Short-term Resource Scheduling for Power systems with Energy Storage Systems

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***Abstract*--Energy Storage Systems (ESS) could be widely available in power systems, in which case the short-term scheduling is one of the essential problems that need to be addressed. This paper presents a resources scheduling method for the optimal operation plan with the energy storage systems, which utilizes the Mixed Integer Programming (MIP) based on the branch and bound method. The proposed method is evaluated on two case studies. One study examines a daily optimal operational plan for power supply resources and energy storage systems in an isolated micro-grid system. Another examines the optimal operational plan in a conventional power system with a large-scale energy storage system.**

***Index Terms*—Short-term scheduling, Energy Storage Systems, Renewable Energy System, Mixed Integer Programming.**

I. Introduction

Energy Storage Systems (ESSs) are being raised as important resources. They have the potential to extend and optimize the operating capabilities of the grid since power can be stored and used at a later time. This allows for flexibility in generation and distribution, improving the economic efficiency and utilization of the entire system while making the grid more reliable and robust. Additionally, as alternatives to traditional power generation, including variable wind and solar energy technologies may require back-up power storage. The most negative drawback of current ESS technology is its high cost. To overcome it, various researches are in progress [1]. The EES could also be used for various applications [2, 3], such as for stability enhancement of the renewable energy system [4, 5], for frequency control in an isolated power system [6, 7], and for load leveling [8].

Short-term scheduling is one of the essential problems for power system operation. It is composed of unit commitment (UC) and economic dispatch (ED). It has a significant impact on secure and economic operation of power systems. The UC problems involve scheduling the on/off states of generating units, which minimizes the operating cost, start-up cost and shut-down cost for a given planning horizon under various operating constraints [9]. In the UC problem, the decisions are the selection of the time for each unit to be on- and/or off-line (binary variables) as well as the unit's economic generation level (continuous variables). Thus, the UC problem can be formulated as a nonlinear mixed integer combinatorial optimization problem [10]-[15]. Over the past decades, many salient methods have been developed for solving the UC problems using methods such as Lagrangian relaxation [11], genetic algorithms [12], simulated annealing [13], particle swarm optimization [14], and so on. Recently, the UC problems have also included new elements, such as ESSs and virtual power plants (VPPs) [15, 16].

This paper describes a resource scheduling method for optimal operation of power systems utilizing the energy storage systems. The method employs the Mixed Integer Programming (MIP) based on the branch and bound method. The proposed method is evaluated on two case studies. One study examines a daily optimal operational plan for power supply resources and energy storage system in an isolated micro-grid system. Another examines the optimal operational plan in a conventional power system with a large-scale energy storage system. The simulation is performed in the commercial MATLAB package program.

II. Modeling for Resources Planning

A. Objective Function for System Operation

The objective the resource planning is to minimize the fuel cost, start-up cost, shut-down cost, and operating cost on all resources during a planning horizon, while satisfying all system constraints. The total costs are minimized by economically committing and dispatching the units. Therefore, the objective function of the resource planning problem is given by the minimization of the following cost function:

$$\min \sum_{t=1}^{T} \sum_{j=1}^{N} \left[F_j(P_{j,t})u_{j,t} + SU_{j,t}(1-u_{j,t-1})u_{j,t} \right] \quad (1)$$

where T is the number of scheduling period, N is the number of generating units, and $u_{j,t}$ is the on/off status of unit j at hour t (i.e., $u_{j,t}$ = 1 when unit j is on-line, and $u_{j,t}$ = 0 when unit j is off-line).

The main cost, $F_j(P_{j,t})$, is the fuel cost function of unit j at hour t, which can usually be expressed as a second-order polynomial as follows:

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$$F_j(P_{j,t}) = a_j + b_j P_{j,t} + c_j P_{j,t}^2 \tag{2}$$

where $P_{j,t}$ is the power generation of unit *j* at hour *t* and a_j, b_j, c_j are the cost coefficients of unit *j*.

Start-up cost for restarting a de-committed generating unit, which is related to the temperature of the boiler, is included in the objective function. The start-up cost is associated with the number of hours during which the unit has been off. Start-up cost will be high, defined as the *cold cost* ($SU_{C,j}$), when down time duration exceeds the *cold-start hour* ($T_{cold,j}$) in excess of the minimum down time; and will be low, defined as as the *hot cost* ($SU_{H,j}$), when down time duration does not exceed the cold-start hour in excess of the minimum down time. In general, the start-up cost is described as follows:

$$SU_{j,t} = \begin{cases} SU_{H,j} & \text{if } MDT_j \le TOFF_{j,t} \le MDT_j + T_{cold,j} \\ SU_{C,j} & \text{if } TOFF_{j,t} > MDT_j + T_{cold,j} \end{cases} \tag{3}$$

where $TOFF_{j,t}$ is the duration for which unit *j* has remained off-line at hour *t* and MDT_j is the minimum down-time of the *j*-th unit.

Shut-down cost is usually modeled as a constant value for each unit per shutdown. In this paper, the shut-down costs have not been taken into consideration.

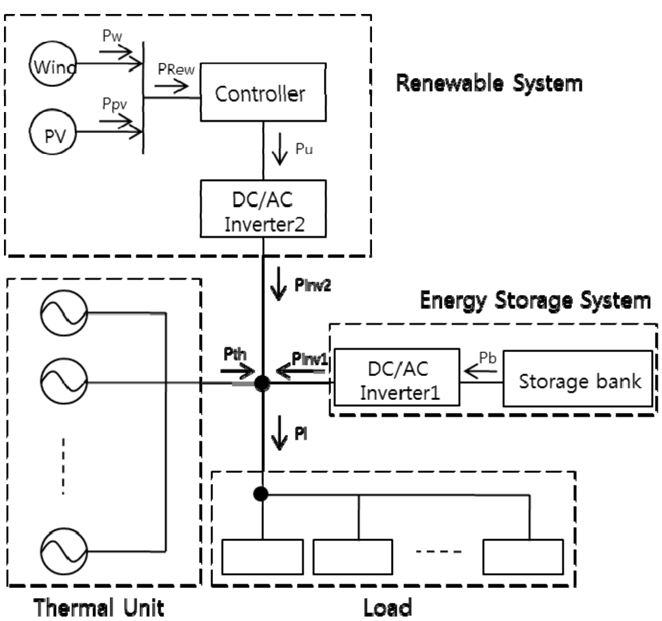

Fig. 1. System configuration.

B. System and Resource Constraints

1) Load balance constraints:

For each time of the considered period, the total summation of real power of the resources in the system must be equal or greater to the electric demand resources.

$$\sum_{j=1}^{N} P_{j,t} u_{j,t} + P_{ESS,t} = D_t - R_{\text{Re},t} \tag{4}$$

where $P_{ESS,t}$ is the output of ESS at hour *t*, D_t is the total system demand at hour *t* and $P_{\text{Re},t}$ is the total of renewable energy at hour *t*.

2) System spinning reserve constraints:

Spinning reserve must be provided so as to minimize the probability of load interruption. The spinning reserve is considered to be a pre-specified amount or a given percentage of the forecasted peak demand. Spinning reserve can be specified in terms of excess megawatt capacity, which is expressed by

$$\sum_{j=1}^{N} P_{j,\max} u_{j,t} \ge D_t^{'} + SR_t \tag{5}$$

$$D_t^{'} = D_t + P_{ESS,t} \times S_{ESS,t} \tag{6}$$

where $P_{j,\max}$ is the maximum output of *j*-th unit and $u_{j,t}$ is the state of *j*-th unit at hour *t*; $D_t^{'}$ is the total system load at hour *t* considering the output of ESS and SR_t is the required spinning reserve at hour *t*; and $S_{ESS,t}$ is the state (charge/idle/discharge) of ESS at hour *t*.

3) Generation limit constraints:

The power produced by each unit must be within its limits as indicated below:

$$u_{j,t} P_{j,\min} \le P_{j,t} \le u_{j,t} P_{j,\max} \tag{7}$$

where $P_{j,\min}$ and $P_{j,\max}$ are respectively the minimum and maximum generation limits of unit *j*.

4) Minimum up-time/down-time constraints:

The unit cannot be turned on/off immediately once it is committed or de-committed. The minimum up/down time constraints indicate that a unit must be on/off during a certain number of hours before it becomes shut-down or start-up, respectively. These constraints are given by

$$u_{j,t} = \begin{cases} 1 & \text{if } 1 \le TON_{j,t-1} < MUT_j \\ 0 & \text{if } 1 \le TOFF_{j,t-1} < MDT_j \\ 0 \text{ or } 1 & \text{otherwise} \end{cases} \tag{8}$$

where $TON_{j,t}$ is the duration for which unit *j* remains on-line at hour *t* and MUT_j is the minimum up-time of unit *j*.

5) Generation ramp up/down constraints:

Due to the mechanical characteristics and thermal stress limitations of a generating unit, the operating range of all on-line units is restricted by their corresponding ramp-rate limits as follows:

$$RD_j \le P_{j,t} - P_{j,(t-1)} \le RU_j \tag{9}$$

where RD_j and RU_j are the ramp-down and ramp-up limits of unit *j*, respectively.

6) Charging/discharging constraints of energy storage system:

The energy storage system has a maximum charging or discharging rate which is similar to the ramp rate of thermal generation units. The charging or discharging power cannot be over this limitation.

$$| SOC_{k,t} - SOC_{k,t-1} | \leq Ch_k^{\max} \quad (10)$$

where $Ch_k^{\max}$ is the maximum charge/discharge rate of the *k*-th ESS. It would be called the C-rates.

7) Generation constraints of energy storage system:

The energy storage system has a maximum and minimum generation constraint such as the thermal generation units.

$$P_{ESS,k}^{\min} \leq P_{ESS,k,t} \leq P_{ESS,k}^{\max} \quad (11)$$

where, $P_{ESS,k}^{\min}$ and $P_{ESS,k}^{\max}$ are respectively the minimum and maximum output for the *k*-th ESS.

8) Initial/ending state of charge (SOC) constraints of energy storage system:

To solve the unit commitment and economic dispatch problem with energy storage systems, the initial and ending state of charge is needed. This means that how much of energy is in the storage system when it is first connected to the system.

$$| SOC_{k,t} |_{t=0} = SOC_{k,ini} \quad (12)$$

$$| SOC_{k,t} |_{t=T} = SOC_{k,fin} \quad (13)$$

where $| SOC_{k,t} |$ is the state of charge of *k*-th ESS, and $SOC_{k,ini}$ and $SOC_{k,fin}$ are respectively the initial and final state of charge of the *k*-th ESS.

9) State of charge (SOC) constraints of energy storage system:

The energy limit of the energy storage system is measured by the state of charge. The ESS has a minimum and maximum state of charge constraint. For real circumstances, the storage systems cannot fully charge their capacity for the efficiency of the system will lower the performance of it. The optimal range of the state of charge for the storage systems are about 90% maximum and 20% for the minimum and this constraint will be formed as bellow.

$$SOC_k^{\min} \leq SOC_{k,t} \leq SOC_k^{\max} \quad (14)$$

where, $SOC_k^{\min}$ and $SOC_k^{\max}$ are respectively the minimum and maximum state of charge for the *k*-th ESS.

10) Output constraints of renewable energy resources:

The generated total renewable energy represents the sum of renewable resources such as photovoltaic, wind, etc. If there is a limit on the renewable output, it uses the minimum value of the two:

$$P_{\mathrm{Re}n,t} = Min(P_{R,t}, P_{R,t}^{Limit}) \quad (15)$$

$$P_{R,t} = P_{pv,t} + P_{w,t} \quad (16)$$

where $P_{R,t}$ is the sum of renewable outputs. $P_{pv,t}$ and $P_{w,t}$ are the output of the photovoltaic (PV), wind power, respectively. They are as follow:

$$P_{pv,t} = \frac{G_a}{G_{a,0}}[P_{Max,0}^M + \pi_{P\max}(T_a + G_a \frac{NOTC-20}{800} - T_{M,0})] \quad (17)$$

$$P_{w,t} = \begin{cases} 0 & V_w < V_{ci} \\ aV_w^4 + bV_w^3 + cV_w^2 + dV_w + e & V_{ci} \leq V_w \leq V_r \\ P_r & V_r \leq V_w \leq V_{co} \\ 0 & V_w > V_{co} \end{cases} \quad (18)$$

where $G_{a,0}$ is the insolation, $P_{Max,0}^M$ is the maximum power, $T_{M,0}$ is the module temperature at the standard condition and *NOCT* is the normal operating cell temperature of PV. For wind power, $P_r, V_{ci}, V_{co}, V_r, V_w$ are the rated power, cut-in speed, cut-out speed, rated speed, and wind speed, respectively.

III. System Analysis and Case Study

Two case studies are considered for scheduling short-term operational plans for power systems with energy storage systems. One study examines a daily optimal operational plan for power supply resources and energy storage system in an isolated micro-grid system. Another examines the optimal operational plan in a traditional power system with a large-scale energy storage system.

A. Isolated Micro-Grid System

A daily operational planning problem is considered for energy storage system and distributed generators in an isolated micro-grid system. The system has an energy storage system, and distributed generators including 10 small generators such as small gas turbines, diesel engines, micro turbines and renewable energy resources such as photovoltaic system and wind power system.

The following tables represent the parameters on PV, Wind, and Energy Storage System. It is assumed that there is no fixed charge required for the ESS. The total capacity of PV system installed is 1440kW (4×360 kWp) and total capacity of wind power installed is 560kW (4×140kWp). The spinning reserve for each hour is considered as 10% of the hourly load.

TABLE 1. LOAD DEMAND FOR 24-HOUR.

Hour	Load [kW]	Hour	Load [kW]	Hour	Load [kW]
1	1100	9	2300	17	2000
2	1200	10	2500	18	1850
3	1400	11	2600	19	1700
4	1600	12	2700	20	1600
5	1700	13	2650	21	1500
6	1900	14	2600	22	1400
7	2000	15	2500	23	1300
8	21000	16	2300	24	1200

TABLE 2. PV SYSTEM DATA.

NOCT	No of cells in a plant	Prated W	μ_{PMax}
44	1000X 10	36	-0.0045

TABLE 3. WIND PLANT DATA.

P_r	V_{ci}	V_r	V_{co}	a	b	c	d	e
140	3	15.01	17	-0.01	0.33	-0.9	-2.1	7.1

TABLE 4. ENERGY STORAGE SYSTEM.

Min [kWh]	Max [kWh]	C-rate	$SOC_{initial}$	SOC_{final}
1250	2500	0.25	50%	50%

TABLE 5. METROLOGICAL DATA.

Hr	G_a (W/m2)	T_a (C)	V_w (m/s)	Hr	G_a (W/m2)	T_a (C)	V_w (m/s)
1	0	24.8	5.7	13	833	29.0	5.9
2	0	24.7	6.5	14	850	29.7	4.9
3	0	24.5	7.5	15	680	29.8	3.5
4	0	24.3	6.9	16	595	30.0	3.4
5	93.5	24.4	8.6	17	255	29.8	2.8
6	212.5	24.5	10.5	18	212.5	29.5	3.1
7	255	25.5	13.6	19	153	29.0	2.3
8	467.5	26.5	10.4	20	68	27.7	2.9
9	637.5	27.5	9.1	21	42.5	26.5	3.5
10	680	28.0	9.3	22	0	26.0	3.8
11	816	28.5	7.7	23	0	25.5	3.8
12	850	28.8	7.0	24	0	25.0	4.7

TABLE 6. THERMAL UNITS DATA.

Unit	Unit1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
$P_{\max}$ (MW)	600	600	400	40	300	300	200	200	100	100
$P_{\min}$ (MW)	100	100	100	100	50	100	100	50	50	50
a	5	5	20	20	30	30	40	40	55	55
b	4	6	8	10	10	12	14	16	15	17
c	10	20	25	25	20	20	15	15	12	12
MUT (Hr)	5	5	3	3	2	2	2	2	1	1
MDT (Hr)	5	5	3	3	2	2	2	2	1	1
SU_H ($)	550	500	450	450	800	750	720	700	560	570
SU_C ($)	1100	1000	900	920	1600	1500	1440	1400	1120	1140
T_{cold} (Hr)	3	3	2	2	1	1	1	0	0	0
Initial status (Hr)	5	5	-3	-3	-2	-2	-2	-2	-1	-1

In Table 7, it represents the daily optimal operation plan of the distributed generators. This case doesn't consider the energy storage system and renewable system. Table 8 represents the daily optimal operation plan in the isolated micro-grid system with the energy storage system and renewable system. Colored block indicates the changed operational plan due to the introduction of energy storage system and renewable systems. Green and purple blocks are the effect of the energy storage system and renewable systems, respectively. To compare with existing studies, the maximum output of renewable energy resources is limited to 1,000kW.

Fig. 1 illustrates the hourly total charge/discharge quantity of the energy storage system.

TABLE 7. OPERATION PLAN WITHOUT ESS.

Hr	Generation Output										Total	Fuel	Startup
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	Power	Cost	Cost
1	600	400	100	0	0	0	0	0	0	0	1,100	6,335	900
2	600	500	100	0	0	0	0	0	0	0	1,200	7,115	0
3	600	600	200	0	0	0	0	0	0	0	1,400	8,810	0
4	600	600	350	0	50	0	0	0	0	0	1,600	10,751	1,600
5	600	600	400	0	100	0	0	0	0	0	1,700	11,760	0
6	600	600	400	100	200	0	0	0	0	0	1,900	13,865	920
7	600	600	400	100	300	0	0	0	0	0	2,000	14,965	0
8	600	600	400	100	300	100	0	0	0	0	2,100	16,215	1,500
9	600	600	400	300	300	100	0	0	0	0	2,300	18,415	0
10	600	600	400	400	300	100	100	0	0	0	2,500	21,045	1,440
11	600	600	400	400	300	150	100	50	0	0	2,600	22,514	1,400
12	600	600	400	400	300	250	100	50	0	0	2,700	23,794	0
13	600	600	400	400	300	200	100	50	0	0	2,650	23,149	0
14	600	600	400	400	300	150	100	50	0	0	2,600	22,514	0
15	600	600	400	400	300	100	100	0	0	0	2,500	21,045	0
16	600	600	400	300	300	100	0	0	0	0	2,300	18,415	0
17	600	600	400	100	300	0	0	0	0	0	2,000	14,965	0
18	600	600	400	100	150	0	0	0	0	0	1,850	13,330	0
19	600	600	400	0	100	0	0	0	0	0	1,700	11,760	0
20	600	600	350	0	50	0	0	0	0	0	1,600	10,751	0
21	600	600	250	0	50	0	0	0	0	0	1,500	9,801	0
22	600	600	200	0	0	0	0	0	0	0	1,400	8,810	0
23	600	600	100	0	0	0	0	0	0	0	1,300	7,935	0
24	600	500	100	0	0	0	0	0	0	0	1,200	7,115	0
	Total Cost											352,934	

TABLE 8. OPERATION PLAN WITH ESS & RENEWABLES.

Hr	Generation Output [MW]											ESS		Fuel	Startup
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	Total Power	Out	State	Cost	Cost
1	600	600	0	0	0	0	0	0	0	0	1,200	**145**	−1	7,090	
2	600	600	0	0	0	0	0	0	0	0	1,200	**77**	−1	7,090	
3	600	600	0	0	0	0	0	0	0	0	1,200	**70**	1	7,090	
4	600	600	0	0	0	0	0	0	0	0	1,200	**303**	1	7,090	
5	600	600	0	0	0	0	0	0	0	0	1,200	**140**	1	7,090	
6	600	600	0	0	0	0	0	0	0	0	1,200	**2**	−1	7,090	
7	600	600	0	0	0	0	0	0	0	0	1,200	**148**	−1	7,090	
8	600	600	0	0	0	0	0	0	0	0	1,200	**100**	−1	7,090	
9	600	600	0	0	0	0	0	0	0	0	1,200	**100**	1	7,090	
10	600	600	0	0	0	0	0	0	0	0	1,200	**300**	1	10,216	
11	600	600	400	0	0	0	0	0	0	0	1,600	**0**	0	10,216	900
12	600	600	400	0	0	0	0	0	0	0	1,600	**100**	1	10,710	
13	600	600	400	0	0	0	0	0	0	0	1,600	**50**	1	10,710	
14	600	600	400	0	0	0	0	0	0	0	1,600	**0**	0	10,343	
15	600	600	300	0	0	0	0	0	0	0	1,500	**0**	0	10,216	
16	600	600	400	0	0	0	0	0	0	0	1,600	**300**	−1	8,366	
17	600	600	400	0	0	0	0	0	0	0	1,600	**32**	−1	9,907	
18	600	600	400	0	0	0	0	0	0	0	1,600	**112**	−1	10,100	
19	600	600	400	0	0	0	0	0	0	0	1,600	**159**	−1	9,183	
20	600	600	400	0	0	0	0	0	0	0	1,600	**115**	−1	10,071	
21	600	600	374	0	0	0	0	0	0	0	1,574	**148**	−1	9,046	
22	600	600	0	0	0	0	0	0	0	0	1,200	**196**	1	8,774	
23	600	600	0	0	0	0	0	0	0	0	1,200	**96**	1	8,331	
24	600	600	0	0	0	0	0	0	0	0	1,200	**17**	−1	8,029	
	Total Cost													208,647	

※ Energy Storage System state : Charge(−1), Discharge(1), Idle(0)

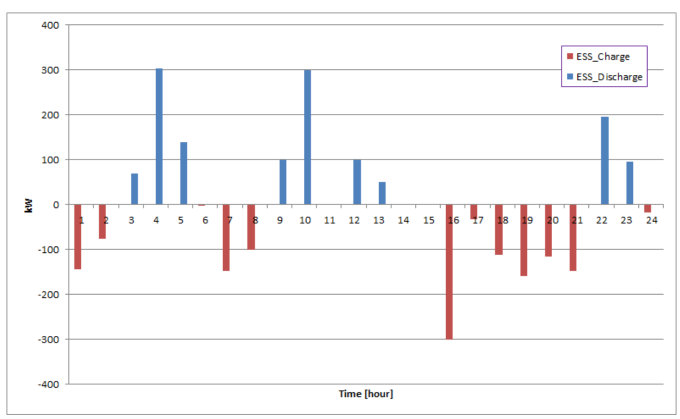

Fig. 2. Hourly total charge/discharge quantity of ESS.

Fig. 2 illustrates the hourly total generation according to the energy storage system and renewable systems.

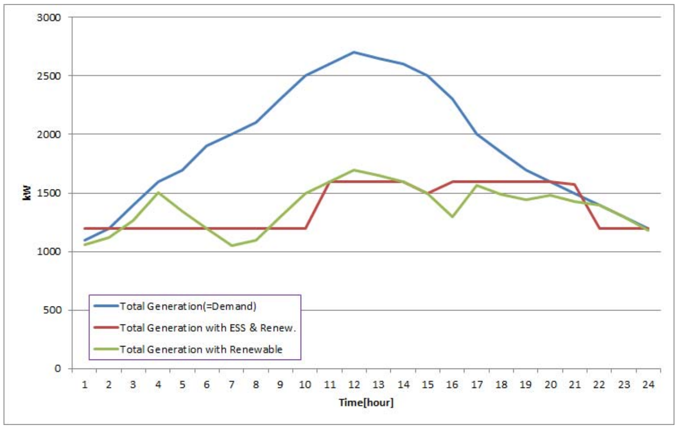

Fig. 3. Hourly total generation according to ESS & renewables: With limit on renewable power.

To the short-term operational plan, energy storage system has performed a load leveling and generation smoothing. The result is compared with previous studies in Table 9.

TABLE 9. COMPARISON OF PREVIOUS STUDIES.

Case	LR [14]	GA [14]	LRGA [14]	MIP
Only thermal generators	378,890	379,380	375,840	352,934
Thermal and renewable	214,140	214,190	214,120	212,684
Thermal, renewable and ESS	202,940	202,870	202,940	209,647

Due to the modeling difference on the energy storage system, the cost level is different in case 3.

In Addition, Fig. 4 shows the case that the renewable output is not limited.

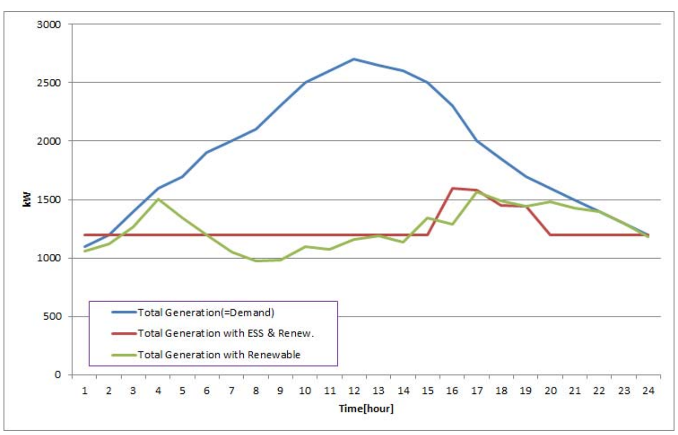

Fig. 4. Hourly total generation according to ESS & renewables: Without limit on renewable power.

B. Conventional Power System

A daily operational planning is performed for the energy storage system and the thermal generators in a conventional power system. The system has an energy storage system, 10 large-scale generators. The unit characteristics of the 10-unit system, ESS and the demand are given in Tables 10-12. The spinning reserve requirements are assumed to be 10% of the hourly demand.

TABLE 10. DEMAND DATA WITH 24-HOUR TIME HORIZON.

Hour	Demand (MW)	Hour	Demand (MW)	Hour	Demand (MW)
1	700	9	1,300	17	1,000
2	750	10	1,400	18	1,100
3	850	11	1,450	19	1,200
4	950	12	1,500	20	1,400
5	1,000	13	1,400	21	1,300
6	1,100	14	1,300	22	1,100
7	1,150	15	1,200	23	900
8	1,200	16	1,050	24	800

TABLE 11. ENERGY STORAGE SYSTEM.

Min[MWh]	Max[MWh]	C-rate	$SOC_{initial}$	SOC_{final}
100	500	0.4	30%	30-40%

TABLE 12. GENERATING UNIT DATA.

Unit	Unit1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
P_{max} (MW)	455	455	130	130	162	80	85	55	55	55
P_{min} (MW)	150	150	20	20	25	20	25	10	10	10
a	1000	970	700	680	450	370	480	660	665	670
b	16.19	17.26	16.6	16.5	19.7	22.26	27.74	25.92	27.27	27.79
c	0.00048	0.00031	0.002	0.00211	0.00398	0.00712	0.00079	0.00413	0.00222	0.00173
MUT (Hr)	8	8	5	5	6	3	3	1	1	1
MDT (Hr)	8	8	5	5	6	3	3	1	1	1
SU_H ($)	4500	5000	550	560	900	170	260	30	30	30
SU_C ($)	9000	10000	1100	1120	1800	340	520	60	60	60
T_{cold} (Hr)	5	5	4	4	4	2	2	0	0	0
Initial status (Hr)	8	8	-5	-5	-6	-3	-3	-1	-1	-1

Tables 13 and 14 represent the optimal operational plan of the thermal units without and with the energy storage system, respectively. Due to the energy storage system, the operational plan is changed as shown in green blocks in Table 14.

TABLE 13. OPERATIONAL PLAN WITHOUT ESS.

Hr	Generation Output										Total Power	Fuel Cost	Startup Cost
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10			
1	455	245	0	0	0	0	0	0	0	0	700	13,683	0
2	455	165	0	130	0	0	0	0	0	0	750	15,153	1,120
3	455	265	0	130	0	0	0	0	0	0	850	16,892	0
4	455	235	130	130	0	0	0	0	0	0	950	19,262	1,100
5	455	285	130	130	0	0	0	0	0	0	1,000	20,133	0
6	455	360	130	130	25	0	0	0	0	0	1,100	22,387	1,800
7	455	410	130	130	25	0	0	0	0	0	1,150	23,262	0
8	455	455	130	130	30	0	0	0	0	0	1,200	24,150	0
9	455	455	130	130	100	20	0	10	0	0	1,300	27,303	400
10	455	455	130	130	162	33	25	10	0	0	1,400	30,058	520
11	455	455	130	130	162	73	25	10	10	0	1,450	31,916	60
12	455	455	130	130	162	80	25	43	10	10	1,500	33,890	60
13	455	455	130	130	162	33	25	10	0	0	1,400	30,058	0
14	455	455	130	130	100	20	0	10	0	0	1,300	27,303	0
15	455	455	130	130	30	0	0	0	0	0	1,200	24,150	0
16	455	310	130	130	25	0	0	0	0	0	1,050	21,514	0
17	455	260	130	130	25	0	0	0	0	0	1,000	20,642	0
18	455	360	130	130	25	0	0	0	0	0	1,100	22,387	0
19	455	455	130	130	30	0	0	0	0	0	1,200	24,150	0
20	455	455	130	130	162	38	0	10	10	10	1,400	30,883	520
21	455	455	130	130	100	20	0	10	0	0	1,300	27,303	0
22	455	365	130	130	0	20	0	0	0	0	1,100	22,348	0
23	455	185	130	130	0	0	0	0	0	0	900	18,392	0
24	455	215	0	130	0	0	0	0	0	0	800	16,022	0
Total Cost												568,820	

TABLE 14. OPERATIONAL PLAN WITH ESS.

Hr	Generation Output [MW]											ESS		Fuel Cost	Startup Cost
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	Total Power	Out	State		
1	455	185	130	130	-	-	-	-	-	-	900	200	-1	18,392	2,220
2	455	150	130	130	-	-	-	-	-	-	865	115	-1	17,784	0
3	455	155	130	130	-	-	-	-	-	-	870	20	-1	17,871	0
4	455	235	130	130	-	-	-	-	-	-	950	0	0	19,262	0
5	455	285	130	130	-	-	-	-	-	-	1,000	0	0	20,133	0
6	455	360	130	130	25	-	-	-	-	-	1,100	0	0	22,387	1,800
7	455	410	130	130	25	-	-	-	-	-	1,150	0	0	23,262	0
8	455	455	130	130	30	-	-	-	-	-	1,200	0	0	24,150	0
9	455	455	130	130	100	20	-	10	-	-	1,300	0	0	27,303	400
10	455	455	130	130	132	20	-	10	-	-	1,332	68	1	27,963	0
11	455	455	130	130	162	30	-	10	10	-	1,382	68	1	29,753	60
12	455	455	130	130	142	20	-	10	10	-	1,352	148	1	29,109	0
13	455	455	130	130	142	20	-	10	10	-	1,352	48	1	29,109	0
14	455	455	130	130	100	20	-	10	-	-	1,300	0	0	27,303	0
15	455	455	130	130	30	-	-	-	-	-	1,200	0	0	24,150	0
16	455	310	130	130	25	-	-	-	-	-	1,050	0	0	21,514	0
17	455	260	130	130	25	-	-	-	-	-	1,000	0	0	20,642	0
18	455	360	130	130	25	-	-	-	-	-	1,100	0	0	22,387	0
19	455	455	130	130	30	-	-	-	-	-	1,200	0	0	24,150	0
20	455	455	130	130	132	-	-	10	10	10	1,332	68	1	29,031	180
21	455	455	130	130	110	-	-	10	10		1,300	0	0	27,628	0
22	455	360	130	130	25	-	-	-	-	-	1,100	0	0	22,387	0
23	455	185	130	130	-	-	-	-	-	-	900	0	0	18,392	0
24	455	150	130	130	-	-	-	-	-	-	865	65	-1	17,784	0
Total Cost														566,508	

※ Energy Storage System state : Charge(-1), Discharge(1), Idle(0)

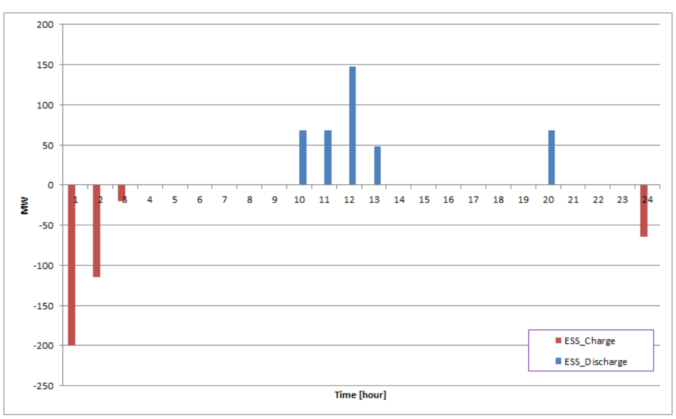

Fig. 5. Hourly total charge/discharge quantity of ESS.

Fig. 5 illustrates the hourly total charge/discharge quantity of the energy storage system, and Fig. 6 illustrates the hourly total generation with and without the energy storage system.

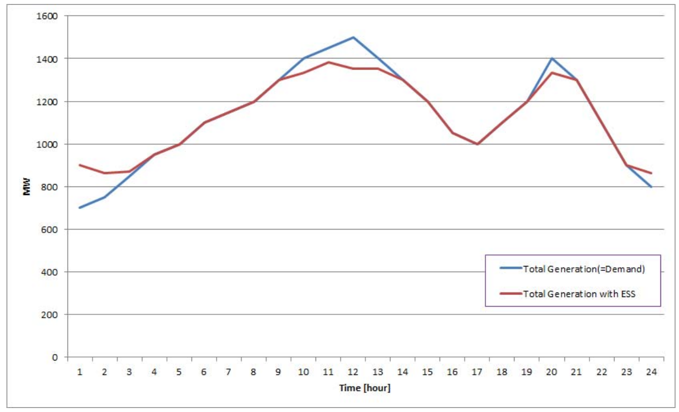

Fig. 6. Hourly total generation according to ESS.

To the short-term operational plan, energy storage system has performed a load leveling and generation smoothing. The result is compared with previous studies only for thermal unit systems in Table 15.

TABLE 15. COMPARISON WITH PREVIOUS STUDIES.

LR [10]	GA [11]	SA [12]	IPSO [13]	MIP
565,825	565,825	565,828	563,954	568,820

IV. CONCLUSIONS

This paper described a resource scheduling method for optimal operational planning of power systems with the energy storage systems. Energy storage system has performed a load leveling and generation smoothing to the short-term resources scheduling. The method utilized the Mixed Integer Programming based on the branch and bound method. A daily optimal operational planning was demonstrated in an isolated micro-grid system with renewable system and energy storage system and in a conventional power system with a large-scale energy storage system.

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VI. Biographies

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