Applied Energy Symposium 2021: Low carbon cities and urban energy systems
September 4-8, 2021, Matsue, Japan
Paper ID: 26

DUAL-STAGE OPTIMAL SCHEDULING FOR A GRID-CONNECTED MICROGRID

Luyao Liu [1], Chenyu Su [2], Qie Sun [12*], Qingxi Huang [2], Ronald Wennersten [2]

1 Institute of Thermal Science and Technology, Shandong University, Jinan 250061, China

2 Institute for Advanced Science and Technology, Shandong University, Jinan 250061, China

ABSTRACT

A dual-stage day-ahead and real-time multi-energy cooperative optimization scheduling scheme is proposed for a grid-connected microgrid including photovoltaic (PV), battery storage (BS), and gas turbine (GT). In the day-ahead stage, the economic optimization is the aim. Based on the relative level of the tiered electricity prices, charge and discharge depreciation cost of BS, power generation cost of GT, day-ahead optimization strategy is proposed and the power allocations of PV, BS, GT, and GRID is formulated. Day-ahead panned interconnection power between the microgrid and main grid is passed to real-time scheduling stage as the constraint. In the real-time stage, the minimization of the operation costs at each dispatching period (15 mins) is taken as the objective. Real-time optimization strategy is proposed to modify the power allocations scheduled in the day-ahead stage. Results prove that the proposed dual-stage optimization of the scheduling has advantages in improving the operation economy of the microgrid.

Keywords: Real-time scheduling, renewable energy, coordinated operation, forecasting uncertainty

NONMENCLATURE

Abbreviations	
RE	Renewable energy
PV	Photovoltaic
BS	Battery storage
GT	Gas turbine
PCC	Public common coupling
PCS	Power conversation system
SOC	State of charge
LP	Low price
MP	Medium price
HP	High price
Symbols	
d	Day-ahead
r	Real-time

1. INTRODUCTION

The microgrid combines distributed energy sources, energy storage, and is a good solution to promote the utilization of distributed renewable energies (RE). RE power is influenced by various meteorological factors, and its prediction is uncertain, which has brought challenges for the optimal operation of the microgrid.

Existing studies put forward two kinds of approaches to deal with the uncertainties in the optimal scheduling: (1) uncertainty modelling using stochastic programming, fuzzy programming, and robust optimization to eliminate effect of the prediction errors in day-ahead scheduling stage [1, 2]; (2) multi-stage optimization that generally combines day-ahead, intraday and real-time dispatching by taking advantages of the higher prediction accuracy in a shorter time [3]. With the improvement of prediction technologies recent years [4], multi-stage optimal scheduling is expected to have good application prospects for energy management of the microgrid.

The energy storage and controllable power sources are important tools to cope with the uncertainty of RE power and load forecast [5]. What's more, the tiered electricity pricing mechanisms can help the microgrid on the customer side to obtain greater economic benefits, as well as to help load shifting for the main grid [6].

Therefore, this paper proposed a dual-stage day-ahead and real-time multi-energy cooperative optimization scheme. In the day-ahead stage, the economic optimization of the dispatching day is taken as the objective. Based on the relative level of the tiered

* Corresponding author: Qie Sun. Mail: qie@sdu.edu.cn

prices, the charge and discharge depreciation cost of BS, the power generation cost of the GT, the optimization strategy is proposed to formulate the power allocation plan in the next 24hrs. The interconnection power plan is submitted to the main grid and transmitted to real-time scheduling as constraints. In real-time stage, the minimization of the operation cost at each dispatching periods is the target. The real-time optimization strategy is proposed to modify the power allocations.

2. METHODS

2.1 Illustration of the grid-connected microgrid

As shown in Fig. 1, the microgrid includes photovoltaic (PV), battery storage (BS), micro gas turbine (GT), and load. The microgrid acts as a distribution unit in the main grid. The microgrid and the 10 kV distribution network can exchange power through the voltage transformer and the public common coupling (PCC). PV and GT are connected to the low voltage bus through DC/AC converters. BS is connected to AC bus through power conversation system (PCS). The power allocations are managed by the energy management system (EMS).

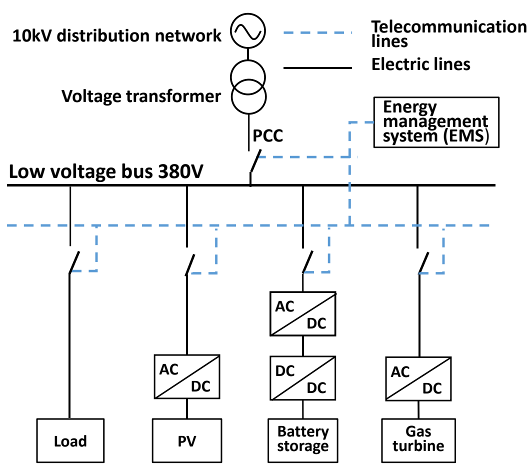


Fig. 1 The grid-connected microgrid

2.2 Framework of the dual-stage scheduling

The framework and timeline of the dual-stage day-ahead and real-time optimal scheduling is shown in Fig. 2 and 3. Day-ahead plan is formulated in the last dispatching period of the previous dispatching day, noted as t=0 (or t=96). *t* is the dispatching period. Real-time schedule is made 15 mins ahead of the dispatching period and is implemented 96 times in a dispatching day.

Day-ahead scheduling:

Step (1) t=0, obtain the 24h-ahead forecasts with a 15-min interval of RE power and load. Based on the day-ahead optimization scheduling strategy (Section 2.4.1), the plan of the 96 dispatching periods on the dispatching day is made. The day-ahead plan includes the power allocation of PV, BS and GT, and GRID. The day-ahead interconnection power plan is submitted to the main grid and passed to real-time scheduling as constraints.

Real-time scheduling:

Step (2) t=0, implement real-time schedule made for this period; meanwhile, make 15-min ahead forecasts for next period. Based on real-time optimization scheduling strategy (Section 2.4.2), make real-time schedule for the next period and issue pre-dispatching instruction.

Step (3) Let t=t+1, implement the real-time plan made for this period; make 15- min ahead forecasts and, based on the real-time optimization scheduling strategy (Section 2.4.2), make real-time plan for next period. Note Step (3) have different roles from Step (2). Step (2) is carried out in t=0 period while the day-ahead plan is made, while Step (3) is carried out in the other periods,

Step (4) t=t+1, if mod(t,96) =0, go to (1); otherwise, go to (3).

2.3 Day-ahead and real-time scheduling models

2.3.1 Day-ahead scheduling model

(1) Objective

In day-ahead stage, the minimum of the operation cost of the dispatching day is taken as the objective, expressed as Eq. (1):

$$minF = \sum_{t=1}^{96} U_{ch}^{d,t} * C_{ch} * P_{ch}^{d,t} + U_{dis}^{d,t} * C_{dis} * P_{dis}^{d,t} + U_{gt}^{d,t} * C_{gt} * P_{gt}^{d,t} + U_{gridp}^{d,t} * C_{gridp}^{d,t} * P_{gridp}^{d,t} - U_{grids}^{d,t} * C_{grids}^{d,t} * P_{grids}^{d,t} \quad (1)$$

Eq. (1) includes the purchasing cost, selling revenue, BS operation cost, and GT power generation cost of the next day. $C_{gridp}^{d,t}$, $C_{grids}^{d,t}$, C_{gt}, C_{ch}, C_{dis} is the purchasing price, selling price, power generation cost of GT, operation cost of charge and discharge of BS per kWh. $P_{gridp}^{d,t}$, $P_{grids}^{d,t}$, $P_{gt}^{d,t}$, $P_{ch}^{d,t}$, $P_{dis}^{d,t}$ is the purchased power, sold power, power output of GT, charged/discharged power of BS. $U_{gridp}^{d,t}$, $U_{grids}^{d,t}$, $U_{gt}^{d,t}$, $U_{ch}^{d,t}$, $U_{dis}^{d,t}$, is the on/off (1-0) state of purchasing and selling, GT, charge/discharge of BS.

1) Operation and maintenance cost of GT

The power generation cost of GT, $N_{gt}^{d,t}$, (Eq. (2)) is related to the price of gas, C_{gt}, the low calorific value of gas, L_{cv}, and the efficiency of GT, η_{gt}, and the time length of operation period, Δt. The maintenance cost of GT, $N_{gtm}^{d,t}$, (Eq. (3).) is directly proportional to the power generated by GT, where K_{gtm} is the maintenance cost coefficient of GT.

$$N_{gt}^{d,t} = \frac{C_{gt} L_{cv} P_{gt}^{d,t}}{\eta_{gt}} \Delta t \quad (2)$$

$$N_{gtm}^{d,t} = K_{gtm} P_{gt}^{d,t} \Delta t \quad (3)$$

2) Operation and maintenance cost of BS

The operating cost, $N_{bs}^{d,t}$ of BS is as Eq. (4). C_{inv} is the initial investment cost of BS; N_{life} is the designed cycle times during life cycle. E_{bs} is the rated capacity of BS. The maintenance cost of BS, $N_{bsm}^{d,t}$, (Eq. (5)) is directly proportional to the amount of charged and discharged power, where K_{bsm} is maintenance cost coefficient of BS.

$$N_{bs}^{d,t} = C_{inv}\frac{U_{ch}^{d,t}P_{ch}^{d,t}+U_{dis}^{d,t}P_{dis}^{d,t}}{2*N_{life}*E_{bs}}\Delta t \qquad (4)$$

$$N_{bsm}^{d,t} = K_{bsm}\left|U_{ch}^{d,t}P_{ch}^{d,t} + U_{dis}^{d,t}P_{dis}^{d,t}\right|\Delta t \qquad (5)$$

(2) Constraints

1) Equality constraints

In Eq. (6)-(14), $P_{load}^{d,t}$, $P_{pv}^{d,t}$ are the day-ahead forecasts of average load and PV power during the t period; $P_{pv-load}^{d,t}$, $P_{grid-load}^{d,t}$, $P_{bs-load}^{d,t}$, $P_{gt-load}^{d,t}$ are the power supplied by PV, GRID, BS and GT. $P_{pv-bs}^{d,t}$, $P_{pv-grid}^{d,t}$, $P_{pv-ab}^{d,t}$ are the PV power allocated to LOAD, BS, GRID and discarded. $P_{grid-bs}^{d,t}$ is the charged power of BS purchased from GRID; $P_{bs-grid}^{d,t}$ is the discharged power of BS sold to GRID; $P_{gt-grid}^{d,t}$ is the selling power generated by GT. $SOC^{d,t}$ and $SOC^{d,t-1}$ are the state of charge of BS in t and the precious

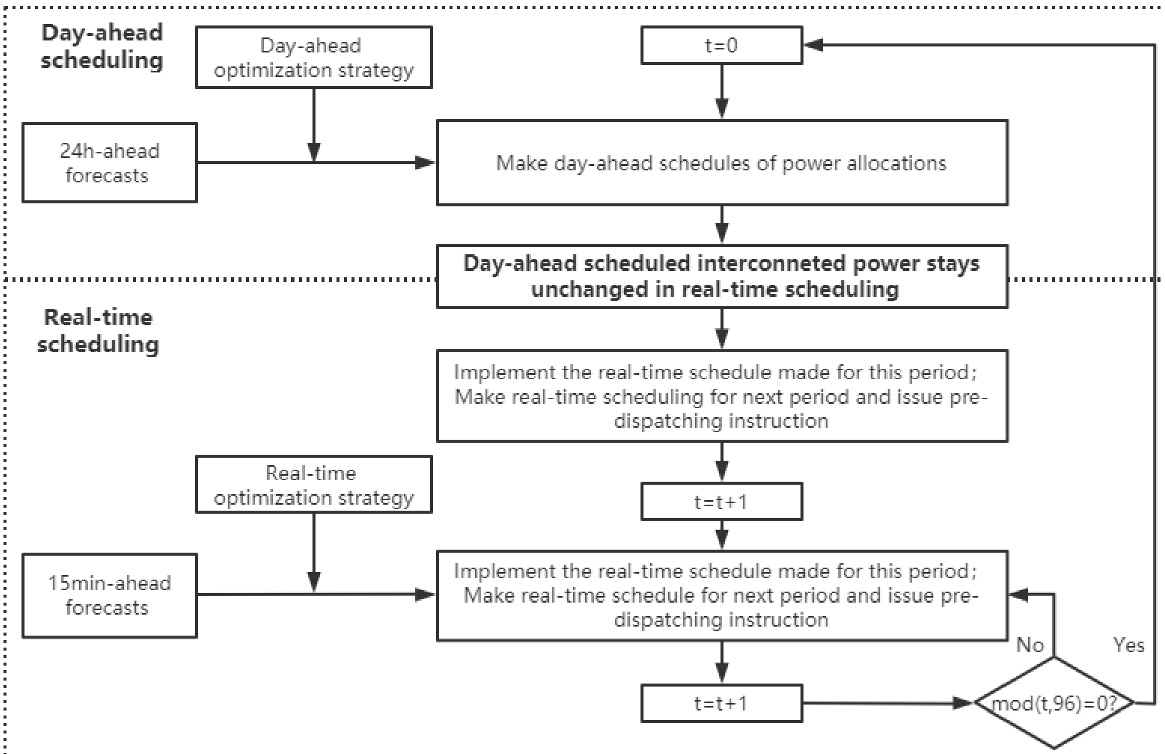


Fig. 2 Framework of the dual-stage day-ahead and real-time optimal scheduling for the grid-connected microgrid

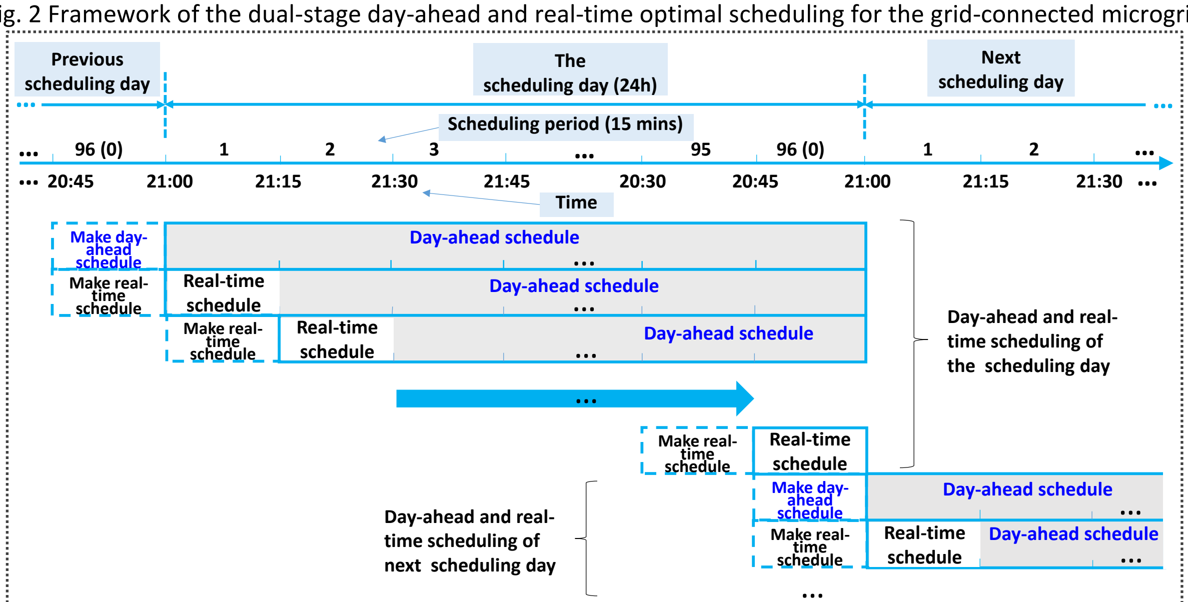


Fig. 3 The timeline of the day-ahead and intraday real-time scheduling

period t-1. $SOC^{d,t}$ and $SOC^{d,t-1}$ are the state of charge of BS at the beginning and the end of the dispatching day. η_c and η_d are the charging/ discharging efficiency of BS.

$$P_{pv-load}^{d,t} + P_{grid-load}^{d,t} + P_{bs-load}^{d,t} + P_{gt-load}^{d,t} = P_{load}^{d,t} \quad (6)$$

$$P_{pv}^{d,t} = P_{pv-load}^{d,t} + P_{pv-bs}^{d,t} + P_{pv-grid}^{d,t} + P_{pv-ab}^{d,t} \quad (7)$$

$$P_{gridp}^{d,t} = P_{grid-load}^{d,t} + P_{grid-bs}^{d,t} \quad (8)$$

$$P_{grids}^{d,t} = P_{pv-grid}^{d,t} + P_{bs-grid}^{d,t} + P_{gt-grid}^{d,t} \quad (9)$$

$$P_{gt}^{d,t} = P_{gt-load}^{d,t} + P_{gt-grid}^{d,t} \quad (10)$$

$$P_{dis}^{d,t} = P_{bs-load}^{d,t} + P_{bs-grid}^{d,t} \quad (11)$$

$$P_{ch}^{d,t} = P_{pv-bs}^{d,t} + P_{grid-bs}^{d,t} \quad (12)$$

$$SOC^{d,t} = SOC^{d,t-1} + \eta_c P_{ch}^{d,t} - P_{dis}^{d,t}/\eta_d \quad (13)$$

$$SOC^{d,0} \approx SOC^{d,96} \quad (14)$$

2) Inequality constraints

In Eq.(15)-(20), P_{gridp}^{max}, P_{grids}^{max}, $P_{dis,up}^{d,t}$, $P_{ch,up}^{d,t}$, P_{gt}^{min}, P_{gt}^{max}, $P_{gt,ramp}^{max}$ are the upper limit of purchased/selling power, charged / discharged power, power output of GT, ramp rate of GT; C,U are the rated capacity and voltage of BS; SOC_{min},SOC_{max} are the minimum and maximum SOC of BS; T_{gt} is the minimum operation time of GT.

$$P_{grid-load}^{d,t} + P_{grid-bs}^{d,t} \le P_{gridp}^{max} \quad (15)$$

$$P_{pv-grid}^{d,t} + P_{bs-grid}^{d,t} + P_{gt-grid}^{d,t} \le P_{grids}^{max} \quad (16)$$

$$P_{dis,up}^{d,t} = min\,[(SOC^{d,t} - SOC_{min}) * U * \frac{C}{\Delta t}, 0.2 * U * C/\Delta t] \quad (17)$$

$$P_{ch,up}^{d,t} = min\,[(SOC_{max} - SOC^{d,t}) * U * \frac{C}{\Delta t}, 0.2 * U * C/\Delta t] \quad (18)$$

$$SOC_{min} \le SOC^{d,t} \le SOC_{max} \quad (19)$$

$$T_{gt} \ge 2 \quad (20)$$

$$P_{gt}^{min} \le P_{gt}^{d,t} \le P_{gt}^{max} \quad (21)$$

$$|P_{gt}^{d,t} - P_{gt}^{d,t-1}| \le P_{gt,ramp}^{max}\Delta t \quad (22)$$

2.3.2 Real-time scheduling model

(1) Objective

The minimization of the operation cost at each dispatching period is adopted as the objective, as expressed in Eq. (23), where 'r' represents real-time.

$$minF = U_{ch}^{r,t} * C_{ch}^{r,t} * P_{ch}^{r,t} + U_{dis}^{r,t} * C_{dis}^{r,t} * P_{dis}^{r,t} + U_{gt}^{r,t} * C_{gt}^{r,t} * P_{gt}^{r,t} + U_{gridp}^{r,t} * C_{gridp}^{r,t} * P_{gridp}^{r,t} - U_{grids}^{r,t} * C_{grids}^{r,t} * P_{grids}^{r,t} \quad (23)$$

(2) Constraints

The equity and inequity constraints in real-time stage is the same as that in day-ahead stage.

To reduce the impact on main grid, the interconnection of real-time scheduling $P_{grid}^{r,t}$ should be consistent with day-ahead interconnection plan $P_{grid}^{d,t}$ (Eq. (24)). $P_{grid}^{d,t}$ is the absolute value of $P_{grids}^{d,t}$ and $P_{gridp}^{d,t}$.

$$P_{grid}^{r,t} = P_{grid}^{d,t} \quad (24)$$

2.3.3 System parameters

Parameters of BS/GT are listed in Table 1-2. The operation cost of PV power, C_{pv} is ignored. The maximum volume of the interconnection is 1700kW. Tiered purchased and selling prices is shown in Table 3.

Table 1 Parameters of GT

Parameter	Value	Parameter	Value
Upper limit of output / kW	1700	Ramp up rate/ (kW /min)	3400
Lower limit of output / kW	340	Ramp down rate/ (kW /min)	3400
Minimum operation time/h	2	Gas price /(￥/kWh)	0.60
Efficiency	0.4	Maintenance cost/(￥/kWh)	0.02

Table 2 Parameters of BS

Parameter	Value	Parameter	Value
Rated capacity /kWh	4325	Charge power upper limit /Kw	1700
Rated power/kW	1700	Discharge power lower limit /kW	1700
SOC upper limit	0.95	Degradation cost /(￥/kWh)	0.0832
SCC lower limit	0.05	Charge/discharge efficiency	0.9

Table 3 Tiered purchasing and selling electricity prices

	Time	Purchasing price (￥/kWh)	Selling price (￥/kWh)
Low	23:00-07:00	0.3094	0.1194
Medium	21:00-23:00,7:00-8:30,11:00-14:30	0.5905	0.4005
High	8:30-11:00,14:30-21:00	0.8716	0.6816

2.4 Dual-stage optimization scheduling strategy

2.4.1 Day-ahead optimization scheduling strategy

The relative level of purchasing/selling electricity prices, and power generation cost of BS/GT is as follows: $C_{pv} < C_{bs} < C_{grids}^{low} < C_{gridp}^{low} < C_{grids}^{med} < C_{gridp}^{lmed} < C_{gt} < C_{grids}^{high} < C_{gridp}^{high}$

where C_{grids}^{low}, C_{gridp}^{low}, C_{grids}^{med}, C_{gridp}^{lmed}, C_{grids}^{high}, C_{gridp}^{high} are the selling and purchasing price during low price (LP), medium price (MP), high price (HP) periods.

To minimize the operation cost in a dispatching day, PV is preferentially used to meet the load. Considering daily distribution of $\Delta P^{d,t}$ (the difference between day-ahead forecasted load and PV output), and tiered prices (Fig. 4), the day-ahead optimization strategy is proposed:

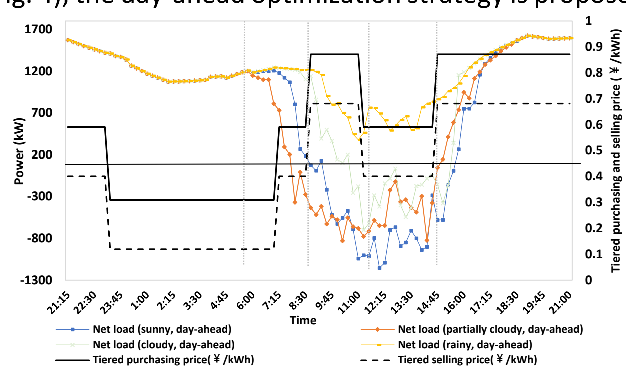


Fig. 4 Distribution of the $\Delta P^{d,t}$ and tiered prices

1) 21:00 - 5:30, LP and MP periods, $\Delta P^{d,t}$ is always positive. Purchase power from main grid first (GRID-LOAD). If there is surplus in the interconnection line, chare the battery (GRID-BS). SOC increases.

2) 5:30-8:30, 11:00 - 14:30, LP and MP, when $\Delta P^{d,t} > 0$, purchase power from main grid first (GRID-LOAD). If there is surplus in the interconnection line, charge the battery (GRID-BS); when $\Delta P^{d,t} < 0$, if $SOC^{d,t}$<SOC_{max}, use PV power to charge BS (PV-BS); If $SOC^{d,t} \ge SOC_{max}$, PV sells power to the main grid (PV-GRID). SOC increases.

3) 8:30 - 11:00, 14:30-21:00, HP periods. Regardless of positive or negative $\Delta P^{d,t}$, GT follows the load or

operate in the minimum stable output (GT-LOAD). When $\Delta P^{d,t} > 0$, GT sells to grid (GT-GRID); When $\Delta P^{d,t} < 0$, PV and the minimum pf GT output sells to grid (PV-GRID &GT-GRID). Then, BS sells power to main grid (BS-GRID). SOC decreases.

To ensure BS and GT can adjust forecasting errors in real-time stage dispatching, three explanations are made for the above strategies:

1) 21:00 - 5:30, SOC of BS rises from SOC_{min}. To avoid negative SOC caused by discharging regulation, the transmission capacity of the interconnection line is set to be greater than the maximum net load, i.e., 1700kW, which can ensure the charging power to be positive.

2) 5: 30-8:30 and 11:00-14:30, SOC rises and is easy to overpass SOC_{max}. By reserving a certain SOC margin, i.e., set the SOC_{up} as 85%, BS can cope with the increase of intraday cumulative regulated power.

3) 8: 30-11:00, 14:30-21:00, If day-ahead power selling plan can't be completed, GT ramps up to make up; If power selling plan is completed in advance, BS can use its surplus power to bear part of the load. BS can reach SOC_{min} to reset before the end of this stage to reset.

<u>2.4.2 Real-time optimization scheduling strategy</u>

Real-time optimization is made according to real-time forecasted net load $\Delta P^{r,t}$. Through the strategy, the day-ahead planned power allocations are revised.

1) 21:00 - 5:30, 5:30 – 8:30, 11:00 - 14:30, when $\Delta P^{r,t} > 0$, purchase power from main grid (GRID-LOAD). If there is surplus purchased power, charge the BS (GRID-BS); if purchased power is lack, use BS to meet the load (BS-LOAD); if $P^{r,t}_{grid} = P^{d,t}_{grids}$, BS discharge to load and sell to grid to meet the selling plan (BS-LOAD & BS-GRID).

When $\Delta P^{r,t} < 0$, PV sells power to main grid (PV-GRID), and if the planned selling power $P^{r,t}_{grids}$ can't be met, BS discharge to grid (BS-GRID); if the planned selling power $P^{r,t}_{grids}$ has been met, use excessive PV power to charge BS (PV-BS); if $P^{r,t}_{grid} = P^{d,t}_{gridp}$, use purchased power and excessive PV power to charge BS (GRID-BS & PV-BS).

3) 8:30 - 11:00, 14:30 - 21:00, use GT to meet load (GT-LOAD). If $P^{r,t}_{grids} \neq 0$ & $SOC^{r,t}$>SOC_{min}, when $\Delta P^{r,t} < 0$, PV and the minimum pf GT output sells to grid (PV-GRID &GT-GRID), then BS sell power to main grid (BS-GRID); when $\Delta P^{r,t} > 0$, GT sells no power or excessive power to grid (GT-GRID), then BS sells power to grid (BS-GRID).

If $P^{r,t}_{grids} \neq 0$ & $SOC^{r,t} < SOC_{min}$, GT ramps to sell power to grid (GT-GRID).

If $P^{r,t}_{grids} = 0$ & $SOC^{r,t} > SOC_{min}$, BS supplies to part of the load (BS-LOAD), while the rest of the load is met by GT (GT-LOAD).

3. RESULTS

The day-ahead, 15-min ahead forecasts and actual values of PV power output (sunny) and load are shown in the Fig.5. The day-ahead and real-time schedule of the power allocations are shown in Fig. 6. Due to space limitation, figures of the other weather conditions don't show on the page.

Results indicate that the real-time interconnection is consistent with day-ahead plan. The amount of the power allocation, e.g., GRID-LOAD, GRID-BE, PV-GRID, etc.) at real-time scheduling is only slightly different from that of the day-ahead plans, which reflects the guiding role of day-ahead scheduling to intraday scheduling.

SOC of BS at the last dispatching period of each tiered price stage of 21:00-5:30, 5:30-8:30, 8:30-11:00, 11:00-14:30, 14:30-21:00 are: 88.1%, 76.5%, 16.7%, 82.5%, and 5.0% (sunny); 88.1%, 85.8%, 40.4%, 89.8%, 5.0% (partially cloudy); 88.1%, 87.3%, 14.8%, 51.0%, 5.0% (cloudy); 88.1%, 87.0%, 8.1%, 82.2%, 5.0% (rainy). The SOC is always within the safe range, and the SOC at the beginning and end of the dispatching day is consistent.

Although GT ramps to meet interconnection plan (sunny, 16:30-17:00), its overall trend is stable.

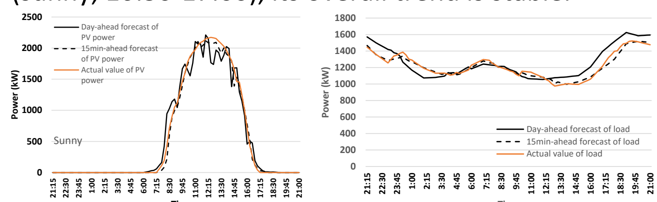
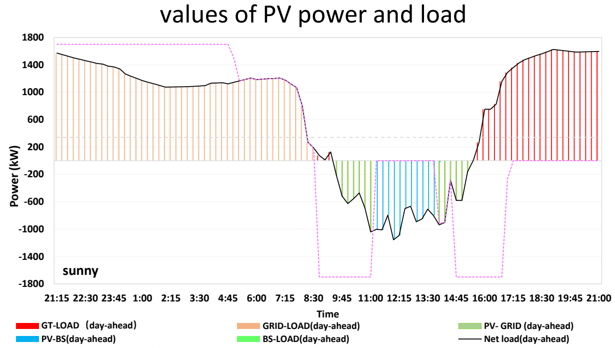
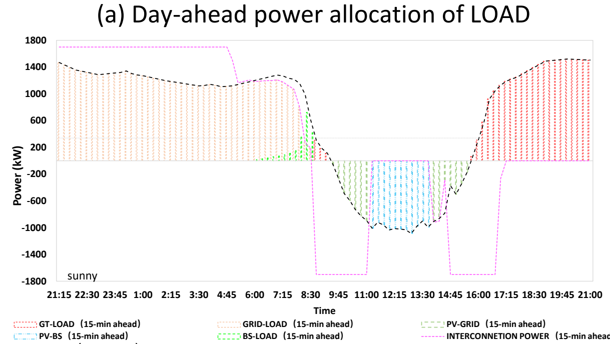


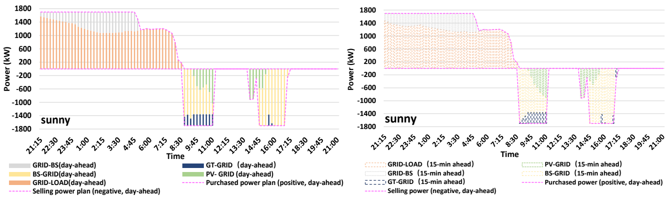
Fig 5. The day-ahead, 15-min ahead forecasts and actual values of PV power and load



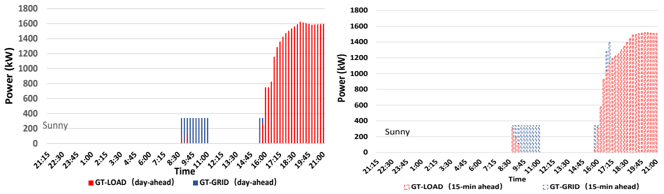
(a) Day-ahead power allocation of LOAD



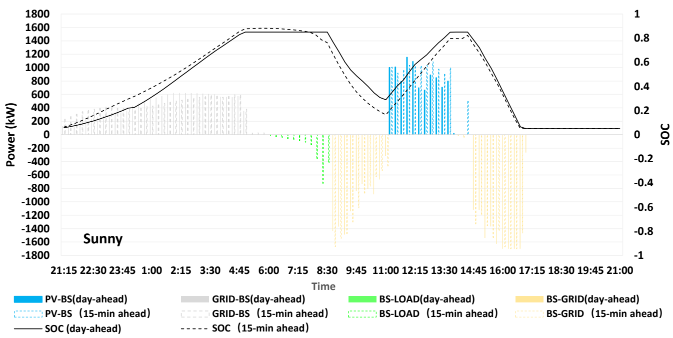
(b) Real-time power allocation of LOAD



(c) Day-ahead power allocation of GRID (d) Real-time power allocation of GRID



(e) Day-ahead power allocation of GT (f) Real-time power allocation of GT



(g) Day-ahead and real-time power allocation of charged/discharged power of BS

Fig. 6 Day-ahead and 15-min ahead schedule of the power allocations of each equipment

A comparison between the two-stage optimal scheduling with an ordinary scenario that only includes day-ahead optimal scheduling is conducted. In the ordinary scenario, GT doesn't only work during HP periods, instead, GT is scheduled to work all day in the day-ahead scheduling stage, i.e., operate with the minimum output or follow the load. The forecasting deviation is compensated by directly discarding PV power, ramping down/up of GT without real-time optimization. The operation result is shown in Fig. 7.

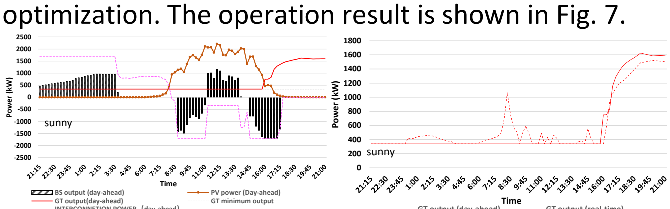


Fig. 7 (a) Output of the equipment according to the day-ahead optimal plan; (b) real-time adjustment by GT of the ordinary scenario

As indicated in Table 4, the operation cost using the dual-stage cooperative optimization significantly lower than that of the ordinary scenario with only day-ahead optimization, with a reduction rate of 31.71%, 36.78%, 20.02%, and 8.92% under four kinds of weather conditions, respectively.

Table 4 Operation costs comparison between the dual-stage optimization and only day-ahead optimization (￥/day)

	Dual-stage optimization	Only day-ahead optimization	Reduction rate
Sunny	5455.86	7989.20	31.71%
Partial cloudy	5023.15	7945.96	36.78%
Cloudy	8366.62	10459.80	20.01%
Rainy	11917.24	13084.99	8.92%

4. CONCLUSION

A dual-stage day-ahead and real-time multi-energy optimal scheduling scheme is proposed for a grid-connected microgrid. In the 24h-ahead scheduling stage, aiming at economy optimization, the day-ahead optimization strategy is established based on the tiered prices, the operation cost of BS and GT to form the power allocation plan. The interconnection power plan between microgrid and main grid was taken as the link between day-ahead and real-time scheduling. In the 15-min ahead stage, the aim is to minimize the operation costs at each dispatching period. New optimization strategy Is built to modify the power allocations of PV, GT, BS, and GRID. Through comparison, this method can effectively improve the economy of the microgrid.

ACKNOWLEDGEMENT

Shandong University Seed Fund Program for International Research Cooperation.

REFERENCE

1. Craparo, E., M. Karatas, and D.I. Singham, *A robust optimization approach to hybrid microgrid operation using ensemble weather forecasts.* Applied energy, 2017. **201**: p. 135-147.
2. Li, Y., et al., *Robust and opportunistic scheduling of district integrated natural gas and power system with high wind power penetration considering demand flexibility and compressed air energy storage.* Journal of Cleaner Production, 2020. **256**: p. 120456.
3. Azarhooshang, A., D. Sedighizadeh, and M. Sedighizadeh, *Two-stage stochastic operation considering day-ahead and real-time scheduling of microgrids with high renewable energy sources and electric vehicles based on multi-layer energy management system.* Electric Power Systems Research, 2021. **201**: p. 107527.
4. Liu, L., et al., *Prediction of short-term PV power output and uncertainty analysis.* Applied energy, 2018. **228**: p. 700-711.
5. Kong, X., et al., *Bi-level multi-time scale scheduling method based on bidding for multi-operator virtual power plant.* Applied Energy, 2019. **249**: p. 178-189.
6. Chen, L., et al., *Multi-time scale coordinated optimal dispatch of microgrid cluster based on MAS.* Electric Power Systems Research, 2019. **177**: p. 105976.