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Carbon-Constrained and Cost Optimal Hybrid Wind-Based System for Sustainable Water Desalination

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ABSTRACT Seawater desalination is one of the prominent solutions to cope with the water crisis. Suppling demanded energy and high investment and operation costs have been the most critical challenges facing the sustainable development of these plants. Previous studies have shown that renewable resources can be used as an alternative for sustainable desalination. Wind energy is a renewable resource with good potential, especially in coastal areas with a severe water crisis. In previous studies of wind-powered desalination units, typical values have been used for turbines, and also, the desalination unit's capacity is considered equal to the peak water demand. In this paper, a new optimization model for wind-powered desalination is presented wherein the optimal number of turbines will be defined based on the technical specifications of different commercially available turbine types. Also, simultaneous selection of several different turbines is modeled and optimized. The proposed mathematical model is implemented on a test case to evaluate its effectiveness. The simulation results show the proposed model's functionality to obtain optimal results while considering available commercial turbine types. The study demonstrates a 2.38 to 35.28 reduction in the net planning cost resulting from multiple turbine technology selections and optimization concerning the various single turbine installation cases.

INDEX TERMS Desalination, wind energy, wind turbine selection, optimal sizing.

NOMENCLATURE

A. SETS

S_H	Day hours
S_M	Year seasons
S_T	Wind turbines technologies

B. PARAMETERS

EM^{Cap}	Yearly system emission cap
EP^{D}	Power consumption of desalination unit (kW/m^3)
EP^{T}	Power consumption of water tank pumps (kW/m^3)
F_{DG}^{Cost}	Unit fuel price of the diesel generator (\$/liter)
FE^{DG}	Carbon content of diesel generator fuel (kg/liter)

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I_r	Interest rate
$IC_{(t)}^{WT}$	Investment cost of wind turbine (\$)
IC^{BS}	Investment cost per kW of battery power rating (\$)
IC^{DG}	Investment cost per kW of diesel power rating (\$)
IC^{WD}	Investment cost per m^3/day of desalination (\$)
IC^{WS}	Investment cost per m^3 capacity of water tank (\$)
K_{Fix}^{DG}	Fix factor of diesel consumption (liter /kW)
K_{Var}^{DG}	Variable factor of diesel consumption (liter /kW)
L_f	Life time
M_{WT}^{Max}	Maximum allowable number of turbine types
M	Large constant value
N_m	Number of the day in each season

$OM^{WT}_{(t)}$	Yearly O&M cost of wind turbine ($)
OM^{BS}	Yearly O&M cost per kW of battery power ($)
OM^{DG}	Yearly O&M cost per kW of diesel power ($)
OM^{WD}	Yearly O&M cost per m^3/day of desalination ($)
OM^{WS}	Yearly O&M cost per m^3 of water tank ($)
$P^{Tur}_{(h,m,t)}$	Total power generated by the wind turbine (kW)
$P^{WTR}_{(t)}$	Rated power of wind turbine (kW)
$v_{(h,m)}$	Wind speed (m/s)
$v^{ci}_{(t)}$	Cut-in speed of wind turbine (m/s)
$v^{r}_{(t)}$	rated speed of wind turbine (m/s)
$v^{co}_{(t)}$	Cut-off speed of wind turbine (m/s)
$WD^{Load}_{(h,m)}$	Local potable water demand (m^3)
WNS	Yearly allowable water not supplied percentage
η^{Dis}	Discharging efficiency of the battery storage (%)
η^{Cha}	Charging efficiency of the battery storage (%)
η^{Rec}_{PC}	Rectifier efficiency of the power converter (%)
η^{Inv}_{PC}	Inverter efficiency of the power converter (%)

C.VARIABLES

$B^{WT}_{(t)}$	Binary variable for selection of each turbine type
$BB^{Cha}_{(h,m)}$	Binary variable for charging mode of battery
$BB^{Dis}_{(h,m)}$	Binary variable for discharging mode of battery
$BT^{Cha}_{(h,m)}$	Binary variable for charging mode of tank
$BT^{Dis}_{(h,m)}$	Binary variable for discharging mode of tank
C^{DG}_{Fuel}	Total yearly fuel cost of diesel generator ($)
$E^{BS}_{(h,m)}$	Energy stored in the battery (kWh)
EM^{Tot}	Total yearly carbon emitted by the system (ton)
ER^{BS}	Optimal energy capacity of the battery (kW)
$F^{DG}_{(h,m)}$	Fuel consumed by the diesel generator (liter)
IC^{Tot}_{WT}	Total investment cost of the wind turbines ($)
IC^{Tot}_{BS}	Total investment cost of the battery ($)
IC^{Tot}_{DG}	Total investment cost of the diesel generator ($)
IC^{Tot}_{WD}	Total investment cost of the desalination unit ($)
IC^{Tot}_{WS}	Total investment cost of the water storage tank ($)
$N^{WT}_{(t)}$	Optimal number of each turbine type (integer)
NPC	Total nep present cost of the system ($)
OM^{Tot}_{WT}	Total O&M cost of the wind turbines ($)
OM^{Tot}_{BS}	Total O&M cost of the battery ($)
OM^{Tot}_{DG}	Total O&M cost of the diesel generator ($)
OM^{Tot}_{WD}	Total O&M cost of the desalination unit ($)
OM^{Tot}_{WS}	Total O&M cost of the water storage tank ($)
$P^{Cha}_{(h,m)}$	Charging power to the battery (kW)
$P^{Dis}_{(h,m)}$	Discharging power from the battery (kW)
$PC^{In}_{(h,m)}$	Incoming power to the power converter (kW)
$PC^{Out}_{(h,m)}$	Outgoing power from the power converter (kW)
$PD^{D}_{(h,m)}$	Electric power demand of the desalination (kW)
$PD^{T}_{(h,m)}$	Electric power demand of the water pumps (kW)
PG^{DG}	Power generated by the diesel generator (kW)
$PG^{WT}_{(h,m)}$	Power generated by the wind turbines (kW)
PR^{BS}	Optimal power rating of the battery (kW)
PR^{DG}	Optimal power rating of the diesel generator (kW)
PR^{PC}	Optimal power rating of the power converter (kW)
$W^{T}_{(h,m)}$	Water stored in the tank (m^3)
$W^{TC}_{(h,m)}$	Water charged to the tank (m^3)
$W^{TD}_{(h,m)}$	Water discharged from the tank (m^3)
WC^{T}	Optimal water storage capacity of the tank (m^3)
$WD^{NS}_{(h,m)}$	Hourly water demand not supplied (m^3)
$WG^{WD}_{(h,m)}$	Hourly water generated by desalination unit (m^3)
WG^{TDC}	Optimal capacity of the desalination unit (m^3/day)
WP^{Cha}	Optimal power of charging water pump (m^3)
WP^{Dis}	Optimal power of discharging water pump (m^3)

I. INTRODUCTION

The provision of safe drinking water has always been one of the human societies' main concerns [1]. Today, with the increase in population on the one hand and human societies' progress, on the other hand, the demand for both quality and quantity of drinking water has increased significantly. On the other hand, the available water resources are steadily declining [2]. The main reasons for the reduction are surface and groundwater pollution, utilizing water resources for agricultural and industrial production, and the increase in water evaporation due to rising air temperatures, especially in coastal, arid and semi-arid regions [3]. In recent years, various methods have been proposed to increase access to drinking water, the most important of which are recycling various urban and industrial effluents, constructing new water storage tanks, and consumption management, especially in production and agriculture seawater desalination [4]. Among these methods, desalination methods have found a special place due to their abundant access to saline waters in areas with severe drinking water problems. Also, if the energy required for the process is provided, a high drinking water volume with acceptable quality can be obtained [5]. There are several ways to desalinate water, the most important of which are reverse osmosis (RO), multi-stage flash (MSF), and multi-effect desalination (MED). Among these methods, the reverse osmosis method has found a special place due to its numerous advantages. About 70% of the world's desalination units currently operate on this method. The reasons for the high share of RO in the desalination market are the ability to produce highly pure water by taking out about 99% of the Total Dissolved Solids (TDS), relatively low investment, operation, and maintenance cost, low energy consumption because of the non-phase change separation process, and modular and compact system offering convenient maintenance and expansion with low space requirements. Besides, this process's energy requirement is based only on electric energy, unlike the other methods with electrical and thermal energy consumption [6].

Currently, the energy required for desalination plants is mainly supplied from the utility grid, which has caused some problems. There is no access to the grid in some coastal areas, or the grid does not have the extra capacity to supply the desalination plants. Besides, in areas with access to the grid, the supply of the desalination units is possible only through the grid's expansion at different parts, including production, transmission and distribution. Even in the absence of the above problems, the grid integrated desalination units' high energy means many work hours of the fossil fuel power plants, resulting in increased environmental pollutants. As a result, the energy supply at a reasonable cost and without carbon emission has become one of the problems in constructing and developing desalination plants. One of the solutions in this regard is the local supply of desalination units using renewable energy sources [7]. The previous studies have substantiated these new resources' economic and technical feasibility for desalination purpose [8]. Sustainable development goals necessitate the cleanness of the energy supply, which renewable energy resources can achieve. The local supply of desalination plants by renewable resources will help achieve sustainability goals by creating local jobs, reducing environmental pollutions, and enhancing supply security by eliminating long-distance transmission and distribution networks. In recent years, many studies have been conducted to validate this solution's technical and economic feasibility. Wind energy is one of the primary renewable sources and has reliable potential, especially in coastal areas with severe potable water crisis [9].

As a result, this potential can be practically used to supply desalination plants [10]. In recent years, various studies have been conducted in this field. In [11], two wind-powered desalination plants with and without battery are simulated and evaluated. The desalination plant is of RO type and installed at Gran Canaria island, Spain. Three machine learning methods, including random forests, support vector machine, and neural networks, are used to predict the system's performance. (Spain). The configuration with battery storage is constant pressure and flow rate, while the other one, without battery, is variable pressure and flow rate. The study results demonstrate the superiority of the random forest and support vector machines with respect to the neural networks in terms of performance prediction. Loutatidou *et al.* [12] have been studied a wind-powered Ro desalination plant. The desalination project Liwa ASR in the United Arab Emirates (UAE) is used to evaluate the study's economic feasibility. The study results denote that wind-driven water desalination can be completive concerning the current thermal desalination plants in the UAE. Segurado *et al.* [13] proposed using a pumped storage plant to minimize wind curtailment. The research includes an optimal sizing methodology in addition to the operation strategy of a wind-pumped hydro-desalination system. The objectives of the total system cost, renewable penetration maximization, and wind energy curtailment minimization are considered. A derivative-free multi-objective optimization method (Direct Multi-Search) is utilized to solve the proposed multi-objective model. The research results denote that higher levels of renewable penetration can be achieved at the expense of the increasing total system cost. Forstmeier *et al.* have been demonstrated the technical feasibility of wind energy to supply desalination plants [14]. To do this, physics-based system models have been established for both reverse osmosis and mechanical vapor compression. The study results verify wind energy feasibility by showing that wind energy cost is in the range of conventional desalination plants. An energy management paradigm for a microgrid consists of a hybrid wind-diesel-battery system that supplies a desalination unit [15]. To this end, a real-time energy management strategy based on the hour ahead wind forecast is proposed. The study's objective is to maximize wind energy extraction and environmental pollutant emission by m minimizing diesel generator operation. In [16], wind energy is hybridized with the solar chimney for supplying electricity and freshwater. The thermal and membrane-based desalination systems are considered in a cascade manner to utilize the heat source of the solar chimney. The authors in [17] have used DesalinationPlant software to design an electric-to-water micro-grid system composed of inexhaustible distributed energy resources, a decentralized storage system and a seawater desalination system. In [18], the HOMER software is used to obtain different topologies of a hybrid wind-solar system. Then, a decision making procedure based on integrated Fuzzy-AHP and Fuzzy-VIKOR decision-making methods is executed to choose the best design considering ten performance criteria. The HOMER software in [19] is used for modelling, designing, and optimizing a hybrid wind-PV system supplying domestic electric energy besides that required for water desalination in a remote area. Maleki in [20] has designed and modelled various wind and solar systems supported by battery or hydrogen storage for desalination purposes. The results indicated that using a battery as energy storage is more affordable than hydrogen production and storage. A hybrid renewable system in [21] was also modelled and compared concerning the technical and economic performance by modifying various design options. A reverse-osmosis process was considered as the desalination technology, and the HOMER software was used for modelling and optimization. In [22], cutting-edge knowledge regarding wind- and PV-powered RO-based desalination was surveyed. For this purpose, technical challenges and possible solutions for large-scale desalination plants were identified. Finally, in [23], a hybrid power and water system based on water desalination and renewable resources is designed to supply local demand. The interrelations between power and water sectors and their interconnection with carbon emission are modelled and considered in the planning. The study results denote the importance of joint planning of both the power and water sector while considering their relation with environmental pollutant emissions.

As the above literature survey demonstrates, to maximize the energy efficiency and the cleanliness of power supplied to the desalination plants, several points should be considered, which are described below. The first one is to present an economic plan for the whole system with the least cost by properly modelling components and their optimization. The second issue is calculating and limiting the amount of carbon emission produced by the system to protect the environment and provide sustainable development. The next issue is to model and calculate the level of water supply reliability to maintain acceptable levels. Finally, wind power-based power supply systems must be supported in various ways so that both the intermittent wind energy nature and its low predictability do not affect the quantity and quality of the water produced. The last point is that besides the number of wind turbines, the turbine types should also be optimized. In other words, the planning model should also decide on the type of turbine. In practice, there are various turbine types with different parameters and characteristics. Simultaneous multiple selections of various turbine type should also be considered. Table 1 presents a summary of the previous research properties along with the differences with the proposed model.

TABLE 1. Previous research properties and differences with the proposed model.

Ref #	Model Consideration					
	Variable desalination size	Diesel generator	Battery energy storage	Water storage tank	turbine type Selection	Multiple turbine selection
[11]	✓	✓	✓	×	×	×
[12]	✓	✓	✓	×	×	×
[13]	×	✓	✓	✓	×	×
[14]	✓	✓	✓	✓	×	×
[15]	✓	✓	✓	✓	×	×
[16]	×	✓	✓	×	×	×
[17]	✓	✓	✓	✓	×	×
[18]	✓	✓	✓	✓	×	×
[19]	×	✓	✓	×	×	×
[20]	×	✓	✓	✓	×	×
[21]	×	✓	✓	✓	×	×
[22]	×	✓	✓	✓	×	×
[23]	×	✓	✓	✓	×	×
Proposed Model	✓	✓	✓	✓	✓	✓

Accordingly, in this paper, an optimization model for optimal desalination system design is proposed based on a combined wind-diesel-battery supply system. In the proposed model, the optimal wind turbine type is defined within a set of available commercial models besides the optimal number. Besides, simultaneous multiple different turbine types selection is modeled and optimized. The battery energy storage has been used to perform a time-shift on energy production due to low wind speeds at some hours, t. The diesel generator will also be used as a system backup during hours with severe limitations in generated or stored energy. The carbon emission produced by the diesel generator is calculated and constrained to a predefined total yearly value. The desalination unit is of the reverse osmosis type, and its capacity will be optimized simultaneously with the components of the power supply system based on the variable pattern of the daily water consumption needs. A water storage reservoir has also been used to perform arbitrage and leveling of the water demand profile. The water storage will significantly reduce the water generation at peak water consumption periods, resulting in a reduction in the desalination unit capacity and the system's overall cost. This cost reduction will be achieved at the expense of a small cost for the reservoir itself and its pumps. The proposed model will provide the optimal size and capacity of each system component to meet the water consumption needs with the desired level of supply reliability and control of environmental pollutants at the lowest cost. In summary, the innovations of this research can be enumerated as follows.

- Novel optimization formulation for water desalination based on hybrid wind-based system.
- Wind turbine type is optimized besides the number of turbines.
- Simultaneous selection of the multiple different turbine types is modeled and optimized

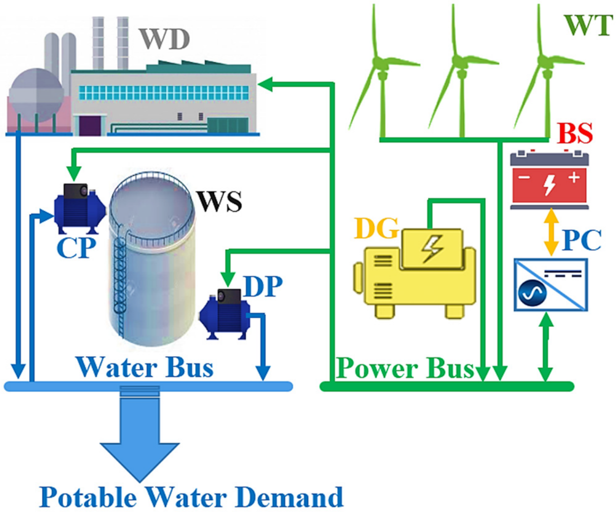

FIGURE 1. **Configuration of the proposed system.**

- Optimizing sizing of the desalination plant concurrent with the power supply equipment

The remainder of the paper is as follows. After this introductory part and in Section 2, the proposed configuration and model is introduced. In this section, first, the model layout is explained by defining the function of each part. Then, mathematical formulations of equipment and relations between them are presented. Then, in Section 3, input parameters related to the case study are presented. Results of the simulation, in addition to the relevant discussions, are provided in Section 4. Finally, the conclusions of the research are given in Section 5.

II. THE PROPOSED MODEL

The general layout of the proposed system is depicted in Figure 1. In the figure, black and blue arrows denote power and water flow, respectively. Besides, acronyms WT, DG, BS, WD, and WS stand for wind turbines, diesel generator, battery storage, water desalination, and water storage. The role of each component in the whole system mission is introduced in the following.

A. COMPONENTS FUNCTION

As shown in Figure 1, the system's primary source is energy produced from the wind. The wind turbines arranged in a farm constitute the primary source of energy required for desalination. The power produced by the wind turbines is gathered and then injected into the main bus of the desalination supply.

The required turbines' number and technical specifications will be optimized based on the wind regime and variable power demand. The hourly fluctuations in the wind speed will also result in variations in the generated power. At the hours with abundant wind speed, the produced power is more than the required amount, and in the others with low wind speed, it is not enough. Therefore, it is necessary to shift some of the energy produced in the hours with high wind speed to the other critical hours with low wind speeds. This application is known as renewable energy time-shift and is performed utilizing battery storage. A part of the excess energy produced by wind turbines is stored in the battery at high wind speeds. The excess stored energy is used later to meet demand during critical hours with low wind speeds. Considering that the battery packs' energy is a DC type, a double conversion AC to DC and DC to AC converter is needed to connect the battery pack with the main AC power supply bus. The converter works at rectifier mode in the battery charging state by converting the main supply AC power to battery DC one.

On the contrary, in the battery discharging mode, the converter works at inverter mode by converting the battery's DC output power to the AC supply needed. The optimal power and energy rating of the battery and the optimal power rating of the attached converter will be determined through the proposed formulation. Even with a battery, the wind speed may not be high enough to produce the required power in certain critical situations, nor may the battery have enough storage. In this case, the power supply must not be cut off and should be continued. A diesel generator unit is therefore used for this purpose. Due to its fossil fuel consumption and the resulting environmental pollution production, the diesel generator is turned on only minimal hours of the year with severe power shortage. Pollution generated by the diesel generator fuel consumption will be calculated and limited to ensure the whole system's cleanness.

The power injected by the wind turbines, battery, and a diesel generator is used to supply the desalination system. The desalination system consists of two parts, water desalination (production) and water tank (storage). Potable water demand is mainly met by using a water desalination unit. The water storage tank is used to leveling the water demand profile. The water demand profile's peak shaving helps reduce water desalination capacity and, consequently, the supply system. This reduction in capacity reduces the total system at the expense of a small water tank's small cost. Besides the water tank itself, to account for real-life systems, charging and discharging pumps are also modeled. The electricity demand of the tank is related to these pumps. Using the proposed optimization model, the optimal rating of the desalination unit, water tank capacity, and power rating of the charging and discharging pumps will be determined. Finally, the potable water demand is supplied directly from the desalination unit or the tank's discharged water. As it was explained, the system possesses various parts and equipment. The optimization problem aims at finding the optimal size of each part based on an objective function and a set of constraints. Accordingly, the system equipment's technical characteristics, limitations, and features must be first modeled mathematically. In the following, each component's mathematical model is introduced first, and then objective function and system constraints are explained and mathematically formulated. Since the paper focuses on modelling and optimizing different wind turbines types, solar resources have been omitted. The proposed model can be easily transformed into a hybrid wind-solar system

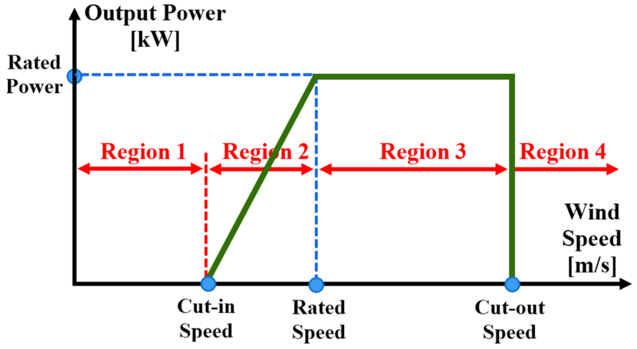

FIGURE 2. Typical wind turbine power curve.

by adding photovoltaic panels. Accordingly, in addition to adding solar cells' cost to the objective function, its output power must also be added to the battery bus due to its direct current nature.

B. COMPONENTS MODEL

The mathematical model of the system components is introduced and formulated in the following. The model contains technical limitations and the cost components related to the system equipment, including wind turbines, battery storage and attached converter, diesel generator, water desalination unit, and water storage reservoir.

1) WIND TURBINES

A wind turbine is a machine capable of converting wind energy into electricity. The most critical factor in wind-based energy production is wind speed. The higher the wind speed, the greater the possibility of producing power. The function describing the relation between wind speed and produced power by the turbine is a known turbine power curve. It should be noted that the original wind power curve is a third-order function of the wind speed. A linear model is used commonly in optimization and planning problems to get rid of non-linearity. The original non-linear model can be defined based on experimental data, which are not usually accessible for all commercial wind turbines. The experimental data in the form of input-output (wind speed-generated power) values is used to fit a curve with the desired order; usually third-order, to obtain the turbine power curve. There is a minor error in calculating generated power using a linear model by neglecting this effect. This error will consequently cause a deviation in optimizing the required wind turbines capacity.

A typical linear wind power curve is depicted in Figure 2. As the figure shows, the curve can be classified into four regions. The classification is based on wind speed and technical parameters of the turbine, including rated power in addition to the cut-in, rated, and cut-off speed. The manufacturer defines the cut-in and cut-off speed (also known as 'cut-out) to protect the turbine from damage. The cut-in speed is a point wherein the turbine begins producing power by rotation. The cut-out point represents the highest rotation speed the turbine can withstand before damage. The turbine's rated speed is the wind speed at which the turbine generates rated power [24]. Based on the comparison of wind speed with these speeds, the curve's area and thus the amount of electricity generation will be determined. The wind power curve can be mathematically represented by (1) [24].

$$P^{Tur}_{(h,m,t)} = \begin{cases} 0, & v_{(h,m)} \le v^{ci}_{(t)} \\ P^{WTR}_{(t)} \left(\dfrac{v_{(h,m)} - v^{ci}_{(t)}}{v^{r}_{(t)} - v^{ci}_{(t)}} \right), & v^{ci}_{(t)} \le v_{(h,m)} \le v^{r}_{(t)} \\ P^{WTR}_{(t)}, & v^{r}_{(t)} \le v_{(h,m)} \le v^{co}_{(t)} \\ 0, & v^{co}_{(t)} \le v_{(h,m)} \end{cases}$$
$$\times \forall h \in S_H, \quad m \in S_S, \ t \in S_T \tag{1}$$

In this representation, for simplicity and without loss of generality, a linear function is used to express power production at Region 2. As the mathematical model denotes, power production is severely dependent on the turbine parameters for a certain wind speed and regime. Each manufacturer produces wind turbines with various power ratings and associated speeds (cut-in, rated, and cut-off) [25]. There are some points in this regard which have to be taken into account. The first one is that the previous studies do not model a particular commercial turbine and use general and typical values for its parameters. This matter makes the study results differ from reality in practice, as there may not be a turbine with the specifications used. The next problem is that even if a particular commercial turbine has been used in the study, its type has not been optimized according to the problem's conditions. In other words, the selection of the turbine type is made before the optimization process is performed. In this case, better results may be obtained by changing the turbine's selection inside the optimization process.

The third problem is that even if the turbine is selected during the optimization of the whole problem, due to the seasonal changes in wind speed, the turbine will not have the best performance in each season because its selection has been based on a compromise for all seasons. As a result, it is appropriate to model the problem so that the optimization process can select several turbines with different parameters. In this case, the best results will be obtained in terms of optimization results. All of the points mentioned above are considered in the following. In other words, turbine technology is optimized among several commercial options available in the market as part of the problem, and besides, it can simultaneously select and use several different turbines. Accordingly, a binary variable is assigned to ta turbine type. The problem can use a turbine's desired number if it has previously switched-on the relevant binary variable, mathematically modeled in (2).

$$N^{WT}_{(t)} \ge B^{WT}_{(t)} \quad \forall\, t \in S_T \tag{2}$$

The number of selected turbines can be limited to a specific and predetermined number using the binary variable. This is performed in (4), where the problem is confined to choose a certain number of turbine types.

$$\sum_{t} B^{WT}_{(t)} \leq M^{Max}_{WT} \tag{3}$$

The total power produced inside the wind park is equal to the sum of the power generated by all the selected turbines, as represented by (4). Accordingly, investment and the operation and maintenance (O&M) of the whole park are the summation over the utilized turbines multiplied by the corresponding unit cost. These cost terms, investment and O&M, for the wind park are denoted by (5) and (6), respectively.

$$PG^{WT}_{(h,m)} = \sum_{t} N^{WT}_{(t)} P^{Tur}_{(h,m,t)} \quad \forall\, h \in S_H,\ m \in S_M \tag{4}$$

$$IC^{Tot}_{WT} = \sum_{t} N^{WT}_{(t)} IC^{WT}_{(t)} \tag{5}$$

$$OM^{Tot}_{WT} = \sum_{t} N^{WT}_{(t)}\, OM^{WT}_{(t)} \tag{6}$$

2) BATTERY AND POWER CONVERTER

As it was stated earlier, the battery is used for renewable energy time-shift. Relations (7) and (8) indicated that the battery's charging and discharging power have to be lower than the rated power. This limitation is also the case for the battery's energy, as denoted by (9) [26].

$$P^{Cha}_{(h,m)} \leq PR^{BS} \quad \forall\, h \in S_H,\ m \in S_M \tag{7}$$

$$P^{Dis}_{(h,m)} \leq PR^{BS} \quad \forall\, h \in S_H,\ m \in S_M \tag{8}$$

$$E^{BS}_{(h,m)} \leq ER^{BS} \quad \forall\, h \in S_H,\ m \in S_M \tag{9}$$

The stored energy in the battery at any time is a function of the previously stored value and the net charging and discharging values at the present period, as shown by (10). It should be noted that the battery cannot charge and discharge simultaneously [26]. This is modeled using an indicator binary variable for each of the charging and discharging actions [27]. The problem is then forced to use only one of these binary variables at each time period, as denoted by (11). Based on (12) and (13), the battery can charge or discharge if the relevant binary variable is turned-on [28].

$$E^{BS}_{(h,m)} = E^{BS}_{(h-1,m)} + P^{Cha}_{(h,m)} \eta^{Cha} - \frac{P^{Dis}_{(h,m)}}{\eta^{Dis}} \times \forall\, h \in S_H,\ m \in S_M \tag{10}$$

$$B^{Cha}_{(h,m)} + B^{Dis}_{(h,m)} \leq 1 \quad \forall\, h \in S_H,\ m \in S_M \tag{11}$$

$$P^{Cha}_{(h,m)} \leq B^{Cha}_{(h,m)} M \quad \forall\, h \in S_H,\ m \in S_M \tag{12}$$

$$P^{Dis}_{(h,m)} \leq B^{Dis}_{(h,m)} M \quad \forall\, h \in S_H,\ m \in S_M \tag{13}$$

Considering that the battery cells work with and store DC power, a power converter is required to communicate with the main AC supply. The power converter will work at one of the following conversion modes. In the battery's charging state, the converter works at the AC to DC conversion mode, also known as rectifier mode. In this case, the relation between the battery's DC charging power and the AC power drawn from the converter system is based on (14). On the contrary, when the battery is discharging, the converter works at the DC to AC conversion mode, also known as inverter mode. In this situation, the relation between the battery's DC discharge power and the AC power injected into the system by the converter is based on (15). As presented by (16) and (17), the converter's input and output power should respect rating value. Finally, the whole battery system's cost can be calculated by summing up costs related to the battery system itself and the converter. Accordingly, the whole battery system's total investment cost is presented by (18), while (19) presented operation and maintenance cost.

$$PC^{In}_{(h,m)} = P^{Cha}_{(h,m)} / \eta^{Rec}_{PC} \quad \forall\, h \in S_H,\ m \in S_M \tag{14}$$

$$PC^{Out}_{(t,s)} = P^{Dis}_{(h,m)} \eta^{Inv}_{PC} \quad \forall\, h \in S_H,\ m \in S_M \tag{15}$$

$$PC^{Out}_{(h,m)} \leq PR^{PC} \quad \forall\, h \in S_H,\ m \in S_M \tag{16}$$

$$PC^{In}_{(h,m)} \leq PR^{PC} \quad \forall\, h \in S_H,\ m \in S_M \tag{17}$$

$$IC^{Tot}_{BS} = PR^{BS} ICP^{BS} + ER^{BS} ICE^{BS} + PR^{PC} IC^{PC} \tag{18}$$

$$OM^{Tot}_{BS} = PR^{BS} OMP^{BS} + ER^{BS} OME^{BS} + PR^{PC} OM^{PC} \tag{19}$$

3) DIESEL GENERATOR

The diesel generator is the only conventional power source of the system. Also, it is the only fuel consumer component of the system. The produced power by the diesel generator, as denoted by (20), can be at most as large as the rated power. The fuel consumption rate is a function of the power rating and the generated power, as denoted by (21). The total cost of the fuel consumed by the diesel generator can be calculated by multiplying unit fuel price by the total hours the generator consumed power, which is shown by (22). The diesel generator's investment cost is only a function of the unit price and the rated power, modeled by (23). Finally, as shown by (24), yearly operation and maintenance cost has to be considered as the cost of the generator itself and also the fuel cost [29].

$$PG^{DG}_{(h,m)} \leq PR^{DG} \quad \forall\, h \in S_H,\ m \in S_M \tag{20}$$

$$F^{DG}_{(h,m)} = K^{Fix}_{DG} PR^{DG} + K^{Var}_{DG} P^{DG}_{(h,m)} \quad \forall\, h \in S_H,\ m \in S_M \tag{21}$$

$$C^{Fuel}_{DG} = F^{Cost}_{DG} * \sum_{h} \sum_{m} N_m F^{DG}_{(h,m)} \tag{22}$$

$$OM^{Tot}_{DG} = PR^{DG} OM^{DG} + C^{Fuel}_{DG} \tag{23}$$

$$IC^{Tot}_{DG} = PR^{DG} IC^{DG} \tag{24}$$

4) WATER DESALINATION UNIT

The water desalination unit is the primary water source of the system. The capacity of this unit is publicly announced in liters per day. However, it will be operated hourly based on the water demand changes. Therefore, hourly water production capacity can be calculated based on (25). The power consumed by the water desalination unit is a function of the produced water and used process. In general, hourly required power can be calculated by multiplying the hourly generated water and power consumption factor (PCF) of the process. Several factors affect the energy consumption of the desalination unit. The first and most important factor is the type of technology used for desalination. The two main methods are in the field of thermal methods and membranes. Thermal methods require both thermal and electrical energy. In contrast, membrane methods, the most important of which is reverse osmosis, require electrical energy. Accordingly, the reverse osmosis method has the lowest energy consumption among all desalination technologies. The second factor is the desalination unit's size, which is generally divided into three categories: small, medium and large. As the size of the unit increases, its energy consumption per unit of water produced will decrease. The third factor is the salt content as well as the temperature of the incoming water. The next influential factor is the quality of water produced in terms of purity and the percentage of compounds. The water desalination unit's investment and operation and maintenance costs are straightforward linear functions of the unit cost and the daily water production capacity, as represented by (27) and (28), in turn.

$$WG^{WD}_{(h,m)} \leq WG^{TDC}/24 \quad \forall\, h \in S_H,\ m \in S_M \tag{25}$$

$$PD^{D}_{(h,m)} = EP^{D} WG^{WD}_{(h,m)} \quad \forall\, h \in S_H,\ m \in S_M \tag{26}$$

$$IC^{Tot}_{WD} = WG^{TDC} IC^{WD} \tag{27}$$

$$OM^{Tot}_{WD} = WG^{TDC} OM^{WD} \tag{28}$$

5) WATER STORAGE TANK

The water storage tank is used to relieve stress on the water desalination unit and the power supply system at the hours with peak water demand. The tank is filled during hours with abundant power production or low water demand. Two water pumps are used for charging and discharging the tank. As shown by (29) and (30), charging and discharging water cannot exceed the water pump's corresponding rating. Besides, to prevent the consumption of additional energy in both pumps' simultaneous operation, the tank is allowed to be in only one of the charging and discharging modes at any time. Similar to the battery storage, this limitation is also modeled by using binary variables as in (31) and (32) and then the tank is enforced to choose one based on (33).

$$W^{TC}_{(h,m)} \leq WP^{Cha} \quad \forall\, h \in S_H,\ m \in S_M \tag{29}$$

$$W^{TD}_{(h,m)} \leq WP^{Dis} \quad \forall\, h \in S_H,\ m \in S_M \tag{30}$$

$$W^{TC}_{(h,m)} \leq BT^{Cha}_{(h,m)} M \quad \forall\, h \in S_H,\ m \in S_M \tag{31}$$

$$W^{TD}_{(h,m)} \leq BT^{Dis}_{(h,m)} M \quad \forall\, h \in S_H,\ m \in S_M \tag{32}$$

$$BT^{Cha}_{(h,m)} + BT^{Dis}_{(h,m)} \leq 1 \quad \forall\, h \in S_H,\ m \in S_M \tag{33}$$

The water stored at the tank at any time period is equal to the remained water from the previous time period and the water added and minus water released at the present time period as modeled by (34). The water stored in the tank can be at most as large as the tank capacity, which is shown by (35). Also, to respect the health issues related to water quality, the water stored each day should be used on the same day. This issue is mathematically modeled in (36).

$$W^{T}_{(h,m)} = W^{T}_{(h-1,m)} + W^{TC}_{(h,m)} - W^{TD}_{(h,m)} \times \forall\, h \in S_H,\ m \in S_M \tag{34}$$

$$W^{T}_{(h,m)} \leq WC^{T} \quad \forall\, h \in S_H,\ m \in S_M \tag{35}$$

$$\sum_{h} WD^{TC}_{(h,m)} = \sum_{h} WG^{TD}_{(h,m)} \forall m \in S_M \tag{36}$$

The power demanded by the tank is related to the water pumps used for charging and discharging. As explained and modeled previously, at most, one of the charging and discharging pumps work at any time period. Therefore, the power demanded by the pumps can be modeled by (37), wherein it is a function of the power consumption ratio of the pump as well as the pumped water. Finally, the tank's investment and operation and maintenance costs are related to the tank capacity itself and power raring of the attached pumps presented by (38) and (39), respectively.

$$PD^{T}_{(h,m)} = EP^{T} \left(WD^{TC}_{(h,m)} + WG^{TD}_{(h,m)} \right) \forall h \in S_H, m \in S_M \tag{37}$$

$$IC^{Tot}_{WS} = WC^{T} IC^{WS} + (WP^{Cha} + WP^{Dis}) IC^{WP} \tag{38}$$

$$OM^{Tot}_{WS} = WC^{T} OM^{WS} + (WP^{Cha} + WP^{Dis}) OM^{WP} \tag{39}$$

C. OBJECTIVE FUNCTION AND SYSTEM CONSTRAINTS

The fitness function or equivalently objective function of the formulated optimization problem is defined and explained in the following. The whole system's general constraints, including water balance, electric power balance, and limitation on the reliability level and emission, are described and modeled.

1) POWER BALANCE

There is a main power bus in the system which works with AC power. The balance of the incoming and outgoing powers to this bus should be kept. The power balance for this bus is shown in (40). As in the equality, inputs to the bus are power generated by the diesel generator, wind turbines, and AC power output of the converter at the inverter mode. On the contrary, outputs from the bus comprise input power to the converter at rectifier mode in addition to the power demand of the desalination unit and water tank charging and discharging pimps.

$$PG^{DG}_{(h,m)} + PC^{Out}_{(h,m)} + PG^{WT}_{(h,m)} = PC^{In}_{(h,m)} + PD^{D}_{(h,m)} + PD^{T}_{(h,m)} \times \forall\, h \in S_H,\ m \in S_M \tag{40}$$

2) WATER BALANCE

Similar to the power, the balance between the generated and the consumed water should also be maintained in the system. This balance necessitates a water balance equation as denoted by (41). Accordingly, positive flows are water generated by the desalination unit and the discharged water from the tank, while negative ones are charging water to the tank and net supplied water demand. The net supplied water demand is equal to the real water demand minus not supplied water, as declared in the equation. It should be noted that not supplied water demand is a positive value lower than the hourly water demand. In other words, this item cannot act as a water source and can only reduce hourly water demand, as shown by (42)

$$W^{TC}_{(h,m)} + WD^{Load}_{(h,m)} - WD^{NS}_{(h,m)} = W^{TD}_{(h,m)} + WG^{WD}_{(h,m)} \times \forall\, h \in S_H,\; m \in S_M \quad (41)$$

$$0 \leq WD^{NS}_{(h,m)} \leq WD^{Load}_{(h,m)} \times \forall\, h \in S_H,\; m \in S_M \quad (42)$$

3) RELIABILITY AND CARBON EMISSION LIMIT

The unmet water demand level has to be controlled based on the designer preferences to ensure a reliable supply of the demanded water. In (43), the total yearly unmet water value with respect to the total demanded water is calculated and limited to the water not-supplied index defied by the project designer. Also, to ensure the system's environmental friendliness, the total yearly emitted carbon of the whole system is limited to a predefined cap, as modeled in (44). It should be noted that the only pollutant emitter component of the system is the diesel generator because of the fuel consumption. Its carbon emission is calculated in (45), a function of the fuel consumed and the fuel carbon content.

$$\sum_{(h,m)} \left(WD^{NS}_{(h,m)} / WD^{Load}_{(h,m)} \right) \leq WNS \quad (43)$$

$$EM^{Tot} \leq EM^{Cap} \quad (44)$$

$$EM^{Tot} = FE^{DG} \left[\sum_{(h,m)} N_m F^{DG}_{(h,m)} \right] \quad (45)$$

4) OBJECTIVE FUNCTION

The optimization process has to be based on achieving a predefined fitness or objective function. As shown in (46), the problem's objective function is the total net present cost (NPC). There are two points behind using the NPC for economic evaluation instead cost of energy. The first one is that the cost of energy is usually used to compare various energy production systems with each other. Here, we have a hybrid system. Accordingly, we have modeled all sources and let the optimization problem to decide on optimal share of each one. The second and more important note here is that we have not an energy-only system. In other word, minimizing only cost of energy did not make sense while a considerable share of the system cost is related to the water sector equipment. Accordingly, we have used NPC which reflects cost of the all system equipment regardless of their nature and role. The NPC is equal to the total investment cost and the converted total yearly operation and maintenance cost of the whole system. The value of NPC should be minimized to ensure minimum cost system design.

$$\begin{aligned} NPC &= IC^{Tot}_{WT} + IC^{Tot}_{DG} + IC^{Tot}_{BS} + IC^{Tot}_{WD} + IC^{Tot}_{WS} \\ &\quad + \frac{(1+I_r)^{L_f} - 1}{I_r(1+I_r)^{L_f}} \Big(OM^{Tot}_{WT} + OM^{Tot}_{DG} + OM^{Tot}_{BS} \\ &\quad + OM^{Tot}_{WD} + OM^{Tot}_{WS} \Big) \end{aligned} \quad (46)$$

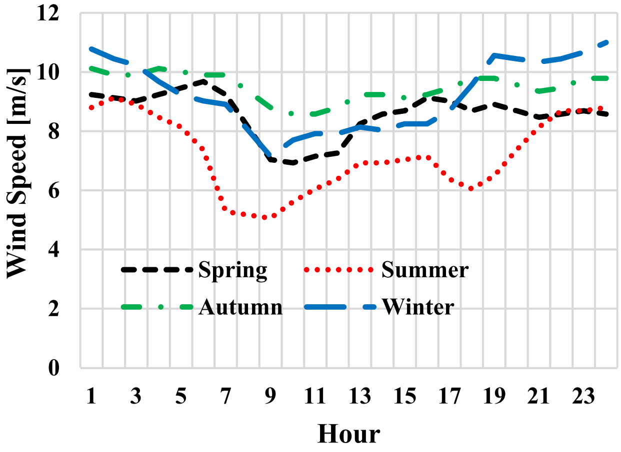

FIGURE 3. Seasonal hourly wind speed.

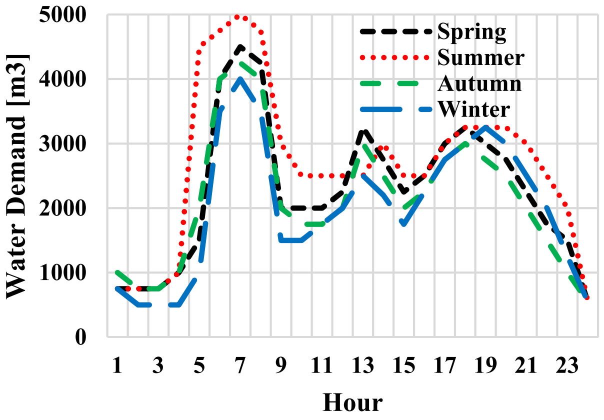

FIGURE 4. Seasonal hourly water demand.

The proposed model's limitations are the deterministic treatment of the input data, not considering reactive power demand, and not considering wind turbine control methods.

III. CASE STUDY

The optimization problem introduced and modeled in the previous section is tested in this section. The wind speed and water consumption data are for Doha, Qatar. The representative wind speed, measured at 10 m height, of the studied location is depicted in Figure 3. Also, Figure 4 shows representative hourly water demand for seasons of the year wherein peak water demand is 5000 m^3/h. An RO-based desalination unit is used with 3.5 kW/m^3 energy consumption. The pumps used for water tank charging and discharging consume 0.4 kW/m^3 electric energy.

TABLE 2. Investment and O$M cost for system components.

Component	Investment		O&M	
Desalination unit	1200	$\$/\text{m}^3$-day	0.35	$\$/\text{m}^3$-year
Water storage tank	80	$\$/\text{m}^3$	0.01	$\$/\text{m}^3$-year
Water tank pumps	50	\$/kW	0.05	\$/kW-year
Diesel generator	200	\$/kW	10	\$/kW-year
Power converter	40	\$/kW	5	\$/kW-year
Battery power	200	\$/kW	3.4	\$/kW-year
Battery energy	300	\$/kWh	0.4	\$/kWh-year

TABLE 3. Data for the commercial wind turbines [35].

ID	Rated Power (kW)	Speed (m/s)			Invest. Cost (\$)	O&M Cost (\$/year)
		Cut-in	Rated	Cut-off		
t1	100	3.5	10	25	159440	4385
t2	100	4	9	20	159440	4385
t3	100	3.5	11	25	159440	4385
t4	108	3.5	15	27	172147	4734
t5	130	3.7	13	25	207054	5694
t6	150	3.5	10	20	238740	6565
t7	150	4	12	25	238740	6565
t8	150	4	12.6	20	238740	6565
t9	150	4	14	24	238740	6565
t10	200	3	11	25	317760	8738
t11	225	3.5	14.5	25	357165	9822
t12	225	3.5	14	25	357165	9822
t13	300	3.5	12	20	474960	13061
t14	335	3.5	12	25	529715	14567

TABLE 4. Optimal sizing results for system components.

Part	Unit	Optimal Size
Desalination Unit	m^3/day	68,000
Storage Tank	m^3	8,100
Charge Pump	m^3/h	2,100
Discharge Pump	m^3/h	2,200
Wind Turbines	kW	17,800
Diesel Generator	kW	3800
Power Converter	kW	2,100
Battery Power	kW	2,100
Battery Energy	kWh	6,200

The project lifetime is 15 years, and the interest rate is equal to 0.05. The efficiency of the power converter and the battery are, in turn, 96 and 95 % [30]–[32]. The fuel price, constant, and variable fuel consumption coefficient for the diesel generator are also 0.8 \$/liter, 0.16 4/kW, and 0.25 \$/kWh, respectively [32]. The yearly carbon emission cap for the system is set to 2500 tons. Table 2 demonstrates cost data related to the system equipment, including investment and O&M costs [33], [34]. Finally, Table 3 offers data related to the considered commercial wind turbine technologies [35]. The hub height for the considered turbine is 50 m.

It should be noted that a maximum number of 3 turbine types are allowed for installation. The proposed mathematical model is implemented in GAMS optimization software and solved using the CPLEX solver. The case study' model possesses 91 blocks of equations and 8301 single equations. Also, it has 75 blocks of variables and 8929 single variables. It should be noted that the GAMS software calls internal Solvers for solving the optimization problem. Each Solver is itself composed of various solve procedures for specific types of optimization problems. The CPLEX Solver within the GAMS is used for solving the problem. The CPLEX optimizers are designed to solve large, difficult problems quickly and with minimal user intervention. Access is provided to CPLEX solution algorithms for linear, quadratically constrained and mixed-integer programming problems. This Solver is one of the most powerful tools for solving Mixed Integer Linear Programming (MILP) models like our proposed one. The CPLEX uses a Branch and Cut algorithm, which solves a series of LP sub-problems. There are many details beyond the Branch and Cut method, out of this paper scope, which can be found in the literature [36], [37].

IV. RESULTS AND DISCUSSIONS

The optimal sizing results of the simulation are shown in Table 4. As the results denote, the optimal desalination unit size is calculated as 68,000 m^3/day. This value indicates a maximum of 2833 m^3/h (daily desalination capacity divided by day hours) water production capacity, compared with the peak water demanded. Considering the value of 5000 m^3/h peak water demand, if the model with water and energy storage had not been used, a desalination unit with a capacity of 120,000 m^3/day (day hours multiplied by the peak water demand) would have been built. This value is comparable with the capacity found by the proposed model as the optimal size. As a result, the desalination unit's size is decreased by more than 43 %, which is a notable figure. This reduction is achieved by simultaneous sizing and optimising storage devices, namely battery energy storage and water storage tank.

The water storage tank should have a capacity of 8,100 m^3 to achieve this reduction in the water desalination unit. Also, two pumps with 2,100 and 2,200 m^3/h water pumping capacity are needed to charge and discharge the tank. By comparing the tank's capacity with the water pumps, it can be concluded that the water pumps work about 4 hours to charge or discharge the tank entirely. The total optimal capacity of all wind turbines should be equal to 17,800 kW. This figure is related

TABLE 5. Investment, O&M, and NPC cost for system components ($).

Component	IC	O&M	NPC
Wind Turbines	28,336,640	779,257	36,424,548
Diesel Generator	760,000	869,819	9,787,851
Power Converter	84,000	10,500	192,980
Battery Storage	2,280,000	8,457	2,367,775
Desalination Unit	81,600,000	6,855,975	152,758,165
Tank and Pumps	863,000	208,109	3,022,963
Total System	113,923,640	90,630,642	204,554,282

TABLE 6. Optimal sizing results for wind turbine optimization.

Item		Turbine Technology		
		t1	*t2*	*t10*
Speeds (m/s)	Cut-in	3.5	4	3
	Rated	10	9	11
	Cut-out	25	20	25
Rated Power (kW)		100	100	200
Optimal Number		60	40	39
Optimal Rating (kW)		6000	4000	7,800

TABLE 7. Simulation results for different maximum number of turbine types.

Maximum Turbine Type		1	2	3	4
Total Cost (M$)		215.732	204.965	204.554	204.554
Total Wind (kW)		18600	17600	17800	17800
Number of Turbines Selected	*t1*	-	100	60	60
	t2	-	-	40	40
	t10	92	38	39	39

TABLE 8. Conventional single turbine results versus proposed model.

Input Turbine Type		Rated Power (kW)	Optimal Number	Total Power (kW)	Total Cost	
					Value (M$)	Diff. (%)
Proposed Model		100,100,200	60,40,39	17,800	204,554	-
Conventional Single Turbine	*t1*	100	193	19,300	210,471	2.893
	t2	100	203	20,300	276,733	35.286
	t3	100	171	17,100	209,426	2.382
	t4	108	221	23,868	227,167	11.055
	t5	130	159	20,670	220,334	7.714
	t6	150	129	19,350	210,423	2.869
	t7	150	128	19,200	218,501	6.818
	t8	150	135	20,250	221,421	8.246
	t9	150	154	23,100	228,090	11.506
	t10	200	92	18,600	215,732	4.576
	t11	225	103	23,175	224,837	9.916
	t12	225	98	22050	222,687	8.865
	t13	300	64	19,200	213,790	4.515
	t14	335	57	19,095	213,723	4.482

to all turbine types installed, which will be analyzed in the following. Besides, a diesel generator with a power rating of 3,800 kW is needed to support the system. As the power converter communicates only with the battery, its optimal power rating is obtained equal to the battery's power rating, i.e., 2,100 kW. Finally, the battery's optimal energy capacity is equal to 6,200 kWh, which indicates 4 hours charging and discharging period.

Table 5 demonstrates the breakdown of the system costs for the whole system. The table presents investment cost in addition to the operation and maintenance cost of each part of the system and the whole system. As the results show, the whole system requires a 204 M$ net present cost, wherein 113 M$ should be paid at the beginning of the project. The remained value is related to the yearly O$M cost. By analyzing the results, it can be seen that the desalination unit and wind turbines impose the highest initial investment costs on the system. The share of the desalination unit is almost four times that of wind turbines. On the contrary, the highest O&M cost share is related to the desalination unit. After that, wind turbines and diesel generator place at the second rank with almost equal values. The high share of the diesel generator O&M cost is due to fuel consumption and, consequently, fuel payment.

Simulation results related to the optimal turbine type selection are presented in Table 6. The results demonstrate that due to the conditions of the problem, wind pattern, and parameters related to the turbines' types, an optimal result cannot be achieved with one type of turbine. As a result, the optimal sizing result is a combination of 3 different types, including 60, 40, and 39 turbines of t1, t2, and t10 type. The result means a 6000, 4000, and 7800 kW of investment on these turbine types. Table 7 displays how the results would have changed if the problem had allowed selecting more or fewer turbine types. As the results show, enforcing the problem to choose fewer turbine types will result in higher total system costs.

Also, by increasing the allowable number of turbine types to more than 3, the optimal results will not change. For comparison purposes, the results of the proposed model are evaluated with respect to the previous model. To this end, the model is executed similarly to the previous models. In this case, the typical data for a single turbine type is used. The results are then compared to the proposed model ones. Table 8 presents the comparison results by showing the optimal number of the input turbine models, total wind power, and total cost. As can be seen, the proposed model's total cost is considerably lower than the single turbine models. This cost reduction is achieved by less installation of the wind

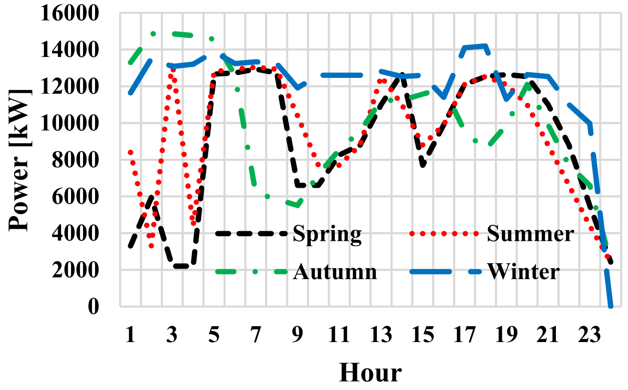

FIGURE 5. Seasonal hourly power produced by the wind turbines.

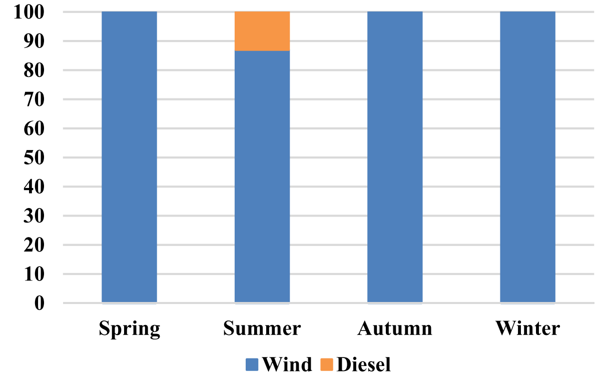

FIGURE 7. Share of power production from wind and diesel generator [%].

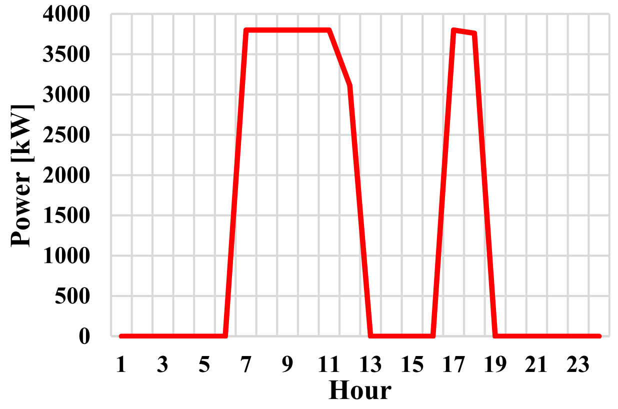

FIGURE 6. Hourly power produced by the diesel generator (summer).

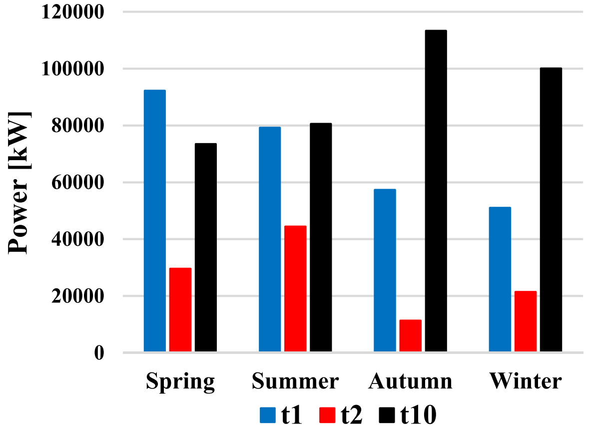

FIGURE 8. Total yearly power generated by each turbine type.

turbines, namely 17,800 kW. The total system planning cost will be at least 209,426 M$ using a single turbine model, meaning 2.382 % higher NPC than the proposed model.

Figure 5 presents the hourly power produced by the wind turbines for each season. Also, Figure 6 demonstrates the power generated by the diesel generator. It should be noted that the diesel generator contributes in the power generation only in summer, when wind speed and generated power has the minimum values. As in the figures, power generation by the wind turbines in the winter is considerable. Although wind power production is lowest in the autumn, water demand is also relatively low at this season. As a result, diesel power is not required. According to the figures, the power generation by wind turbines is lower than the demand for water desalination and therefore, water desalination energy consumption in the summer is not entirely met by renewable energy. This has led to the diesel generator's power production during critical hours, namely 6 to 13 and 16 to 19. This power production by the diesel generator has been led to 2227 tons of carbon emissions in the whole year.

Figure 7 depicts the share of each resource for all seasons of the year. As the figure shows, the diesel generator produces power, with about 12 % of the total generated power only in the summer. The other seasons of the year clean energy produced from the wind are used to supply water desalination unit and water tank pumps. Figure 8 demonstrates the total power produced by each turbine type for each season. As the figure denotes, the power produced by the turbines is different for various seasons. This is due to the wind speed variability and also turbine parameters. In this regard, in the spring, turbine type t1 generates the highest power in the wind park. Conversely, in autumn and winter, the turbine type t10 constitutes the most generated power.

Last but not least, Table 9 presents the status of the water balance in the system. In other words, the amount of water generated, demanded, charged, and discharged for each season is tabulated. As the results denote, the water demand profile peak is shaved for all seasons by utilizing and optimizing water storage. This, in turn, helps to level the water production profile. Also, the figures indicate that three cycles of water charging and discharging are used. The first cycle, which is the most important one, is performed to supply water at the first peak water initial hours of the morning. Accordingly, the required water is charged previously during the initial hours of the day. After that, two smaller water charging and discharging cycles are performed. The first one is to supply at the noon hours' water demand, and the second one is for the initial hours of the night. This cyclic water storage operation is optimized to achieve the minimum cost

TABLE 9. Seasonal hourly generated, demanded, charged, and discharged water (1000 m^3).

h	Gen	Dem	Cha	Dis	Gen	Dem	Cha	Dis
	Spring				Summer			
1	2.8	0.8	2.1	0.0	1.4	0.8	0.7	0.0
2	2.8	0.8	2.1	0.0	0.5	0.5	0.0	0.0
3	0.8	0.8	0.0	0.0	0.5	0.5	0.0	0.0
4	1.1	1.0	0.1	0.0	0.5	0.5	0.0	0.0
5	1.5	1.5	0.0	0.0	2.8	1.0	1.8	0.0
6	2.8	4.0	0.0	1.2	2.8	3.5	0.0	0.7
7	2.8	4.5	0.0	1.7	2.8	4.0	0.0	1.2
8	2.8	4.3	0.0	1.4	2.8	3.5	0.0	0.7
9	2.0	2.0	0.0	0.0	1.5	1.5	0.0	0.0
10	2.0	2.0	0.0	0.0	1.5	1.5	0.0	0.0
11	2.0	2.0	0.0	0.0	1.8	1.8	0.0	0.0
12	2.7	2.3	0.4	0.0	2.0	2.0	0.0	0.0
13	2.8	3.3	0.0	0.4	2.8	2.5	0.3	0.0
14	2.8	2.8	0.0	0.0	2.8	2.2	0.6	0.0
15	2.7	2.3	0.4	0.0	1.9	1.8	0.2	0.0
16	2.8	2.5	0.3	0.0	2.3	2.3	0.0	0.0
17	2.8	3.0	0.0	0.2	2.8	2.8	0.1	0.0
18	2.8	3.3	0.0	0.4	2.8	3.0	0.0	0.2
19	2.8	3.0	0.0	0.2	2.6	3.3	0.0	0.6
20	2.8	2.8	0.0	0.0	2.6	3.0	0.0	0.4
21	2.3	2.3	0.0	0.0	2.5	2.5	0.0	0.0
22	1.8	1.8	0.0	0.0	2.0	2.0	0.0	0.0
23	1.5	1.5	0.0	0.0	1.3	1.3	0.0	0.0
24	0.6	0.6	0.0	0.0	0.6	0.6	0.0	0.0
h	Autumn				Winter			
1	1.9	1.0	0.9	0.0	1.4	0.8	0.7	0.0
2	2.8	0.8	2.1	0.0	0.5	0.5	0.0	0.0
3	1.5	0.8	0.8	0.0	0.5	0.5	0.0	0.0
4	1.0	1.0	0.0	0.0	0.5	0.5	0.0	0.0
5	2.0	2.0	0.0	0.0	2.8	1.0	1.8	0.0
6	2.8	4.0	0.0	1.2	2.8	3.5	0.0	0.7
7	2.8	4.3	0.0	1.4	2.8	4.0	0.0	1.2
8	2.8	4.0	0.0	1.2	2.8	3.5	0.0	0.7
9	2.0	2.0	0.0	0.0	1.5	1.5	0.0	0.0
10	1.8	1.8	0.0	0.0	1.5	1.5	0.0	0.0
11	1.8	1.8	0.0	0.0	1.8	1.8	0.0	0.0
12	2.3	2.0	0.3	0.0	2.0	2.0	0.0	0.0
13	2.8	3.0	0.0	0.2	2.8	2.5	0.3	0.0
14	2.5	2.5	0.0	0.0	2.8	2.2	0.6	0.0
15	2.0	2.0	0.0	0.0	1.9	1.8	0.2	0.0
16	2.3	2.3	0.0	0.0	2.3	2.3	0.0	0.0
17	2.8	2.8	0.0	0.0	2.8	2.8	0.1	0.0
18	2.8	3.0	0.0	0.2	2.8	3.0	0.0	0.2
19	2.8	2.8	0.0	0.0	2.6	3.3	0.0	0.6
20	2.5	2.5	0.0	0.0	2.6	3.0	0.0	0.4
21	2.0	2.0	0.0	0.0	2.5	2.5	0.0	0.0
22	1.5	1.5	0.0	0.0	2.0	2.0	0.0	0.0
23	1.0	1.0	0.0	0.0	1.3	1.3	0.0	0.0
24	0.6	0.6	0.0	0.0	0.6	0.6	0.0	0.0

of water desalination and storage requirements. The simulation results show that commercial wind turbines' modeling and optimization will reduce the system's total cost. Also, variable consideration of the desalination unit's size and its optimization has significantly reduced the entire system's cost.

Reduction of the size of the desalination with respect to the peak demand for water consumption has been achieved by modeling and optimal sizing of the water storage tank as well as the energy storage battery. The use of these two storage devices, battery energy storage and water storage, will also increase water supply security. Because in cases when the desalination plant cannot produce water for any reason, part of the water demand can be met from the water storage tank. Also, if components related to energy production such as wind turbines and diesel generator cannot produce the required energy, the battery can provide the required energy up to the stored value. As a result, previously stored freshwater and electrical energy are available for emergency cases.

V. CONCLUSION

Utilizing desalination plants can be a fundamental solution to overcome the global crisis of water. Using renewable resources to supply these units can also solve the problems of providing cheap and clean energy. Accordingly, in this paper, an optimal installation model of a wind-powered desalination unit is presented. In addition to the number of wind turbines, the optimal type will also be selected from a predetermined list of commercial models with different technical and economic factors. A diesel generator and a battery energy storage are also used to support wind turbines in critical hours in terms of power production shortage.

Furthermore, a water storage tank is integrated with the water desalination unit to flatten the water production pattern. The reliability of water supply and carbon emission have been modeled and limited. The simulation results of the proposed model on a case study show that considering the variety of turbines reduces the system's total cost. The diesel generator works at a limited hour of the day, resulting in lower carbon emissions.

The desalination plant's size will be reduced by 43% concerning the peak water demand based on the simulation results. This reduction in the desalination capacity will be achieved by the joint water and energy storage for a duration of about 4 hours. Additionally, a combination of three different commercial wind turbines is optimal with respect to the cost and technical performance. Using the proposed multi-turbine model has resulted in a 2.38 to 35.28 % reduction in the conventional single turbine model's total cost concerning the employed turbine type. The limitation of this study in terms of uncertainty management can be addressed as future work. Besides, the effect of selecting other new types of turbines, namely invelox turbine, can be addressed.

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