A mixed-integer unit commitment economic dispatch model (MIUD)

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1 Mixed-Integer Unit commitment and Dispatch (MIUD) Model

The mixed-integer unit commitment and dispatch model simulates the electric power system for 8,760 hours. We formulated the optimal generation decision using the unit commitment model. The day-ahead unit commitment is an optimization model to determine how to operate various power plants to satisfy the electricity demand required for a certain period. The model was implemented on GAMS using a CPLEX solver and solved using two machines with 16 CPU cores and 64 GB RAM. For further descriptions of the models, we have used the notations summarized in Table S1-S3.

1.1 Nomenclature

Lowercase letters denote decision variables, while uppercase letters denote constant parameters.

Table S1 Sets and indices used in the MIUD model

Set and index	Description
$h \in H$	Planning time interval
$g \in G$	Power plants
$s \in S$	Energy storage devices (e.g., Pump, BES)
$c \in C$	Partial load operation indicator (e.g., $c = 1$: low-efficiency operation, $c = 2$: normal operation)
$g \in AMC$	Coal-Ammonia (NH_3) co-firing power plants
$g \in HMC$	LNG-Hydrogen (H_2) co-firing power plants

Table S2 Decision variables in the MIUD model

Variable	Description	Unit or Domain
$y(g,c,h)$	State of generating power plant g in segment c at time h	$\in 0{,}1$
$z(g,c,h)$	Energy generated using power plant g in segment c at time h	GWh
$z_{SR}(g,c,h)$	Reserved energy using power plant in segment c at time h	GWh
$z_o(h)$	Outage of generation below demand at time h	GWh
$z_{SR,o}(h)$	Outage of spinning reserve at time h	GWh
$u(g,h)$	State of start-up of power plant g	$\in 0{,}1$
$d(g,h)$	State of shutdown of power plant g	$\in 0{,}1$
$z(s,h)$	Energy discharged from storage s at time h	GWh
$sz(s,h)$	Energy used to charge storage s at time h	GWh
$st(s,h)$	Among of stored energy of storage s at time h	GWh

Table S3 Parameters used in the MIUD model

Parameter	Description	Unit
$FC(g,c,h)$	Fixed cost of power plant g	USD/GWh
$VC(g,c,h)$	Variable O&M cost of power plant g	USD/GWh
$CU(g)$	Start-up cost of power plant g	USD/GWh
$E(s)$	Discharge efficiency of storage s	%
$D(h)$	Demand during the time h	GWh
$SMX(s)$	Installed energy capacity of storage s	GWh

$SU(s)$	Maximum charge/discharge limit for storage s	GW
$SP(g,c,h)$	Maximum generation of technologies g in segment c at time h	GW
$SN(g,c,h$	Minimum generation of technologies g in segment c at time h	GW
$MU(g)$	Minimum up time that technologies g must be running before shutting down	h
$MD(g)$	Minimum down time that technologies g must be running before starting up	h
$RU(g)$	Maximum ramp up rate of power plant g	GW/h
$RD(g)$	Maximum ramp down rate of power plant g	GW/h
$SRT(g)$	Amount of ramp up time available of power plant g for the reserve generation	-
$SR(h)$	Target spinning reserve at time h	GWh
QR	Target quick start reserve at time h	GWh
V_L	Penalty for the occurrence of under-generation events in the system	USD/GWh
V_M	Penalty for the occurrence of reserve-shortage events in the system	USD/GWh
$hr(g)$	Heat ratio (inverse number of efficiency) of power plant g	-
λ_{AMC}	Ammonia co-firing ratio	-
$F_{GWh}(g)$	Fuel price per GWh used in power plant g	USD/GWh
$F_{Gcal}(g)$	Fuel price per Gcal used in power plant g	USD/Gcal
F_{NH3}	Ammonia price per ton	USD/ton
F_{H2}	Hydrogen price per kg	USD/kg

1.2 Day-ahead MIUD Model Formulation

The formulation of the MIUD model is described in equations (1)-(25). The objective function is to minimize the total cost. The total cost consists of fixed, variable, start-up, and penalty costs. The variable expenses are calculated as the sum of the variable cost inherent in the power plant and the fuel cost that varies depending on the heat ratio of the power plant. The optimal amount of power generation should satisfy the demand for each time (equation (2)) while being constrained by the available generation (equations (3)-(6)). Equation (7) represents the relationship between start-up, shutdown, and operating.

In all cases, energy consumption and CO2 emission are assumed to be higher under a partial loading operation due to the reduced efficiency of combustion chambers when temperature and pressure are below the design limits. In this paper, the index indicates partial load operation. Equation 8 represents that the sum of the values for all partial load operation intervals cannot exceed 1. Therefore, it is possible to operate only for any one of the possible partial load operating intervals.

Equations (9) and (10) represent the spinning reserve that is defined as a reserve power resource constraint. The spinning reserve can be output within the time when power is supplied and is assumed to be 30 minutes (equation (11)). Equations (12) and (13) represent the upward and downward operating reserves and constrain the electricity generation changes in conventional power plants, respectively. The changes are determined by taking between ramp-up and start-up capability or between ramp-down and shutdown capability. Equations (14) and (15) represent each power plant's minimum up and down times. Equation (16) expresses the relationship between the charge and discharge of the storage device. Each storage device can store up to (17) and charge or discharge up to (18)-(19).

1.2.1 Objective Function

$$\min \sum_h \left[\sum_g \left\{ \sum_c \big(FC(g,c,h) y(g,c,h) + VC(g,c,h) z(g,c,h) \big) + CU(g) u(g,h) \right\} + V_L z_o(h) + V_M z_{SR,o}(h) \right] \tag{1}$$

1.2.2 Constraints

- Demand balance

$$\sum_{(g,c)} z(g,c,h) - \sum_s \big(sz(s,h) - E(s) z(s,h) \big) + z_o(h) \ge D(h), \qquad \forall h \tag{2}$$

- Generation limits

$$SN(g,c,h) y(g,c,h) \le z(g,c,h) + z_{SR}(g,c,h), \qquad \forall \mathrm{c}, \mathrm{h}, \mathrm{g} \in \mathrm{GS} \tag{3}$$

$$z(g,c,h) + z_{SR}(g,c,h) \le SP(g,c,h) y(g,c,h), \qquad \forall \mathrm{c}, \mathrm{h}, \mathrm{g} \in \mathrm{GS} \tag{4}$$

$$SN(g,c,h) y(g,c,h) \le z(g,c,h), \qquad \forall \mathrm{c}, \mathrm{h}, \mathrm{g} \in G - \mathrm{GS} \tag{5}$$

$$z(g,c,h) \le SP(g,c,h) y(g,c,h), \qquad \forall \mathrm{c}, \mathrm{h}, \mathrm{g} \in G - \mathrm{GS} \tag{6}$$

$$u(g,h) - d(g,h) = \sum_c y(g,c,h) - \sum_c y(g,c,h-1), \qquad \forall g, h \tag{7}$$

$$\sum_c y(g,c,h) = 1, \qquad \forall \mathrm{g}, h \tag{8}$$

- spinning and quick start reserve requirements

$$\sum_{g \in GS} \sum_c z_{SR}(g,c,h) + z_{SR,o}(h) \ \ge SR(h), \qquad \forall h \tag{9}$$

$$\sum_{g \in GQ} \left(SP(g,c=2,h) - \sum_c z(g,c,h) \right) \ge QR(h), \qquad \forall h \tag{10}$$

- Ramping limits

$$\sum_c z_{SR}(g,c,h) \le RU(g) SRT(g), \qquad \forall h, g \in GS \tag{11}$$

$$\sum_c z(g,c,h+1) - \sum_c z(g,c,h) \le \mathrm{u}(g,h) SN(g,c=1,h) + \big(1 - u(g,h)\big) RU(g), \qquad \forall \mathrm{g}, h \tag{12}$$

$$\sum_c z(g,c,h) - \sum_c z(g,c,h+1) \le \mathrm{d}(g,h) SP(g,c=2,h) + \big(1 - d(g,h)\big) RD(g), \qquad \forall \mathrm{g}, h \tag{13}$$

- Minimum uptime and downtime

$$\sum_{h'=h+1}^{h+MU(g)+1} \sum_c y(g,c,h') \ge u(g,h) MU(g), \qquad \forall g, h \tag{14}$$

$$\sum_{h'=h+1}^{h+MD(g)+1} \sum_{c} (1 - y(g,c,h')) \geq d(g,h)MD(g), \qquad \forall g,h \quad (15)$$

◆ Battery Energy storage

$$sz(s,h) - z(s,h) = st(s,h) - st(s,h-1), \qquad \forall h,s \quad (16)$$
$$st(s,h) \leq SMX(s), \qquad \forall h,s \quad (17)$$
$$z(s,h) \leq SU(s), \qquad \forall h,s \quad (18)$$
$$sz(s,h) \leq SU(s), \qquad \forall h,s \quad (19)$$

2 Coal-ammonia/LNG-hydrogen Co-firing Model

◆ Coal-ammonia co-firing power plant heat ratio

$$hr_{NH3}(g) = hr_{coal}(g) \times \frac{\lambda_{AMC}}{0.88}, \qquad g \in AMC \quad (20)$$
$$hr_{coal}(g) = hr_{coal}(g) \times (1 - \lambda_{AMC} \times 10 \times 0.04545), \qquad g \in AMC \quad (21)$$
$$F_{GWh}(g) = F_{Gcal,coal}(g) \times 860.42 \times hr_{coal}(g) + \frac{F_{NH3}}{18.6} \times 3600 \times hr_{NH3}(g), \qquad g \in AMC \quad (22)$$

◆ LNG-hydrogen co-firing power plant heat ratio

$$hr_{H2}(g) = hr_{H2}(g) \times 0.5, \qquad g \in HMC \quad (23)$$
$$hr_{LNG}(g) = hr_{LNG}(g) \times 0.5, \qquad g \in HMC \quad (24)$$
$$F_{GWh}(g) = F_{Gcal,LNG}(g) \times 860.42 \times hr_{LNG}(g) + F_{H2} \times 860.42 \times 29.44 \times hr_{NH3}(g), \qquad g \in HMC \quad (25)$$

The efficiency of coal-ammonia co-firing power plants was assumed to decrease by 12% from the efficiency of conventional (100% coal burning) coal power plants. We assumed that more ammonia should be burned as the efficiency decreased (equation (20)). In the case of coal used in a coal-ammonia co-firing power plant, the efficiency was increased by about 4.5% when 100% of the coal was burned according to the co-firing ratio (equation (21)), which means that coal consumption is reduced as ammonia is added. The fuel cost per GWh was calculated by applying the efficiency of the power plant to the fuel price of coal and ammonia (equation (22)). 860.42 is a physical parameter for converting Gcal to GWh, 18.6 is the calorific value of ammonia (GJ/ton), and 3,600 is a value for converting GJ to GWh. We modeled the LNG-hydrogen co-firing in the same way as the coal-ammonia co-firing. Still, unlike the coal-ammonia co-firing, we could not find the efficiency data, and we assumed that hydrogen and LNG split the efficiency by 50% each. 29.44 is the calorific value of hydrogen (kg/Gcal).

3 Phase-outs and New Capacities from 2019 to 2030

3.1 Coal Capacities

Table S4 Phase outs and new coal capacities from 2019 to 2030

	Coal Capacity (GW)		
	Out	**New**	**Total**
2019	-	-	35.611

2020	Yeongdong#2 (-0.2)	Yeongdong#2 retrofit (0.2)	35.611
2021	Boryeong#1 (-0.5) Boryeong#2 (-0.5) Honam#1 (-0.25) Honam#2(-0.25) Samcheonpo#1 (-0.56) Samcheonpo#2 (-0.56)	Goseonghigh#1 (1.04) Goseonghigh#2 (1.04) Sinseoheon#1 (1.018)	36.089
2022	Yeosu#2 (-0.329) Pocheon (-0.003)	Gangreunganin#1 (1.04) Sinseoheon#2 (1.0) Yeosu#2 retrofit (0.329)	38.126
2023	-	Gangreunganin#1 (1.04) SamcheokHwaryok#1 (1.05)	40.216
2024	Boryeong#3 (-0.5) Boryeong#4 (-0.5) Samcheonpo#3 (-0.56) Samcheonpo#4 (-0.56)	Boryeong#3 retrofit (0.5) Boryeong#4 retrofit (0.814) SamcheokHwaryok#1 (1.05) Yeosugreen (0.152)	40.612
2025	Boryeong#5 (-0.5) Boryeong#6 (-0.5) Taean#1 (-0.5) Taean#2 (-0.5)	-	38.612
2026	Hadong#1 (-0.5)	-	38.112
2027	Hadong#2 (-0.5) Samcheonpo#5 (-0.5)	-	37.112
2028	Hadong#3 (-0.5) Hadong#4 (-0.5) Samcheonpo#6 (-0.5) Taean#3 (-0.5)	-	35.112
2029	Dangjin#1 (-0.5) Dangjin#2 (-0.5) Taean#4 (-0.5)	-	33.612
2030	Dangjin#3 (-0.5) Dangjin#4 (-0.5)	-	32.612

3.2 LNG Capacities

Table S5 Phase outs and new LNG capacities from 2019 to 2030

	LNG Capacity (GW)		
	Out	**New**	**Total**
2019	-	-	40.425
2020		Jeju#2 (0.115)	40.540
2021	Anyang (-0.45)	-	40.090
2022	Mokdong (-0.021)	Sinsejong (0.495) Yeoju (1.00) Ansangukga (0.037) Chungnam (0.097) Gimpo (0.495) Naepogreen (0.495) Jeju#1 (0.126) Jeju#2 (0.125)	42.939
2023	Bundang#1 (-0.574) Ilsan#1 (-0.6)	Ilsan#1 retrofit (0.6) Magok (0.285) Sejong#2 (0.585) Yangsan (0.119)	43.354
2024	-	Eumseong (1.122) Samcheonpo#3 LNG (0.56) Samcheonpo#4 LNG (0.56) Tongyeong (0.92) UlsanGPS (1.122) Cheongju (0.261)	48.160

		Daeju (0.261)	
2025	Ulsan#1 (-0.3)	Boryeong#5 LNG (0.5) Boryeong#6 LNG (0.5) Bucheon#2 (0.498) Dangjineco#1 (0.970) Dangjineco#2 (0.970) Taean#1 LNG (0.5) Taean#2 LNG (0.5)	52.298
2026	Ilsan#2 (-0.3)	Hadong#1 LNG (0.5)	52.498
2027	Bundang#2 (-0.348) Ulsan#2 (-0.45) Ulsan#3 (-0.45) Nowon (-0.037)	Hadong#2 LNG (0.5) Samcheonpo#5 LNG (0.5)	52.213
2028	Bucheon#1 (-0.45) Seoincheon#1 (-0.225) Seoincheon#2 (-0.225) Seoincheon#3 (-0.225) Seoincheon#4 (-0.225) Seoincheon#5 (-0.225) Seoincheon#6 (-0.225) Seoincheon#7 (-0.225) Seoincheon#8 (-0.225)	Bucheon#2 (0.498) Hadong#3 LNG (0.5) Hadong#4 LNG (0.5) Samcheonpo#6 LNG (0.5) Taean#3 LNG (0.5)	52.461
2029	Posco#3 (-0.45)	Dangjin#1 LNG (0.5) Dangjin#2 LNG (0.5) New#1 (0.5) New#2 (0.485) Taean#4 LNG (0.5)	54.496
2030	Incheonairport#1 (-0.127)	Dangjin#3 LNG (0.5) Dangjin#4 LNG (0.5) Incheonairport#1 retrofit (0.127)	55.496

3.3 Nuclear Capacities

Table S6 Nuclear power plants scheduled to operate in 2030 (total 28.9 GW)

Plant name	Capacity (GW)	Closed year	Life extension	New plant (Completion year)
Gori#2	0.65	2023	O	
Gori#3	0.95	2024	O	
Gori#4	0.95	2025	O	
Hanhit#1	0.95	2025	O	
Hanhit#2	0.95	2026	O	
Hanhit#3	1	2034	O	
Hanhit#4	1	2035	O	
Hanhit#5	1	2041		
Hanhit#6	1	2042		
Hanul#1	0.95	2027	O	
Hanul#2	0.95	2028	O (2036)	
Hanul#3	1	2037		
Hanul#4	1	2038		
Hanul#5	1	2043		

Hanul#6	1	2044		
Singori#1	1	2050		
Singori#2	1	2051		
Singori#3	1.4	2075		
Singori#4	1.4	2058		
Singori#5	1.4	2062		O (2024)
Singori#6	1.4	2063		O (2025)
Sinhanul#1	1.4	2061		O (2022)
Sinhanul#2	1.4	2061		O (2023)
Wolseong#2	0.7	2026	O	
Wolseong#3	0.7	2027	O	
Wolseong#4	0.7	2029	O	
Sinwolseong#1	1	2051		
Sinwolseong#2	1	2054		

3.4 Co-firing Capacities

Table S7 Number of ammonia co-firing power plant and capacity

	# of plant	Capacity (GW)
Total coal-used power plant	44	31.7
Coal power plant	13	9.8
Coal-NH_3 power plant	31	21.8

Table S8 Coal-ammonia co-firing plant names and capacity

Plant name	Capacity (GW)
Boryeong#7	0.5
Boryeong#8	0.5
Bukpyeong#1	0.595
Bukpyeong#2	0.595
Dangjin#5	0.5
Dangjin#6	0.5
Dangjin#7	0.5
Dangjin#8	0.5
Dangjin#9	1.02
Dangjin#10	1.02
Hadong#5	0.5

Hadong#6	0.5
Hadong#7	0.5
Hadong#8	0.5
Samcheokgreen#1	1.022
Samcheokgreen#2	1.022
Sinboryeong#1	1.019
Sinboryeong#2	1.019
Taean#5	0.5
Taean#6	0.5
Taean#7	0.5
Taean#8	0.5
Taean#9	1.05
Taean#10	1.05
Yeongheung#1	0.8
Yeongheung#2	0.8
Yeongheung#3	0.87
Yeongheung#4	0.87
Yeongheung#5	0.87
Yeongheung#6	0.87
Yeosu#1	0.34

Table S9 Number of hydrogen co-firing power plant and capacity

	# of plant	Capacity (GW)
Total LNG-used power plant	119	58.3
LNG power plant	99	46.8
LNG-H_2 power plant	20	11.5

Table S10 LNG-hydrogen co-firing plant names and capacities

# of plant	Capacity (GW)
Dongducheon#1	0.8584
Dongducheon#2	0.8584
GSDangjin#4	0.846
Paju#1	0.8476
Paju#2	0.8476
Pocheoncheonyeon	0.8742
Posco#8	0.3756

Posco#9	0.3756
Seoul#1	0.4
Seoul#2	0.4
Sinpyeongtaek#1	0.996
YeongnamPower	0.4428
Anyang	0.96338
Busanjeonggwan	0.04584
Chuncheon	0.4312
Dongtan#1	0.37838
Dongtan#2	0.37838
Hanam	0.363811
Sinohsan	0.4361
Wirye	0.4126

4 Hourly capacity factors of PV and WT

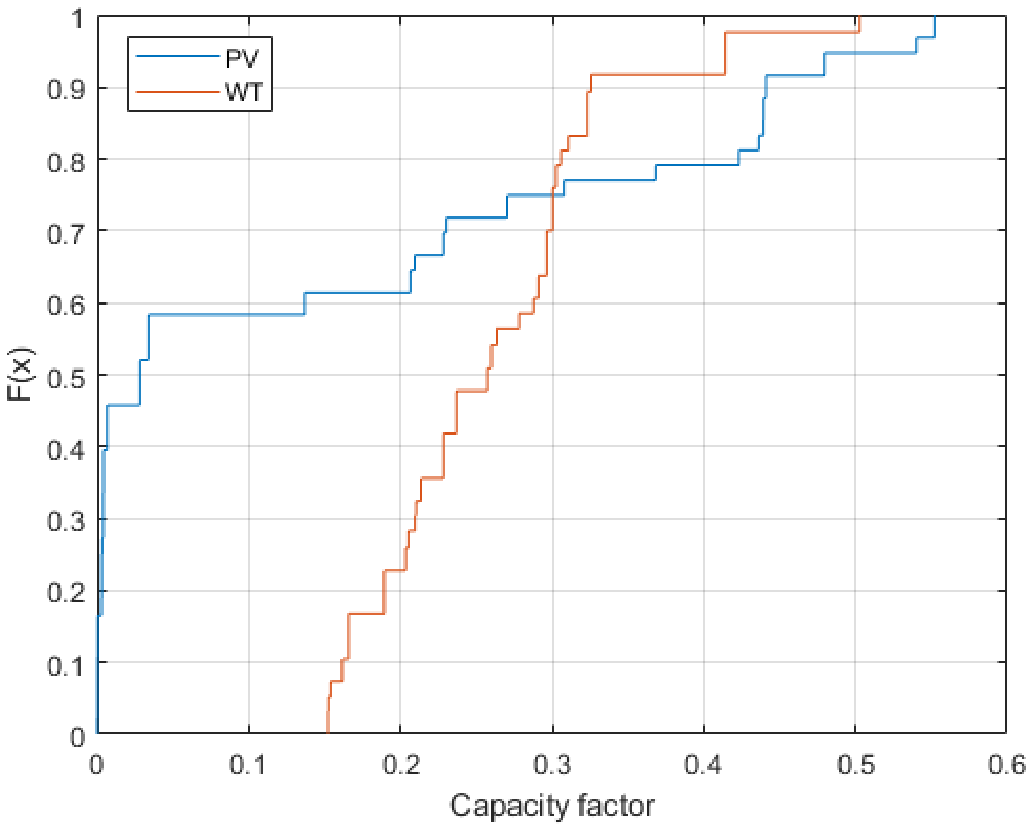

Figure S1 Cumulative distribution function of hourly capacity factors of PV and WT

5 Results for PW1 configurations in a low price assumption

Table S11 Results for PW1 configurations in a low price assumption

Indicator	Units	PW1					
		CT0	CT5	CT5.5	CT6	CT10	CT15
Utility-scale PV	GW	34.0	34.0	34.0	34.0	34.0	34.0
Utility-scale WT	GW	17.7	17.7	17.7	17.7	17.7	17.7
Total costs w/o carbon taxes	Bil USD	40.4	42.1	42.7	44.2	45.4	45.5
Total costs w carbon taxes	Bil USD	40.4	50.3	51.2	52.2	57.1	63.0
ΔOperational costs	Bil USD	-	1.7	2.3	3.8	5.0	5.0
ΔCapital costs	Bil USD	-	-	-	-	-	-
ΔTotal costs	Bil USD	-	1.7	2.3	3.8	5.0	5.1
CO_2 emissions	MtonCO_{2e}	223.9	184.5	173.4	147.5	130.1	129.4
CO_2 reduction	%	-	17.6	22.6	34.2	41.9	42.2
LCOE	USD/MWh	68.4	71.3	72.3	74.9	76.9	77.0
ΔLCOE	%	-	4.2	5.7	9.4	12.3	12.5
CoA	USD/tonCO_{2e}	-	42.7	45.3	49.6	53.0	53.4
Fossil fired generation	TWh	331.5	327.9	327.0	325.2	323.8	323.8
Coal Share	%	34.5	21.3	17.1	7.3	0.5	0.2
LNG Share	%	18.7	31.8	35.9	45.6	52.3	52.6
PV Generation	TWh	45.5	45.5	45.5	45.5	45.5	45.5
WT Generation	TWh	40.1	40.1	40.1	40.1	40.1	40.1
PV Share	%	7.4	7.4	7.4	7.5	7.5	7.5
WT Share	%	6.5	6.5	6.5	6.6	6.6	6.6
RE Generation	TWh	125.1	125.5	125.5	125.5	125.5	125.5
RE Share	%	20.3	20.4	20.5	20.5	20.6	20.6
RI	%	-	38.6	50.7	79.0	98.7	99.6