An Optimization Analysis of Cross-border Electricity Trading between Afghanistan and its Neighbor Countries

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Abstract: A landlocked country, Afghanistan, located between energy surplus regions and energy deficit areas is blessed with abundant renewable energy sources (RESs) which can exploit not only to cover its power demand but also to earn remarkable export revenue. This paper focuses on generation scheduling problem along with the optimal sizing of the hybrid renewable energy system (HRES) integrated with the northeast power system (NEPS) of Afghanistan to electrify northeast region of Afghanistan as well as to meet power shortages of Afghanistan's longest shared border neighbor, Pakistan. The NEPS of Afghanistan is an isolated power system supplied by Afghanistan's own generations and imported powers from Uzbekistan and Tajikistan. Genetic Algorithm (GA) is used to schedule all units' output power as well as to find the on/off status of thermal units and the optimal values of the total area occupied by the set of photovoltaic (PV) panels, total swept area by the rotating turbines' blades and the volume of the upper reservoir of pumped hydro energy storage (PHES) system. The objective of this research is to minimize the total operation cost of thermal units, aggregate imports power tariffs, and the total net present cost of HRES and to maximize the income from selling electricity to Pakistan.

Keywords: Electricity trade optimization, generation scheduling, system sizing, hybrid renewable energy system, genetic algorithm.

1. INTRODUCTION

South Asian countries with about 1.8 billion population have one of the fastest growing regional economies in the world (see Worldometers (2018)). These countries have been experiencing significant growth in electrical power demand and utility infrastructures. Electricity demand of them is outstripping supply, so all of them are seeking for import of electricity as long-term option for their energy supply mix (IRADe (2013)). Pakistan, the dominant country after India in the area, is facing its worst power crisis which is hindering its economic and social development. The country has already faced year-round load shedding of about 4,000-5,000 MW (see Sediqi et al. (2017b); Faheem (2016)). On the contrary, Central Asian Republics and Iran are energy rich countries. In addition of 100% accessibility to electricity, they have excess power. Afghanistan is a landlocked country located within South Asia and Central Asia, and fortunately, is also endowed with large renewable energy sources (RESs). Afghanistan's feasible solar potential exceeds 220 gigawatts (GW), feasi-

ble wind potential is over 66 GW and technical hydropower potential is estimated at 23 GW (Sediqi et al. (2017b)). In addition to the aforesaid resources, the country is also blessed with substantial biomass and geothermal potentials. Therefore, by installation of power plants using RESs as well as by importing power from Central Asian neighbors, Afghanistan can increase its power supply capacity to meet its energy demand as well as to gain significant income from exporting power to South Asian countries such as Pakistan. Due to the stochastic nature of RESs, it is rather better to use a hybrid renewable energy system (HRES) by which the system's reliability increases. If a hybrid system is optimized, it would be cost effective and more reliable (see Sediqi et al. (2016); Askarzadeh and Coelho (2015); Hong and Lian (2012); Kaabeche and lbtiouen (2014)).

Besides, the generation scheduling problem known as unit commitment (UC) with consideration of HRES plays a prominent role in minimizing the total operation cost of thermal units plus aggregate imports power tariffs of the
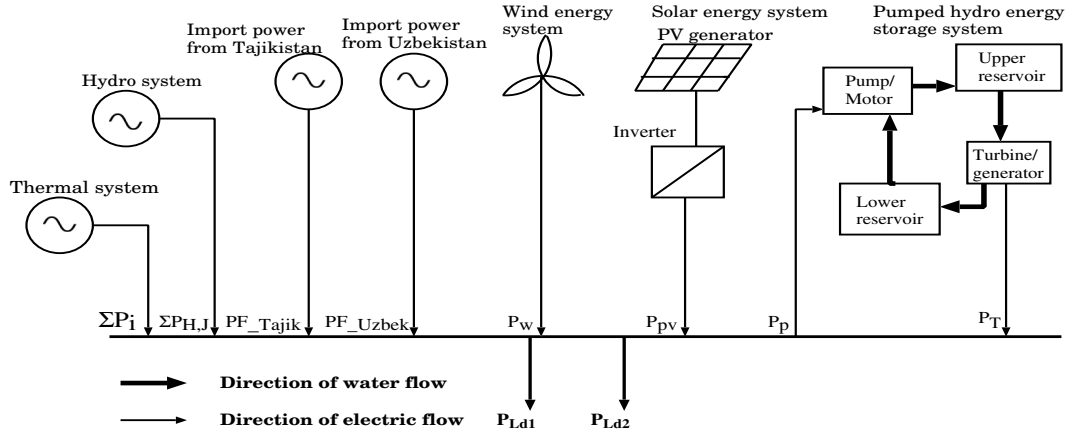
Fig. 1. Simplified generation system under study.

country, since the country imports 78% of electrical energy from its neighbor countries and the remaining 22% gets from its own sources, minorly thermal units with high fuel costs (see Sediqi et al. (2017a)).

This study involves the northeast power system (NEPS) of Afghanistan having thermal units, hydro units, and imported powers which electrify northeast region of Afghanistan with high thermal operation cost and imports power tariffs. As a result, a HRES consists of photovoltaic panels (PV), wind turbines (WTs) and pumped hydro energy storage (PHES) is added to the grid (NEPS) to minimize the total operation cost of thermal units, aggregate imports power tariffs, and maximize the income from selling electricity to Pakistan and simultaneously minimize the total net present cost of the HRES. In the proposed system, the decision variables are all units' output power, on/off schedule of thermal units, the total area occupied by PV panels, total swept area by the rotating turbines' blades, and the volume (V_{UR}) of the upper reservoir of PHES system.

2. PROBLEM FORMULATION

The optimized generation system under study is depicted in Fig. 1. This is the NEPS of Afghanistan with inclusion of PV, WTs, and PHES in the generation side and Pakistan's power shortage (P_{Ld2}) in the demand side of the system. This actual problem model does not consider system configuration and line impedances.

2.1 Objective Function

$$Min.TC \tag{1}$$

where

$$TC = \sum_{t=1}^{T} \sum_{i=1}^{NG} [FC_i(P_{i,t}) + SC_i(1 - U_{i,t-1})]U_{i,t}$$
$$+ \sum_{t=1}^{T} \sum_{z=1}^{Z} c_{z,t} \cdot PF_{z,t} + \sum_{k \in HRES} C_k + OM_{npv,k} \tag{2}$$
$$+ R_{npv,k} - S_{npv,k} - \sum_{t=1}^{T} \sum_{zp=1}^{Zp} c_{zp,t} \cdot PF_{zp,t}$$

where TC is the total cost of the system over the study time. FC_i is the fuel cost of the ith thermal unit. $P_{i,t}$ is power output of the ith thermal unit at time t, T is the number of considered time intervals under study (24 hours in this research) and NG is the number of thermal units generations. SC_i is the start-up cost for unit i, $U_{i,t}$ depicts the on/off [0,1] status of unit i at time t, $c_{z,t}$ is cost of power/MWh import of Afghanistan from country z (Tajikistan and Uzbekistan in this research) and $PF_{z,t}$ is power flow from country z to Afghanistan at time t (PF_Tajik and PF_Uzbek).

Also, C, OM, R, and S are the capital cost, operating and maintenance cost, replacement cost and salvage cost of the HRES respectively. The npv subscript means the net present value of each factor. $c_{zp,t}$ is cost of power/MWh export of Afghanistan to country zp (Pakistan in this paper). $PF_{zp,t}$ is power flow from Afghanistan to country zp at time t (PF_Pak).

2.2 System Constraints

Power balance constraint

$$P_{Ld1,t} + \sum_{zp=1}^{Zp} PF_{zp,t} + P_{P,t} = \sum_{i=1}^{NG} P_{i,t} + \sum_{j=1}^{J} P_{H,j}$$
$$+ \sum_{z=1}^{Z} PF_{z,t} + P_{w,t} + P_{PV,t} + P_{T,t} \tag{3}$$

where $P_{Ld1,t}$ is the power demand of Afghanistan and $P_{P,t}$ is the input power from the system to the pump at time t. $P_{H,j}$, $P_{PV,t}$, $P_{w,t}$, and $P_{T,t}$ are the output power of the jth hydro unit, power supplied by PV, WT and PHES at hour t respectively.

In addition, the power export of Afghanistan to country zp at hour t should be equal to the shortage of the country zp at time t.

$$PF_{zp,t} = P_{Ld2,t} \tag{4}$$

2.3 Generator Physical Constraints

Generating unit limit

$$P_{i,min} \leq P_{i,t} \leq P_{i,max} \tag{5}$$

where, $P_{i,min}$ and $P_{i,max}$ are the minimum and maximum real power output of ith generation respectively. Also,

$$PF_{z,t} \leq Max\_PF_{z,t} \qquad (6)$$

where $Max\_PF_{z,t}$ depicts the maximum power export capacity of country z.

Units minimum up and down time constraints

$$T_i^{on} \geq MUT_i \qquad (7)$$

$$T_i^{off} \geq MDT_i \qquad (8)$$

where T_i^{on}, T_i^{off}, MUT_i and MDT_i are the total up-time, total down time, minimum up-time, and the minimum down-time of ith unit respectively.

Ramp rate up/down constraint

$$P_{i,t} - P_{i,t-1} \leq UR_i, if\ generation\ increases \qquad (9)$$

$$P_{i,t-1} - P_{i,t} \leq DR_i, if\ generation\ decreases \qquad (10)$$

In the above equation, UR_i and DR_i show the ramping up and ramping down of ith unit respectively.

2.4 Modeling of PV, WT and PHES Subsystem

In this paper, the mathematical model of PV, WTs and PHES is adopted from (see Sediqi et al. (2017b, 2016); Ma et al. (2015, 2014) which is briefly described as follows:

Modeling of PHES subsystem

Pumping mode: pump/motor unit

$$q_{p,t} = \frac{\eta_p \cdot P_{P,t}}{\rho \cdot g \cdot h} = c_p \cdot P_{P,t} \qquad (11)$$

where $q_{p,t}$ is the water flow rate elevates from the lower reservoir by the pump at hour t, h is the elevating height (m), g is the gravity acceleration (9.81 m/s^2), ρ is water density (1000 kg/m^3), η_p is the overall pumping efficiency, and c_p is the water pumping coefficient of the unit in (m^3/kWh).

Generating mode: turbine/generator unit

$$P_{T,t} = \eta_t \cdot \rho \cdot g \cdot h \cdot q_{t,t} = c_t \cdot q_{t,t} \qquad (12)$$

where η_t denotes the overall efficiency of the turbine-generator unit, $q_{t,t}$ depicts the water volumetric flow rate input into the turbine (m^3/s) at time t, and c_t shows the turbine generating coefficient (kWh/m^3).

Upper reservoir (UR)

$$Q_{UR,t} = Q_{UR,t-1} \cdot (1-\alpha) + q_{p,t} - q_{t,t} \qquad (13)$$

where $Q_{UR,t}$ and $Q_{UR,t-1}$ are the quantity of water stored in UR at hour t and $t-1$ respectively. α is the evaporation and leakage loss. The SOC of the storage system is expressed as:

$$SOC_t = \frac{Q_{UR,t}}{Q_{UR_{max}}} \qquad (14)$$

The water quantity of upper reservoir is subject to the following constraint:

$$Q_{UR_{min}} \leq Q_{UR} \leq Q_{UR_{max}} \qquad (15)$$

where Q_{URmin} and Q_{URmax} are the minimum and maximum limits of the UR.

2.5 PV panels output power

$$P_{PV,t} = \eta_{PV} \cdot A_{PV} \cdot I_t \qquad (16)$$

where η_{PV} depicts PV panels efficiency, and I_t is the hourly solar insolation in kW/m^2.

2.6 Wind generator output power

$$P_{w,t} = \frac{1}{2} \cdot C_p \cdot \rho_a \cdot \eta_g \cdot A_w \cdot V_t^3 \qquad (17)$$

where C_p is power coefficient, ρ_a is the density of air in kg/m^3, η_g is the efficiency of WT, and V_t is the wind speed in a instant of time t in m/s.

2.7 Economic Analysis of HRES

$$TNPC_k = C_k + OM_{npv,k} + R_{npv,k} - S_{npv,k} \qquad (18)$$

where $k \in PV, w, PHES$. $TNPC$ is the total net present cost.

The $TNPC$ of the HRES is the sum of $TNPC$ of all the components:

$$TNPC = TNPC_{PV} + TNPC_W + TNPC_{PHES} \qquad (19)$$

2.8 PV array TNPC

PV array capital cost

$$C_{PV} = \alpha_{PV} \cdot A_{PV} \qquad (20)$$

C_{PV} is the capital cost, and α_{PV} is the initial cost \$/m^2 of PV array.

PV panels operation and maintenance cost

$$OM_{npv,PV} = \beta_{PV} \cdot A_{PV} \cdot \sum_{j=1}^{N} (\frac{1 + \mu_{PV}}{1 + i})^j \qquad (21)$$

β_{PV} is the annual operation and maintenance (O&M) cost in \$/m^2/year, μ_{PV} is the escalation rate, i is the interest rate and N denotes the project lifetime.

PV array replacement cost By assuming the lifetime span of PV panels equal to the project lifetime, the total replacement cost for PV panels is zero ($R_{PV} = 0$).

PV panels salvage cost By considering the resale price of λ_{PV} in \$/m^2 the total income obtained from resale is:

$$S_{npv,PV} = \lambda_{PV} \cdot A_{PV} \cdot (\frac{1 + \delta}{1 + i})^N \qquad (22)$$

where δ denotes the inflation rate. Finally, the $TNPC$ of PV array is obtained by Eq. 18.

2.9 Wind turbines TNPC

The $TNPC$ of the WTs is obtained same as for the PV panels, only except replacing the subscript PV by w.

Table 1. Data for the UC problem.

	(Th-1)	(Th-2)	(Th-3)	(H-1)	(H-2)	(H-3)	PF_Tajik	PF_Uzbek
P_{max} (MW)	105	22	23	22	66	100	300	300
P_{min} (MW)	15	5	5				0	0
a ($/h)	680	660	665					
b ($/MWh)	16.5	25.92	27.27				20	60
c ($/MW^{2}h)	0.00211	0.00413	0.00222					
MUT (h)	4	1	1					
MUD (h)	4	1	1					
h-cost ($)	560	30	30					
c-cost ($)	1,120	60	60					
cshour (h)	4	0	0					
initial status (h)	4	1	1					

Table 2. Parameters used for the HRES in this research.

Interest rate	i		0.1
Project lifetime	N	(years)	20
Inflation rate	δ		0.04
Escalation rate	$\mu_{pv,w}$		0.075
Inverter efficiency	η_{inv}		0.9
Inverter initial cost	α_{inv}	($/5kW)	4,480
Inverter lifetime	L_{inv}	(years)	15
PV initial cost	α_{PV}	($/m^2)	519.7
Annual O&M cost of PV	β_{PV}	($/m^2/year)	1 % of α_{PV}
Resale price of PV	λ_{PV}	($/m^2)	25 % of α_{PV}
PV efficiency	η_{PV}		0.14
Lifetime of PV	L_{PV}	(years)	20
Initial cost of Wind turbine	α_w	($/m^2)	544.2
Annual O&M cost of wind	β_w	($/m^2/year)	2 % of α_w
Resale price of wind turbine	λ_w	($/m^2)	30 % of α_w
Wind generator lifetime	L_w	(years)	20
Power coefficient	C_p		0.59
Air density	ρ_a	(kg/m^3)	1.225
Wind generator efficiency	η_g		0.85
Reinforce concrete (reservoir)	α_{UR}	($/m^3)	170
Reservoir lifetime	L_{UR}	(years)	35
Pump initial cost	α_P	($/45kW)	10,749
Pump lifetime	L_P	(years)	10
Turbines and pipes	$\alpha_{T\&Pi}$	($/kW)	1,000
Turbines and pipes lifetime	$L_{T\&Pi}$	(years)	10

Fig. 2. Daily power demand for NEPS of Afghanistan.
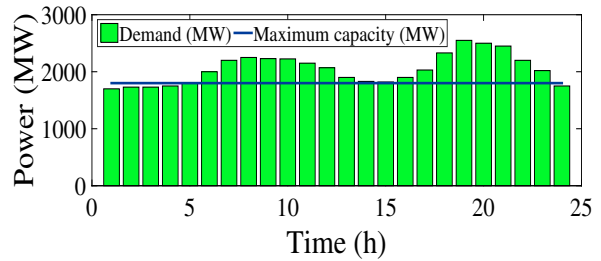
Fig. 3. Daily load demand and total power supply capacity of Pakistan.

2.10 pumped hydro energy storage TNPC

The cost of UR of PHES is majorly from the reinforced concrete. The TNPC for the UR is obtained same as that explained for the PV panels except the subscript PV is replaced by UR. The system lifetime is assumed as 20 years.

3. GENETIC ALGORITHM (GA)

There are many researches carried out regarding UC and sizing and optimization of RESs with different methods. Among them, GA has been widely studied. GA is based on natural selection (survival of the fittest), the process that drives biological evolution. In GA, at each iteration, individuals from the current population (called parents) are randomly selected and are used to produce next generation (called children). After successive iterations, the population evolves toward an optimal solution. The following steps show how GA works:

3.1 How GA Works

GA works as following steps:

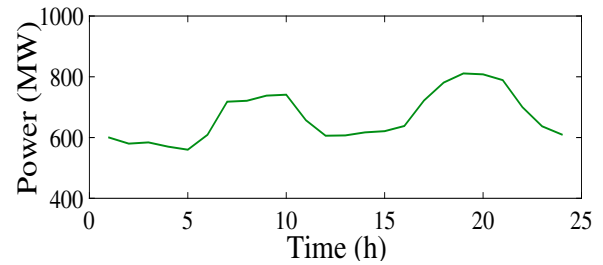*1) Initial Population* GA begins with the creation of random initial populations. The default value of population size in the population options is 20 individuals. Also, one can change the population size as he/she wants.

2) Calculation of Fitness Function The individuals are placed into fitness function and its value is calculated.

3) Creating Next Generation At each step, GA uses the current population to create the children that make up the next generation. GA creates three types of children for the next generation: (1) Elite children (2) Crossover children (3) Mutation children.

4) Stopping Conditions for GA If the stopping condition is satisfied, the technique is stopped and the fitness values are selected as optimal solution, otherwise steps 2-3 are repeated.

The MATLAB software has been applied to code and simulate the GA. It is not to be unsaid that this optimization is a sequential optimization problem. Using Optimization Toolbox (optimtool), the parameters of the algorithm were set to:

- Fitness Function: Eq. 1
- Number of Variables: 219
- Population size: 200
- Number of Generations: 100*number of variables.

Table 3. The results obtained by the GA.

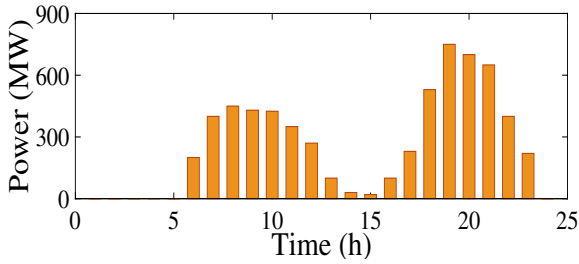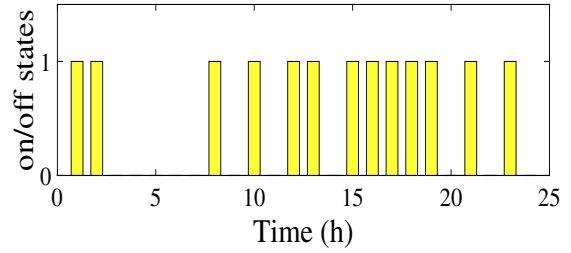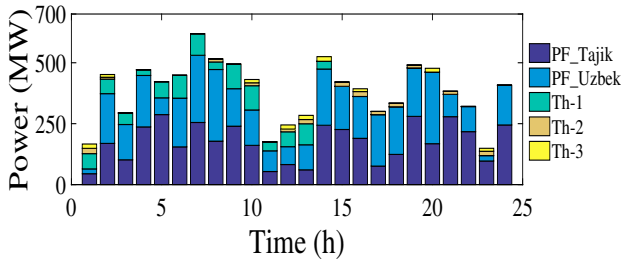| $A_{PV}(m^2)$	$A_w(m^2)$	$V_{UR}(m^3)$	$TNPC(\$)$	$TC(\$)$	$PF\_Pak(MW)$	Income (\$) from selling PF_Pak
8,131,600	9,350,000	17,055	1,485,100	1,832,900	6,255	56,295

Fig. 4. Optimal power export to Pakistan.

Fig. 5. Optimal power import and output power of thermal units.
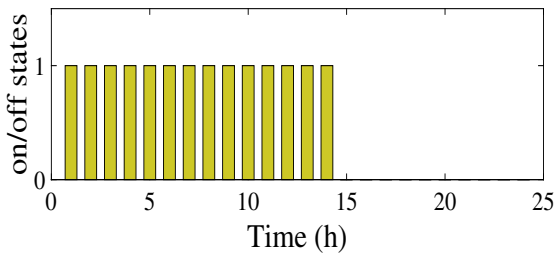
Fig. 6. On/off schedule of Th-1.

Fig. 7. On/off schedule of Th-2.

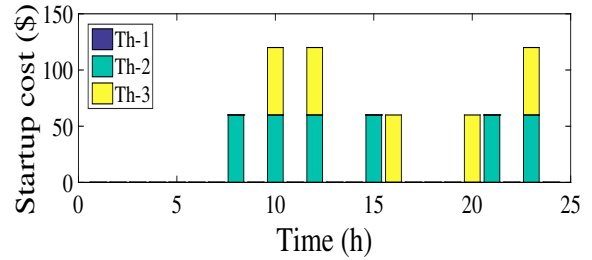Fig. 8. On/off schedule of Th-3.

Fig. 9. Start-up cost of thermal units.

Fig. 10. Optimal output power of all units in the proposed system.

4. SIMULATION RESULTS AND DISCUSSIONS

4.1 Simulation conditions

The proposed system shown in Fig. 1 consists of three thermal units, three hydro units, two sources of import power, one equivalent PV power, one source of WTs power, and one equivalent PHES system. The data for generating units are given in Table 1. In this table, Th-1, Th-2, Th-3 indicate thermal unit 1, 2, 3 and H-1, H-2, H-3 depict hydro unit 1, 2, 3 respectively. The parameters used for the sizing and optimization of HRES is shown in Table 2. The hourly load profile for NEPS of Afghanistan is shown in Fig. 2 and daily power demand and maximum power supply capacity of Pakistan is depicted in Fig. 3.

4.2 Simulation Results

The objective function (section 2.1) subject to the constraints (section 2.2-2.4) is solved and the results are presented. In the proposed model, there are 219 decision variables namely, the optimal power output of Th-1 (24 h), Th-2 (24 h), Th-3 (24 h), on/off status of Th-1 (24
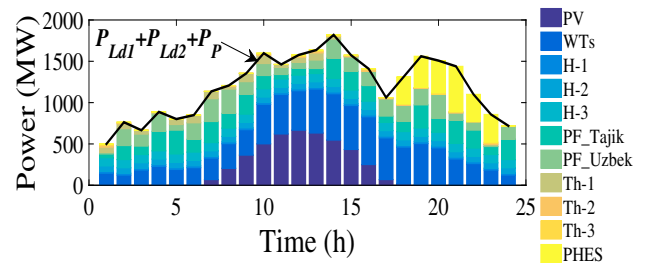
h), Th-2 (24 h), Th-3 (24 h), optimal power import from Tajikistan (24 h), from Uzbekistan (24 h), A_{PV}, A_w, V_{UR} and the optimal power export to Pakistan (24 h). The results obtained by the studied GA are shown in Table 3, and Figs. 4-13. The optimal values of A_{PV}, A_w, V_{UR} are 8,131,600 m^2, 9,350,000 m^2, and 17,055 m^3, respectively and their $TNPC$ is 1,485,100 \$. The total optimal power export to Pakistan is 6,255 MW (for each hour graphically shown in Fig. 4) and the total income for Afghanistan from selling this much power is 56,295 \$. The import powers from Tajikistan and Uzbekistan and the output power
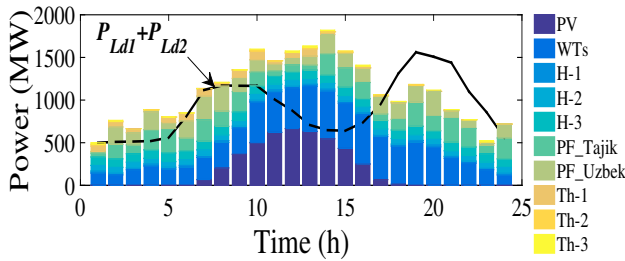
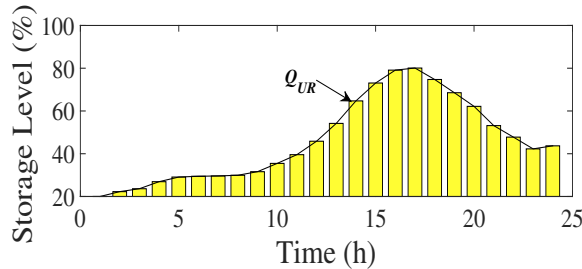Fig. 11. optimal output power of all units without PHES.
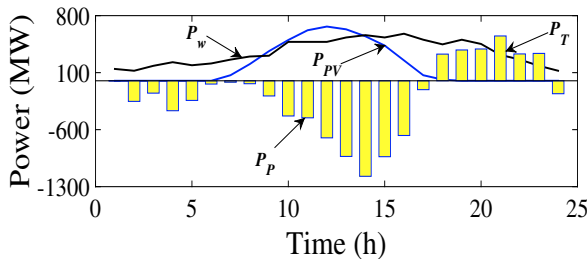

Fig. 12. State of operation of PHES.

Fig. 13. Optimal output power of PV, WTs, and PHES.

and on/off status of thermal units are shown in Figs. 5-8. Compare to import powers (Fig. 5), the output power of thermal units is much less. In addition, we can observe from the on/off status of the units, most hours they are off. These are because of two reasons: first, thermal units are expensive than import powers, as thermal units need extra cost for startup too (Fig. 9) and secondly, this is due to much availability of power from neighbor countries. The total operation cost of thermal units plus aggregate import power tariffs are 404,040 $ and TC of the proposed system is 1,832,900 $. Furthermore, we can observe from the results that the system constraints have been obeyed and satisfied by the proposed algorithm.

Fig. 10 depicts output power of all units in the system. In this study, PHES is introduced as a storage system to keep the surplus power and generate it in deficit periods (Fig. 11). It is obvious that the available surplus power from the system is first used to cover the local power demand of Afghanistan and the shortage of Pakistan and accordingly support the pumping units to increase water storage in the UR (Fig. 12). When energy deficit exists, the turbine units are launched, releasing water from the UR to produce electricity and thus meet the net load of the country and the shortage of Pakistan. As we can observe (Fig. 10), the daily load profile of Afghanistan plus the power shortage of Pakistan is covered by installation of new power plants of PV, WTs, and PHES. Fig. 13 illustrates the output power

of PV, WTs and PHES system over the 24 h scheduling period.

5. CONCLUSION

In this paper, optimal unit commitment (UC) along with the optimal sizing of the HRES added to NEPS of Afghanistan was solved using GA optimization technique to economically electrify the northeast region of Afghanistan as well as to cover Pakistan's power shortage. The objective of this research was to minimize the total operation cost of thermal units, import power tariffs, and the total net present cost ($TNPC$) of the HRES and to maximize the income from selling electricity to Pakistan. As it was shown Afghanistan can sell 6,255 MW to Pakistan. By utilizing its location and exploiting its abundant RESs, Afghanistan can not only cover its power demand but also can sell to energy deficit countries such as Pakistan and India to obtain significant income for its own economy.

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