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Article

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Economic analysis of pumped hydro storage under Korean governmental expansion plan for renewable energy

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Abstract

A government plan was announced to expand the share of renewable energy to 20 percent by 2030 in Korea and to construct additional pumped hydro storage (PHS) to prepare for the uncertainty of renewable generation. However, due to the distortion of the Korean electricity market, pumped storage power plants are operating in the red, which may cause controversy over the economic feasibility of additional construction. In this study, we intend to analyze the exact economic value of the PHS in Korea under the plan for supplying electricity in 2030. To this end, an annual economic dispatch algorithm was developed using linear programming model and various scenarios were analyzed, including securing reserve power to cope with the variability of renewable energy. As a result of the analysis, we can confirm the economic feasibility of PHS prepare for expansion of renewable energy if PHS are correctly compensated according to the value contributing to the stable operation of the grid in the electricity market.

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Keywords: Economic analysis; Pumped hydro storage; Renewable energy; Linear programming

1. Introduction

Renewable energy is presented as an important solution to climate change and fossil fuel depletion. As a result, the share of renewable energy generation is expanding worldwide, and Korean government is also increasing the share of renewable energy generation through a national plan called 'Implementation Plan for 3020 New and Renewable Energy' that will increase the share of renewable energy generation by 20 percent by 2030 [1].

However, solar and wind energy, which account for the bulk of renewable energy, have problems of variability and intermittency, causing frequency fluctuations in power system and difficulties in maintaining balance in power supply and demand [2]. In addition, Korean power system has been electrically isolated after the Korean War and has relatively small inertia compared to other linked power systems in Europe or the US. Therefore, it is relatively

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Nomenclature

G	Set of thermal units, $g \in G$
H	Set of cogeneration for heat, $g \in H$
$X_{g.t}$	Generation of unit g at time period t
C_g	Fuel cost of generator unit g
L_t	Load at time period t
$X_{g,t}^{GF}$	Governor Free reserve of unit g at time period t
$X_{g,t}^{AGC}$	Automatic Generation Control reserve of unit g at time period t
$X_{g,t}^{QS}$	Quick-Start reserve of unit g at time period t
$X_{g,t}^{RP}$	Replacement reserve of unit g at time period t
C_g^{NL}	Quick-start reserve cost of unit g (heuristic term)
$P_{g,t}$	Supply capacity of generator unit g at time period t
$Ramp_g$	Ramp of generator unit g
$Z_{s,t}$	Generation of slack unit s at time period t
C_s	Cost of slack unit g
R_t	Generation of renewable energy power at time period t
YG_t	Power generation of PHS at time period t
YGC	Maximum capacity the PHS in the power generation mode.
YP_t	Pump of PHS at time period t
YPC	Maximum capacity the PHS in the pump mode.
WL_t	Water level(capacity) of PHS at time period t
EC	Energy capacity of PHS
u_t	1 if PHS is pumping, 0 otherwise
v_t	1 if PHS is generating, 0 otherwise
E	Pumping efficiency of PHS

vulnerable to frequency stability, if the variability of renewable power increases. As a result, it is essential to secure flexible resources that can effectively cope with frequency fluctuations in Korean power system, and Korean government refers the importance of securing flexible resources through 'The 8th basic Plan for Korean Power System' that includes a facility construction plan for the next 15 years.

This study deals with the benefit of pumped hydro storage (PHS) to system operation as a flexible resource. For this, a LP-base optimization model is defined and yearly operating cost of Korean power system in 2030 is analyzed. These results are expected to help improve Korean electricity market system so that PHS can receive adequate compensation.

2. Optimization model

2.1. Basic formulation

$$\mathbf{min}\Big(\sum_{g\in G}\sum_{t\in T} X_{g,t}C_{g,t} + \sum_{s\in S}\sum_{t\in T} Z_{s,t}C_s + \sum_{g\in G}\sum_{t\in T} X_{g,t}^{QS}C_{g,t}^{NL}\Big) \tag{1}$$

$$\boldsymbol{s.t.}\quad L_t - Z_{1,t} = \sum_{g\in G} X_{g.t} + R_t + (YG_t - YP_t), \forall\, t \tag{2}$$

$$HC_t \le \sum_{g\in H} X_{g,t}, \forall t \tag{3}$$

$$X_{g,t+1} - X_{g,t} \leq Ramp_g, \forall g,\ t \tag{4}$$

$$X_{g,t} - X_{g,t+1} \leq Ramp_g, \forall g,\ t \tag{5}$$

$$GF - Z_{2,t} \leq \sum_{g\in G} X_t^{GF} + YG_t^{GF}, \forall\ t \tag{6}$$

$$AGC - Z_{3,t} \leq \sum_{g\in G} X_t^{AGC} + YG_t^{AGC}, \forall\ t \tag{7}$$

$$QS - Z_{4,t} \leq \sum_{g\in G} X_t^{QS} + YG_t^{QS}, \forall\ t \tag{8}$$

$$RP - Z_{5,t} \leq \sum_{g\in G} X_t^{RP} + YG_t^{RP}, \forall\ t \tag{9}$$

$$X_{g,t} + X_{g,t}^{GF} + X_{g,t}^{AGC} + X_{g,t}^{QS} + X_{g,t}^{RP} \leq P_{g,t}, \forall g,\ t \tag{10}$$

$$X_{g,t}^{GF} \leq X_g^{GFC}, \forall g,\ t \tag{11}$$

$$X_{g,t}^{AGC} \leq X_g^{AGCC}, \forall g,\ t \tag{12}$$

$$X_{g,t}^{QS} \leq X_g^{QSC}, \forall g,\ t \tag{13}$$

$$u_t + v_t \leq 1, \forall\ t \tag{14}$$

$$YG_t + YG_t^{GF} + YG_t^{AGC} + YG_t^{QS} + YG_t^{RP} \leq YGC * u_t, \forall\ t \tag{15}$$

$$YP_t \leq YPC * v_t, \forall\ t \tag{16}$$

$$WL_{t+1} = WL_t - YG_t + E * YP_t, \forall\ t \tag{17}$$

$$WL_t \leq EC, \forall\ t \tag{18}$$

$$WL_0 = EC/2 \tag{19}$$

$$WL_{8760} = EC/2 \tag{20}$$

$$YG_t^{GF} \leq \mathrm{YG}^{GFC}, \forall\ t \tag{21}$$

$$YP_t^{QS} \leq YP_t, \forall\ t \tag{22}$$

Objective function Eq. (1) indicates the yearly operating cost. The first term of Eq. (1) is the thermal generation cost. The second term is a penalty cost of the slack variables, which represent unmet constraints. The third term is a heuristic representation of the no-load cost of generators, which are additionally committed to secure quick-start (QS) reserve. Eqs. (2)–(13) are constraints on the operation of the generator. Eq. (2) indicate a power balance in which supply and demand match over time. Eq. (3) indicate the minimum cogeneration for heat supply over time. Eqs. (4), (5) show the limits of the ramp-up/ down speed. Eqs. (6)–(9) indicate the minimum amount of operational reserve by reserve power over time. Eq. (10) indicate the maximum capacity each generator can have within its supply capacity over time. The supply capacity reflects the generator maintenance scheduling. Eqs. (11)–(13) indicate the reserve capacity that the generator can take, which will be determined by the droop and ramp characteristics of the generator. Eqs. (14)–(22) are constraints on the operation of PHS. Eq. (14) indicate that the PHS may only be capable of power generation or pump operation. Eq. (15) indicate the maximum capacity that PHS can have in the power generation mode. Eq. (16) indicate the maximum capacity the PHS can have in the pump mode. Eq. (17) indicate the relationship between power generation, pump volume and water level of PHS over time. Eq. (18) represents the maximum capacity according to water level of the PHS, Eqs. (19) and (20) represent the boundary condition of the PHS water level. Eq. (21) indicates the governor free (GF) constraints considering the drop characteristics when the PHS operates in the power generation mode. For PHS, the ramp characteristics are superior to those of other generators, so there are no constraints on automatic generation control (AGC) and other reserve powers. If PHS is operated in pumped mode, by stopping the scheduled pumping, may have the same effect as the QS reserve. In this case, the available reserve capacity is the scheduled pumping and can be expressed as shown in Eq. (22)

2.2. Heuristic constraints

The optimization problem of this paper is the optimal solution obtained by LP-base formulation, so the optimal result obtained from the MIP-base formulation of 'unit commitment problem' can be somewhat different from the result. Typically, LP-base formulation cannot reflect the minimum power constraints of generator. This model may derive physically impossible solutions, which assume that a generator with low output can provide a large amount of reserve power. In particular, these problems will be further highlighted if the number of decision variables are reduced by combining generators of the same fuel type to reduce the simulation time. To compensate for these problems of LP-base formulation with reduced decision variable, the following heuristic constraints were added.

$$X_g^{GF} \leq a_g X_{g,t}, \forall g,\ t \tag{23}$$

$$X_g^{AGC} \leq b_g X_{g,t}, \forall g,\ t \tag{24}$$

$$X_g^{QS} \leq c_g X_{g,t}, \forall g,\ t \tag{25}$$

$$X_{g,t}^{GF} + X_{g,t}^{AGC} + X_{g,t}^{QS} + X_{g,t}^{RP} \leq r_g * P_{g,t}, \forall g,\ t \tag{26}$$

$$YG_t^{GF} \leq \alpha YG_t, \forall\ t \tag{27}$$

$$YG_t^{AGC} \leq \beta YG_t, \forall\ t \tag{28}$$

$$YG_t^{GF} + YG_t^{AGC} + YG_t^{QS} + YG_t^{RP} \leq w * WL_t, \forall\ t \tag{29}$$

Eqs. (23)–(25) represent that a generator can secure the reserve power in proportion to its output, and this implicitly implies that a stationary generator cannot take its reserve power. Eq. (26) indicates the maximum capability of an individual generator to provide reserve power. Since the network condition may limit the capability of a generator to provide reserve power, the value of r_g may be affected by the location of each generator's connection point. Eqs. (27)–(28) defines the available reserve power of the PHS as Eqs. (23) and (24). However, the capability of the PHS to provide QS reserve power is not limited, since even a stationary PHS can reach its maximum output within minutes [3]. Eq. (29) indicate that the reserve power supplied by a PHS may be limited by the energy being stored, or the water level.

3. Numerical simulation

3.1. Simulation setting

Based on 'The 8th basic Plan for Korean Power System' announced in 2017, the situation of Korean power system was assumed in 2030 [4]. A total of 200 generators were condensed into 16 thermal generators and one PHS, as shown in Tables 1 and 2, considering the type of generator and unit cost of production. Based on the research report the constraints by the type of reserve power were determined as shown in Table 3. In order to analyze the effects of additional installation of the PHS determined in 'The 8th basic Plan for Korean Power System' on the power system operation, the simulation results were compared to the current capacity of the PHS (4.7 GW, 32.9 GWh) as of 2019.

Table 1. Plant characteristic.
(NP: Nuclear Power, CP: Coal Power, GT: Gas Turbine, CHP: Combined Heat and Power).

ID	Capacity (MW)	Fuel cost (€/MWh)	Ramp-Up/Dn (MW)	Max reserve (%)	Max GF (MW)	Max AGC (MW)	Max QS (MW)	C_g^{NL} (€/MWh)
NP	20400	4.25	169.93	0	0	0	0	0.00
CP1	9304	37.40	1163	20	465.2	1174.5	4698	0.78
CP2	9770	39.17	1221.25	20	488.5	1288.5	5154	2.69
CP3	7600	41.12	950	20	380	936	3744	3.07
CP4	10040	42.90	1255	20	502	840	3360	3.07
CP5	1069	50.42	133.625	20	53.45	66	264	4.59
GT1	988	45.34	494	40	49.4	186	744	1.61
GT2	3678.2	60.53	1839.1	40	183.91	1504.5	6018	3.70
GT3	9738	67.67	4869	40	486.9	2700.5	10802	2.81
GT4	19274	73.41	9637	40	963.7	4359.5	17438	4.05
GT5	5143	93.27	2571.5	40	257.15	725.55	2902.2	5.79
CHP1	3431	63.98	1715.5	40	171.55	0	1185	5.41
CHP 2	2446	73.51	1223	40	122.3	0	2412	4.28
CHP 3	1569	84.44	784.5	40	78.45	0	1448.2	5.26
CHP 4	311	93.15	155.5	40	15.55	0	276	2.92
CHP 5	1153	143.98	576.5	40	57.65	0	792	22.31

Table 2. Pumped hydro storage.

	CASE-I	CASE-II
Generation capacity (MW)	5500	4700
Pumping capacity (MW)	6128	5237
Pumping efficiency (%)	0.75	0.75
Energy capacity (MWh)	38500	32900

Table 3. Reserve requirement.

	Req. (MW)
GF	2000
AGC	2000
QuickStart	4200
RP	1800

3.2. Simulation results

Calculated under the simulation conditions of 3.1, it is estimated that the annual cost of 17,879 MEUR will be incurred if the additional PHS is not built, and the additional PHS construction will result in 17,814 MEUR, thereby reducing the cost of 66 MEUR per year. Table 4 shows the monthly operation costs incurred by CASE-II without additional PHS and CASE-I with additional PHS. As shown in the table, we can see that the saving costs

Table 4. Monthly operation costs in 2030 (MEUR).

	Jan.	Feb.	Mar	Apr	May	Jun
CASE-I	1,826	1,595	1,629	1,404	1,173	1,338
CASE-II	1,830	1,601	1,642	1,409	1,186	1,339
Diff.	3.7	5.8	13.2	4.8	13.4	1.2
	Jul.	Aug.	Sep	Oct	Nov	Dev
CASE-I	1,504	1,591	1,413	1,262	1,406	1,671
CASE-II	1,505	1,592	1,420	1,269	1,409	1,676
Diff.	1.0	0.6	6.8	7.1	2.9	5.1

are especially high in spring and fall. These seasonal variations in costs can be interpreted from the monthly output pattern results for each generator in Figs. 1 and 2. In other words, due to the seasonal characteristics of low demand and high renewable energy generation in spring, it is inevitable to reduce the power output of nuclear power plants that are cheap but difficult to vary power in order to secure reserve power, in which case PHS may act as a deterrent to the reduction of power in nuclear power plants. In fact, Fig. 3 shows that the utilization rate of PHS in spring is higher than that of summer, and CASE-I shows that the minimum power of nuclear power plants is 4991MW, which is 891MW higher than the 4100 MW of CASE-II.

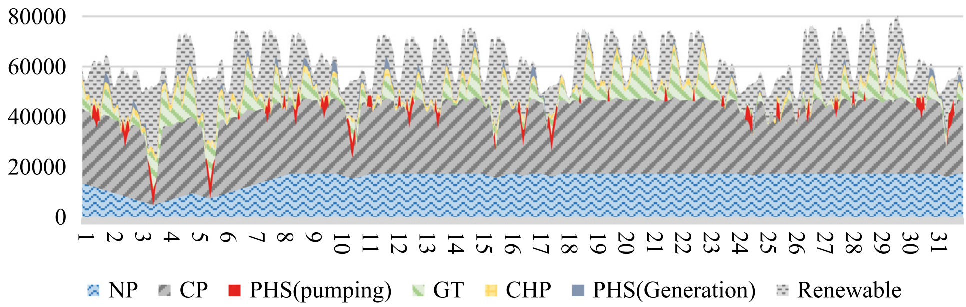

Fig. 1. CASE-I result of simulation in May (spring).

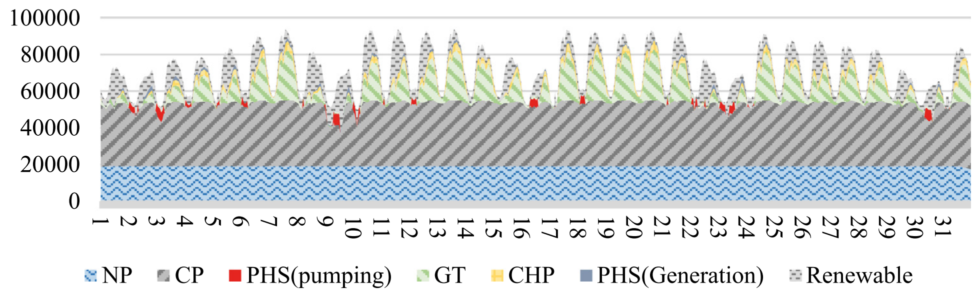

Fig. 2. CASE-I result of simulation in Aug (summer).

4. Conclusion

This study quantitatively analyzed the utility of the system operation of PHS under the Korean government's energy conversion policy announced in 2017. In order to effectively analyze annual fuel costs in 2030, the issue of optimizing the LP-based algorithm, which has been abbreviated by fuel/cost, was defined, and suitable heuristic constraints were added to make the proposed problem elicited a similar value to the MIP-based UC problem without the use of the binary integer variable. The numeral simulation confirmed that the 0.8 GW expansion of the PHS in 2030 under 'The 8th basic Plan for Korean Power System' would reduce the cost of electricity production by about

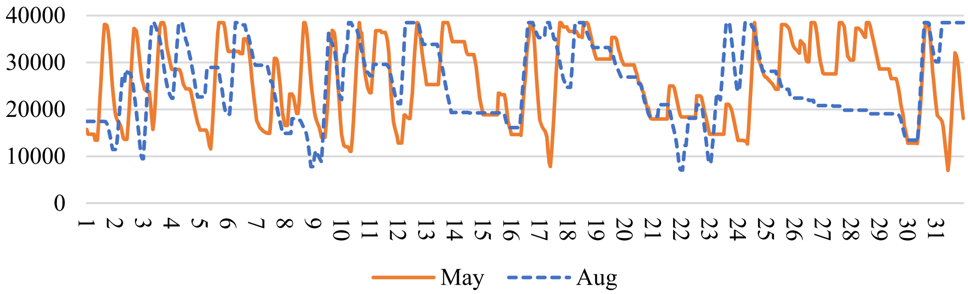

Fig. 3. CASE-I utility of system operation of PHS in May, Aug.

66 MEUR per year. In particular, it was possible to confirm that the role of PHS is essential to cover the volatility of renewable energy, especially in the spring–fall season when demand is low.

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