculated according to HEPPs design values were 24.4 rpm for 500 rpm (turbine revolution; n) and 48.8 for 1000 rpm. The appropriate turbine type for both values was determined to by a Francis turbine type for the HEPP. The turbine

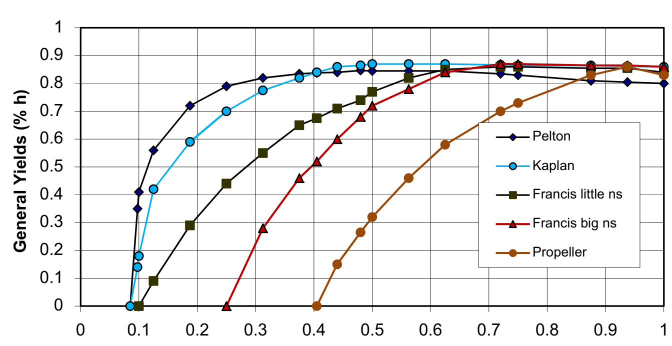

Fig. 6. General yields for small turbines discharge rates [17].

type selection ranges according to specific speed values are given in Table 1 [17].

2.1. Calculation methodology for economic analysis

In this study, three evaluation methods, which are Net Present Value (NPV), Internal Rate of Return (IRR) and the Basic Payback Period (BPB), are used for the economic feasibility analysis of the project. BPB is the value in years that shows amount of the minimum time to recover the total investment and it is calculated with Eq. (4).

$$BPB = (C/AS) \tag{4}$$

where, C is the total capital cost and AS is the net annual saving.

NPV is calculated by discounting all future income and expenditure flows to the present with Eq. (5) [18].

$$NPV = \sum\left[(B - C)/(1 + r)^n\right] \tag{5}$$

where, B is the benefit, C is the cost, r is the discount rate and n is lifecycle year of the project. In this study, the project lifespan was taken as 25 years for the analysis as suggested by many turbine manufacturer companies and the overall annual interest rate (r) is assumed to be 2.5%. Salvage cost was not taken into account which was estimated to be equal to the disassembly cost of the wind power system components at the end of the project lifespan.

IRR is the rate, which would make NPV value zero and it can be calculated with Eq. (6), where the parameters are same as the ones of NPV [18].

$$\sum\left[B/(1 + r)^n\right] = \sum\left[C/(1 + r)^n\right] \tag{6}$$

3. Results and discussion

The Konya Water Treatment Plant became operational in April 1995. The water level of the dam, output flow rate, input flow rate and electricity consumption amount values recorded from 1995 to 2009 have been analyzed. This period consists of 15 years (177 months); however, water could not be transmitted to the facility for 21 of those months because there was not water to flow during November and December. This value shows that the rational working time of the dam and the water treatment plant is 88.14%.

The input flow rate values to design the turbine or to choose the turbine type are given in Fig. 2, and the monthly mean unit values are calculated and given in Fig. 3. The mean flow rate of the water going through the HEPP was 23 million m^3/year excluding the dry years. The monthly mean amount of this flow rate was 1.917 Million m^3/month or 0.665 m^3/s.

The mean water level for the HEPP is chosen as 40 m, which is the minimum water level measured in 1996. The minimum water level is taken as the mean water level in the calculations because we wanted the worse possible HEPP operating conditions. Because there will be a loading pool and a balance chimney constructed in the HEPP, the ratio of the fullness of the loading pool and the balance chimney will be used as the power booster. There will be more power generated at approximately a 58 m water level, which is nearly 50% of the minimum net altitude in case a balance chimney is constructed. This system will still work even if the dam's water level drops below 40 m or if there is an increase of friction losses, such as pipe friction losses.

Table 1
Classification of turbine types according to specific speed [17].

Turbine type	Specific speed, n_q
Pelton turbines (single nozzle)	0–13
Francis turbines	20–140
Kaplan turbines	100–300
Bulp turbines	140–400

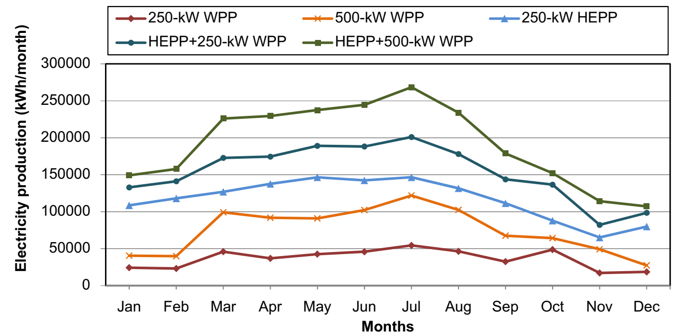

Fig. 7. The electricity production amounts of the HEPP and the WPP.

The efficiency of the Francis turbine is calculated using the monthly mean flow rate and the water level values. In the 15-year period, the turbine power was approximately 250 kW in 100 out of 156 months, a ratio of 65%, which is an excellent full-power working ratio. A Francis turbine with 250 kW of power capacity was chosen according to specific speed values from Table 1.

The Cp and the monthly mean wind velocity values of two similar wind turbines with the same powers chosen from the wind power calculator program were used to determine the electricity generated with 250- and 500-kW WPPs on Akyokus Hill [16].

The monthly and yearly mean electricity generations of the 250-kW wind turbine at a 40-m elevation and a 500-kW wind turbine at a 50-m elevation were calculated. The monthly electricity generations of the 250-kW WPP, 500-kW WPP, HEPP, HEPP+250-kW WPP and WPP+500-kW HEPP are shown in Fig. 7. The yearly electricity generation amounts are the following: 436,019 kWh/year for the 250-kW WPP, 897,081 kWh/year for 500-kW WPP and 1,402,741 kWh/year according to regular losses, and 1,262,460 kWh/year according to the value with a 10% safety margin for the 250-kW HEPP. The maximum electricity consumption of the water treatment plant was 1,373,270 kWh/year, and the mean electricity consumption was 1,300,000 kWh/year. It is shown in Fig. 8, from bottom to top, the energy production of the HEPP with a safety margin, energy consumption of the WTP, energy production of the HEPP, energy production of the HEPP + 250-kW WPP and the energy production of the HEPP + 500-kW WPP. Although the graph shows that the HEPP appears to meet the electrical energy demand in today's

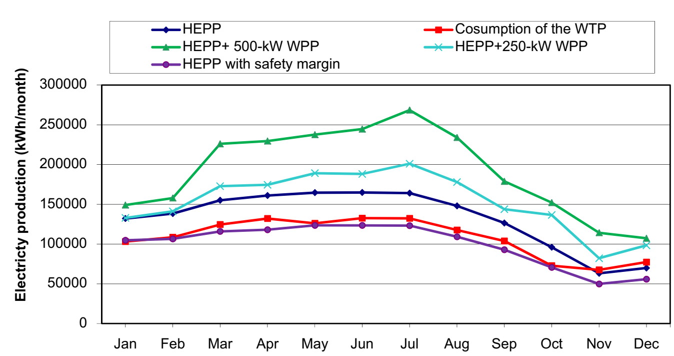

Fig. 8. The electrical energy demand of the water treatment plant and generation amounts of the HEPP and the WPP.

Table 2
Economic feasibility analysis results for various installation options.

Turbine type	Only hydraulic turbine (250 kW)	Hydraulic turbine (250 kW) + wind turbine (250 kW)	Hydraulic turbine (250 kW) + wind turbine (500 kW)
Investment cost[a] (€)	250,000	670,000	950,000
Annual energy production (kWh/year)	1,262,460	1,698,479	2,159,541
Annual cost saving (€/year)	113,621.40	152,863.11	194,538.69
Operation and maintenance cost (€/year)	2563	5179	7945
Net annual cost saving[b] (€/year)	111,058.40	147,684.11	186,593.69
Basic payback period (years)	2.25	4.54	5.1
NPV (€)	1,796,182	2,050,988	2,487,872
IRR (%)	44.42	21.89	19.41

[a] Investment cost includes installation and other additional costs except O&M costs.
[b] Net annual cost saving is calculated by subtracting yearly O&M costs from annual cost saving.

conditions, it must be supported with at least a 250- or 500-kW WPP because otherwise, it would not meet the energy demand if the capacity increases or during dry years.

The monetary electricity generation values of the HEPP and WPP, the investment costs and operation and maintenance costs (O&M) of the plants are used for the economic feasibility analysis. With reference to this, the installation cost of the 250-kW Francis Turbine was approximately 250,000 €, and the installation costs of the 250- and 500-kW wind turbines were approximately 420,000 € and 700,000 €, respectively. The electricity generation amount will be 1,698,479 kWh/year and the investment cost will be 670,000 € if there is one HEPP and one 250-kW WPP installed. If there is one 250-kW HEPP and one 500-kW WPP installed, the investment cost will be 950,000 €, and the electricity generation amount will be 2.159.541 kWh/year. The monetary value of the yearly electricity generation will be 152,863.11 € when two 250-kW turbines (one HEPP, one WPP) are used and will be 194,358.69 € for the system with a 250-kW HEP and a 500-kW WPP according to the electricity price of the municipalities, which is approximately 0.09 €/kWh. It is given in reference [19] that the O&M costs are approximately 0.3–0.4 c€/kWh during the first two years and approximately 0.6–0.7 c€/kWh after six years for wind turbines; the O&M costs for HEPPs is given as 0.203 c€/kWh in reference [20]. In our calculations, we considered the values 0.6 c€/kWh for wind turbines and 0.203 c€/kWh for HEPPs.

The BPB, NPV and IRR values are calculated according to Eqs. (4), (5) and (6), respectively. The BPB, NPV and IRR will be 2.25 years, 1,796,182 € and %44.82, respectively, for 250 kW HEPP, 4.54 years, 2,050,988 € and %21.89 for two 250-kW turbines (one HEPP, one WPP), 5.1 years, 2,487,872 € and %19.41 for the system with one 250-kW HEPP and one 500-kW WPP, as shown in Table 2.

4. Conclusion

The Turkish government has been working to find a solution to decrease energy dependency on other countries. Studies indicate that Turkey has a good potential to produce electricity from renewable energy sources. Because solar energy is still expensive to use, it is more logical to invest in wind and hydraulic energy. However, the stochastic behavior of wind speed and the irregularity of flow regimes in rivers suggest that it is not appropriate to use these systems without supporter systems to produce reliable power. In this study, we have analyzed a hybrid system consisting of wind and hydropower plants to meet the energy demand of the Konya water treatment plant. As a result, it was determined that wind and hydropower generation systems complement each other well, and the electric energy demand of the plant can be covered using this hybrid system. There are plans to install a 250-kW HEPP and a 250-kW WPP to meet the electrical energy demand of the Konya water treatment plant. Despite the capacity increasing by 20%, the electricity demand can still be met. If two 250-kW or one 500-kW wind turbine were additionally installed with the HEPP, the energy demand would still be met, even if there was up to a 50% capacity increase. It is remarkable that almost all the energy demanded of the water treatment plant can be provided from the HEPP. The energy demand of the plant can be fulfilled for 10 months in a year with the HEPP; however, it cannot be met for the remaining 2 months. The energy demand can be met just for 4 months (January, February, May, October) with a 10% safety margin calculation, and it is concluded that a WPP is necessary to guarantee non-stop production of electricity and provide the energy demand of the water treatment plant throughout the year, as shown in Fig. 8. The payback period of investment cost will be 4.54 years if a 250-kW HEPP and a WPP are installed, 5.1 years if a 250-kW HEPP and a 500-kW WPP are installed, which are quite reasonable payback periods. The HEPP and WPP have short payback periods because the HEPP is constructed on an existing pipeline, the HEPP is domestic production and the distance between the WPP and the WTP is short.

Acknowledgments

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Abbreviations

HEPP	hydroelectric power plant
WPP	wind power plant
WTP	water treatment plant
PRV	pressure reduction valve
η_g	general efficiency
η_j	generator efficiency
P_T	turbine power
P_w	wind power
E	monthly mean power production
r	water density
g	gravitational acceleration
Q	flow rate
H	net water level
ρ_a	air density
Cp	capacity factor
A	sweeping area of turbines rotor
n	mean wind velocity
Q	flow rate
n	turbines revolution per minute
n_j	wind turbine efficiency

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