**Appendix**

# Nomenclature

*Parameters*

|  |  |
| --- | --- |
| *a*fe | Minimum ratio of daily electricity consumption for ferroalloy |
| *α*su, *α*in | Positive/negative allowable deviation factors in the energy market |
| , | Electricity sales price from distribution network (DN) to ferroalloy/thermostatically controlled loads (TCLs) |
|  | Comfort loss factor of TCLs |
| , | Charging/discharging cost of microgrid (MG) |
| , | Charging/discharging subsidized prices of MG |
| *c*trfe | Capacity tariff of ferroalloy (converted to daily) |
| , | Electricity prices sold by wind farm to ferroalloy/TCLs |
| *k*fe | Electricity price discount coefficient for ferroalloy, *k*fe∈[0,1] |
| , | Segmentation points in the contract between the ferroalloy load and the wind farm |
| , | Segmentation points in the contract between the TCLs and the wind farm |
| , | Minimum/maximum power of ferroalloy |
| , | Initial power of ferroalloy/TCLs |
| , | Minimum/maximum power of TCLs |
| , | Maximum charging/discharging power of MG |
| *P*Tfe | Transformer capacity of ferroalloy in DN |
|  | Wind-restricted value |
|  | Maximum available wind power |
| *T*limit | Set of wind-restricted periods |

*Variables*

|  |  |
| --- | --- |
|  | Revenue from the wind farm selling electricity to the main grid |
|  | Electricity trading cost between the wind farm and the load-side |
| , | Revenues of the wind farm from selling electricity to ferroalloy/TCLs |
|  | Compensation for dispatching MG |
| , | Power supplied by DN to ferroalloy/TCLs |
| , | Power on the distribution lines between the wind farm and ferroalloy/TCLs |
| , | Bidirectional power on the distribution line between the wind farm and the MG |
|  | Operation baseline of W-FJOS |
|  | Power at wind farm-grid connection point |
|  | Power schedule submitted by the W-FJOS in the energy market |
| , | Power supplied by the wind farm to ferroalloy/TCLs |
| , | Bidirectional power between the wind farm and the MG |
| , | Power supplied from the main grid to ferroalloy/TCLs |

# 1. Supplementary constraints

## 1) Dispatch constraints for flexible loads









## 2) Constraints of W-FJOS under cooperative mode





















This paper utilizes the Bilateral Shapley Value (BSV) method [1] for initial profit distribution and employs for redistribution. Considering the independence of the participants [2] and the accuracy of the load response, this paper uses and to corrects the revenues of each participant.









where *φi*,0 is the allocated profit of participant *i*, *M* is the set of all players, *M*-{*i*} is the set of all participants except *i*, *C*{*i*} is the revenue of participant *i* when it operates independently, *φi* is the ultimate allocated revenue of participant *i* under the BSV, *vi* is used to denote the sign of *φi*,0, if *φi*,0>0, then *vi* is equal to 1, otherwise, it is -1, *μ* is a constant that reflects the preferences of the participants, *φi*,ID is the independent operational profit of participant *i*, which is equal to *C*{*i*}, is the average response accuracy of load *i* within a preceding time duration *T*acc, which can be calculated from the historical data, *T*acc can be measured in weeks or months.

The revenues of each participant in the cooperative model can be calculated by the ISV method:







where *Ii* is the comprehensive bargaining power coefficient of participant *i*, *ω*ID and *ω*ACC are the weights of independence and response accuracy indicators, respectively, *n* is the number of participants, ∆*Ii* is the improvement factor, *φi*,mod is the revenue distribution of participant *i*.

## 3) Constraints of W-FJOS under contractual mode

(1) First stage















(2) Second stage









where *θ* is a coefficient slightly less than 1, is the maximum value obtained from the first stage.

# 2. Parameters in case studies

The installed capacity of the wind farm is 100 MW, and the forecast and actual wind power output data from EirGrid on October 24, 2020 [3] are used and converted to the required scale. Wind power scenarios are simulated based on the statistical distribution of the prediction errors and fluctuations [4]. Subsequently, the K-means clustering method is used for scenario reduction, yielding six wind power output scenarios as shown in Fig. A1. The energy market and peak regulation market are cleared every 15 minutes. The grid operator issues wind restricted commands in the day-ahead stage, requiring that the wind power output cannot exceed 42 MW during the valley price period. The electricity selling prices of the DN and the main grid, as well as the feed-in tariff for wind power, follow the time-of-use (TOU) pricing format, as shown in Table A1. The purchasing and selling price of electricity within W-FJOS under the contractual mode are shown in Table A2. The main grid organizes valley filling auxiliary service during the valley price period. In this paper, it is assumed that the distribution lines connecting the wind farm to the flexible loads are constructed and maintained by the wind farm, and no network fees imposed on the loads. The building central air conditioning system is set to operate in cooling mode. The initial power and the adjustable range of TCLs are shown in Fig. A2. The transmission capacity of the line between the wind farm and the main grid is 100MW. The transmission capacities between the wind farm and the ferroalloy, TCLs and MG are 55MW, 10MW, and 7MW, respectively. The transmission capacities between the DN and the ferroalloy and TCLs are 50MW and 10MW, respectively. The accuracy indicators for the wind farm, ferroalloy, TCLs, and MG are set to 1, 0.9, 0.95, and 0.85, respectively. In the intraday stage, the adjustable capacity range for MG to participate in wind curtailment consumption service at period *t* is [0, 8MW]. Table A3 shows the values of the other parameters in the case studies.



**Fig. A1.** Wind power output scenarios.



**Fig. A2.** Initial power and the adjustable range of the TCLs.

**Table A1** Purchasing and selling price of electricity.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Period | Time duration | /($/MWh) | /($/MWh) | /($/MWh) |
| Peak | 10:00-12:00,  14:00-19:00 | 112 | 154 | 140/137.2 |
| Valley | 00:00-08:00 | 28 | 49 | 35/32.2 |
| Flat | 08:00-10:00,12:00-14:00,19:00-24:00 | 56 | 91 | 84/82.6 |

**Table A2** Purchasing and selling price of electricity within W-FJOS.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Period | /($/MWh) | /($/MWh) | /($/MWh) | /($/MWh) |
| Peak | 119 | 126 | 21 | 210 |
| Valley | 28.42 | 28.98 |
| Flat | 63 | 70 |

## **Table A3** Values of the other parameters in case studies

|  |  |
| --- | --- |
| Parameter | Value |
| , | 280 $/MWh |
|  | 28 $/MWh |
| *a*fe | 0.95 |
| *α*su, *α*in | 1% (wind restricted periods)  10% (wind-unrestricted periods) |
| *θ* | 0.9915 |
| *ω*ID, *ω*ACC | 0.3, 0.7 |
|  | 56 $/MWh |
|  | 28.7 $/MWh |
|  | 0.7$/MWh |
| , | 14 $/MWh, 175 $/MWh |
| , | 22 $/MWh, 215 $/MWh |
| *c*trfe | 130.67 $/(MW·day) |
| *k*fe | 0.5 |
| , | 46MW, 55MW |
|  | 50MW |
| , | 5MW, 7MW |
| *P*Tfe | 50MVA |

# 3. Supplementary figures and tables in case studies



**Fig. A3.** Electric power consumption and composition of ferroalloy.



**Fig. A4.** Electric power consumption and composition of TCLs.



**Fig. A5.** Electric power consumption and composition of MG.

**Table A****4** Revenue and cost of each participant with different allowed output deviations.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Participant | ±5% | | | ±15% | | |
| *C*0 | *C*joint | ∆*C*/*C*0 | *C*0 | *C*joint | ∆*C*/*C*0 |
| WF | 67.93 | 88.25 | 29.91 | 70.93 | 89.65 | 26.39 |
| Ferroalloy | -108.64 | -93.17 | 14.24 | -108.64 | -94.10 | 13.38 |
| TCLs | -14.83 | -11.17 | 24.68 | -14.83 | -11.38 | 23.26 |
| MG | 0 | 0.56 | -- | 0 | 0.52 | -- |
| Total | -55.54 | -15.53 | 72.04 | -52.54 | -15.31 | 70.86 |

**Table A5** Impact of different services on revenue and cost of each participant.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Participant | B1 | | B2 | |
| *C*joint | Difference from A1 | *C*joint | Difference from A1 |
| WF | 89.21/79.42 | -0.12/-0.33 | 89.68/80.25 | 0.35/0.50 |
| Ferroalloy | -94.07/-85.65 | -0.14/0.12 | -93.94/-85.77 | -0.01/0 |
| TCLs | -11.39/-11.24 | -0.06/-0.04 | -11.37/-11.20 | -0.04/0 |
| MG | 0.42/0.48 | -0.10/-0.17 | 0.96/0.89 | 0.44/0.24 |
| Total | -15.83/-16.99 | -0.42/-0.52 | -14.67/-15.83 | 0.74/0.74 |

# 4. Characteristics of two business modes

Cooperative mode can maximize the collaborative potential of the wind farm and the load-side, achieving a fair distribution of profits. However, unclear rewards and penalties may impede timely regulation of participant response behavior. The advantage of the contractual mode lies in providing more explicit sources of income and settlement criteria for each participant. The drawback is the difficulty in formulating incentives and compensation standards that balance the interests of both the wind farm and the load-side. Therefore, in the initial stage, JODC could opt for the contractual model, which provides clearer guidelines for different revenue settlements. By adjusting the supply prices from the wind farm to the flexible loads and the compensation prices for load dispatching, the revenue expectations of all parties can be satisfied. After the joint operation mode has gradually matured, a cooperative model can be adopted to further increase the total revenue of the W-FJOS. Therefore, JODC should choose the appropriate business model according to its actual operational needs.

# Reference

[1] Y. Li, C. Yu, Y. Liu, Z. Ni, L. Ge, X. Li, Collaborative operation between power network and hydrogen fueling stations with peer-to-peer energy trading, IEEE Trans. Transp. Electrif. 9 (1) (2023) 1521-1540.

[2] Z. T., Z. X., O. W., L. T., L. Z., Y. L., Robust-based market bidding strategy and profit allocation method for the alliance of wind power generators considering shared energy storage (2022) 1356-1361. 10.1109/SSCI51031.2022.10022253.

[3] Annual renewable report. https://www.eirgrid.ie/grid/system-and-renewable-data-reports, 2024.

[4] X. Ma, Y. Sun, H. Fang, Scenario generation of wind power based on statistical uncertainty and variability, IEEE Trans. Sustain. Energy. 4 (4) (2013) 894-904.