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Application of Wind Energy to Withdraw Groundwater for Irrigation Management

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Abstract: Increases in greenhouse gases emissions have encouraged the replacement of fossil fuels with renewable energy sources. This paper investigates the potential of wind energy as a renewable resource for producing agricultural water in Eghlid city, Iran. The purpose of the optimization model herein considered is to maximize the net benefit from crop production by selecting an optimal cropping pattern. This paper's results demonstrate that wind energy can be efficiently applied to provide irrigation water and optimize cropping patterns. Specifically, the application of wind energy to withdraw irrigation water increases agricultural production benefits in the amount of 1,254 million Rials (US$45,000). **DOI: 10.1061/(ASCE)WR.1943-5452.0000706.** *© 2016 American Society of Civil Engineers.*

Author keywords: Windmill; Optimization; Crop pattern; Wind energy; Groundwater.

Introduction

Many techniques have been developed and applied in water resources systems, such as reservoir operation (Bozorg-Haddad et al. 2008b, c, 2009, 2011a; Afshar et al. 2010; Fallah-Mehdipour et al. 2011b, 2012), cultivation rules (Moradi-Jalal et al. 2007; Noory et al. 2012), pumping scheduling (Bozorg-Haddad and Mariño 2007; Rasoulzadeh-Gharibdousti et al. 2011; Bozorg-Haddad et al. 2011b), water distribution networks (Bozorg-Haddad et al. 2008a; Soltanjalili et al. 2011; Fallah-Mehdipour et al. 2011a; Seifollahi-Aghmiuni et al. 2011; Ghajarnia et al. 2011; Sabbaghpour et al. 2012), operation of aquifer systems (Bozorg-Haddad and Mariño 2011), and site selection of infrastructures (Karimi-Hosseini et al. 2011). None of these works dealt with the application of wind energy to withdraw groundwater for irrigation management.

Wind energy has been used since ancient times. This energy was commonly used to provide mechanical power for pumping water and grinding grain until the early twentieth century. The emergence of fossil fuels was synchronous with the decline of wind as a power source for the remainder of the twentieth century. Increasing concerns with the adverse impacts of fossil fuels on the environment has encouraged the development of clean, renewable energy sources, wind among them, over the last decade. Although wind energy was used for elementary applications in the past, it is currently a clean resource for electricity production or energy supply in agriculture and other activities in rural areas and has not been given due consideration in previous water resources investigations (Ashofteh et al. 2013, 2015a, b, c; Beygi et al. 2014; Bozorg-Haddad et al. 2013, 2014, 2015a, b; Bolouri-Yazdeli et al. 2014; Fallah-Mehdipour et al. 2013; Orouji et al. 2013, 2014; Shokri et al. 2013, 2014; Soltanjalili et al. 2013).

Research on applications of wind energy to hydraulics and water resources has thrived over the last decade. That research can be classified into two general categories: (1) feasibility of wind projects and (2) development of wind energy tools and turbines. Several pertinent studies are briefly reviewed next.

Regarding the feasibility of wind projects, Parikh and Bhattacharya (1984) discussed the possibility of using windmills for lifting irrigation water. For the wind velocity pattern considered in their study, it was found that 1.214 ha of wheat and mustard could be irrigated during winter if the daytime pumped volume of water is used for irrigation. If nighttime discharge is also utilized the minimum cropping area could be 1.94 ha. Panda et al. (1998) determined the investment per unit amount of water supplied and the levels of daily irrigation demand satisfied by the most economic windmill irrigation system at various levels of risk. Mohsen and Akash (1998) determined locations with high, medium, and low potential for water pumping with wind power in Jordan. According to the results of Al Suleimani and Rao (2000), the wind resources in remote areas of Oman are sufficient for extracting groundwater using a wind-powered, electric, water-pumping system. Lu et al. (2002) simulated the annual generated power from wind turbines in the Hong Kong islands. Bakos (2002) investigated inexpensive electricity generation using a wind–hydropower system and confirmed the feasibility of this method. Buenoa and Carta (2006) proposed a wind-powered pumped hydro-storage system installation in the Canary Islands. Kumar and Kandpal (2007) estimated and compared the utilization potential of different renewable energy–based pumps for irrigation water pumping in India. Results showed that solar photovoltaic (SPV) pumps have the maximum utilization potential in India, followed by windmill pumps. Renewable energy technologies (RETs) for irrigation water pumping were evaluated financially by Purohit (2007). Keyhani et al. (2010) studied the wind energy potential in Tehran, Iran, and explained that although

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the wind energy resources in this region are not suitable for electricity generation at a large scale, it can be used for nongrid electrical and mechanical applications such as water pumping. Guerrero et al. (2010) investigated alternative energy sources for irrigation systems and noted that conversion from natural gas irrigation systems to electric systems is more feasible than adoption of hybrid ones. According to Cloutier and Rowley (2011), during a 20-year life of a water pumping project, the cost of pumping with fossil fuels exceeds the cost of providing the same service using renewable energy. Therefore, replacing fossil fuels with wind renewable energy for water pumping would be economical in that instance. Paul et al. (2012) established that the wind speed in the southern part of Nigeria falls into the Class 1 wind resource category. Thus, it is suitable for electricity generation at small scales. Lashin and Shata (2012) evaluated the wind speed data of Port Said in Egypt and stated that in this area wind energy can be used for electricity generation in wind farms and for water pumping from springs. Gopal et al. (2013) reviewed articles on renewable energy water pumping systems (REWPSs) and concluded that using renewable energy sources is effective at decreasing the conventional energy consumption and its harmful effects on the environment. Díaz-Méndez et al. (2014) investigated the feasibility of wind pumps technology and concluded that wind pumps usage is not competitive in places connected to the grid. They stated that, in places with no accessibility to the grid, the water elevation is the most effective factor influencing the economic feasibility of wind pump technology. Vick and Almas (2011) mentioned (1) using center pivot irrigation system, (2) using excess wind and solar electricity instead of selling it, and (3) utilizing federal incentives as approaches to achieve an economical irrigation system powered with renewable energy.

Concerning the development of wind energy tools and turbines, Valdés and Raniriharinosy (2001) designed three different types of simple wind pumps for the agricultural and lighting supply in Madagascar. Garcia-Gonzalez et al. (2008) proposed using hydro pumped-storage units to cope with wind speed variability and unpredictability. Zhao et al. (2009) developed an analytical model to investigate the effective factors of wind energy on industry by adding a new component to the Porter's Diamond model. Fripp (2011) introduced a new model for uncertainty estimation in short-term prediction of wind power. Sun et al. (2011) designed an optimum pump for wind water pumping systems that can be used in a wide range of wind speeds. Brahmi and Chaabene (2012) presented an algorithm to investigate the wind potential and calculate the optimum area of wind turbine blades. This algorithm was based on the Weibull distribution. Celik and Kolhe (2013) proposed that artificial neural network (ANN) is the best method for calculating the energy discharge from commercial wind turbine generators.

Many past studies attempted to evaluate the wind potential to generate electricity and select locations to provide power for water pumping. Other studies dealt with turbines, their development, and methods for accurate energy calculations. Although most residential places are connected to the electrical grid, many farms and other relatively isolated productive facilities are distant from residential areas and grid access. Therefore, electricity is not readily available to them. Windmills are simple wind turbines that convert wind energy to mechanical energy that is used to withdraw water from aquifers directly. This energy conversion is direct and no electricity is generated. Windmills are well suited and cost-effective tools for withdrawing groundwater in areas in which access to the electric grid is difficult and expensive. A schematic of a basic windmill is portrayed in Fig. 1.

This study focuses on developing an optimization model to investigate the feasibility of using windmills to withdraw groundwater for agricultural irrigation without electricity production. The extracted groundwater is used for increased agricultural production, which determines the benefit of wind power production in this application. These turbines are available in different wheel sizes. Although the wind speed is not stable in all seasons, using wind energy to supply agricultural water demand can be made feasible by optimizing the crop pattern in any region. Therefore, this paper presents an optimization model with which to determine the optimal parameters that govern wind energy application to irrigation. Due to the random nature of the wind, it is customary to include a reservoir to store volumes of water in excess of the required irrigation amount when high wind speeds prevail. This excess water can be used during periods with high water demand or when there is low wind speed. It is essential to investigate conditions in wind energy application areas and cultivate crops that meet the following requirements: (1) their water demand and the times of irrigation must be compatible with windy conditions, when sufficient groundwater can be extracted from aquifers; and (2) the net benefit from their cultivation must exceed that which might accrue from cultivating alternate crops. This study assesses the feasibility of wind energy use in the Eghlid region of Iran, and determines the optimal cropping pattern compatible with the local wind energy resources. The latter task was accomplished with an optimization model that was solved using the software *LINGO 11*.

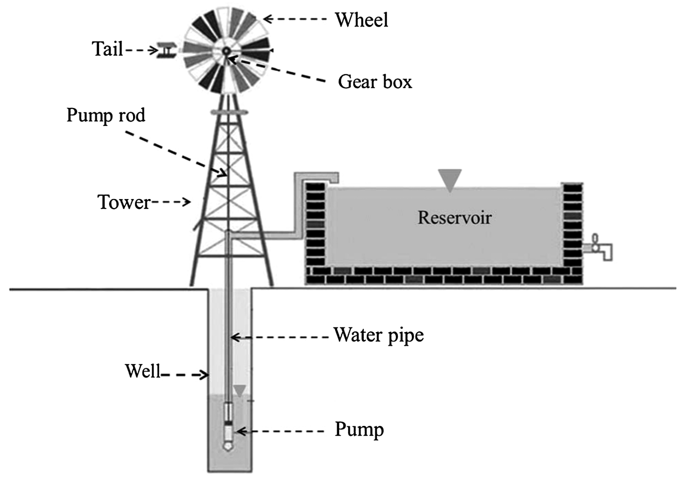

Fig. 1. Schematic of a windmill and its components

Methods

The local output energy of each turbine and corresponding pumped water must be determined prior to using wind energy for agricultural purposes. Thereafter, the number of turbines, the types of crops, the area devoted to each crop, the reservoir storage capacity, and the releases from each reservoir are calculated with the aim of achieving the largest annual net benefit. In this regard, this paper considers the objective function of maximizing the annual net benefit from agriculture

$$\max \text{ANB} \tag{1}$$

where ANB = annual net benefit. The decision variables of this model are (1) the number and type of windmills (size of wheel diameter), (2) reservoir capacity, and (3) area devoted to each crop. In order to calculate the ANB, a simulation model must be developed that includes the following tasks: (1) calculation of the extractable wind power; (2) converting the output power to amount of withdrawn groundwater; (3) reservoir design and water balance; (4) determination of the cropping pattern; and (5) optimization of the benefit and costs of agriculture irrigated with water produced with wind energy. The mathematical formulation of the model follows.

Calculation of Extractable Wind Power

The theoretical power generated by a windmill is given by (Jain 2011)

$$P_t = \frac{1}{2}\rho_a A_r v_t^3 \tag{2}$$

where P_t = wind power (W) at time t; ρ_a = air density (kg/m^3), which is approximately 1.2; A_r = area of the wheel (m^2); and v_t = wind speed (m/s) at time t. Windmills have a cut-in speed of approximately 2.5 m/s and their cutoff speed is 15 m/s (Isfahan Talash Co., Isfahan, Iran). Consequently, they do not produce power when the wind speed is slower than 2.5 m/s or faster than 15 m/s.

The total theoretical wind power at time t is given by the following equation when there are multiple windmills, each with a specific wheel size and well to produce water for irrigation:

$$\mathrm{TP}_t = \sum_{n=1}^{N} P_{nt} \times \mathrm{Nt}_n \quad \text{for } t = 1, 2, 3, \ldots, T \tag{3}$$

where TP_t = total derived power (W) from all windmills at time t, $t = 1, 2, 3, \ldots, T$; P_{nt} = derived power (W) from a windmill of the nth type ($n = 1, 2, 3, \ldots, N$) at time t, where P_{nt} is given by Eq. (2) applied to a windmill of type n; N = number of available types of windmills (each windmill type has a specific wheel diameter); Nt_n = number of windmills of the nth type; and T = number of time steps, $T = 360$ days in this study. The total number of windmills equals $\mathrm{NW} = \mathrm{Nt}_1 + \mathrm{Nt}_2 + \mathrm{Nt}_3 + \cdots + \mathrm{Nt}_N$.

Converting Wind Power to Pumped Water

Mechanical energy is generated in a windmill to power a well pump that withdraws water when the wind speed permits it. The calculation time step is equal to 1 s in this work. The calculated wind energy is converted to daily quantities for modeling purposes.

The wind energy needed to withdraw groundwater with windmills (E_t, in joules) is calculated by multiplying power and the duration of power production together (Halliday et al. 2010). Therefore

$$E_t = \mathrm{TP}_t \times \eta_t \times t = \gamma_w \times \sum_{k=1}^{\mathrm{NW}} Q_{tk} \times \mathrm{HT}_{tk} \quad k = 1, 2, \ldots, \mathrm{NW} \tag{4}$$

where t = time interval (s); η_t = total efficiency of the windmill in interval t; γ_w = unit weight of water (9.81 N/m^3); NW = number of windmills; Q_{tk} = pumping rate (m^3/s) in interval t in groundwater well k; and HT_{tk} = height of water in groundwater well k (m) corresponding to the pumping rate at time t. The height of water equals the sum of the water depth in a well below ground surface (HG_{tk}) plus the water height in a reservoir above the ground surface (HR_{tk}, Fig. 1), therefore

$$\mathrm{HT}_{tk} = \mathrm{HG}_{tk} + \mathrm{HR}_{tk} \tag{5}$$

where HG_{tk} = depth of water in well k (m) in interval t; and HR_{tk} = height of water in storage reservoir by well (and windmill) k (m) in interval t. Because there is one reservoir for all wells, HR_{tk} is the same for all of the wells, and therefore it is denoted by HR_t. The changes in well water depth are negligible due to the low groundwater discharge rate. Therefore, HG_{tk} is assumed to be constant and can be denoted by HG. Therefore, Eq. (5) is rewritten as follows:

$$\mathrm{HT}_t = \mathrm{HG} + \mathrm{HR}_t \tag{6}$$

Also Eq. (4) is rewritten in a simpler form as follows:

$$E_t = \mathrm{TP}_t \times \eta_t \times t = \gamma_w \times \mathrm{HT}_t \times \mathrm{TQ}_t \quad k = 1, 2, \ldots, \mathrm{NW} \tag{7}$$

where TQ_t = total pumping rate from all wells in interval t

$$\mathrm{TQ}_t = \sum_{k=1}^{\mathrm{NW}} Q_{tk} \quad k = 1, 2, \ldots, \mathrm{NW} \tag{8}$$

The total windmill efficiency is influenced by two efficiencies: (1) the efficiency of converting wind energy to mechanical energy and (2) the mechanical efficiency of the windmill. Based on the Betz law (Betz 1926), the largest amount of obtainable energy from windmills in an ideal condition equals 59%. Therefore, the energy conversion efficiency equals 59%. The mechanical efficiency of windmills varies with wind speed and is calculated by multiplying the windmill's components' efficiencies

$$\eta_t = \eta(M)_t \times \eta(E) \tag{9}$$

$$\eta(M)_t = \eta w_t \times \eta b_t \times \eta g_t \times \eta p_t \times \eta r_t \tag{10}$$

$$\eta(M)_t = \left\{\begin{array}{lll} 0.25 & \text{if} & 2.5 \le v_t < 4.5 \\ 0.50 & \text{if} & 4.5 \le v_t < 8 \\ 1 & \text{if} & 8 \le v_t < 15 \end{array}\right\} \tag{11}$$

where in Eq. (9), η_t = efficiency of the windmill with respect to wind speed at time t; $\eta(M)_t$ = mechanical windmill efficiency at time t; and $\eta(E)$ = energy conversion efficiency. In Eq. (10), ηw_t = wheel efficiency at time t; ηb_t = bearing efficiency at time t; ηg_t = gearing efficiency at time t; ηp_t = pump efficiency at time t; ηr_t = water pump efficiency at time t; and v_t = wind speed at time t (m/s).

Reservoir Design and Water Balance

The equations related to reservoir design and water storage simulation are written for discrete time steps. The time index is changed to p in this section. The pertinent equations are (assuming one reservoir is supplied by one well pumped with one windmill)

$$S_{p+1} = S_p + Q'_p + \mathrm{Pr}_p - \mathrm{Loss}_p - \mathrm{TR}_p - \mathrm{Sp}_p \tag{12}$$

$$Q'_p = \mathrm{TQ}_t \times \mathrm{pl} \times 86{,}400 \tag{13}$$

where in Eq. (12), S_p = volume of water stored in a reservoir in period p (m^3); S_{p+1} = volume of water stored in a reservoir in period $p+1$ (m^3); Q'_p = volume of groundwater withdrawn in period p (m^3) [which is calculated with Eq. (13)]; Pr_p = volume of rainfall onto a reservoir in period p (m^3); Loss_p = evaporated volume of water in period p (m^3); TR_p = total water released from a reservoir in period p (m^3); Sp_p = spill from the reservoir in period p; and pl = length of periods (days), in which each period is 10 days long, and 86,400 is the number of seconds in 1 day. The irrigation intervals in this study are 10 days long for the selected irrigation method and crops. Because the reservoir area is limited and evaporation and precipitation depth have the same average amounts during the year, yearly average depth of rainfall minus evaporation is negligible. Therefore, the water balance in a reservoir is primarily governed by the volume of withdrawn groundwater. Therefore, Eq. (12) is rewritten as follows:

$$S_{p+1} = S_p + Q'_p - \mathrm{TR}_p - \mathrm{Sp}_p \tag{14}$$

The shape of the reservoir is considered to be cubic or cylindrical. Hence, its capacity is

$$S_{\max} = \mathrm{AR} \times H_{\max} \tag{15}$$

where in Eq. (15) $S_{\max}$ = reservoir capacity (m^3); AR = reservoir area (m^2); and $H_{\max}$ = reservoir height (m).

The data received from the Iran Meteorological Organization (2014) are recorded as an average wind speed over each 10 min. This paper's model uses daily averaged data. The wind power was determined using 10-min data and then the daily average power was calculated. Therefore, the determined reservoir capacity is multiplied by an adjustment coefficient to ensure a capacity to store excess water produced during the periods of groundwater withdrawal. This coefficient equals

$$\text{Adjustment coefficient} = \frac{\mathrm{COV}_{10\ \min}}{\mathrm{COV}_{\mathrm{daily}}} \tag{16}$$

where $\mathrm{COV}_{10\ \min}$ = coefficient of variation (COV) of 10-min wind speed data; and $\mathrm{COV}_{\mathrm{daily}}$ = COV of the daily averaged wind speed data.

Determination of the Cropping Pattern

Viable crops are selected for optimization of the cropping pattern. The net irrigation demand of each crop at different times of the growing season is specified. The pumped water satisfies the crops' irrigation demand. Therefore

$$\mathrm{TD}_p = \sum_{j=1}^{m} D_{pj} \times A_j, \quad \text{for } p = 1, 2, 3, \ldots, p_{\mathrm{no}} \tag{17}$$

where TD_p = total net irrigation demand by all cultivated crops in period p (m^3); D_{pj} = net irrigation demand of the jth crop in period p (m^3/ha); A_j = area devoted to the jth crop ($1\ \mathrm{ha} = 10^4\ \mathrm{m}^2$); m = number of crops; and p_{no} = number of irrigation periods. The water released from the reservoir in each period p (TR_p) is equal to or less than the total net irrigation demand in the same period (TD_p)

$$\mathrm{TR}_p \leq \mathrm{TD}_p \tag{18}$$

The wind speed may be too low on some days of the year. Therefore, there is not sufficient water in all irrigation periods. The effect of water deficit on crop production must, therefore, be considered. The decrease in crop production is estimated using the following equation (Allen et al. 1998):

$$\frac{Y_j}{Y_{\max j}} = 1 - ky \cdot \left(1 - \frac{\mathrm{Re}_j}{\mathrm{De}_j}\right) \tag{19}$$

where $Y_{\max_j}$ = maximum yield of the jth crop with no water stress; De_j = irrigation demand; Y_j = yield when there is water stress ($Y_j < Y_{\max_j}$); Re_j = irrigation supply for the jth crop; and ky = yield response factor representing the effect of a reduction in irrigation on yield losses. The coefficients ky for crops are found in the Food and Agricultural Organization's (FAO's) publication No. 56 (Allen et al. 1998). The water devoted to the jth crop in period p, R_{pj}, is given by

$$\mathrm{Re}_j = \frac{\sum_{p=1}^{p_{\mathrm{no}}} R_{pj}}{p_{\mathrm{no}}}, \quad \text{for } j = 1, 2, 3, \ldots, m \tag{20}$$

where R_{pj} = water devoted to the jth crop in period p, which will be determined as part of the crop pattern optimization.

Benefit and Costs

Costs determine the reservoir design and the number of windmills. Costs are divided into two main categories: (1) capital costs and (2) uniform annual costs. The uniform annual costs consist of operation and maintenance (O&M) costs of windmills, the O&M costs of the reservoir, and cultivating and harvesting costs. The O&M cost is equal to a fraction of the total capital cost. The benefit gained from selling agricultural yields is calculated annually. All the project costs are converted to an annual uniform cost stream for the purpose of comparing them. The latter is the sum of the O&M annualized cost plus the stream of costs arising from annualizing the total capital cost over the life of the project using a suitable interest or discount rate. Present values are converted to annualized values using the following equations:

$$\mathrm{CRF} = \frac{i \times (1+i)^{np}}{(1+i)^{np} - 1} \tag{21}$$

$$\mathrm{PMT} = \mathrm{NPV} \times \mathrm{CRF} \tag{22}$$

$$\mathrm{AC} = [\mathrm{CRF} \times (\mathrm{CT} + \mathrm{CR} + \mathrm{CE})] + \mathrm{CC} + \mathrm{COM} \tag{23}$$

where in Eq. (21), CRF = capital recovery factor; i = annual interest rate ($i = 0.2$); and np = life of the project (year). In Eq. (22), PMT = annual uniform payment, and NPV = net present value (generic). In Eq. (23), AC = total annual cost, CT = cost of buying windmills and accessories, CR = reservoir construction costs, CE = farm construction costs, CC = annual cultivation and harvesting costs, and COM = O&M costs of the reservoir and windmills. The O&M costs of the windmills are low. Thus, the O&M costs are made equal to 0.01 (1%) of the annual capital costs.

The capital costs (incurred during project construction) are converted to annual uniform costs using Eqs. (22) and (23). The total windmill cost (CT) equals the cost of each windmill type times the number of each windmill type (Nt_n)

$$\mathrm{CT} = \sum_{n=1}^{N} (\mathrm{CT}_n \times \mathrm{Nt}_n) \tag{24}$$

where CT_n = cost of the nth windmill type.

If electricity is used instead of wind energy for pumping groundwater, the corresponding costs are calculated with the following equation:

$$\mathrm{PC} = E \times \mathrm{EC} \tag{25}$$

where PC = electricity supply cost; E = necessary energy for pumping water (kWh); and EC = unit cost of supplying 1 kWh from the electric grid.

Cultivation and harvesting costs are calculated by summing the costs for each crop, where the cost of a crop equals the unit (per hectare) cost times the cultivated area (in hectares). The revenue from selling crop products is given by

$$\mathrm{AB} = \sum_{j=1}^{m} (A_j \times Y_j \times \mathrm{Pc}_j) \tag{26}$$

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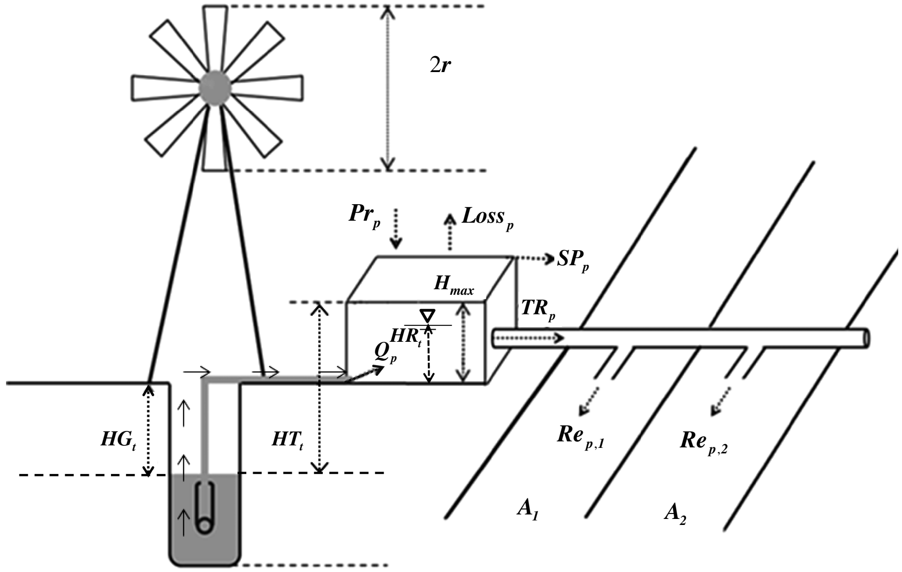

Fig. 2. Schematic of the optimization model (it is assumed that the optimization results correspond to one windmill and two different crops)

where AB = revenue from selling crop products in each year; A_j = devoted area to the jth crop; Y_j = jth crop's yield; and Pc_j = jth product's unit price per ton (1 ton = 1,000 kg).

The annual benefit function and the ratio of annual revenue to the annual cost are equal to

$$\mathrm{ANB} = \mathrm{AB} - \mathrm{AC} \tag{27}$$

$$\mathrm{BC} = \frac{\mathrm{AB}}{\mathrm{AC}} \tag{28}$$

where ANB = annual benefit; and BC = ratio of annual revenue to the annual cost (the annual benefit to cost ratio).

The model's constraints are listed as follows:

- The volume of water in a reservoir is equal to or less than the reservoir's capacity

$$S_p \leq S_{\max} \tag{29}$$

- The volume of water in a reservoir in the final period of the project is equal to or greater than its volume in the first period

$$S_{\text{final}} \geq S_1 \tag{30}$$

- The water release from the reservoir is equal to or less than the crops' irrigation demand in each period

$$\mathrm{TR}_p \leq \mathrm{TD}_p \tag{31}$$

- The ratio of the water devoted to each crop to its irrigation demand is equal to or larger than 0.4 in all periods

$$\frac{R_{pj}}{D_{pj}} \geq 0.4 \tag{32}$$

A schematic of the proposed model (considering two crops and one windmill) is given in Fig. 2.

Case Study

Eghlid city is one of the windiest places of Fars Province in Iran. According to the meteorological reports the maximum wind speed in this city is approximately 160 km/h. The area of the city is equal to 5,956 km^2. The meteorological and agricultural data for the Eghlid city region are presented in the following.

Wind Data

The 10-min wind speed data at 10-m height for Eghlid city were obtained from the Iran Meteorological Organization for the years 2012–2013 (http://www.irimo.ir/eng/index.php). The extractable power was calculated from these data, removing periods of useless wind speeds (too low or too high). All calculations are reported as daily averaged data. Figs. 3 and 4 display the daily average wind speed and the extractable power from windmills, respectively.

Groundwater

The extractable wind energy was used to pump water in this study. The depth to groundwater in a well is a governing factor in determining the production rate from a well [Eq. (4)]. According to the available data, the ground water depth ranges between 50 and 70 m

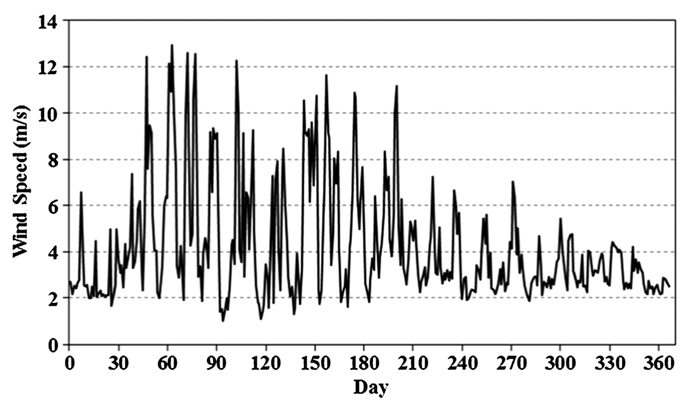

Fig. 3. Daily average wind speed in Eghlid, Iran

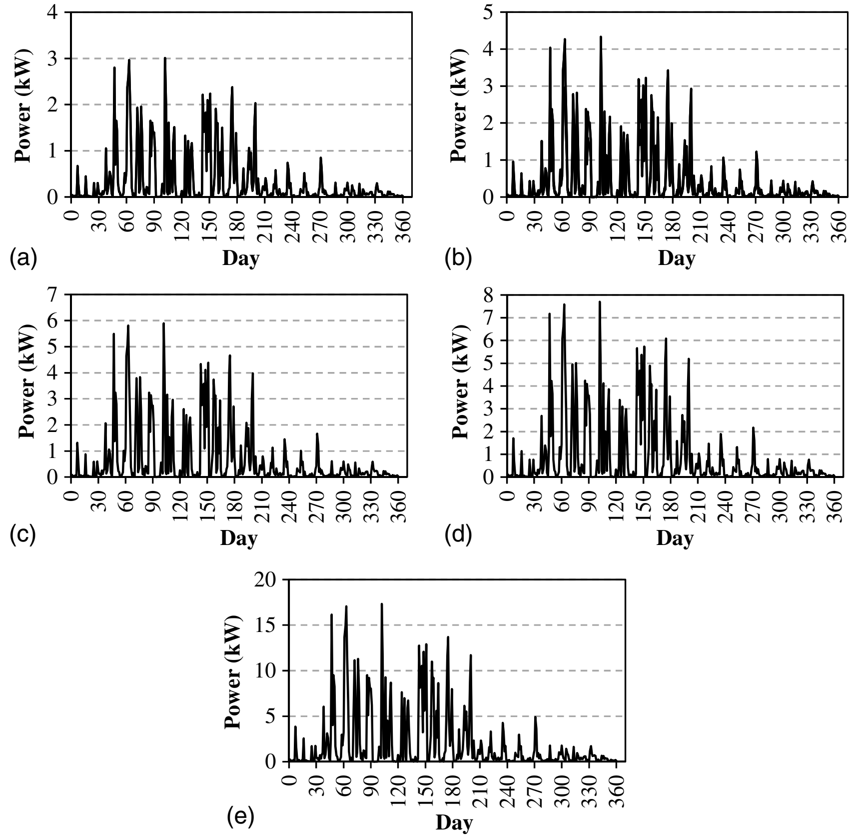

Fig. 4. Extractable power by (a) 2.44 m (8 ft); (b) 3.05 m (10 ft); (c) 3.66 m (12 ft); (d) 4.27 m (14 ft); (e) 6.10 m (20 ft) windmills in Eghlid, Iran

(below ground surface) in this region (Fars Water Organization 2013; Fars Meteorological Bureau 2014). Changes in the depth of groundwater are negligible due to low pumping rates. The well-water depth is assumed equal to 60 m in this study.

Agricultural Products

Several crops can be cultivated in Eghlid city, which were divided into two main groups: (1) field crops and (2) horticultural drops. Field crops are lentils, peas, beans, potatoes, cucumbers, sunflowers, corn, sugar beets, wheat, barley, and hay. Horticultural crops are pomegranates, plums, almonds, walnuts, apples, pears, cherries, and cranberries. Eleven of these crops were selected in this study regarding their quantity and time of irrigation demand. These were beans, lentils, peas, cucumbers, beets, potatoes, wheat, barley, walnuts, almonds, and apples. The farmed area was assumed to be 20 ha.

The net irrigation requirement, cultivation costs, and benefits from crops were key factors in choosing the crops. The net irrigation requirement of the chosen crops was determined using the Iranian software *NETWAT*. Table 1 shows the depth of irrigation demand of each crop obtained from the software in millimeters. The main irrigation method in this region is furrow irrigation, and thus it was selected for in this study. The water efficiency for a well-designed furrow system is estimated to be 70%. The water efficiency is defined as the percentage of the water applied to a crop that is used by the crop. The production cost and the revenue for the chosen crops in Iran are listed in Table 2.

The *ky* coefficient needed to calculate the production decrease due to water deficits were obtained from FAO publication No.56 (Allen et al. 1998) and are listed in Table 3.

Available Windmill Specifications

The windmills used in this study are available in different wheel sizes. The windmill prices were obtained from the Iranian Isfahan Talash Co. and their maximum calculated discharges (using 2012–2013 wind speed data) in Eghlid city are listed in Table 4. The windmills can lift groundwater to the surface given the depth to groundwater in the Eghlid city region.

Defined Modeling Scenarios

Three modeling scenarios were defined in this study:

1. Design the optimal reservoir capacity, calculate its water release in each period, and determine the optimal number of windmills and their wheel diameter for a given cropping pattern. The type of crops and their cultivated areas are input data for the model. The irrigation demand is specified and the model determines the number of windmills and their wheel diameters to maximize the benefit achieved from the project. The reservoir capacity and the number of windmills and their wheel diameters are the model's decision variables. The changes in volume of water in the reservoir, the volume of water spilled from the reservoir, and the cost and revenues are the state variables of the optimization model.
2. Determine the optimal cropping pattern, reservoir capacity, the water released from the reservoir in each period, and the number of turbines and their wheel diameters such that 70% of the products are from field crops and the remaining 30% are devoted to horticultural crops. The dominant crops produced in the region of study and their net irrigation demands are inputs to the model. The decision variables are the area cultivated with each crop, the number of windmills

Table 1. Net Irrigation Demand for Chosen Crops in 10-Day Periods of Each Month

		Net irrigation demand (mm)										
Month	10-day period number	Beans	Lentils	Peas	Cucumbers	Sugar beets	Potatoes	Wheat	Barley	Walnuts	Almonds	Apples
January	1	0	0	0	0	0	0	4	4	0	0	0
	2	0	0	0	0	0	0	10	11	0	0	0
	3	0	0	0	0	0	0	13	14	0	0	0
February	1	0	0	0	0	0	0	18	19	0	0	0
	2	0	0	0	0	0	0	14	15	0	0	0
	3	0	5	5	0	0	0	21	23	0	0	0
March	1	0	5	5	0	0	0	23	24	0	0	0
	2	0	10	7	0	0	0	31	31	0	7	0
	3	0	20	14	0	0	0	36	36	11	7	9
April	1	0	37	25	0	0	0	43	43	12	9	9
	2	0	52	43	17	0	19	52	52	21	27	19
	3	18	56	54	30	0	23	56	48	25	38	31
May	1	21	66	66	58	19	23	59	39	35	58	57
	2	33	64	66	57	18	34	40	21	40	60	59
	3	57	54	68	59	19	62	22	0	47	62	61
June	1	78	43	73	67	30	78	0	0	59	70	69
	2	74	25	55	60	41	79	0	0	62	67	66
	3	73	0	54	55	53	88	0	0	68	66	65
July	1	78	0	27	54	71	79	0	0	79	71	70
	2	53	0	0	0	73	77	0	0	71	62	62
	3	29	0	0	0	72	76	0	0	69	61	60
August	1	0	0	0	0	73	67	0	0	70	61	61
	2	0	0	0	0	65	61	0	0	61	51	55
	3	0	0	0	0	59	53	0	0	57	43	50
September	1	0	0	0	0	61	34	0	0	59	41	51
	2	0	0	0	0	48	0	0	0	44	29	42
	3	0	0	0	0	38	0	0	0	35	24	35
October	1	0	0	0	0	28	0	0	0	27	0	27
	2	0	0	0	0	19	0	7	7	19	0	20
	3	0	0	0	0	14	0	6	6	15	0	16
November	1	0	0	0	0	0	0	5	5	0	0	0
	2	0	0	0	0	0	0	5	5	0	0	0
	3	0	0	0	0	0	0	5	5	0	0	0
December	1	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	1	1	0	0	0
	3	0	0	0	0	0	0	8	8	0	0	0

Table 2. Annual Cost of Production and Revenue From Each Crop per Hectare in Million Iranian Rials in 2012

Crops	Beans	Lentils	Peas	Cucumbers	Sugar beets	Potatoes	Wheat	Barley	Walnuts	Almonds	Apples
Cost per hectare	9	9	9	15	20	14	4	3	9	9	16
Revenue per hectare	20	20	20	28	74	28	13	9	28	24	80

Note: 1 million rials = US$36.

and their wheel diameters, and the reservoir capacity. The decision variables are determined to maximize the benefit achieved from the project. The state variables are changes in water volume in a reservoir, water released from the reservoir, volume of water spilled from the reservoir, and costs and revenues.

3. Determine the optimal cropping pattern, reservoir capacity, and the number of windmills and their wheel diameters without any limitation on crop pattern. The decision variables are the types of crops and their cultivated area, the number of windmills and their wheel diameters, and the reservoir capacity. The state variables are irrigation demand of each crop (depends on cultivated area), changes in water volume in the reservoir, water volume pumped into the reservoir (from windmill selection), water released from the reservoir (due to the crop pattern selection), and costs and revenues.

Table 5 lists the three modeling scenarios and their decision and state variables.

In the second and third scenarios the cropping pattern is chosen taking into account the irrigation demand and its compatibility with the available wind energy. The choice of cropping pattern produces the largest possible benefit.

Table 3. *ky* Coefficient for Each Crop

Crops	*ky*
Beans	1.15
Lentils	1.15
Peas	1.15
Cucumbers	1
Sugar beets	1.2
Potatoes	1.1
Wheat	1.15
Barley	1
Walnuts	1.1
Almonds	1.5
Apples	0.57

Note: Raw data from Allen et al. (1998) were used to calculate the data provided in the table.

Table 4. Specifications of Windmills Manufactured by the Isfahan Talash Co in 2012 prices

Windmill [m (ft)]	Wheel diameter (m)	Price (million Iranian rials)	Maximum water discharge in Eghlid (m^3/h)
2.44 (8)	2.5	37	28
3.05 (10)	3	42.5	40
3.66 (12)	3.5	61	54
4.27 (14)	4	73	71
6.10 (20)	6	106.3	159

Note: 1 million Rials = US$ 36.

In the analysis of the three scenarios with the proposed model, two additional considerations were made to calculate project benefits and to assess the possible advantage of using wind energy. The first consideration concerns the calculation of the project's annual benefit when considering the possibility of producing electricity with the windmills outfitted with a generator. Wind energy may be used to drive well pumps. In fact, this is the reason for which water-pumping windmills are designed. The use of renewable wind energy avoids the emissions of greenhouse gases and reduces environmental pollution. The Iranian government guarantees a relatively high price for renewable electricity to encourage investors to construct renewable power plants. Therefore, energy that is produced by wind-powered agricultural projects can be sold at a relatively high price, and grid electricity can be bought at a relatively low price to withdraw groundwater for irrigation. This means that a benefit accrues that is proportional the price difference between the renewable electricity sold (sold at 4,400 rials/kWh = US$0.1584/kWh) and the grid electricity (bought at 400 rials/kWh = US$0.01440 kWh). The second consideration was about the excess power produced with windmills during high-wind conditions, when water is pumped in excess of irrigation requirements. The energy produced during high-wind conditions in excess of that needed to support crops can be sold as renewable electricity, and that was counted as a project benefit.

Results

The COVs were calculated for the available wind speed data to determine the adjustment coefficient for the reservoir. The adjustment coefficient for the Eghlid region's wind speed is equal to 1.33.

Table 6 shows the calculated optimal decision variables and the cost and benefit associated with them in the project. It is seen in Table 6 that by decreasing the model's constraints the project annual net benefit increased significantly. Also, selecting a proper cropping pattern effectively increases the project benefit. It is seen in Table 6 that with the same windmills, and therefore with the same

Table 5. Modeling Scenarios, Decision Variables, and State Variables

Variable	Scenario 1	Scenario 2	Scenario 3
Decision variables	Reservoir capacity Number of windmills Diameter of wheels	Area of each crop Number of windmills Diameter of wheels Reservoir capacity	Types of crops Area of each crop Number of windmills Wheel diameters Reservoir capacity
State variables	Change in reservoir storage Water spilled Water released Cost and revenue	Change in reservoir storage Water released Water spilled Cost and revenue	Irrigation demand for each crop Change in reservoir storage Water pumped Water released Water spilled Cost and revenue

Table 6. Optimal Decision Variables and the Cost and Benefit in Millions of Iranian Rials Corresponding to the Defined Scenarios

Scenario number	Crop pattern constraint	Crop pattern	Windmill type and its number	Produced energy (kWh)	Optimum reservoir capacity (m^3)	Adjusted reservoir capacity (m^3)	Annual net benefit (ANB)	BC ratio
1	Specified pattern	Wheat (9 ha) Barley (7 ha) Apple (2 ha) Walnut (2 ha)	Five 6.10-m (20-ft) wheels	82,590	828	1,100	−130	0.74
2	Optimized (70% farm products)	Sugar beet (14 ha) Apple (6 ha)	15 6.10-m (20-ft) wheels	247,765	3,600	4,790	263	1.25
3	Optimized (no constraint)	Apple (20 ha)	15 6.10-m (20-ft) wheels	247,765	2,870	3,820	480	1.48

Note: 1 million rials = US$36.

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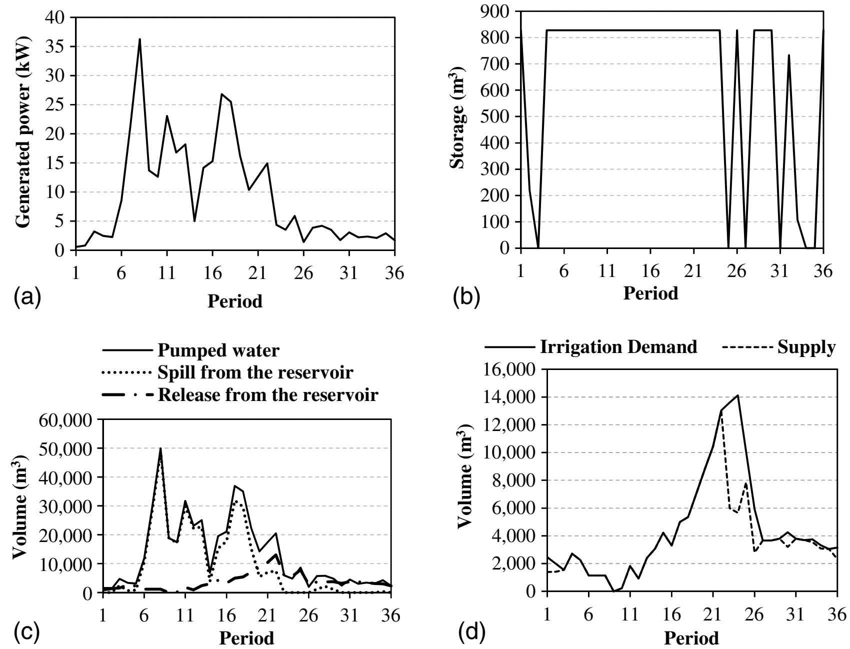

Fig. 5. Changes in (a) generated power; (b) water stored in the reservoir; (c) pumped water (incoming water to the reservoir) and spilled and released water from the reservoir; (d) water supply corresponding to the first scenario

energy input, the net benefit is approximately 1.8 times larger by omitting constraints and choosing the optimal cropping pattern with Scenario 3 than that obtained with Scenario 2. The model prefers windmills with the largest energy generation given that windmill prices do not differ substantially. In other words, the benefit of using the most capable windmills compensates for their higher price. The cropping pattern calculated for a project corresponding to the first scenario leads to a negative benefit (it is not affordable). Changes in power generation, water storage in the reservoir, the water pumped into the reservoir, spill and release from the reservoir, and the irrigation demand and supply are shown in Figs. 5 and 7 for the three considered scenarios.

It is seen in Figs. 5–7 that the reservoir capacity is very low in comparison with the incoming water and most of the water flows out as spill from the reservoir. It is concluded from this that the reservoir cost is high in comparison with the turbine price and the project's benefit. Therefore, the model prefers more windmills to pump sufficient groundwater during low wind speeds, rather than

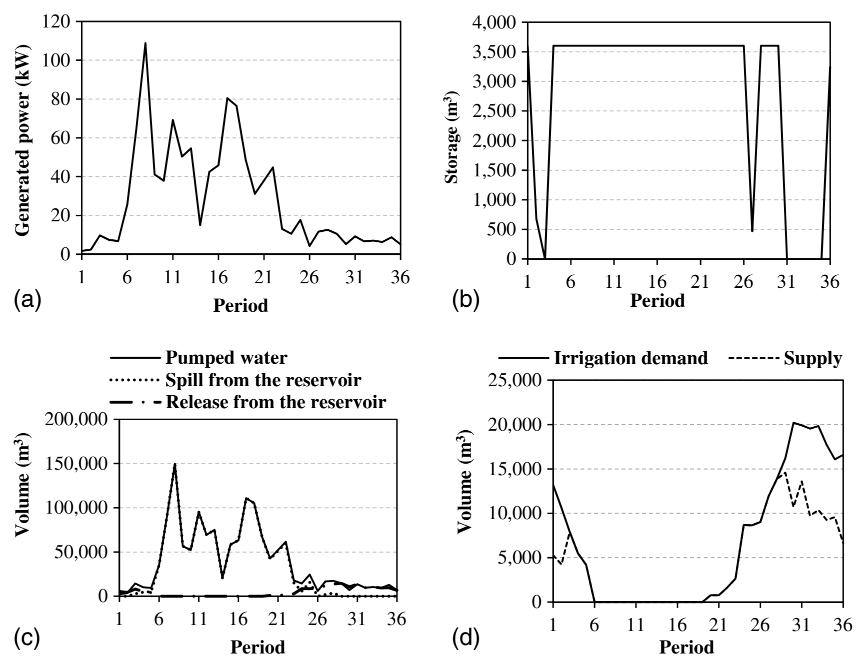

Fig. 6. Changes in (a) generated power; (b) water stored in the reservoir; (c) pumped water (incoming water to the reservoir) and spilled and released water from the reservoir; (d) water supply corresponding to the second scenario

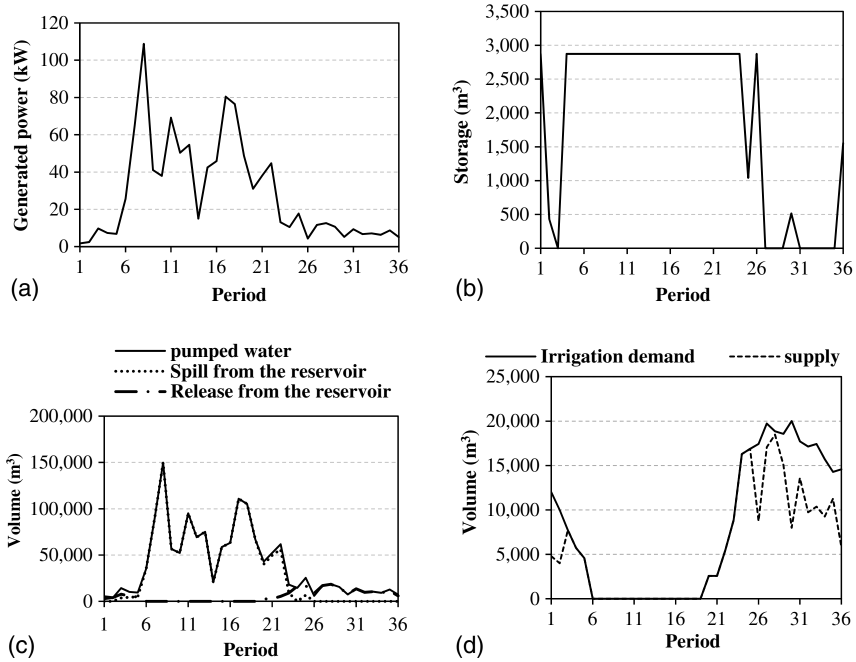

Fig. 7. Changes in (a) generated power; (b) water stored in the reservoir; (c) pumped water (incoming water to the reservoir) and spilled and released water from the reservoir; (d) water supply corresponding to the third scenario

Table 7. Net Benefit in Millions of Iranian Rials and Benefit to Cost Ratio for Defined States of Each of the Three Scenarios with Four Optional Uses of Renewable Energy

	Option 1		Option 2		Option 3		Option 4	
Scenario	Net benefit	BC ratio	Net benefit	BC ratio	Net benefit	BC ratio	Net benefit	BC ratio
1	−136	0.74	150	1.64	194.35	1.38	267.8	1.52
2	263.5	1.25	206.6	1.18	1,255	2.17	1,524	2.43
3	480	1.48	698.26	1.9	1,471	2.48	1,734	2.74

Note: 1 million rials = US$36.

designing a large reservoir to store excess water and use it during low wind speeds. With the former design, a large volume of water would be pumped and spilled without being used during high-speed winds, which is wasteful. Such wasteful spills can be mitigated using two approaches. In the first approach, the excess water can be used to satisfy other functions such as aquaculture, shrimp farming, and livestock water supply. Excess water used to meet these functions produces benefits for a project when there is excess wind power and groundwater extracted during high-speed winds. In the second approach water pumping is controlled. That is, water withdrawal is made compatible with the irrigation demand, and the excess energy is converted to electricity by adding a generator to the windmill and sold. This option is not expensive and the project costs would be slightly larger. The renewable electricity generated in such a fashion was calculated for the three scenarios in one year. The renewable electricity has a price of 4,400 Iranian rials for each kWh, which generates a revenue stream to the project's benefits. Therefore, in addition to the benefits from agricultural produce, the benefit of electricity generation is allocated to the project. In order to compare these two different approaches, the project's benefit was calculated with four options:

1. Use wind energy to pump water.
2. Use grid electricity (which is allocated to the farmers and gardeners by the government and costs 400 Iranian rials for each kWh) for pumping water.
3. Consider relative prices of renewable electricity and agricultural grid electricity. This means using wind to generate the energy required for groundwater pumping. Because using renewable energy resources avoids greenhouse gas emissions and reduces environmental pollution, the Iranian government allocates a higher price for buying renewable-powered electricity to motivate investors to construct renewable power plants. If one sells the energy that is produced by the wind-powered agricultural projects and buys grid electricity to supply the pumping energy, a benefit accrues that is proportional to the difference between the prices of the renewable electricity (4,400 rials per kWh) and the agricultural grid electricity (400 rials per kWh).
4. Consider the value of excess renewable energy generation. This means calculating the revenue generated by the excess renewable energy generated during high-speed wind conditions and adding it to the agricultural benefit of the project.

Results of these applications of these four options for three defined scenarios are listed in Table 7.

The results indicate that using wind energy to supply pumping energy demand for the first scenario results in negative benefit (a disadvantage). By considering the renewable energy advantages, its benefit increases significantly. Using agricultural grid electricity results in larger benefit with Scenario 1. However, using wind energy to supply pumping energy demand in remote places that do not have any electricity facilities can be useful in the first scenario.

According to this paper's results, by considering the benefits of using renewable energy, using wind energy for groundwater pumping would be more beneficial than using grid electricity for this same purpose.

Discussion and Conclusion

Using wind energy to supply irrigation water for crop production was analyzed in this study. The optimal cropping pattern and reservoir capacity were determined, and the benefit of using wind energy to pump groundwater yielded optimal decision variables for three different scenarios and four optional uses of energy. The model's results indicate that the annual net benefit that accrues when using optimal decision variables is approximately 480 million Iranian rials (1 million rials = US$36), and it can be increased to 1,734 million rials by using renewable energy resources. Although constructing a larger reservoir can store and regulate large volumes of water, it would be more expensive than installing more windmills to pump groundwater to meet crop water requirements.

Using wind energy to supply irrigation water for crop production is a useful method for decreasing fossil fuel consumption and its adverse effects on the environment. Although in many areas using wind energy to pump water for agricultural consumption is usual, determining crop patterns with low cost and high revenue has been neglected. This paper developed an optimization model to achieve the most profitable crop pattern in the researched case study. The optimal cropping pattern and reservoir capacity were determined, and the benefit of using wind energy to pump groundwater yielded optimal decision variables for three different scenarios and four optional uses of energy. The model's results indicate that the annual net benefit that accrues when using optimal decision variables is approximately 480 million Iranian rials (1 million rials = US$36), and it can be increased to 1,734 million rials by using renewable energy resources. Although constructing a larger reservoir can store and regulate large volumes of water, it would be more expensive than installing more windmills to pump groundwater to meet crop water requirements. The produced energy when using optimal decisions was approximately 247,765 kWh. The maximum water discharge that can be achieved while using the 6.10-m (20-ft) windmill is approximately 159 m^3/h for one windmill in Eghlid, Iran. The presented model can be used in any other area with its related data and it may also produce more net benefit than this paper's case study. The calculated benefits considered only the costs and benefits from selling agricultural products, while a lot of excess water can be derived in some months and it be used for other purposes leading to additional revenue generation.

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