Hybrid strategy for optimal scheduling of an integrated electrical water distribution system in presence of water and power producer under uncertain electricity price based on stochastic/robust approach

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Recently, seawater desalination is known as a way to face water distribution network challenges related to increasing water demand. A seawater desalination process generally requires a significant amount of heat generated by an electrical energy source. Therefore, the combined water and power (CWP) generating units are applied to reduce the electrical consumption of seawater desalination processes. In the CWP units, the heat energy required for seawater desalination is supplied by using the waste heat of the flue gases exhausted from the power generation part. Therefore, it is highlighted that the freshwater of the CWP unit is dependent on the amount of electrical power generated by this unit. The CWP power generation is usually related to the electrical price in separated electrical and water distribution networks. However, this value can be scheduled based on the value of water demand and electrical price in an integrated electrical-water distribution network. In this paper, a hybrid scheduling model based on stochastic/robust is proposed to minimize the operation cost of an integrated water-electrical system by considering the uncertainty of electricity price and technical constraints of electrical and water distribution systems. The proposed hybrid scheduling model is solved based on the price information obtained by executing an interval forecasting model. In other words, the upper and lower bound of price is forecasted in an interval forecasting model. Then, such parameters are used to find the worst of integrated electrical-water distribution systems against the electrical price uncertainty.

keywords: *Integrated electrical and water networks, combined water and power generating unit, robust /stochastic scheduling*

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NOMENCLATURE

Indices

n	nth distribution bus
s	Scenario
t	Scheduled time
CWP	Combined water and power (CWP) generating
Ro	Water reservoir

Parameters

π^s	Scenario probability
λ_t^w	Fresh water price
λ_t^e	Price of purchased electrical power
$\bar{\lambda}_t$	Forecasted electrical price value

$\hat{\lambda}_t$	Maximum devotion of electrical price value
Γ	Robust budget
a	Quadratic coefficient cost of water and electricity generation cost
b	Linear coefficient cost of water and electricity generation cost
c	Quadratic coefficient cost of water and electricity generation cost
d	Linear coefficient cost of water and electricity generation cost
e	Linear coefficient cost of water and electricity generation cost
f	Constant coefficient cost of water and electricity generation cost
$W_{cwp}^{\min}$	Minimum amount of CWP fresh water output
$W_{cwp}^{\max}$	Maximum amount of CWP fresh water output
$R_{cwp}^{\min}$	Minimum ratio of generated power to fresh water
$R_{cwp}^{\max}$	Maximum ratio of generated power to fresh water
$p_{cwp}^{\min}$	Minimum CWP electrical power output
$p_{cwp}^{\max}$	Maximum CWP electrical power output

1. INTRODUCTION

A. Motivation

Nowadays, the scarcity of freshwater resources is one of the major concerns of governments. Authors of reference[1] argued that water scarcity, the limited value of fossil fuels for electrical power generation, and environmental pollution are three major challenges of 40 of the global population. Also, the authors of reference[1, 2] reported that the electrical and water demands are increased about %80 and%50, respectively at 2050. The first published application of microwave rectifiers for extraction of DC power was performed in the 1960's using diode-based rectifiers.

Also, it is cleared that the safe operation of a water distribution network is dependent on the electrical distribution network. The reason for this fact is the presence of variable speed pumps, supplied by the electrical distribution network in the water distribution network. Such pumps are located for responding to the water demands in all of the water network nodes. Also, a way to face water scarcity is seawater desalination. The seawater desalination units generally are a major electrical consumption. In such units, electrical energy is used to provide the heat required for water purification.

A novel technique to reduce the electrical consumption in the seawater desalination units is combining such units with the thermal power generation units. In the combined system, the waste heat of the flue gases exhausted from the power generation is applied for the seawater purification. Therefore, the electrical power consumption of a seawater desalination unit can be omitted. Such units are known as combined water and power (CWP) generating units.

However, it is cleared that the volume of freshwater obtained based on CWP is dependent on the power generation value. Therefore, the optimal scheduling of a CWP unit needs to consider both electrical and water distribution network conditions. Also, as mentioned above, the water distribution system is a large consumer of electrical distribution system due to the presence of variable speed water pumps. Therefore, providing a model including the constraints of the electrical distribution and water distribution systems can reduce the total operation cost of both systems. This model is known as the integrated electrical-water distribution system. The authors of reference[4] presented a study, which can lead to providing an integrated electrical-water distribution system. In this study, the benefit of participation of a water distribution system in electrical demand response programs is maximized. The results of this study indicate the significant effect of the water distribution system on the electrical distribution system. In similar studies, different scheduling models of variable speed water pumps were proposed based on the electrical price deviations to reduce the total operation cost of a water distribution system in [5–7]. Finally, the authors of reference[8] presented a power-water flow model for co-optimizing the operation of water systems by considering the operation of both electrical and water distribution networks. In other words, this study proposed an integrated electrical-water distribution system. In the integrated electrical-water distribution system, the variable speed water pumps, water storage tanks were scheduled to minimize the total operation cost of the integrated distribution system.

This study was improved by reference[9]. This reference tried to highlight the benefit of considering an integrated electrical-water distribution system. For this aim, this reference presented a mathematical model of an integrated micro electrical-water system. The results of the proposed model for an integrated electrical-water system were compared by results obtained by considering a separated electrical-water distribution system and concluded that the total operation cost can be significantly decreased by considering the integrated system. Also, the impact of the electrical storage unit on the operation cost of an integrated electrical distribution system was investigated in this reference.

B. Literature Review

There are considerable publications for investigating CWP generation units from different viewpoints. Such studies can be classified into two major groups. In the first group, the researchers focused on designing a novel CWP unit to reduce fuel consumption or increase the volume of freshwater procedure. In[10], a mathematical optimization model was proposed to design a CWP plant by considering the electrical and water demand. The components considered for designing the proposed CWP plant included power generation capacity, multistage flash (MSF), and reverse osmosis (RO). The proposed mathematical model of this reference was solved by using a modified genetic algorithm with mixed coding. At last, this study concluded that if the volume of water demand is lower than 8000 m3/h, the combined thermal power unit with extraction steam turbine and MSF is the optimal design. If the volume of water demand is higher than 8000m3/h, the combined thermal power plan with backpressure steam turbine, MSF and RO is the optimal design. In[11], a small-scale thermal desalination system is designed. Also, the Authors of reference[12] presented an optimal design of the CWP unit included RO and MSF by considering the maximization of CWP owner profit. In[13], the application of the wave energy-powered desalination plant on the facing with water scarcity of Canary Islands is investigated. This reference combined a renewable power generation source with desalination components. Authors of reference[14] provided an optimal renewable-based CWP plant. This study combined the grid-tied and off-grid solar PV/diesel generator/battery/inverter and seawater desalination instrument for the construction of a novel CWP plant. In[15], performance analysis of combined humidified gas turbine power generation and multi-effect thermal vapor compression desalination systems is investigated. At last, the Authors of reference[16] presented a comprehensive review of the hybrid desalination study. In the second group of CWP studies, authors attempted to find the optimal CWP scheduling for maximizing the CWP owner profit. In[17], a dynamic optimization model was presented to find optimal scheduling of thermal units, combined heat and power units, CWP plants. In this study, the desalination plants and CWP unit was co-dispatched to ensure that the water demand was supplied. In the other paper of this group, authors of reference[18] used the information gap decision theory for making a robust or risk-aversion schedule of the multi-generation system. The uncertainty sources considered in this reference were included the load and climatic condition. In[19], a robust technique is used to find optimal self-schedule of a CWP to model the uncertainty of electrical price without knowing the probability density function of electrical price uncertainty. This study tries to maximize the profit of CWP unit. In[20], a self-scheduling model for multi-energy customers is proposed by considering multiples uncertainty set. Also, this reference models the service shifting among energies. To simulate the uncertainty of the power demand in optimal system operation, the authors in[21] have used an information gap decision theory method to attain a robust optimal operation of multi-carrier networks considering power, gas, heat, and water carriers. In[22], the impact of interconnections among energy sources, also known as multi-carrier energy systems, on the operation of energy networks is investigated considering gas, power, heating, and water energy sources.

C. Contribution and Paper Structure

According to the above description, it can be highlighted that the researchers provide different optimization models for self-scheduling of the CWP unit. Also, such self-scheduling of the CWP plant can meet the uncertainty sources. However, the impact of constraints of electrical and water distribution systems such as distribution line congestion, limitation of water distribution arcs flow on CWP scheduling are ore not investigated. In this paper, a stochastic/robust scheduling model is proposed to minimize the operation cost of an integrated water-electrical system by considering the uncertainty of electricity price, electrical and water demands, and technical constraints of electrical and water distribution systems.

The remainder of this paper is organized as follows: Section 2 presents the mathematical formulation of the proposed model. Section 3 describes case studies. Simulation results are also discussed in this section. Finally, conclusions are drawn in Section 4.

2. PROBLEM FORMULATION

In this section, the mathematical model of the proposed stochastic-robust scheduling of an integrated electrical water distribution system considering a combined water and electrical producer unit is provided. The goal of this model is to minimize the operation cost of the integrated electrical water distribution network by considering the worst-case of electrical price uncertainty and all of load scenarios. In this paper, Monte Carlo simulation is used to generate a set of possible electrical and water demand scenarios by normal distribution, which is described in[23]. A way of scenario reduction is clustering technique[24]. In this paper, a multi-objective clustering method, which is able to determine optimal size of reduced scenario, is applied to scenario reduction. This scenario reduction technique is described in[25]. In this model, the electrical load should be supplied with electrical power purchased in the electrical market and the output of the combined water and electrical producer unit. Also, the reservoir water source and freshwater provided in the combined water and electrical producer unit are used to supply the water demand. The load and water demand uncertainties are modeled by stochastic model. At last, the robust budget is considered to tune the worst-case conditions. In the robust budget, the variance of the uncertainty variable (energy price) is controlled from the forecasted value. As a result, the problem is finding the worst time to deviate energy prices from the predicted value. According to the explanations given, the objective function of the problem can be written as:

$$Min(\sum \pi^{s} \times (\sum_{t} C^{t,s}_{CWP} + \sum_{t} \lambda^{w}_{t} W^{t,s}_{ro} + \max(\sum_{t} \lambda^{e}_{t} P^{t,s}_{po}))) \tag{1}$$

Two terms are used to construct the robust short-term scheduling of the integrated electrical water distribution network objective function. In the first term, the operation cost of the combined water electrical producer unit and the reservoir freshwater cost is minimized. In this term, the operation cost of the combined water electrical producer unit, the fresh water price, and the water injected by the water reservoir are illustrated by $C^{t,s}_{cwp}$,λ^{w}_{t},and$W^{t,s}_{ro}$ respectively. In the second term of objective function, the worst-cost of purchased power is minimized. This term is constructed by a maximization problem to find the worst case of electrical price deviation from forecasted value. In this term, the price of purchased electrical power and the purchased power are represented by λ_t^e andP_{po}^t, respectively.

This objective function should be minimized by satisfying the economic and technical constraints of each component of the integrated electrical and water distribution system network. Such constraints are described in the following:

A. Robust constraints

In the first step of the robust condition constraint description, the price of purchased electrical power is divided into two terms. The first term is used to consider the forecasted electrical price. In the second term, the value of price deviation at each time is modeled. The price deviation value should be lower than the maximum value of deviation, which is obtained based on the interval forecasting results. Also, the total price deviation should be equal to or lower than the robust budget. Therefore, the worst-case condition can be set by changing the robust budget. If the robust budget is set as zero, the robust scheduling model results are equal to deterministic scheduling model results. In other words, the electrical price uncertainty is not considered in the mentioned condition. When the robust budget is considered as (24), the robust scheduling model should be able to consider maximum price deviation for each scheduling time. According to the above description, the mathematical model of electrical price can be written as (2). In this equation, the forecasted electrical price value and the maximum devotion of electrical price value carried out by using an interval forecasting model are illustrated by$\bar{\lambda}_t$ and$\hat{\lambda}_t$, respectively. Also, the deviation price value is controlled by using a decision variable indicated byz_t . This variable can be assigned between 0 and 1 for each time by considering the optimization conditions. For instance, if this variable is equal to zero, the deviation of electrical price is considered as zero at this time. The mentioned limitation is represented in (3). At last, constraint (4) is formulated to model the robust budget. It should be noted that such limitations should be considered in the second term of objective function. This term of objective function is a maximization problem to find the value of that the objective function is maximized in the conditions.

$$\lambda_t = \bar{\lambda}_t + z_t^s \hat{\lambda}_t \tag{2}$$

$$\lambda_t = \bar{\lambda}_t + z_t^s \hat{\lambda}_t \tag{3}$$

$$\sum \sum_t \pi^s z_t \leq \Gamma \tag{4}$$

B. Combined water and electrical producer unit limitation

The cost of this unit depends on the value of electrical power generated and the value of fresh water output. Therefore, the mathematical model of a combined water and electrical producer unit can be calculated by using (5). In this equation, a, b, c, d, e, and f are water and electricity generation cost coefficients of a combined water and electrical producer unit. Also, the output fresh water and electrical power generation output are illustrated by$W_{cwp,i}^{t,s}$ and $P_{cwp,i}^{t,s}$, respectively.

The maximum / minimum fresh water by these power plants at time t is shown in (6). In this regard, the minimum and maximum amount of fresh water of this plant are shown with $W_{cwp}^{\min}$ and$W_{cwp}^{\max}$, respectively. The electrical production capacity limit of this power plant is shown in Equation (7). Finally, the constraints on the ratio of generated power to fresh water, which must be in a range, are modeled in Equation (8). The minimum and maximum values of this ratio are also shown with$R_{cwp}^{\min}$ and$R_{cwp}^{\max}$. These parameters depend on the power plant and desalination equipment and the salt concentration of the water in the area.

$$C_{CWP}^{t,s} = \sum_j \begin{array}{l} (aP_{cwp,i}^{t,s^2} + bP_{cwp,i}^{t,s} W_{cwp,i}^{t,s} + cW_{cwp,i}^{t,s^2} + \\ dP_{cwp,i}^{t,s} + e_j W_{cwp,i}^{t,s} + f_j) \end{array} \tag{5}$$

$$W_{cwp}^{\min} \leq W_{cwp,i}^{t,s} \leq W_{cwp}^{\max} \tag{6}$$

$$P^{\min} \leq P_{cwp,i}^{t,s} \leq P^{\max} \tag{7}$$

$$R_{cwp}^{\min} \leq \frac{P_{cwp,i}^{t,s}}{W_{cwp,i}^{t,s}} \leq R_{cwp}^{\max} \tag{8}$$

C. Electrical grid constraints

The limitations connecting two networks is the electrical power balance. In this constraint, the generation and injection power of each electrical bus is equal to the load demand and extraction power of the mentioned bus. The water pump demand is considered in this constraint. The power balance of an integrated electrical- water system is formulated based on DistFlow model. The nonlinear form of this model is formulated as:

$$\sum_{h|(i,j)\in L} p_{hi}^{t,s} = p_{ij}^{t,s} - P_i^{d,t,s} + P_{cwp,i}^{t,s} + P_{po,i}^{t,s} - P_{k,i,t}^{pump,s} \tag{9}$$

$$\sum_{h|(n,h)\in L} q_{nh,t,s} = q_{mn,t,s} - x_{mn} \frac{p_{mn,t}^{s2} + q_{mn,t}^{s2}}{v_{n,t}^2} - Q_{n,t,s} \tag{10}$$

In such equations, the active and reactive power flow of line-connected buses n-h and m-n is shown byp_{nh} and , respectively. The impedance and reactance of such lines are modeled by using r_{ij}, x_{ij} . The active and reactive load power located at the nth distribution bus is illustrated by P_n and Q_n, respectively.The power consumption of water pump connected into nth bus of electrical system is illustrated by $P_{k,n,t}^{pump}$. Other electrical technical limitations are provided as:

$$v_j^{t,s^2} = v_i^{t,s^2} - 2(r_{ij} p^{t,s}{}_{ij} + x_{ij} q^{t,s}{}_{ij}) + (r_{ij}^2 + x_{ij}^2)(\frac{p_{ij}^{t,s^2} + q_{ij}^{t,s^2}}{v_i^{s^2}}) \tag{11}$$

$$v_n^{\min} \leq v_n^{s,t} \leq v_n^{\max} \tag{12}$$

$$-P_{nh}^{\max} \leq p_{nh,t,s} \leq P_{nh}^{\max} \tag{13}$$

$$-Q_{nh}^{\max} \leq q_{nh,t,s} \leq Q_{nh}^{\max} \tag{14}$$

Where, the bus voltage of the nth distribution bus is modeled by . The voltage of jth bus is calculated based on the voltage of previous bus, which is connected into jth bus by i-j distribution line. In (11),$v_i^{t,s}$ is the voltage of previous distribution bus, connected by i-j distribution line into jth bus. Constraint (12) is formulated to consider that the bus voltage is lower than its maximum value and higher than its minimum value. Constraints (13) and (14) are formulated to ensure that the electrical line is operated in the safe conditions.

D. Water network constraints

The technical constraints of water distribution system are provided as:

$$P_{k,t}^{pump,s} = \Omega_{k,t,s}^{3}(d_k - e_k(\frac{1}{\Omega_{k,t,s}}W^{s}{}_{ij})) \tag{15}$$

$$\Delta h_{p,k,t,s} = \Omega_{k,t,s}^{2}(a_k - b_k(\frac{1}{\Omega_{k,t,s}}W^{s}{}_{ij})^{c}) \tag{16}$$

$$\sum_{ij=1}^{m} A.W_{ij}^{t,s} + W_{i}^{T,t,s} + W_{i}^{R,t,s} + W_{cwp,i}^{t,s} = W_{i}^{D,t,s} \tag{17}$$

$$W^{t,s}{}_{ij} \geq 0 \tag{18}$$

$$W_{\min}^{R} \leq W_{t}^{R,s} \leq W_{\max}^{R} \tag{19}$$

$$H_{j,t,s} - H_{i,t,s} - (Z_j - Z_i) + \Delta h_{p,k,t,s} = F_{ij}Q_{ij}^{t,s1.85} \tag{20}$$

$$W_{\min}^{T} \leq W_{i,t}^{T,s} \leq W_{\max}^{T} \tag{21}$$

$$V_{i,t}^{T,s} = V_{i,t}^{T,s} + Q_{i,t}^{T,s} \tag{22}$$

$$V_{\min}^{T} \leq V_{i,t}^{T,s} \leq V_{\max}^{T} \tag{23}$$

In such constraints, the power consumption of water pumps is calculated according to (15). The use of water network pumps increases the pressure at the end of the pipe and facilitates the transfer of water between the nodes of the water network. The amount of pressure increase by water network pumps is calculated in relation (16). The injection pressure of water pump and the water pump consumption are illustrated by $\Delta h_{p,k}$and P_{k}^{pump}, respectively. The water pump characterizations are accounted by using ak, bk, ck, and dk. Also, it is cleared that the water pump consumption and injection pressure are related to pump speed at time t. In the mentioned constraints, the pump speed of kth pump is modeled by Ω_k . Also, the pipe water flow connected ith and jth nodes of water distribution is represented by Wij. The water balance constraint is shown in Equation (21). The water storage tank flow and water reservoir are shown by WT and WR, respectively. Also, the water load demand is represented by WD. The amount of water passing through the water pipes depends on the pressure of the nodes connected to it and also the height of each node, which is obtained in Equation (20). In this equation, the pressure of ith node and the height of the mentioned node are illustrated by Hi and Zi, respectively. Also, Fij is used to model the head loss of a pipe. This factor can be calculated based on Hazen-Williams equation b (24)[26]. The inlet and outlet water volume of water storage tanks must be in a suitable range and equal to zero in the event of an attack, which is the limit in equation (21). In this equation, the minimum and maximum water flow of water storage tank are shown by $W_{\min}^{T}$ and $W_{\max}^{T}$, respectively. The water storage volume is updated based on (22). In this equation, the water storage volume is illustrated by $V_{i,t}^{T}$. Also, it should be noted that the water storage tank flow is a free variable. Therefore, the positive value of it is used to model inlet water into storage tank. The negative value of it models the outlet water of storage tank. At last, the water volume of water storage tank should be higher than the maximum value of storage tank be lower than the minimum value of the storage tank. This constraint is formulated in (23). In this equation, the minimum and maximum volume of water storage tank are shown by $V_{\min}^{T}$ and $V_{\max}^{T}$, respectively.

$$F_{ij} = \frac{L_{ij}}{(0.278 \times C \times D_{ij}^{2.63})^{1.85}} \tag{24}$$

The length and diameter of the pipe connecting nodes I and j are modeled by L_{ij} and D_{ij} , respectively. Also, C is the friction factor of the pipe, assumed to be 100 for this study, which is the factor for a 20-year old cast iron pipe.

3. SOLUTION PROCEDURE

The objective function of an interconnected water and electricity network robust optimization by considering distributed generation power plants can be rewritten as the equation shown in (25). According to this equation, the first part of the objective function is a minimization problem that the decision variables of the minimization problem include production capacity and volume of fresh water by the cogeneration plant, flow through distribution network lines, water flow through water network pipes, pressure Each node of the water network is the volume and flow of inlet / outlet of water storage tanks, the amount of water withdrawn from the water basin and also the speed of the variable speed pumps in the water network. While the decision variable of the maximization problem includes the z_t variable.

$$\begin{aligned} &Min(\sum \pi^{s} \times (\sum_{t} C_{cwp}^{t,s} + \sum_{t} \lambda_{t}^{w} W_{ro}^{t,s} + \\ &\min \max_{z_t} \sum_{t} (\bar{\lambda}_t + z^{s}{}_{t}\hat{\lambda}_t) P_{po}^{t,s} \end{aligned} \tag{25}$$

The objective function written in Equation (25) cannot be solved by using conventional optimization methods due to the existence of a min-max problem. For solving the proposed robust scheduling problem, Karush Kuhn Tucker (KKT) condition or the dual problem is applied to convert the min-max problem into a min-min problem that can be solved by using conventional optimization methods. For this purpose, it is necessary to write the dual problem shown in (26).

$$\begin{aligned} &\max_{z_t} \sum_{t} (\bar{\lambda}_t + z^{s}{}_{t}\hat{\lambda}_t) P_{po}^{t,s} \\ &0 \leq z^{s}{}_{t} \leq 1 \\ &\sum_{t}\sum \pi^{s} z_t \leq \Gamma \end{aligned} \tag{26}$$

Since this optimization problem involves a decision variable, the written dual problem must contain a constraint. Also, given the number of problem constraints shown in Equation (26), which is equivalent to 2 constraints, the number of dual problem decision variables is equal to 2 variables. The dual problem of optimization problem is formulated in

(27). In this constraints, ξ is the dual variable related to the constraint (3). Also, is the dual variable of robust budget constraint shown in(4).

$$\begin{aligned} &\min \sum_t \Gamma\beta + \xi_t \\ &\Gamma\beta + \xi_t \geq \hat{\lambda}_t P_{po}^t \\ &\beta, \xi \geq 0 \end{aligned} \tag{27}$$

The final objective function can be written as (28). This objective function should be minimized as well as satisfied the combined water and electrical producer unit limitation, electrical and water grid constraints and constraint illustrated in (28).

$$Min \sum_t C_{cwp}^t + \sum_t \bar{\lambda}_t P_{po}^t + \sum_t (\Gamma\beta + \xi_t) \tag{28}$$

$$\Gamma\beta + \xi_t \geq \hat{\lambda}_t P_{po}^t \tag{29}$$

4. CASE STUDY AND DISCUSSION

In this section, an integrated electrical and water distribution system is used to prove the performance of the proposed scheduling model in modeling the electrical price uncertainty. Also, the impact of combined water and power generation system on the total operation cost of integrated water and electrical distribution system is highlighted. For this aim, the IEEE 33-bus test system is considered as the electrical distribution system. In the electrical test system, the electrical demand should be supplied by power purchased from the electrical market and the power output of the combined water and power generation unit. In addition, the 15-node water distribution is used to model the water distribution system. This test system includes 15 nodes and 14 arcs. As mentioned in the problem formulation, a water distribution system is connected to an electrical distribution system by using the variable speed water pump units. Such pumps should be considered in a water distribution system to satisfy the head pressure of each water distribution node for increasing the water flow of arcs. In the test study, three variable water pumps are considered and installed in the 1st, 4th, and 7th arcs. The electrical consumption of water pumps is supplied by using the electrical distribution system. These pumps are located on the 10th, 23th, and 33rd electrical buses. The water test system includes two water storage tanks located in the 10th and 13th water nodes to increase the flexibility of the water distribution system. The water test system should supply the residential, commercial, and industrial water demands. Such demands are located in the 4th, 11th, and 15th nodes of the water distribution system. At last, a freshwater reservoir located in the 1st and a combined water and electrical generation unit installed in the 6th water node are used to respond to the water distribution demands. The characteristics of the water pump unit considered in this study are reported in Table 1. Also, the water storage tank data is illustrated in Table 2. Table 3 presents the characteristic of the combined water and electrical generation unit, which is connected to the 23rd electrical distribution bus. Also, the water distribution system data can be found in[27]. At last, the probability of scenarios reported in Table 4. In addition, the electrical point forecast and interval forecast curves are depicted in Fig.1. The proposed model is a mixed integer nonlinear problem, which is implemented in general algebraic mathematical modeling system (GAMS) and solved by using convex over and under envelopes for nonlinear estimation (COUENNE) solver.

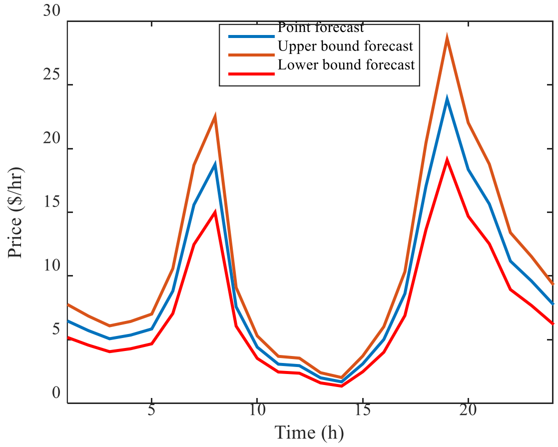

Fig. 1. Fig.1. the forecasted values, upper bound and lower limit of the electricity prices.

The expected of electrical power purchased from the electrical power market is illustrated in Fig. 2. This figure is depicted by considering two conditions. In the first condition, the CWP unit is considered. Also, the second condition is modeled to highlight the impact of CWP on the electrical power purchased from the electricity market. According to this figure, it can be pointed out that the amount of energy purchased is significantly increased in the second conditions. In the mentioned condition, the purchased power from the electricity market is the only electrical power source. Therefore, it is expected that the purchased electrical power is higher than the first condition to cover the CWP power output. However, it should be noted that the difference between the two mentioned conditions is higher than the CWP power output. The reason for this is to increase the power consumption of the variable speed pump installed near the network water reservoir because the total volume of water required must be provided by this freshwater source, so more water must pass through the pipe connected to this pump. Therefore the electrical demand of this pimp is increased. The expected extra power of this pump is shown in Fig. 3. The expected operation cost of each electrical source for different times is illustrated in Fig.4. In this figure, the cost of purchased power from the electricity market, CWP cost, which is included the electrical power generation and the freshwater output of CWP, and total operation cost for each operation time can be compared. Also, the total operation cost with/without considering the CWP unit is depicted in this figure. According to this figure, the impact of CWP unit on total operation cost reduction is highlighted. This unit can be reduced the total operation cost of the studied case study at all of the operation horizons. The expected of power and freshwater production by the CWP unit for the operation time is reported in Table 5. In order to evaluate the performance of the CWP unit, the ratio between power and

Table 1. Characteristics of water pump units

Pumps	a	b	c	d	e
	(m/rpm^2)	$(m/(rpm)m^3)$		$(KW/(rpm)^3)$	$(KW/(rpm)^2.m^3)$
P1	178	95	2	295	134
P2	178	42	2	295	134
P3	178	30	2	295	134

Table 2. Table 2. Characteristics of water storage tanks

Tanks	Volume	Maximum Charge/Discharge Flow Rate
	(m3)	(m3/hour)
T1	5000	720
T2	5000	720

Table 3. Characteristics of combined water and electrical generation unit

Parameter	a	b	c	d
	e	f	Pmin	Pmax
	Wmin	Wmax	Rmin	Rmax
Value	0/434	0/435	0/325	-3/106
	-4/126	937/4	10	800
	10	200	4	15

Table 4. Probability of scenarios

Scenario	Probability	Scenario	Probability
S1	8/3549	S9	9/8191
S2	9/2888	S10	9/8948
S3	1/3022	S11	1/6163
S4	9/3665	S12	9/9533
S5	6/4848	S13	9/8156
S6	1/0003	S14	4/9775
S7	2/856	S15	8/2068
S8	5/6082	S16	1/455

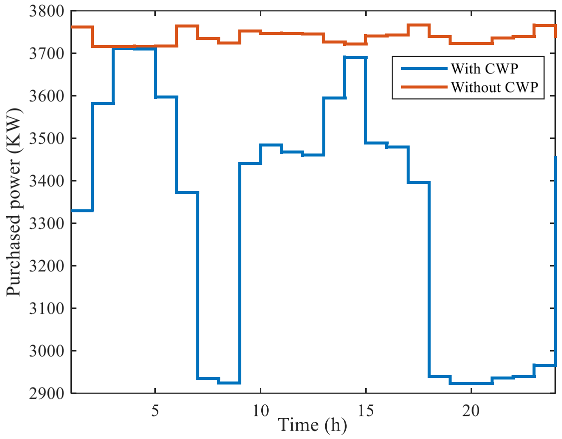

Fig. 2. Fig.2. Expected purchased power from the network in the state with and without CWP unit

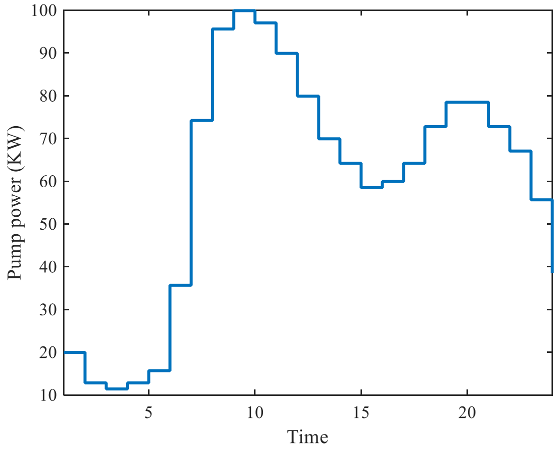

Fig. 3. Fig.3. Expected extra power of variable speed pump connected to fresh water reservoir

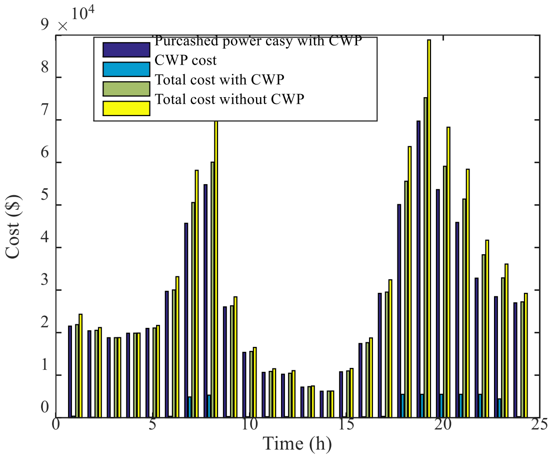

Fig. 4. Fig.4. the expected operation cost of each term of objective function with/ without CWP

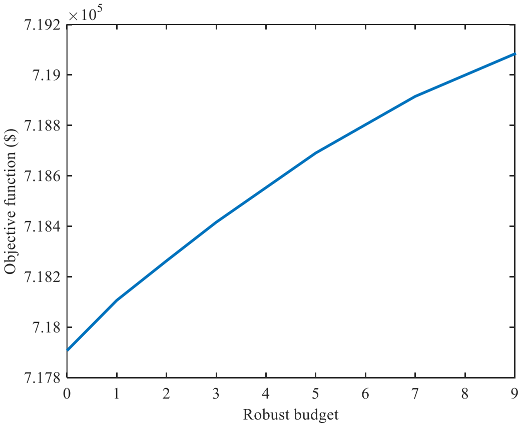

Fig. 5. Fig. 5. Impact of robust budget on the expected total operation cost

water has been reported to validate the proper simulation performance of CWP power plants. Based on the results shown in this table, the amount of production capacity and freshwater over the whole range is simulated in the range of 4 to 15, which shows the accuracy of modeling the CWP power plant.

Figure 5 shows the effect of robust budget on increasing the expected total operation cost. For this purpose, the robust budget has been changed from 0 to 9 and the objective function of the optimization problem has been drawn. As it turns out, it can be concluded that increasing the robust budget increases the total operation cost value. The reason for this fact can be pointed out that the robust budget increasing causes increasing the number of deviations from the point forecasted value of electricity prices.

5. CONCLUSION

In this paper, a stochastic/robust scheduling model is proposed to minimize the operation cost of an integrated water-electrical system by considering the uncertainty of electricity price, water and electrical demand, and technical constraints of electrical and water distribution systems. Also, the impact of the CWP unit on the total operation cost reduction is investigated. According to the simulation results, it can be concluded that a CWP unit can be significantly reduced the total operation cost of an integrated electrical and water distribution micro gird. In addition, A CWP unit can reduce the electrical demands by decreasing the variable speed pump electrical consumption. At last, the proposed robust scheduling model is solved based on the price information obtained by executing an interval forecasting model.

Table 5. Expected scheduled data of CWP unit

Time	Fresh water output	Electrical output	Ratio (R)
1	108/065	432/261	4
2	33/543	134/17	4
3	1/37	5/48	4
4	1/541	6/166	4
5	30/023	120/093	4
6	97/753	391/011	4
7	77/264	800	10/35
8	64/927	800	12/32
9	78/115	312/46	4
10	65/636	262/543	4
11	69/799	279/194	4
12	71/36	285/439	4
13	32/873	131/494	4
14	7/707	30/826	4
15	63/053	252/213	4
16	65/873	263/491	4
17	92/651	370/604	4
18	59/423	800	13/46
19	59/324	800	13/48
20	59/324	800	13/48
21	59/324	800	13/48
22	59/324	800	13/48
23	90/667	800	8/82
24	71/373	285/491	4

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