Journal of Operation and Automation in Power Engineering

Vol. 7, No. 2, Oct. 2019, Pages: 141-147

http://joape.uma.ac.ir

Optimal Short-Term Coordination of Desalination, Hydro and Thermal Units

F. Jabari[1], *B. Mohammadi-ivatloo*[1*], *M.B. Bannae-sharifian*[1], *H. Ghaebi*[2]

[1] *Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran.*

[2] *Department of Mechanical Engineering, University of Mohaghegh Ardabili, Ardabil, Iran.*

Abstract- *The fossil fuels consumption is rapidly growing due to increased water and electricity demands. An interconnected water-energy nexus is generally composed of thermal power plants, combined potable water and power (CWP) generation units, and desalination only processes. Hence, participation of hydro power plants in electricity generation facilities not only reduces the total fuel consumption of the thermal generators and CWP units, but also mitigates the greenhouse gas emissions. In addition, CWP producers reduces the fossil fuels consumption of the conventional thermal power plants and desalination only units, especially when the water treatment and the power generation capacities of the desalination only processes and the conventional thermal units are insufficient for satisfying on-peak potable water and electricity demands. Hence, the main objective of the current paper is to schedule the water-power hub networks in the presence of the hydro units. The generalized algebraic mathematical modeling system is used to model the proposed method as the mixed-integer non-linear program. The on/off status of the units, the value of the power generation of the thermal/hydro/CWP units, the volume of the water produced by the CWP/desalination units are selected as the decision variables of the optimization problem. The sum of the fuel cost of mentioned units is minimized as the single objective function. The optimization constraints consist of the ramp up and down rates of thermal units, water and electricity generation capacities, balance constraints, relationship between the water head, spilled and released water of the reservoirs with output power of hydro power plants.*

Keyword: Water-power nexus, Co-producer of water and power (CWP), Seawater desalination, Hydro power plant, Thermal generation unit.

Nomenclature

t	Time [hour]
g	Thermal power plant
w	Desalination unit
c	CWP unit
h	Hydro unit
C_p	Fuel cost of thermal units [$]
C_{cwp}	Fuel cost of CWP units [$]
C_w	Fuel cost of desalination units [$]
$P_{g,t}$	Power generation of unit g [MW]
$P_{c,t}$	Power generation of unit c [MW]
$W_{c,t}$	Fresh water generation of unit c [m^3/h]
$W_{w,t}$	Potable water generation of unit w [m^3/h]
a_g,b_g,c_g	Fuel cost factors of unit g
α_c,β_c,γ_c ζ_c,ς_c,ξ_c	Fuel cost factors of unit c
$U_{g,t}$	The binary variable, that equals to 1 if unit g is on, else it will be 0.
$U_{c,t}$	The binary variable, that equals to 1 if unit c is on, else it will be 0.
a_w,b_w,c_w	Fuel cost factors of unit w
P_g^{min}, P_g^{max}	Minimum and maximum power generation of unit g [MW]
P_c^{min}, P_c^{max}	Minimum and maximum power generation of unit c [MW]
W_c^{min}, W_c^{max}	Minimum and maximum fresh water generated by unit c [m^3/h]
W_w^{min}, W_w^{max}	Minimum and maximum fresh water generated by unit w [m^3/h]
E_t	Energy demand [MW]
W_t	Water demand [m^3/h]
L_t^h	Reservoir volume [Million m^3]
I_{t+1}^h	Water inflow [Million m^3]
R_t^h	Released water [Million m^3]
S_t^h	Spilled water [Million m^3]
R_h^{max}	Maximum released capacity per hour [Million m^3]

Received: 13 Apr. 2018
Revised: 25 Aug. 2018
Accepted: 07 Jan. 2019
∗Corresponding author:
E-mail: ivatloo@gmail.com (B. Mohammadi-ivatloo)
Digital object identifier: 10.22098/joape.2019.4640.1359
Research Paper

L_{ini}^{h}, L_{fin}^{h}	Volume of water in dam at beginning and ending of study horizon [Million m^3]
$L_{\min}^{h}, L_{\max}^{h}$	Minimum and maximum levels of reservoirs for hydro unit h [Million m^3]
$P_{h,t}$	Output power of hydro unit h $[\mathrm{MW}]$
$P_{h}^{\min}, P_{h}^{\max}$	Minimum and maximum power of hydro unit h $[\mathrm{MW}]$
c_{k}^{h}	Operation characteristics of hydro unit h for $k = 1, 2, ..., 6$
ψ_{h}	Operation cost of hydro unit h $[\$/\mathrm{MWh}]$
$U_{h,t}$	A binary variable that equals to 1 if hydro unit h is on, otherwise it will be zero

1. INTRODUCTION

In southern Iran, the people face with the fresh water shortage and the energy crisis [1, 2]. Obviously, the pure water is employed for power generating as well as the electricity is used for desalting the gross water [3, 4]. Hence, the optimal cooperation of the seawater desalination units, conventional thermal power plants, hydro units, and the cogenerators of power and potable water can alleviate the cascaded outages of the electricity and the potable water shortage [5, 6].

In the literature, many remarkable works have been presented about short-term investigation of desalination and power generation cycles. Authors of [7] determined the volume of the water required for producing 1 kW electrical power from wind resource and the energy consumed for generating 1 m^3 fresh water. Wind power production is subject to seasonal variations. It may be higher in winter and lower in summer. Hence, impacts of wind speed and power fluctuations on potable water procurement process should also be modelled. Moreover, different energy storage technologies such as battery, compressed air energy storage, aggregated plug-in electric vehicles, pumped hydro storage, etc. can be considered to save energy at time intervals with surplus wind power and releases it at weak wind hours.

The scholars of Ref. [8] studied the physical interconnection of the power and water distribution systems in Jordan. They also determined the dominant agencies, which combine the water and energy networks. It is found that the higher energy efficiency in agriculture and municipal wastewater recovery reduces the pure water demand of industrial sector, significantly. But, development of oil-shale in Jordan imposes a huge value of water requirements in water stressed regions. The global strategic water and electricity trade between different countries such as China, South and Central America, Middle East, Africa, and Australia is presented by Ref. [9]. It is revealed that global energy trade mitigates the serious water shortage problems in China. Moreover, the water consumption for generating 1kW power products in China is high. In addition, the indirect water utilization in power generation is unavoidable, which has been neglected. In Refs. [10, 11], optimal long-term co-scheduling of joint electricity and water generation systems is performed by simulations on Western United States grid aiming to minimize total carbon cost and maximize water conservations. In is found that CO_2 reduction and water conservation scenarios are cost-effective at carbon prices of 50–70 $ per ton carbon and water prices more than $4000 per acre-foot, respectively. In these studies, operation of fossil fuels based power generation facilities have only been optimized. But, renewable energy sources should be incorporated into dynamic economic and environmental dispatch of conventional thermal power plants, which may lead to higher electricity saving for distillate water production. In Ref. [12], it is demonstrated that if the water sources are optimally utilized, the risk of the electricity outage will be decreased. In this research, the long-term analysis over a 1-year period should be carried out for analyzing the system reliability against the uncertainties associated with demands and availability of the water reservoirs. Moreover, optimal charge of energy storage units in off-peak hours and their discharge during on-peak electricity demand hours could reduce both water and energy curtailments, especially in summer season. Ref. [13] introduced a food/water/power hub model. In this model, the grey water is purified for using in industrial and agricultural sectors. Impact of renewable energy resources such as solar, wind, hydro should also be considered. Because, high solar irradiations in summer and wind speed in winter can be used for electricity and desalinated water productions. Moreover, participations of hydro power plants and pumped storages in power generation and seawater desalination processes reduces water scarcity and energy crisis. In Refs. [14, 15], the humidification dehumidification (HDH) desalination unit is combined with the organic Rankine cycle (ORC) to generate the potable water and power in the residential scale. The demand side management programs could be implemented on ORC-HDH plant in order to evaluate the feasibility and the cost-effective impact of the demand response programs in cogeneration process.

In the literature, the day-ahead economic dispatch of the water-energy hub systems has been studied. But, the participation of the hydro units in water-power generation facilities has not been discussed. Therefore, the current paper proposes a simple model for co-optimization of generation schedules for desalination plants, co-generators of pure water and electricity, thermal and hydro units.

The problem formulation of the economic dispatch strategy is presented in Section 2. The case study is discussed in Section 3. The conclusion is provided in Section 4.

2. PROBLEM FORMULATION

Figure1 shows the structure of the fresh water and energy production grid. Obviously, the thermal units/combined water and power (CWP) production systems/desalination only units consume the fossil fuels for generating electricity. In addition, the hydro power plants is linked with the system to reduce the fuel cost. Similarly, the desalination only unit and the CWP generators are co-dispatched for supplying the fresh water consumptions.

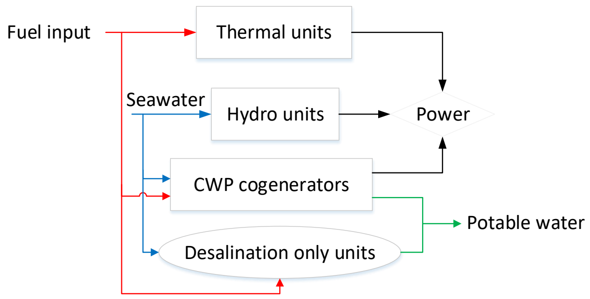


Fig. 1. The proposed system

The objective function of the optimization problem is the fuel cost of the proposed system, which is stated by (1)-(5).

$$\text{Objective function} = C_p + C_{cwp} + C_w + C_h \tag{1}$$

$$C_p = \sum_{g,t} \left(a_g P_{g,t}^2 + b_g P_{g,t} + c_g U_{g,t} \right) \tag{2}$$

$$C_{cwp} = \sum_{c,t} \left(\alpha_c P_{c,t}^2 + \beta_c P_{c,t} W_{c,t} + \gamma_c W_{c,t}^2 + \zeta_c P_{c,t} + \varsigma_c W_{c,t} + \xi_c U_{c,t} \right) \tag{3}$$

$$C_w = \sum_{w,t} \left(a_w W_{w,t}^2 + b_w W_{w,t} + c_w U_{w,t} \right) \tag{4}$$

$$C_h = \sum_{h,t} \psi_h P_{h,t} \tag{5}$$

Subject to:

$$\sum_{g \in \Omega_p} P_{g,t} + \sum_{c \in \Omega_{cwp}} P_{c,t} + \sum_{h \in \Omega_h} P_{h,t} = E_t \tag{6}$$

$$\sum_{w \in \Omega_w} W_{w,t} + \sum_{c \in \Omega_{cwp}} W_{c,t} = W_t \tag{7}$$

$$P_g^{\min} \times U_{g,t} \le P_{g,t} \le P_g^{\max} \times U_{g,t} \tag{8}$$

$$P_c^{\min} \times U_{c,t} \le P_{c,t} \le P_c^{\max} \times U_{c,t} \tag{9}$$

$$P_h^{\min} \times U_{h,t} \le P_{h,t} \le P_h^{\max} \times U_{h,t}$$

(10)

$$W_w^{\min} \times U_{w,t} \le W_{w,t} \le W_w^{\max} \times U_{w,t} \tag{11}$$

$$W_c^{\min} \times U_{c,t} \le W_{c,t} \le W_c^{\max} \times U_{c,t} \tag{12}$$

$$P_c^{\min} \times U_{c,t} \le P_{c,t} \le P_c^{\max} \times U_{c,t} \tag{13}$$

$$\text{Max}(P_g^{\min}, P_g^{t-1} - DR_g) \le P_{g,t} \le \text{Min}(P_g^{\max}, P_g^{t-1} + UR_g) \tag{14}$$

$$R_c^{\min} \le \frac{P_{c,t}}{W_{c,t}} \le R_c^{\max};\ \forall c \in \Omega_{cwp}, \forall t \in T \tag{15}$$

In this research, it is assumed that a hydro power plant composes of some cascaded up-stream and down-stream reservoirs, as shown in Fig. 2. As obvious from this figure and formulated by equation (16), the volume of water in a reservoir of hydro unit h at each hour t will be equal to its value at hour $t-1$ plus the water inflow to this reservoir plus the spilled and the released water of all reservoirs at period t with time delay $\tau_{\hat{h}}$ minus the spilled and the released water of this reservoir at time t. Moreover, constraints (17) and (18) limit the water volume and the released water of reservoir h at each operating period t, respectively. Equation (19) shows that the volume of water in dam at beginning and end of operation period is equal to L_{ini}^h and L_{fin}^h, respectively. Finally, output power of hydro unit h which depends on L_t^h and R_t^h, is described in equation (20).

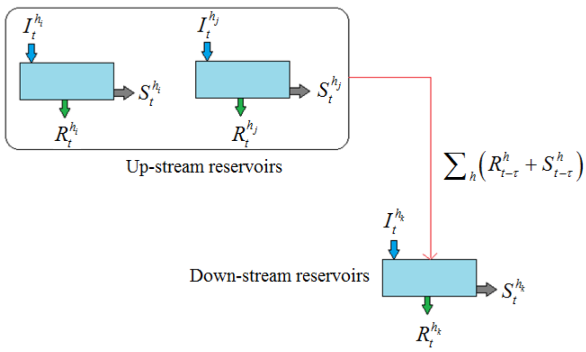


Fig. 2. The cascaded hydro reservoirs

$$2L_{t+1}^{h}=L_{t}^{h}+I_{t+1}^{h}-R_{t+1}^{h}-S_{t+1}^{h}+\eta\sum_{h}\left(R_{t+1-\tau_h}^{h}+S_{t+1-\tau_h}^{h}\right) \quad (16)$$

$$L_{\min}^{h}\le L_{t}^{h}\le L_{\max}^{h} \quad (17)$$

$$R_{t}^{h}\le R_{\max}^{h} \quad (18)$$

$$L_{t_0}^{h}=L_{ini}^{h},\ L_{t_{24}}^{h}=L_{fin}^{h} \quad (19)$$

$$P_{t}^{h}=c_1^h(L_t^h)^2+c_2^h(R_t^h)^2+c_3^hL_t^hR_t^h+c_4^hL_t^h+c_5^hR_t^h+c_6^h$$

(20)

3. SIMULATION RESULT AND DISCUSSIONS

A standard test system, which consists of 3 CWP units, 1 desalination unit, 2 thermal units, and 2 hydro power plants [16], is studied. The constant factors related to the generation units are reported in Tables 1-4. The proposed system is optimally scheduled over the 24-hour period by solving the mixed integer nonlinear programming (MINLP) problem under branch-and-reduce optimization navigator (BARON) [17] of general algebraic mathematical modeling system (GAMS) [18]. Table 5 shows the hourly water inflows for the hydro power plants. In addition, the fresh water and electrical loads during the sample day are shown in Fig. 3. The hourly operation cost of the hydro units is equal to 14 \$/MWh. As shown in Table 1, the potable water generation capacity of the coproducers are equal to 200, 150 and 100 m^3. Moreover, their power generation capacities are equal to 800, 600 and 400 MW. In other words, they generate 1800 MW (1.8 GW) electricity and 450 m^3 potable water at the worst operating condition. In addition to cogeneration plants, a desalination only unit with 100 m^3 capacity is considered in pure water production process. Hence, the potable water demand is equal to (at hour 11) or less than (at other hours) sum of water generation capacities of coproducers and desalination only unit (550 m^3). As stated previously, the sum of the electricity production capacity of the combined water and power generation units is equal to 1800 MW. According to Tables 3 and 4, we considered two hydro power plants with 100 MW capacity and two thermal units with 400 and 300 MW power generation capability. Hence, the electrical demand of the test system is considered to be less than (on-peak demand occurs at hour 9 and equals to 2626 MW) sum of power generation capacities of thermal, hydro and coproducers (400+300+100+100+800+600+400=2700 MW).

According to Fig. 3, the maximum values of the electrical and desalinated water demands are equal to 2626 MW and 550 m^3, which occur at $t = 11$ and $t = 9$, respectively. As mentioned, the electricity generation capacities of the conventional thermal power plants, CWP producers and the hydro units are equal to 700 MW, 1800 MW and 200 MW, respectively. Hence, it is infeasible to satisfy the on-peak electrical demand either by their separate operations or by the cooperation of power only units and CWP plants or hydro producers. In other words, CWP units, thermal generators and hydro power plants should be co-scheduled to supply 2626 MW on-peak electrical demand. Moreover, the water only unit produces a maximum volume of the fresh water up to 100 m^3 which cannot satisfy the desalinated water demand at all hours.

Table 1. The constant factors of the CWP units

Parameters	$c=1$	$c=2$	$c=3$
α_c	0.0004433	0.0007881	0.001773
β_c	0.003546	0.006305	0.01419
γ_c	0.007093	0.01261	0.02837
ζ_c	-1.106	-1.475	-2.213
ς_c	-4.426	-5.901	-8.851
ξ_c	737.4	737.4	737.4
$P_c^{\min}$	160	120	80
$P_c^{\max}$	800	600	400
$W_c^{\min}$	30	23	15
$W_c^{\max}$	200	150	100
$R_c^{\min}$	4	4	4
$R_c^{\max}$	9	9	9

Table 2. The constant factors of the desalination unit

Unit	a_w	b_w	c_w	$W_w^{\min}$	$W_w^{\max}$
$w=1$	0.00182	-0.374	7.374	0	100

Table 3. The constant factors of the thermal units

g	a_g	b_g	c_g	$P_g^{\min}$	$P_g^{\max}$
1	0.0002069	-0.1483	57.11	0	400
2	0.0003232	-0.1854	57.11	0	300

Table 4. The constant factors of the hydro units

Parameters	$h=1$	$h=2$
c_1	-0.0042	-0.0043
c_2	-0.44	-0.32
c_3	0.040	0.013
c_4	0.8	0.012
c_5	11	9.7
c_6	-53	-71
Delay (hour)	2	1
$L_{\min}^h$	80	60
$L_{\max}^h$	150	120
L_{ini}^h	100	80
L_{fin}^h	120	70
$R_{\min}^h$	5	6
$R_{\max}^h$	15	15
$P_h^{\min}$	0	0
$P_h^{\max}$	100	100

Table 5. The hourly water inflows for the hydro units

Time	$I_t^{h_1}$	$I_t^{h_2}$
t_1	10	8
t_2	9	8
t_3	8	9
t_4	7	9
t_5	6	8
t_6	7	7
t_7	8	6
t_8	9	7
t_9	10	8
t_{10}	11	9
t_{11}	12	9
t_{12}	10	8
t_{13}	11	8
t_{14}	12	9
t_{15}	11	9
t_{16}	10	8
t_{17}	9	7
t_{18}	8	6
t_{19}	7	7
t_{20}	6	8
t_{21}	7	9
t_{22}	8	9
t_{23}	9	8
t_{24}	10	8

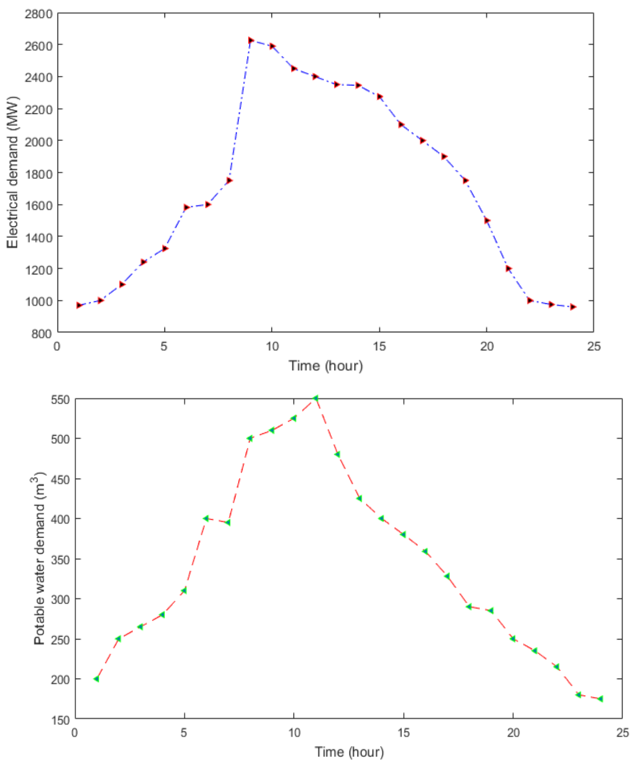


Fig. 3. The total desalinated water and electricity loads over a 24-hour study horizon

Therefore, CWP producers and water only units are co-dispatched. According to load-generation balance criteria, the water-power nexus is optimally scheduled by solving the MINLP problem (1)-(20). The hourly generation schedules of the conventional thermal units, CWP producers and desalination only process have optimally been found as shown in Figs. 4-6, respectively. Optimal hourly dispatch of hydro power plants is shown in Fig. 7. As expected from equation (2) and Table 3, the quadratic fuel cost coefficient (a_g) and the power generation capacity ($P_g^{\max}$) of the first thermal unit are respectively smaller and bigger than those of the second one. Hence, the first thermal power plant generates more electricity than the second unit. According to equation (3) and Table 1, 1st CWP unit has smaller operational coefficients $(\alpha_c, \beta_c, \gamma_c)$ and more generation capacities $(P_c^{\max}, W_c^{\max})$ than 2nd and 3rd units. Hence, it generates more electricity and potable water than 2nd and 3rd ones, as obvious from Fig. 5. Similar comparison can be considered for CWP units 2 and 3. Obviously, 2nd cogenerator has smaller parameters $(\alpha_c, \beta_c, \gamma_c)$ and larger generation capacities $(P_c^{\max}, W_c^{\max})$ than CWP unit 3. Hence, it provides more electrical power and desalinated water in comparison with 3rd coproducer. Tables 1 and 2 show that the operational cost coefficients of the desalination only unit are larger than those of CWP units 1 and 2 and lower than cogenerator 3. Therefore, it provides less pure water than CWP units 1 and 2. In addition, its output is compatible with potable water generation of CWP unit 3 due to same capacities and lower difference between their operational coefficients. Because of constant operation cost of both hydro units, their daily generation patterns are approximately flat except at on-peak electrical demand hours. It is found that total fuel cost of desalination plant, hydro units, thermal generators and co-producers are equal to zero, \$21768.7, \$741.3 and \$27617.6, respectively. Hence, objective function will be equal to 50127.7 \$.

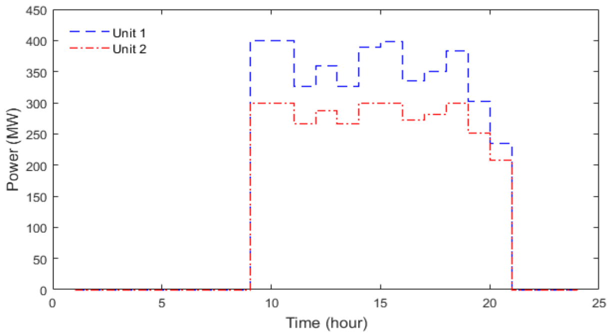
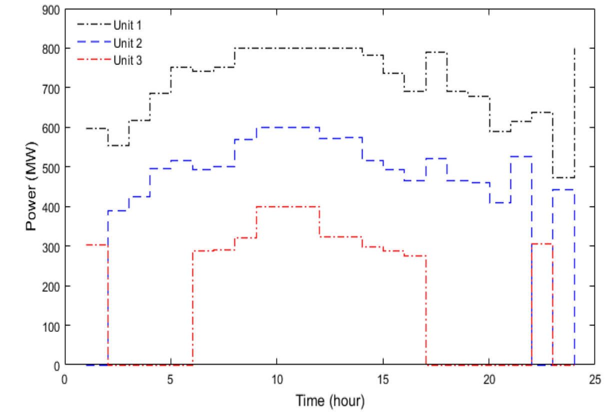
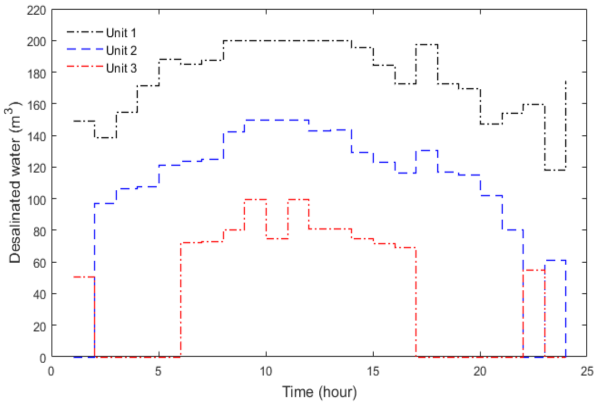


Fig. 4. The output power of the conventional thermal units



(a) Electrical power output



(b) Potable water output

Fig. 5. The hourly generation schedules of the CWP plants

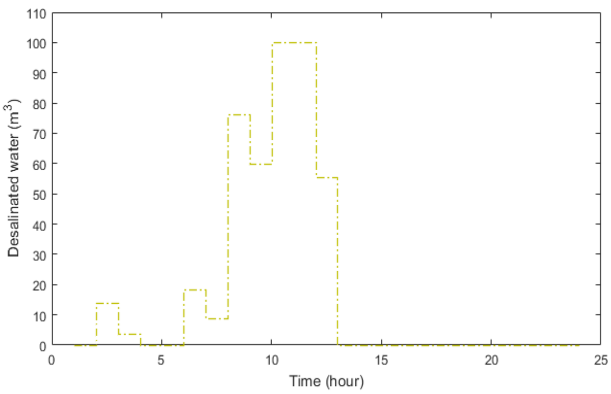


Fig. 6. The potable water produced by the desalination plant

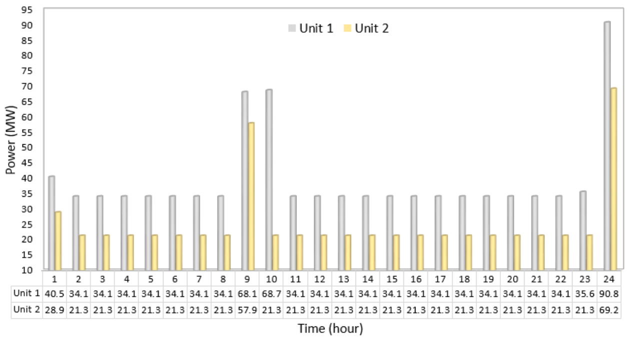


Fig. 7. The output power of the hydro units

4. CONCLUSION

In the presented paper, the economic benefit of the hydro power plants in supplying the electrical demand of the water-power hub systems was proved. The simulation result demonstrated that the peak electrical demand is not satisfied by the single operation of the thermal units and the co-operation of the thermal and CWP units. Similarly, the potable water requirement of the test system is not supplied without participation of desalination units and CWP plants. Therefore, hydro-thermal-desalination units were co-dispatched for procuring the energy and water demands of the standard network. The best operating points of the thermal/hydro/desalination/CWP units were found by developing a mixed-integer non-linear programming problem using BARON solver of GAMS. Sum of fuel cost of producers was minimized. Moreover, the ramp rate limits, power/water balance constraint, generation capacity, dependency between water head/spilled water/released water, and the output power of the hydro reservoirs are considered as optimization limits.

REFERENCES

[1] X. Zhang and V. V. Vesselinov, "Integrated modeling approach for optimal management of water, energy and food security nexus," *Adv. Water Resour,* vol. 101, pp. 1-10, 2017.

[2] J.-L. Fan, L.-S. Kong, H. Wang, and X. Zhang, "A water-energy nexus review from the perspective of urban metabolism," *Ecol. Modell.*, vol. 392, pp. 128-136, 2019.

[3] F. Jabari, B. Mohammadi-Ivatloo, and M. Rasouli, "Optimal planning of a micro-combined cooling, heating and power system using air-source heat pumps for residential buildings," *Energy Harvesting Energy Effic.*: Springer, 2017, pp. 423-455.

[4] F. Jabari, S. Nojavan, and B. M. Ivatloo, "Designing and optimizing a novel advanced adiabatic compressed air energy storage and air source heat pump based μ - Combined Cooling, heating and power system," *Energy,* vol. 116, pp. 64-77, 2016.

[5] G. Krajačić, N. Duić, M. Vujanović, Ş. Kılkış, M. A. Rosen, and M. d. A. Al-Nimr, "Sustainable development of energy, water and environment systems for future energy technologies and concepts," *Energy Convers. Manage.*, vol. 125, no. Supplement C, pp. 1-14, 2016.

[6] T. Amjath-Babu *et al.*, "Integrated modelling of the impacts of hydropower projects on the water-food-energy nexus in a transboundary Himalayan river basin," *Appl. Energy,* vol. 239, pp. 494-503, 2019.

[7] J. Yang and B. Chen, "Energy–water nexus of wind power generation systems," *Appl. Energy*, vol. 169, no. Supplement C, pp. 1-13, 2016.

[8] A. Siddiqi, A. Kajenthira, and L. D. Anadón, "Bridging decision networks for integrated water and energy

planning," *Energy Strategy Rev.*, vol. 2, no. 1, pp. 46-58, 2013.

[9] C. Duan and B. Chen, "Energy–water nexus of international energy trade of China," *Appl. Energy,* vol. 194, pp. 725-734, 2017.

[10] F. Ackerman and J. Fisher, "Is there a water–energy nexus in electricity generation? Long-term scenarios for the western United States," *Energy Policy,* vol. 59, pp. 235-241, 2013.

[11] B. Tarroja, A. AghaKouchak, and S. Samuelsen, "Quantifying climate change impacts on hydropower generation and implications on electric grid greenhouse gas emissions and operation," *Energy,* vol. 111, pp. 295-305, 2016.

[12] B. Gjorgiev and G. Sansavini, "Water-energy nexus: Impact on electrical energy conversion and mitigation by smart water resources management," *Energy Convers. Manage.,* vol. 148, pp. 1114-1126, 2017.

[13] H. Wa'el A, F. A. Memon, and D. A. Savic, "A risk-based assessment of the household water-energy-food nexus under the impact of seasonal variability," *J. Cleaner Prod.*, vol. 171, pp. 1275-1289, 2018.

[14] W. He, W. Zhu, D. Han, L. Huang, Y. Wu, and X. Zhang, "Performance simulation of a power-water combined plant driven by low grade waste heat," *Energy Convers. Manage.,* vol. 145, pp. 107-116, 2017.

[15] W. F. He, D. Han, L. N. Xu, C. Yue, and W. H. Pu, "Performance investigation of a novel water–power cogeneration plant (WPCP) based on humidification dehumidification (HDH) method," *Energy Convers. Manage.*, vol. 110, no. Supplement C, pp. 184-191, 2016.

[16] A. Soroudi, "Power System Optimization Modeling in GAMS," ed: Springer, 2017.

[17] https://www.gams.com/docs/solvers/baron/.

[18] https://www.gams.com/.