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Multi-time-scale Optimized Operation Method for Integrated Energy Systems Considering Equipment Dynamic Performance

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According to statistical data from the International Energy Agency (IEA, 2024), the electricity sector emitted 15.3 Gt of carbon dioxide, accounting for 40% of global carbon emissions.[1] The high reliance on fossil fuels is the main reason why this industry struggles to reduce its carbon emissions. Integrated energy systems enable a high proportion of renewable energy adoption and facilitate the cascade utilization of energy, which helps reduce fossil fuel consumption. As a result, related research has gradually gained attention.

Integrated energy systems can effectively coordinate various types of energy, such as electricity, heat, natural gas, and hydrogen, offering advantages in multi-energy complementarity. It has been reported that existing integrated energy systems achieve a renewable energy utilization rate of over 90%.[2] However, the significant differences in response times among various devices (such as batteries and gas boilers), coupled with the inevitable deviations in source-load forecasting, make it essential to implement multi-time-scale operation in integrated energy systems (as shown in Figure 1 *Multi-time-scale operational architecture of integrated energy systems*). Studies indicate that multi-time-scale optimization methods can effectively improve renewable energy integration and primary energy utilization rates in integrated energy systems.[3]

MULTI-TIME-SCALE OPERATION METHODOLOGY

Multi-time-scale operation is typically conducted in three stages: day-ahead, intra-day, and real-time.

- The day-ahead stage requires scheduling one day in advance, where the system operational plan for the next 24 hours (with a 1-hour dispatch interval) is formulated in a single execution.
- The intra-day stage incorporates Model Predictive Control (MPC) technology. Based on the equipment output plan from the day-ahead stage, it adjusts the equipment output for the next 2 hours (or 4 hours) at 15-minute intervals.
- The real-time stage is nested within the intra-day stage. Building upon the 15-minute operational plan from the intra-day stage, it further shortens the time scale to formulate equipment operational plans for the next 15 minutes at 5-minute intervals.

During optimization scheduling, the system's energy supply plan formulated in the "day-ahead" and "intra-day" stages operates on relatively long adjustment intervals, while the "real-time" stage requires the development of an energy supply plan on a much shorter time scale. Therefore, in the "day-ahead" and "intra-day" stages, all controllable equipment—such as gas turbines, waste heat boilers, electrical storage, and thermal storage—participate in the optimization scheduling. In contrast, the "real-time" stage only dispatches fast-response electricity-related devices, such as electrical storage and power grid, to ensure power supply reliability, while cold and heat-related equipment continue to follow the intra-day plan. This approach guarantees the feasibility of the system operational schedule.

In terms of constraints, the supply-demand balance for various types of energy—cold, heat, and electricity—often constitutes rigid constraints (equality constraints). However, the optimization scheduling in the day-ahead stage is often relatively coarse, with its primary task being to determine unit commitment (or a rough output plan) rather than precise output levels. Therefore, to enhance the flexibility of system optimization scheduling, Reference[4] introduces a 5% flexible constraint (inequality constraint) into the energy balance of the day-ahead stage, creating a certain margin of imbalance between energy supply and demand. Since the cooling and heating supply plans will be finalized in the "intra-day" stage, and the electricity supply plan will be subject to the real-time schedule, strict energy balance equality constraints will be imposed during both the "intra-day" and "real-time" stages.

To further enhance the feasibility of the energy supply scheme, Reference[4] thoroughly considers the dynamic performance of slow-response devices and optimizes their power ramping-up and -down processes during the intra-day stage. The slow-response devices primarily include internal combustion engines, absorption heat pumps, and gas boilers—all of which are driven by natural gas or heat. The optimization of ramping rates is achieved using a genetic algorithm, with the corresponding objective function being the minimization of equipment adjustment frequency.

Distinct forms of energy conversion result in significant variations in the response times of different equipment. If a uniform 15-minute control time interval is adopted during the intra-day stage, it may lead to considerable discrepancies between the scheduling results and the actual operating conditions, thereby compromising the overall system performance. To address this issue, Reference[4] proposed a hybrid multi-time-scale operational strategy for slow-response devices in the intra-day stage. First, an exhaustive search is applied to determine the optimal time scale for the participation of internal combustion engines, gas boilers, and absorption heat pumps in intra-day scheduling, with the objective of minimizing economic cost. Subsequently, accounting for the off-design performance of these three

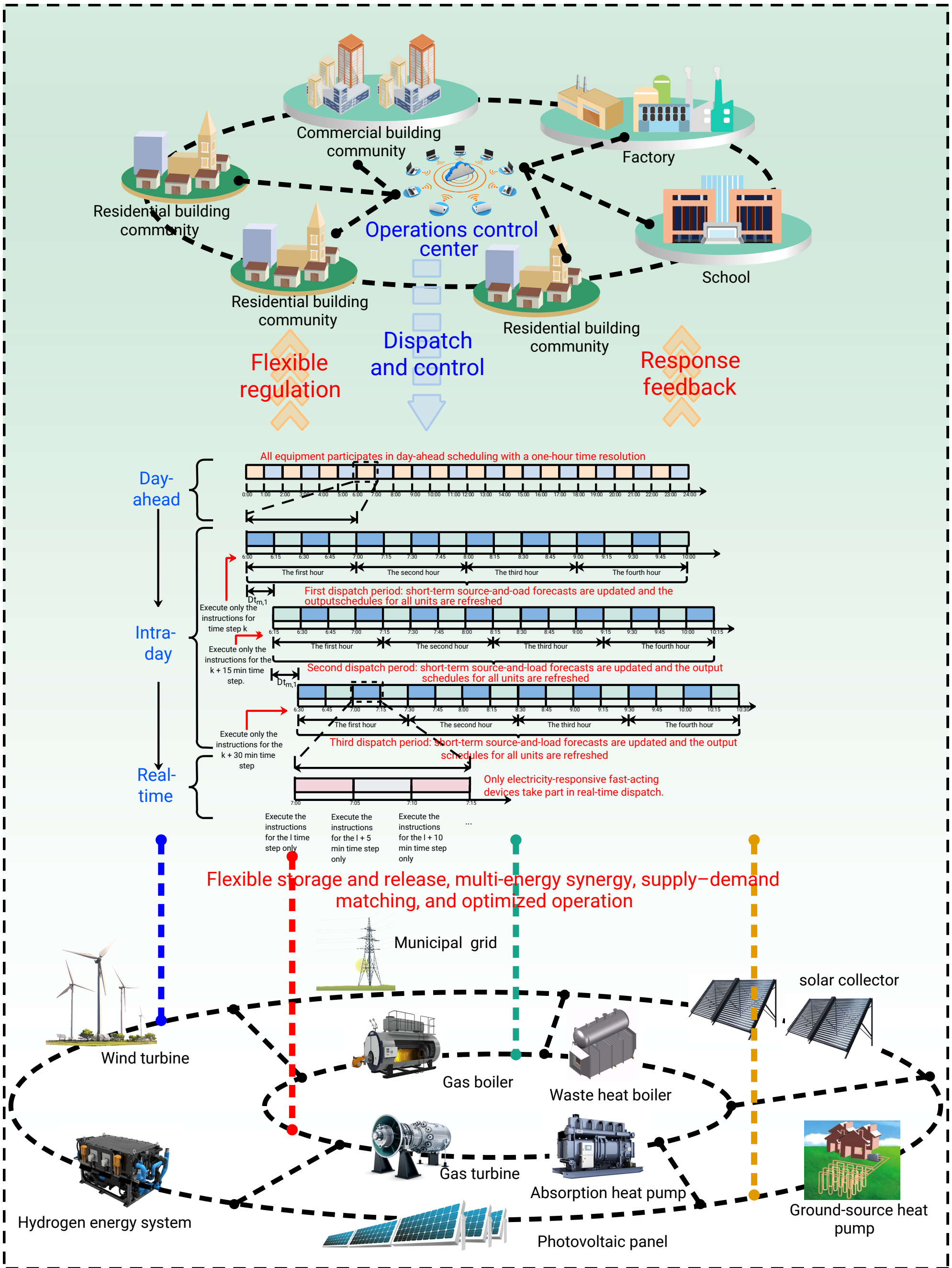

Figure 1. Multi-time-scale operation methodology.

types of equipment, a hybrid multi-time-scale scheduling scheme is constructed for the intra-day stage.

ANALYSIS AND DISCUSSION OF RESULTS

Taking Arizona State University in the United States as a case study, an integrated energy system architecture was constructed, which includes equipment such as gas turbines, waste heat boilers, electrical storage, thermal storage, and photovoltaics.[5] Multiple optimization operation strategies were formulated:

Strategy 1: Day-ahead single-time-scale optimization only.

Strategy 2: Two-stage "day-ahead and intra-day" optimization.

Strategy 3: Multi-time-scale "day-ahead, intra-day, and real-time" optimization.

Strategy 4: Based on Strategy 3, incorporating flexible constraints for energy supply balance in the day-ahead stage.

Strategy 5: Based on Strategy 3, optimizing the ramping-up/down processes of slow-response devices in the intra-day stage.

Strategy 6: Based on Strategy 5, incorporating flexible constraints for energy supply balance in the day-ahead stage.

Strategy 7: Based on Strategy 6, implementing hybrid multi-time-scale optimal scheduling for slow-response devices in the intra-day stage.

Taking typical winter (January 15) and summer (July 16) days as analysis cases, a series of important conclusions can be drawn.

As the scheduling time scale becomes finer, the total system operating cost shows a decreasing trend. On the typical summer day, the operating cost under Strategy 3 decreased by approximately 2.0% and 3.3% compared to Strategy 2 and Strategy 1, respectively. On the typical winter day, the operating cost under Strategy 3 decreased by approximately 2.15% and 11.07% compared to Strategy 2 and Strategy 1, respectively, while the renewable energy penetration increased by 2.84% and 1.02% compared to Strategy 1 and Strategy 2, respectively. These results indicate that shortening the time scale helps mitigate the adverse impacts of source-load uncertainty on system operation, reduces the supply-demand imbalance caused by forecasting errors, and thereby lowers the system operating cost.

By comparing Strategy 4 and Strategy 3, it can be concluded that incorporating flexible constraints in the day-ahead stage can reduce system operating costs and improve system independence. On the typical summer day, the operating cost obtained under Strategy 4 decreased by approximately 6.4% compared to Strategy 3. Furthermore, Strategy 4 reduced the electricity exchange between the energy supply system and the municipal grid, thereby enhancing system independence. On the typical winter day, the exchange power under Strategy 4 decreased by about 5.0% compared to Strategy 3, and by over 15% compared to Strategy 1.

After considering the ramping-up/down processes of slow-response devices (Strategy 5), the primary energy consumption of the energy supply system on the typical summer day increased by 2.0% compared to Strategy 3, while the cost rose by more than 8.0%. The reason may be that optimizing the ramping processes of slow-response devices reduces their operational flexibility. However, the output curves of slow-response devices change gradually without abrupt power fluctuations, making the energy supply plan more realistic. This more objectively reflects the comprehensive benefits of the system and facilitates the decision-making process.

By simultaneously considering the flexible supply-demand constraints in the day-ahead stage and the ramping-up/down processes of slow-response devices (Strategy 6), both the practicality of the energy supply plan and the energy efficiency of the integrated energy system are improved. On the typical summer day, Strategy 6 significantly reduced the primary energy consumption during system operation, achieving savings of 3.0% and 4.0% compared to Strategy 3 and Strategy 5, respectively. This further demonstrates the advantage of incorporating flexible constraints in the day-ahead stage for multi-time-scale operational optimization.

Using the exhaustive search method to determine the optimal time scales for the participation of slow-response devices in scheduling, it was found that different devices have distinct optimal time scales for optimization. On the typical summer day, the optimal time scales for the optimal scheduling of the internal combustion engine, gas boiler, and absorption heat pump were

12 minutes, 9 minutes, and 17 minutes, respectively. On the typical winter day, the optimization results were 17 minutes, 7 minutes, and 7 minutes, respectively.

Based on the above optimal control time intervals for the internal combustion engine, gas boiler, and absorption heat pump, Strategy 7 enables further reductions in both system operating costs and fossil energy consumption. Compared to Strategy 5 and Strategy 6, Strategy 7 achieved a reduction in system operating costs of approximately 10%, and decreased fossil energy consumption by 7.0% and 3.0%, respectively. Moreover, Strategy 7 effectively reduced incidents of energy supply shortages. On the typical summer day, the heat supply shortage under Strategy 7 decreased by nearly 90% compared to both Strategy 5 and Strategy 6.

In summary, introducing flexible energy balance constraints in the day-ahead optimization stage, optimizing the ramping processes of slow-response devices in the intra-day stage, and implementing hybrid multi-time-scale scheduling for different types of slow-response devices can reduce fossil energy consumption, lower system costs, and thereby promote the commercial adoption of integrated energy systems.

REFERENCES

1. International Energy Agency. World Energy Outlook 2024. (2024).
2. Hu C., Wang H. and Li C. (2026) Integrated energy system modeling and optimal scheduling strategy for supply and demand side resource flexibility. *Renew. Energy* **256**:124073. DOI:10.1016/j.energy.2025.137403.
3. Liu Z., Fan G., Meng X., et al. (2024). Multi-time scale operation optimization for a near-zero energy community energy system combined with electricity-heat-hydrogen storage. *Energy* **291**:130397. DOI:10.1016/j.energy.2024.130397
4. Duan Y. (2024). Research on Multi-Time Scale Operation Method ofIntegrated Energy System Considering Equipment Dynamic Characteristics (in Chinese). North China Electric Power University. DOI:10.27139/d.cnki.ghbdu.2024.001196.
5. Han Z., Han S., Wu D., et al. (2025). Multi-timescale optimization scheduling of integrated energy systems based on high-accuracy predictions. *Energy* **333**:137403. DOI:10.1016/j.energy.2025.137403

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AUTHOR CONTRIBUTIONS

Di Wu: Conceptualization, Methodology. Shaofeng Han: Software, Writing – review & editing. Zhijian Liu: Writing – review and editing, Supervision, Funding acquisition. Cheng Xu: Methodology. Xu Liu: Writing – original draft. Wentao Wu: Writing – original draft, Writing – review & editing. Guangya Jin: Project administration.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.