**A. LPVI Process**

(1) Day-ahead optimization

* + In the day-ahead stage, since the prediction accuracy is high, a fine-grained optimization approach is employed.
  + The day is divided into 24 optimization points, corresponding to hourly optimization decisions.

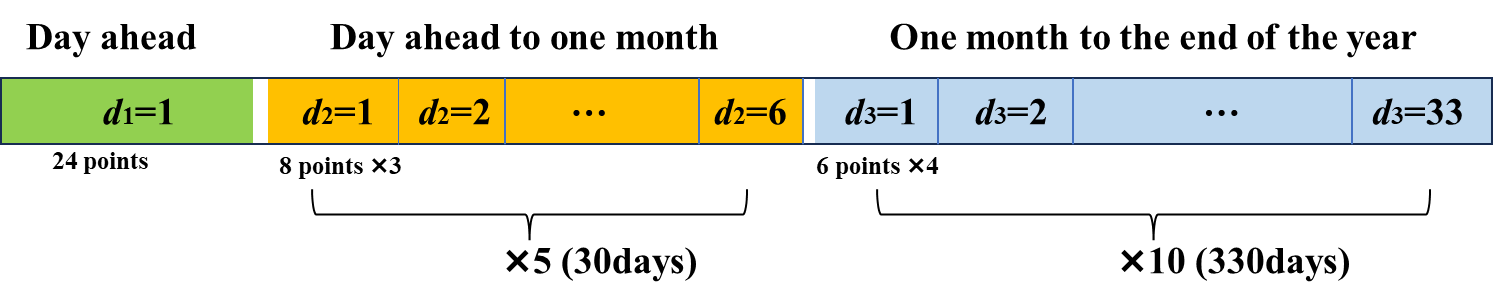
(2) Optimization from the day-ahead to one month

* + As the prediction period extends beyond the next day to a month, uncertainties increase, making hourly optimization less practical. Instead, a representative-day approach is adopted.
  + Six representative days are selected to capture the month’s operational characteristics, with each representative day corresponding to five actual operating days.
  + Each representative day undergoes optimization at eight time points.
  + Consequently, the optimization results for this stage must be scaled by a factor of ×3 (for eight time points per day) ×5 (for five actual days per representative day) to cover the entire period adequately.

(3) Optimization from one month to the end of the year

* + As the prediction horizon extends further, the optimization granularity is further coarsened to reduce computational burden while maintaining representativeness.
  + Thirty-three representative days are selected to represent the remaining 330 days, with each representative day corresponding to ten actual operating days.
  + Each representative day undergoes optimization at six time points.
  + The optimization results for this stage must be scaled by a factor of ×10 (for ten actual days per representative day) to generalize to the full annual period.

Firstly, symbols related to LPVI are introduced. Specifically, *d*1, *d*2, and *d*3 denote the indices of typical days for the following day, the next month, and the period from one month to the end of the year, respectively, with index ranges of 1, 6, and 33. Similarly, *t*1, *t*2, and *t*3 represent the optimization points for each typical day before the day, within one month, and from one month to one year, with index ranges of 24, 8, and 6, respectively. The process is shown in **Fig. 1**.



1. **Explanation of LPVI coordination mechanism.**

It is important to note that the particle size used in this study is chosen based on the selection of steel users as the research focus, given their relatively stable electricity consumption and steel product prices. For other types of users, clustering methods can be employed to determine the typical daily quantity and appropriate particle size for different periods. Users can apply this method for rolling optimization, where the total number of optimized days decreases by one with each rolling step until the entire year is optimized. However, this study focuses on the annual planning framework and does not elaborate on the specific rolling process.

**B. Case Data of PJM-5 System**



1. **The modified PJM 5-node system.**

The cost and performance data for generators G1-G5 are presented in **TABLE 1** and **TABLE 2**. Specifically, the fuel cost for coal-fired generators is set at 725 yuan per ton, while the fuel cost for gas-fired generators is 2.3 yuan per cubic meter. The equivalent emission factor (*ei*) of the wind generator is set to -0.2.

1. **Cost data of units G1-G5**

|  |  |  |  |
| --- | --- | --- | --- |
| Generator No. | Generator type | *a*(t/MW2)/(m3/MW2) | *b*(t/MW)/(m3/MW) |
| G1 | Coal-fired | 0.0007 | 0.2449 |
| G2 | Coal-fired | 0.0010 | 0.2656 |
| G3 | Gas-fired | 0.2998 | 107.0115 |
| G4 | Coal-fired | 0.0008 | 0.1952 |
| G5 | Coal-fired | 0.0008 | 0.2286 |

1. **Performance data of units G1-G5**

|  |  |  |  |
| --- | --- | --- | --- |
| Generator No. | *PG,*min/MW | *PG,*max/MW | *ei*/(tCO2/MWh) |
| G1 | 120 | 600 | 0.525 |
| G2 | 22 | 110 | 0.300 |
| G3 | 20 | 100 | 0.300 |
| G4 | 104 | 520 | 0.875 |
| G5 | 40 | 200 | 0.875 |

### C. Modified IEEE 118-Bus System

The IEEE 118-bus system is applied to demonstrate applicability of the proposed method to large systems. The modified system, as shown in **Fig. 3**, has 118 loads with 5 transferable load and 21 generators and consists of 118 buses, and 186 branches. The 5 transferable load electricity consumption curves are derived from the actual annual electricity consumption curves of five steel users and adjusted proportionally.



1. **The modified IEEE 118 system.**

In this section, RMCEFd represents the use of RMCEF as an incentive and calculates the daily carbon emission responsibility and fee for users (the proposed method). RMCEFt represents the carbon emission responsibility and carbon fee that users bear on an hourly basis, and is compared with the average carbon emission and carbon emission flow theory as the user-side carbon responsibility allocation method. The results are shown in **TABLE 3**.

1. **Comparison of carbon emissions under different carbon emission responsibility in modified IEEE 118 system.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| incentive factors |  | carbon emissions (kt) | system carbon emission(kt) | total carbon fees (kilo yuan) | total net profit (million yuan) |
| RMCEFd | user1 | 62.80 | 2066.7(**—**) | 5068 | 764.02 |
| user2 | 40.26 |
| user3 | 93.98 |
| user4 | 43.95 |
| user5 | 36.45 |
| RMCEFt | user1 | 63.36 | 2067.3(**+657**) | 5756 | 762.01 |
| user2 | 40.57 |
| user3 | 94.77 |
| user4 | 44.29 |
| user5 | 36.71 |
| ACEF | user1 | 62.81 | 2067.8(**+1128**) | 4153 | 766.31 |
| user2 | 40.15 |
| user3 | 92.65 |
| user4 | 43.42 |
| user5 | 36.45 |
| NCI | user1 | 42.09 | 2068.7(**+2028**) | 10125 | 701.87 |
| user2 | 42.48 |
| user3 | 157.88 |
| user4 | 56.96 |
| user5 | 40.51 |

The simulation results of 118 nodes are basically the same as those of 5 nodes. It can be seen that the method proposed in this article reduces the carbon emissions of the system the most, while the carbon emissions of the other three methods increased by 657kt, 1128kt, 2028kt compared to the proposed method. The comparison of the results between RMCEFd and RMCEFt demonstrates the superiority of the proposed daily allocation of carbon responsibility and payment of carbon fees, while the comparison with ACEF and NCI demonstrates the superiority of the proposed carbon emission allocation responsibility.

The difference is that the average carbon emission factor is used as the incentive factor for the user side. The carbon emission factor borne by the user is higher than that of the algorithm proposed in this paper, but the total carbon emissions of the system are reduced. This is because in the IEEE 118 system, the proportion of transferable loads is relatively small. After these 5 loads are transferred, the average carbon emission factor of the system changes, causing the fixed load carbon responsibility in the system to increase from 1506.9 kt to 1517.6 kt, further reducing the carbon responsibility borne by transferable loads, which also leads to inequity in the carbon market.

### D. Annual carbon price data

76.81,73.52,72.33,70.67,72.81,69.67,74.53,74.67,74.67,79.47,83.27,85.66,89.64,87.67,90.60,102.49,101.67,97.42,98.51,95.42,94.67,90.66,90.61,87.50,91.60,91.45,91.29,89.04,93.12,92.80,99.16,100.03,103.42,103.44,105.03,104.78,102.91,100.94,97.52,97.715

The maximum and minimum carbon price coefficient sets to 1.6 and 0.6.