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Day-Ahead Economic Dispatch of Coupled Desalinated Water and Power Grids with Participation of Compressed Air Energy Storages

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Abstract- *Nowadays, water and electricity are closely interdependent essential sources in human life that affect socio-economic growth and prosperity. In other words, electricity is a fundamental source to supply a seawater desalination process, while fresh water is used for cooling this power plant. Therefore, mutual vulnerability of water treatment and energy networks is growing because of increased potable water and electricity demands especially during extremely-hot summer days. In current paper, a novel optimization framework is proposed for short-term scheduling of water-energy nexus aiming to minimize total seawater desalination and electricity procurement cost while satisfying all operational constraints of conventional thermal power plants, co-producers and desalination units. Moreover, advanced adiabatic compressed air energy storage (CAES) with no need to fossil fuels can participate in energy procurement process by optimal charging during off-peak times and discharging at peak load hours. A mixed integer non-linear programming problem is developed under general algebraic mathematical modeling system with the aim of minimizing the water treatment cost of water only units and co-producers, total fuel cost of thermal power plants and co-generators. Ramp rates, water and power generation capacities and balance criteria have been considered as optimization constraints. It is found that without co-optimization of desalination and power production plants, load-generation mismatch occurs in both water and energy networks. By incorporating CAES in water-power grids, total fuel cost of thermal units and co-producers reduce from $1222.3 and $24933.2 to $1174.8 and $24636.8, respectively. In other words, application of CAES results in $343.9 cost saving in benchmark water-power hybrid grid.*

Keyword: Compressed air energy storage (CAES), Combined desalinated water and power (CDWP) generation systems, Day-ahead economic dispatch; Mixed integer nonlinear programming (MINLP).

NOMENCLATURE

Indices

t	Operating time interval [hour]
g	Thermal generating unit
w	Desalination only process
c	CWP plant

Water-power nexus

C_p	The operation cost of thermal units [$]
C_{cwp}	Total water and electricity generation cost of CWP units [$]
C_w	Total water tratment cost of desalination only units [$]
$P_{g,t}$	Active power output of thermal power plant g [MW]
$P_{c,t}$	Electricity output of CWP unit c [MW]
$W_{c,t}$	Potable water output of CWP unit c $[m^3/\text{h}]$
$W_{w,t}$	Fresh water produced by desalination only unit w $[m^3/\text{h}]$
a_g, b_g, c_g	Fuel cost coefficients of thermal generating unit g
$\alpha_c, \beta_c, \gamma_c$ $\zeta_c, \varsigma_c, \xi_c$	Fuel cost coefficients of CWP unit c
$U_{g,t}$	Binary variable (equals to 1 if unit g is on, else 0)
$U_{c,t}$	Binary variable (equals to 1 if unit c is on, else 0)
a_w, b_w, c_w	Fuel cost coefficients of desalination only unit w
P_g^{min}, P_g^{max}	Power generation boundaries for unit g [MW]
P_c^{min}, P_c^{max}	Power generation boundaries for unit g c [MW]
W_c^{min}, W_c^{max}	Water generation boundaries for unit c $[m^3/\text{h}]$
W_w^{min}, W_w^{max}	Water generation boundaries for unit w $[m^3/\text{h}]$

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E_t	Electrical demand [MW]
W_t	Water demand [m^3/h]
Compressed air energy storage	
V_t^{inj}	Energy level of air injected into cavern [MW]
α^{inj}	Efficiency of injecting process
P_t^{comp}	Electricity requirement of compressor train [MW]
P_t^{gen}	Electricity generated by CAES [MW]
α^{pump}	Efficiency of generating mode
V_t^{pump}	Energy level of air pumped into gas expander [MW]
$V_{\min}^{inj}, V_{\max}^{inj}$	Energy boundaries of injected air [MW]
u_t^{inj}	Binary variable (equals to 1 if CAES charges at time *t*, otherwise it will be zero)
u_t^{pump}	Binary variable (equals to 1 if CAES discharges at time *t*, otherwise it will be zero)
$V_{\min}^{pump}, V_{\max}^{pump}$	Energy boundaries of pumped air [MW]
SOC_t	State of charge of storage unit
$SOC_{\min}, SOC_{\max}$	Min and max limits of state of charge

1. INTRODUCTION

The availability of the drinkable water resources is necessary for social welfare. Although the large scale seawater resources are available in the world, but most of the people suffer from water shortage. Meanwhile, water-electricity interdependence is an undeniable issue because the electricity is vital to drive a seawater desalination process, while the fresh water is used for cooling, heating and power generation cycles [1, 2]. Hence, optimal scheduling of water-power nexus is attracting world attention to overcome the global water and energy crises [3].

Recently, many researchers have focused on coordination of water and energy systems. Ref. [4] presented an energy–water nexus framework for wind power generation systems. They quantified how much groundwater, surface and embodied water is required for utilization of 1kWh wind energy and how much wind power is consumed for seawater collection, desalination and wastewater treatment processes. It is indicated that compartment of surface water and groundwater is beneficial for wastewater treatment. Although the extra electrical power of wind turbines is consumed by the wastewater treatment cycle, the economic benefit of the water recycling is more than the energy cost. In this study, impact of wind production uncertainty has not been considered in water-energy nexus. Authors of Ref. [5] presented a systematic and analytic method for optimal co-operating and policy making of joint water and electricity grids in Jordan. This approach consists of three dependent components such as physical inter-connections between water and electricity networks to specify some key operators within each domain, stakeholders of main energy and water policy agencies, and dominant stakeholders for merging water and energy decision making processes. It is found that more energy saving is achieved by reducing water loss or leakages and powering old pumps with renewable energy resources such as photovoltaic. Economic benefits of water loss and leakage detection methods should be investigated in three ways: (a) Monthly reports on cumulative sales and production; (b) leakage reports; (c) find the location of the leak in distribution networks. Duan and Chen [6] combined an input–output analysis (IOA) with ecological network analysis (ENA) for global water and electricity trade. ENA is implemented to model all water-energy pathways during an international competitive energy trade between China, South and Central America, Middle East, Africa, and Australia. Although China is dominant in direct relationships, it becomes an equal competitor with USA in utility mutual relationships. Network mutualism and synergism indices demonstrates that policies and economic suggestions alleviate some potential impacts of international energy trade on water scarcity of China. In Ref. [7], a bi-level energy-water nexus management (BEWM) problem is solved to minimize total electricity generation and water treatment cost. Mass and electricity balance constraints, production limits, energy and water demands, availability of water resources and fossil fuels, and permitted range of CO_2 emission production have been considered. BEWM presents the interconnection of the water and power systems in regional and national levels. In this study, water shedding events have not been discussed. Fresh water required for power production has not been reported. The recycling of the waste water could also be carried out.

In [8], it is proved that the anaerobic digestion of the waste food and gross water slush reduces the total potable water shortage. Geographical conditions, food culture, and dietary habits substantially change in different regions, which can be considered in this work. In [9], a linkage analysis based on input-output model is presented by Fang and Chen to find an optimum operating point of three combined energy resources (a) extraction of petroleum products such as natural gas, (b) processing them, (c) power and heat generation. It is revealed that natural gas fired power generation cycle is major energy supplier, while transportation, agriculture and food processing districts consume more electricity and water than other customers. Moreover, social services sector consumes one fourth of Beijing's virtual water and embodied energy to support its production pattern. Economic and environmental benefits of renewable energy resources in cogeneration of heat and power and participation of electric vehicles in transportation and electricity production facilities should also be studied. Ref. [10] introduced a water-power nexus model for smart utilization of desalination plants and minimization of electricity curtailments caused by river water flow reduction and temperature increase in Ref. [11]. In this study, smart utilization of water resources leads to a significant reduction of electricity risk of hydrothermal plants during extremely-hot summer days or transient heat waves. If the temperature of the river water is maximum threshold value and the water discharge is insufficient, a small rise in temperature causes thermal power plant shutdowns. This contingency may lead to cascading outages of generation units and wide area blackouts. This model should be implemented on a region with drought condition and its impacts on power system vulnerability could be quantified. In Ref. [12], a policy-constrained water-energy programming model is presented for a river basin hosting hydrothermal generators under severe summer days. Studies show that once-through cooling system is more sensitive to abnormal river water flow and temperature. Additionally, lower flexibility of water policy during extreme droughts may cause a large amount of electricity generated by interconnected power system. Different equipment of a thermal generation unit such as generators, pumps, transformers, motors, etc. should also be cooled by river water for evaluating its performance under different values of withdrawn water temperature. In [13, 14], a low-grade waste heat driven combined water and electricity generation plant is suggested by coupling organic Rankine cycle (ORC) and air-heated humidification dehumidification (HDH) desalination process. In this study, ORC could be integrated by Brayton cycle for improving overall efficiency and increasing output pure water and electricity productions. Authors of Ref. [15] presented an alternative model for optimal operation of combined heat and power system in low-income and geographically isolated microgrids. During off-peak demand hours, surplus electricity and heat are employed for production and transportation of fresh water and minimization of total load-generation mismatch in both water and power distribution systems. Use of energy storage systems such as batteries for saving electricity at low-price time intervals and selling it at peak periods with higher energy tariffs to local power system increases daily profit of stand-alone grid, which has not been considered. Ref. [16] demonstrated that in solar Rankine-Brayton power plant, the heat recovered from the compressor inter cooler and the flue gases can be used for absorption refrigeration cycle (ARC) and single stage flash desalination. There is no solar radiation, electricity and potable water productions at night. Hence, molten salt as a solar reserve technology could be used as a heat transfer fluid and a thermal storage medium for cogeneration of heat and power. Akrami et al. in Ref. [17] revealed that a geothermal organic Rankine cycle, ARC, household water heater, and proton exchange membrane electrolyser can be utilized to generate power, cool, hot water and hydrogen, respectively. Total capital investment cost, annual economic benefit, payback period and lice cycle assessment of this poly-generation system could be presented. In Ref. [18], hourly and daily performance investigation of a solar combined cooling and water desalination system is presented to obtain fresh water generation rate, electricity consumption, waste water recovery, cooling capacity and its coefficient of performance under hot and humid climatic regime. Uncertainty of solar radiations in clear and cloudy sky conditions could be modelled for determining its coefficient of performance. In [19, 20], abandoned oil and gas wells are employed as clean heat reservoir for generating power by Brayton combined organic Rankine cycle and water through a multi-effect desalination unit. In this work, biogas should be employed instead of natural gas to make a zero-emission and near-zero energy heat and power generation system in Ref. [21].

As mentioned, several remarkable efforts have been carried out on modelling and analyzing of interdependency between water and energy networks. However, there are some unsolved problem for satisfying both water and electricity demands which typically increase during extremely-hot summer days. Therefore, this paper presents a novel methodology for day-ahead economic coordination of water and power systems consisting of desalination processes, co-producers of fresh water and power, and thermal generation units. The novelties of the presented paper are as follows:

- Short-term economic coordination of water and electricity grids is comprehensively presented. Total water treatment and electricity procurement cost is minimized taking into account all operational constraints of desalination processes, co-production plants and power only units.

- Daily charge (compressed air storage mode) and discharge (expanding the pressurized air) decisions of compressed air energy storage (CAES) are optimally determined to improve the cost saving in water and power generation system. It is shown that if the CAES is charged at low-demand hours and discharged at high-load periods, the value of the power generated by the thermal and cogeneration units as well as the emissions will be reduced, considerably.
- Two cases are studied to participate CAES on daily economic evaluation of seawater desalination plants and electricity producers.

The remainder of the present work is provided as follows: A comprehensive problem formulation is presented in Section 2. Illustrative example and analysis of numerical result are presented in Section 3. Conclusion is given by Section 4.

2. PROBLEM FORMULATION

2.1. Water-power nexus

According to Fig. 1, the energy demand of the water-energy nexus can be supplied by thermal and coproduction units. Moreover, the potable water demand is satisfied by the desalination plants and the combined water and power (CWP) producers.

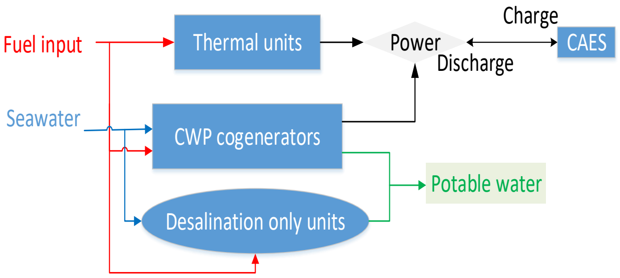


Fig. 1. Input-output diagram of a water-power hub network

In this research, day-ahead optimization of desalination units, CWP plants and thermal generating units are presented. Hence, total seawater desalination and electricity procurement cost is minimized as Eqs. (1)-(4) [22, 23].

$$\text{Objective function} = C_p + C_{cwp} + C_w \quad (1)$$

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

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

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

Subject to:

- Electrical power balance criterion between consumer and generator

The power generated by the thermal units and co-generation plants should meet total electricity demand within each operating time interval, which can be fulfilled by Eq. (5) [24].

$$\sum_{g\in\Omega_p} P_{g,t} + \sum_{c\in\Omega_{cwp}} P_{c,t} = E_t \quad (5)$$

- Water balance constraint

Equation (6) indicates that total potable water produced by CWP plants and desalination only units satisfies the hourly water demand at each time horizon [22].

$$\sum_{c\in\Omega_{cwp}} W_{c,t} + \sum_{w\in\Omega_w} W_{w,t} = W_t \quad (6)$$

- Electricity and water generation limits

The power produced by the thermal generating units and CWP plants are limited as inequality constraints (7) and (8), respectively [22, 25]. Similarly, the amount of the fresh water produced by CWP plants and desalination only units are restricted by constraints (9) and (10), respectively [22].

$$P_g^{min} \times U_{g,t} \le P_{g,t} \le P_g^{max} \times U_{g,t} \quad (7)$$
$$P_c^{min} \times U_{c,t} \le P_{c,t} \le P_c^{max} \times U_{c,t} \quad (8)$$
$$W_w^{min} \times U_{w,t} \le W_{w,t} \le W_w^{max} \times U_{w,t} \quad (9)$$
$$W_c^{min} \times U_{c,t} \le W_{c,t} \le W_c^{max} \times U_{c,t} \quad (10)$$

- Ramp rate limits for thermal power plants

The thermal power plant g increases or decreases its product based on ramp up and ramp down rate limits as inequality constraint (11) [25].

$$\text{Max}\left(P_g^{min}, P_g^{t-1} - DR_{\ g}\right) \le P_{g,t} \le \text{Min}\left(P_g^{max}, P_g^{t-1} + UR_{\ g}\right) \quad (11)$$

- Power-water generation ratio

Equation (12) shows that for simultaneous generation of electricity and water by co-producer c, a power-water ratio constant should be considered [22].

$$R_c^{min} \le \frac{P_{c,t}}{W_{c,t}} \le R_c^{max} \quad (12)$$

2.2. Compressed air energy storage

In a general category, CAES units are divided to diabatic and adiabatic types. According to Fig. 2, diabatic type of CAES utilizes the electrical power at low-demand time intervals to compress the air and stores it in a thermally isolated underground cavern. At high-demand hours, a recuperator heats the pressurized air before passing it through the combustion tank. The natural gas inlets the combustion chamber and rises the temperature of the combustion products before entering the gas turbine and generating power. The recuperator increases the efficiency of the diabatic CAES by 15% [26]. Advance adiabatic CAES is illustrated in Fig. 3. Its energy efficiency is improved to 85% by the heat storage. Another advantage of adiabatic CAES is zero-fuel consumption and zero-emission production in air expanding stage. The charge mode or air compressing and storing stages as well as the discharge mode or power generating process of the advance adiabatic CAES are mathematically formulated as constraints (12)-(18) [27]:

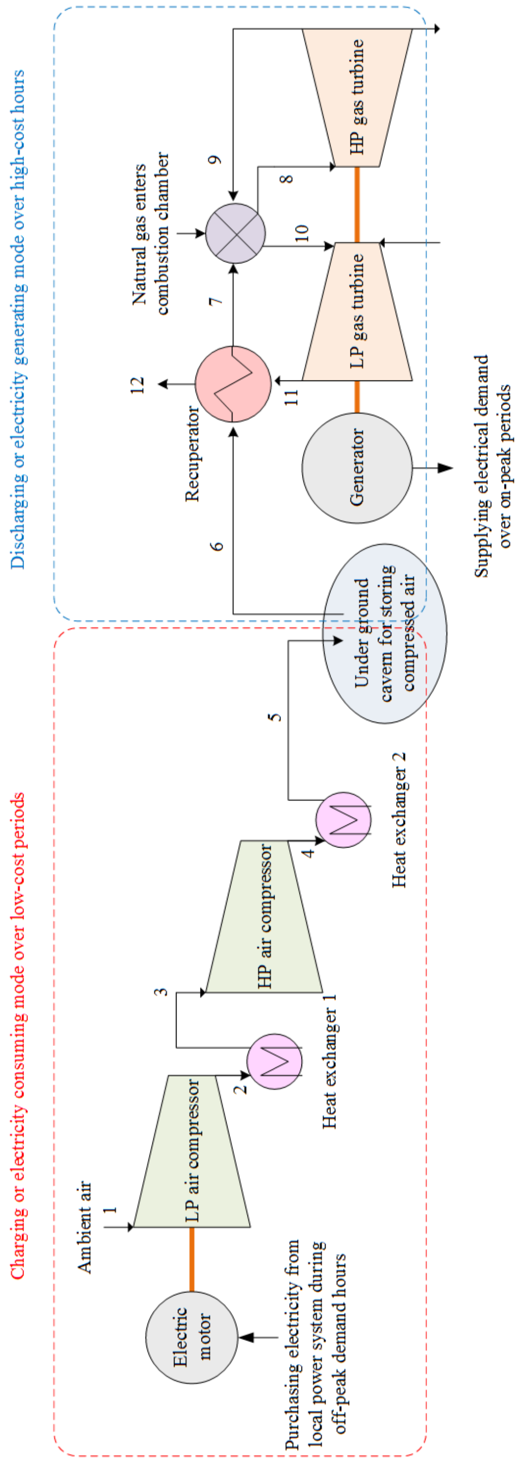


Fig. 2. The single line diagram of the conventional diabetic compressed air energy storage

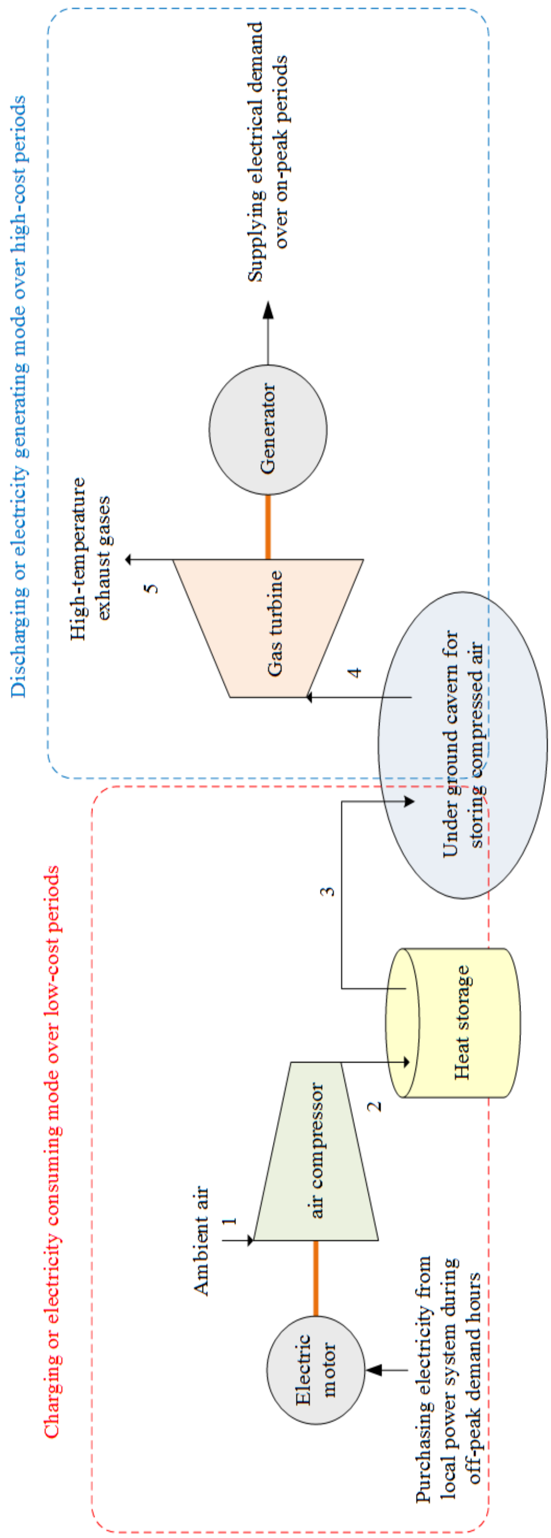


Fig. 3. The schematic presentation of the advanced adiabatic compressed air energy storage

$$V_t^{inj} = \alpha^{inj} P_t^{comp} \tag{13}$$

$$P_t^{gen} = \alpha^{pump} V_t^{pump} \tag{14}$$

$$V_{\min}^{inj} \times u_t^{inj} \le V_t^{inj} \le V_{\max}^{inj} \times u_t^{inj} \tag{15}$$

$$V_{\min}^{pump} \times u_t^{pump} \le V_t^{pump} \le V_{\max}^{pump} \times u_t^{pump}$$
(16)

$$u_t^{inj} + u_t^{pump} \le 1 \quad (17)$$

$$SOC_{t+1} = SOC_t + V_t^{inj} - V_t^{pump} \quad (18)$$

$$SOC_{\min} \le SOC_t \le SOC_{\max} \quad (19)$$

Finally, equation (5) can be rewritten as follows:

$$\sum_{g\in\Omega_p} P_{g,t} + \sum_{c\in\Omega_{cwp}} P_{c,t} + P_t^{gen} = E_t + P_t^{comp} \quad (20)$$

3. SIMULATION RESULT AND DISCUSSIONS

In this work, a typical water-energy nexus model, which is composed of three cogeneration units/one desalination unit/four thermal power plants/one adiabatic CAES, is considered for simulations. All technical and economical characteristics of them is reported in Tables 1-4, respectively. This co-generation grid is modelled as a mixed integer nonlinear programming (MINLP) problem. The branch-and-reduce optimization navigator (BARON) solver of the general algebraic mathematical modeling system (GAMS) [28] is used for finding the best water and power generation scenario. Two cases "Without CAES" and "With CAES" are presented to confirm the economic benefit of the adiabatic CAES in water-energy hub model. Figure 4 depicts the daily changes of the water and power demands for the standard test system.

Table 1. Technical characteristics of CWP plants [22]

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

Table 2. Economical and technical parameters of desalination process [22]

Unit	a_w	b_w	c_w	W_w^{min}	W_w^{max}
$w=1$	0.00182	-0.374	7.374	0	250

Table 3. Operating specifications of thermal units [22]

Units	a_g	b_g	c_g	P_g^{min}	P_g^{max}
$g=1$	0.0002069	-0.1483	57.11	0	500
$g=2$	0.0003232	-0.1854	57.11	0	400
$g=3$	0.001065	-0.6026	126.8	0	400
$g=4$	0.0004222	-0.2119	57.11	0	350

Table 4. Technical characteristics of advance adiabatic CAES [27]

$V_{\max}^{inj}, V_{\max}^{pump}$	$SOC_{\min}$	$SOC_{\max}$	$\alpha^{inj}, \alpha^{pump}$	$V_{\min}^{inj}, V_{\min}^{pump}$
150	0	175	0.85,0.85	0

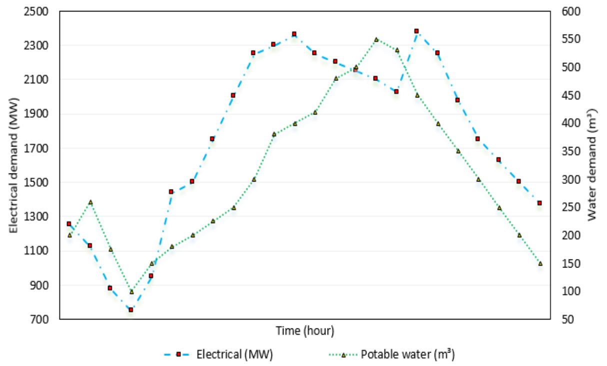


Fig. 4. The hourly variations of desalinated water and electricity loads over a 24-hour study horizon

According to Tables 1 and 3, the power generation capacity of the power only units and CWP producers are 500 MW (1st thermal generating unit), 400 MW (2nd and 3rd thermal generating units), 350 MW (4th thermal power plant), 800 MW (1st cogeneration unit), 600 MW (2nd cogeneration unit), and 400 MW (3rd cogeneration unit). It is obvious from Fig. 4 that high electrical load of test system is 2375 MW, which occurs at $t = 18$. Moreover, the maximum electrical power output of thermal and CWP units are 1650 MW and 1800 MW, respectively. Therefore, if the thermal units and CWP plants don't co-operate, it will not be possible to supply the electrical demand of the studied system at hour 18 and other peak time intervals. Thus, CWP plants and thermal units are co-optimized over a sample day. Optimal charge and discharge decisions of CAES (time and amount) is shown in Fig. 5. The negative part of this figure refers to the CAES's charging or electricity consumption mode and the positive side indicates the discharging or electricity generation process. Optimization of water and power generation schedules with participation of advanced adiabatic CAES changes the output electricity production of thermal units and co-generators as illustrated by Fig. 6. Moreover, day-ahead optimal fresh water generation patterns of desalination only unit and co-producers changes as shown in Fig. 7 because of electricity requirement of seawater desalination processes. According to Table 5, it is obtained that optimum day-ahead scheduling of CAES reduces total electricity generation of thermal power plants and co-producers of water and power from \$26155.5 to \$25811.6.

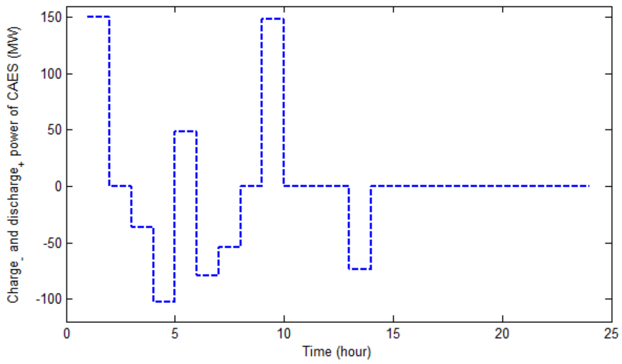


Fig. 5. Time and amount of charge and discharge decisions of advanced adiabatic CAES

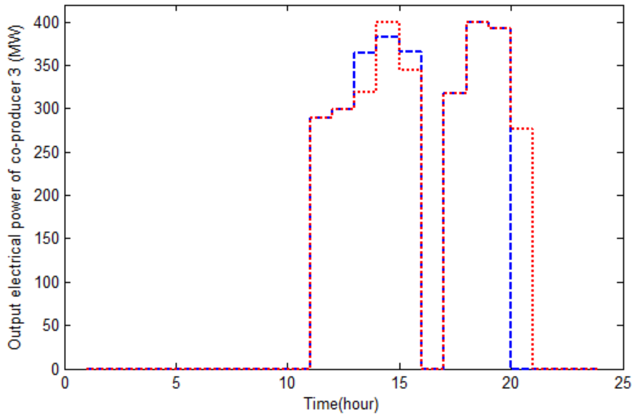
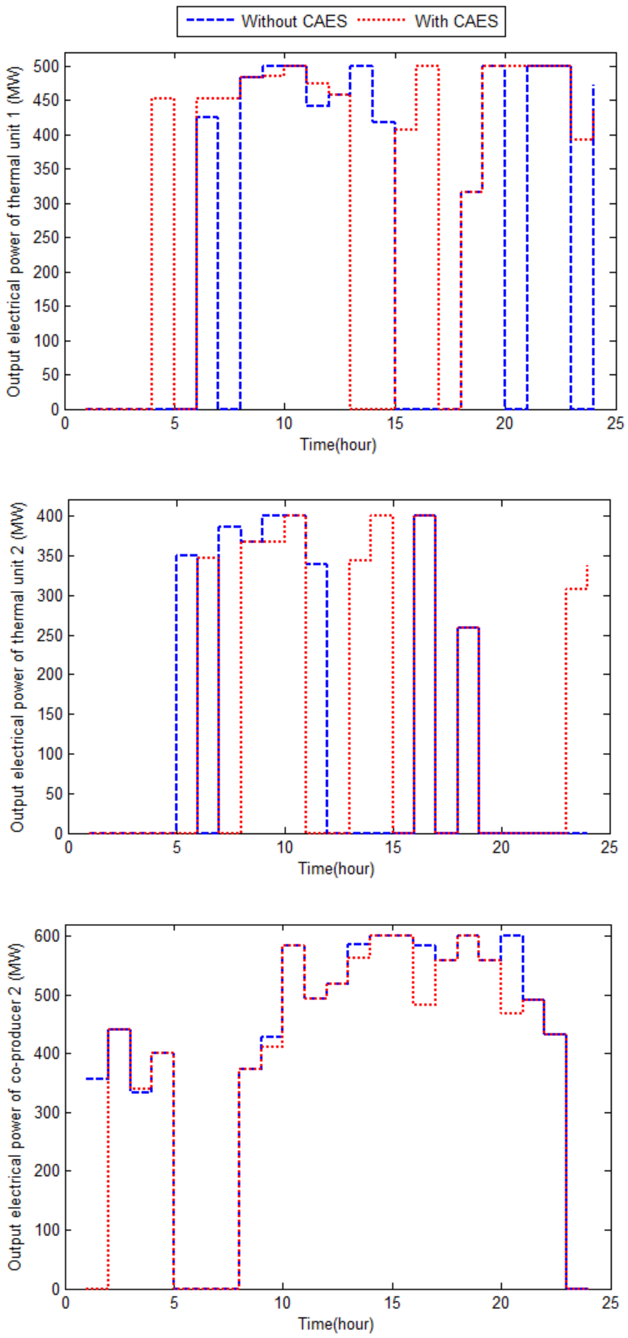


Fig. 6. . The electrical power generated by the conventional thermal units and the co-generators with and without participation of CAES



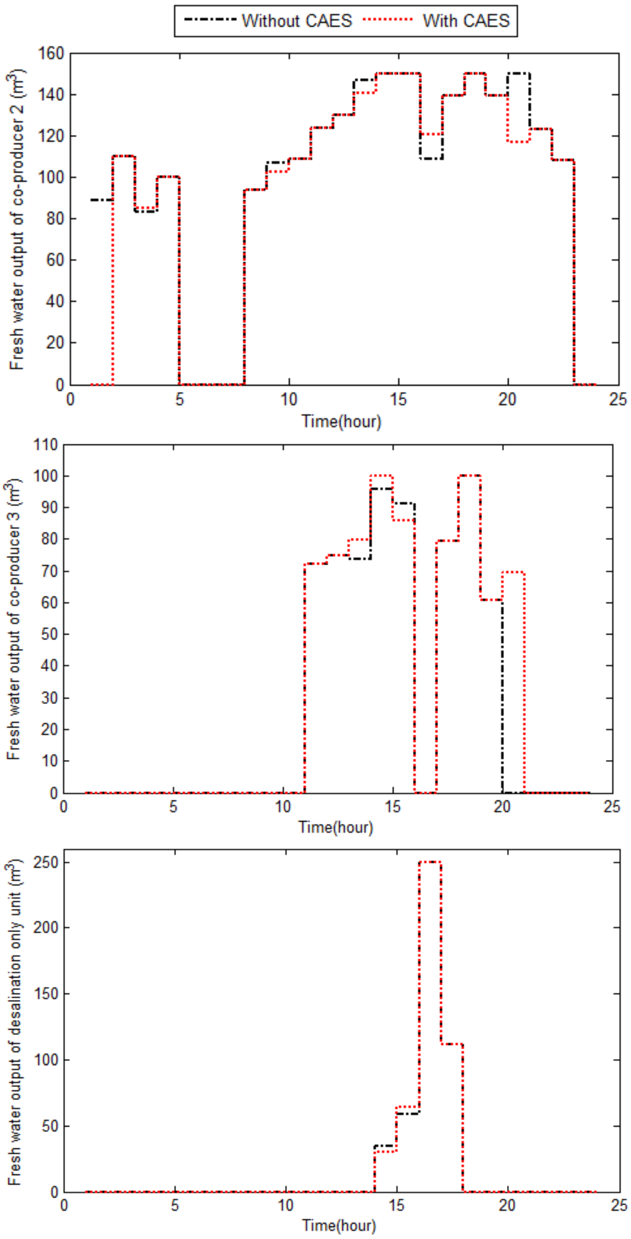


Fig. 7. Fresh water treatment patterns of co-producers and desalination only unit

Table 5. Economic comparison between two cases (Case 1: without CAES, Case 2: with CAES)

Case study	Cost ($)			
	C_p	C_{cwp}	C_w	Objective function
Case 1	1222.3	24933.2	0	26155.5
Case 2	1174.8	24636.8	0	25811.6

4. CONCLUSION

This paper presented a novel framework for economic co-optimization of water and power generation systems that composed of conventional thermal generating unit, desalination processes, and combined potable water and electricity generation units. In addition, optimal charge pattern (power consumption mode) and discharge schedule (power generation stage) of adiabatic CAES are found aiming to minimize the operation cost of the water-energy nexus model as low as possible. The case study shows that the electrical power requirement of the test system over the mid-peak and on-peak periods is only satisfied by cooperating the thermal power plants and CWP units. As stated in Tables 1 and 3, total power generation capacities of co-producers and power only units equal to 1800 and 1750 MW. Based on Tables 1 and 2, maximum water production limits of co-producers and desalination only units are equal to 450 and 250 m^3. If the thermal power plants and CWP units are not co-scheduled, at least 175 MW load-generation mismatch will occur at hour 20. Similarly, if the desalination process and CWP units are not co-dispatched, 30 and 100 m^3 potable water demand will not be supplied at hours 14 and 16, respectively. Therefore, co-optimization of water and energy networks was carried out. Additionally, it is found that participation of advanced adiabatic CAES reduces total fuel cost of thermal generation units from $1222.3 to $1174.8. Moreover, daily operation cost of co-producers decreased from $24933.2 to $24636.8. Moreover, application of CAES in test water-energy hub system has caused $343.9 cost saving.

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