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# Flexible Coordination of Wind Generators and Energy Storages in Joint Energy and Frequency Regulation Market


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# CONTEXT

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1 RESEARCH BACKGROUNDS

2 PROBLEM FORMULATION

3 SOLUTION

4 CASE STUDY

5 CONCLUSION

# 1 Research Backgrounds

## Problem

- **Future power system:** energy storage systems will be widely utilized in wind farms to smooth their power fluctuations
- **The cancellation of clean energy subsidy policy:** how to effectively improve the economic benefits of wind farm with energy storages?

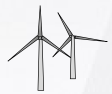
## Solution

**Wind-ESS Co-generation System**

→ **Energy Market** → **Arbitrage**

→ **Regulation Market** → **Regulation Income**

→ **Diversified Market Benefits**

| | Operating Cost | Regulation Accuracy |
|---|---|---|
|  Energy Storages | High | High |
|  Wind Turbines | Low | Low |

**Integrate into a more flexible coordination scheme**

1 **Research Backgrounds**



## Difficulty

- Wind power and frequency fluctuations have multiple uncertainties
- The time scale used for frequency regulation decision-making is at the second level, and a real-time wind turbines and energy storages coordination strategy needs to be formulated

## Existing Solutions

- **Stochastic Optimization:** maximizing expected daily revenue in multiple group of scenarios
- **Disadvantages:** high computational overhead, offline decision-making

## Our Work

- A Two-Stage Coordination Scheme Combining Offline and Online Strategy
- Optimal Power Distribution and Start-stop Control of Individual Wind Generators

## 2 Problem Formulation: Market Framework

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**A Joint energy and frequency regulation market**

### Frequency regulation market

**Regulation capacity:** $P_t^{cap}$

Maximum power for regulation

**Regulation revenue:**

$$r_t^{reg} = \lambda_t^{reg,cap} P_t^{cap} K_t^{pref} + \lambda_t^{reg,mil} P_t^{cap} R_t K_t^{pref}$$

$$R_t = \frac{\Delta k}{3600} \sum_{k \in K} \left( |s_{t,k+1}| - |s_{t,k}| \right)$$

$$K_t^{pref} = \frac{1}{4}\left(2k_t^1 + k_t^2 + k_t^3\right)$$

### Energy market

**Energy bidding:** $P_t^{eng,w}$ $P_t^{eng,b}$

Wind Power Basepoint    Energy Storages Basepoint

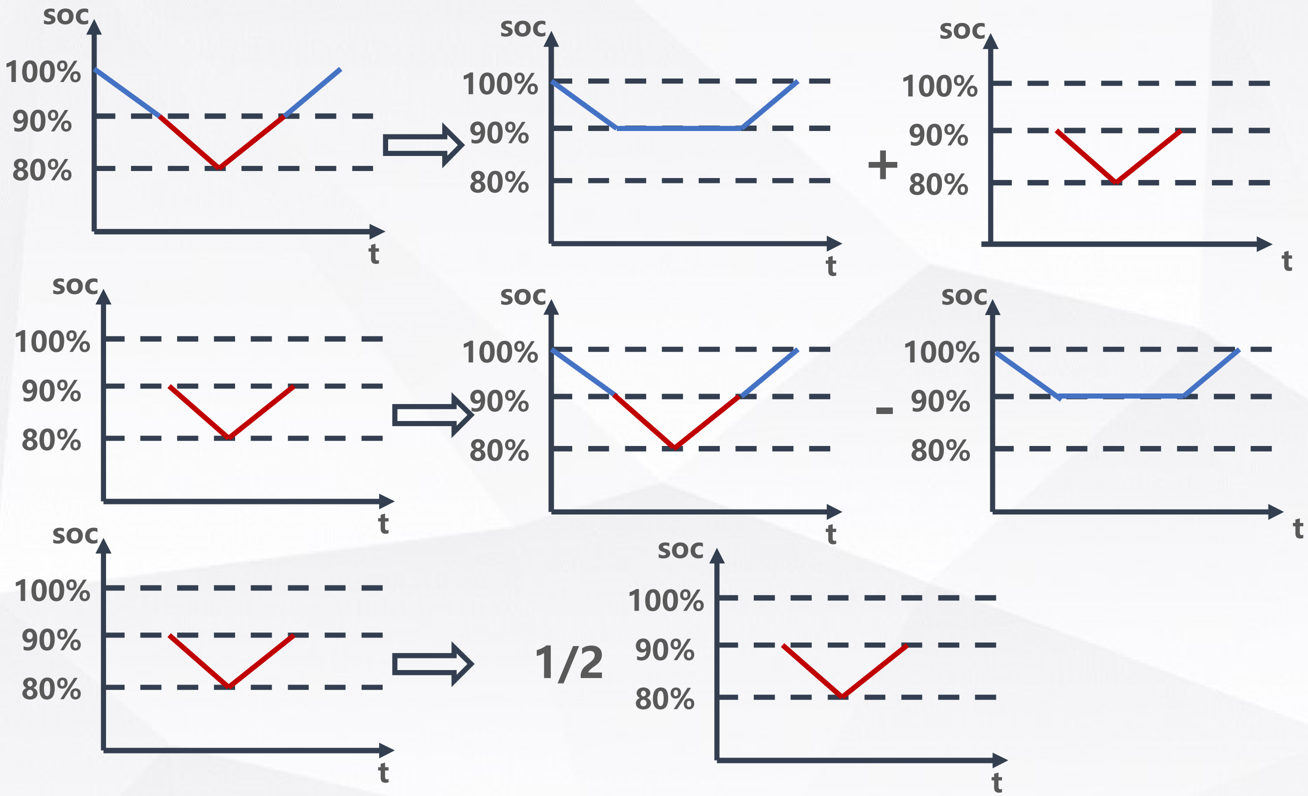
**Energy market revenue:**

$$r_t^{eng} = \lambda_t^{eng} \left( P_t^{eng,w} + P_t^{eng,b} \right)$$

## 2 Problem Formulation: Cost of Battery

**Characteristics:** Energy storage life loss is related to the depth of discharge (DOD) of its charge-discharge cycle

**Equivalent cost:** It is necessary to consider the life loss caused by a single charge or discharge action of the battery




### Equivalent cost of battery

$$L_{eq}=\frac{1}{2}\left|L_{d1}-L_{d2}\right|=\frac{1}{2}\left|\frac{1}{N_{d1}^{fail}}-\frac{1}{N_{d2}^{fail}}\right|$$

$$L_{eq}=\frac{1}{2}\left|\frac{d_1^{K_p}}{N_{100\%}^{fail}}-\frac{d_2^{K_p}}{N_{100\%}^{fail}}\right|$$

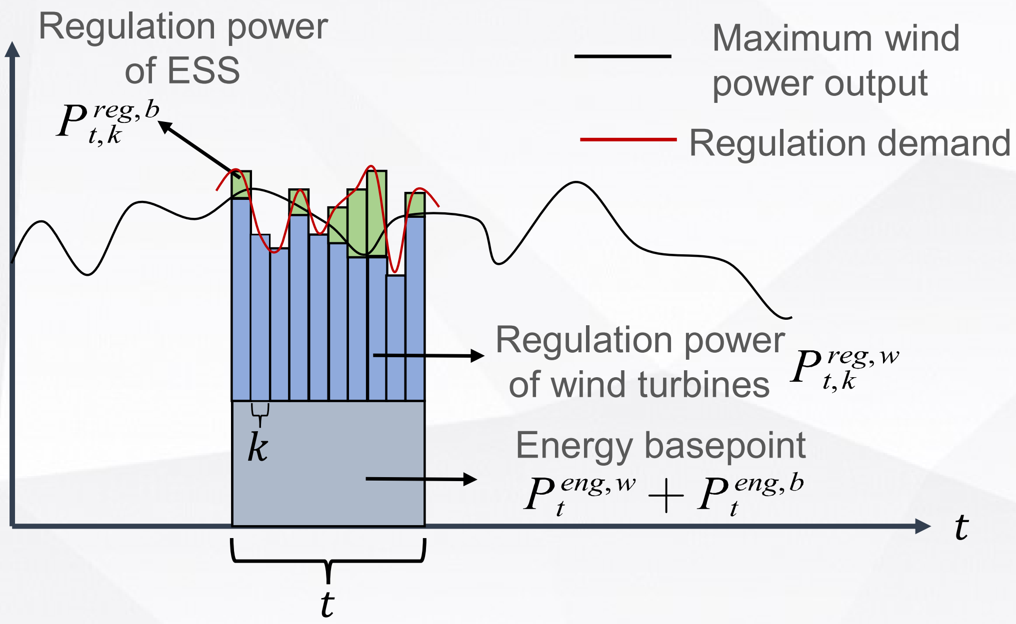
$$L_{eq}=\frac{\left|d_1^{Kp}-d_2^{Kp}\right|}{2N_{100\%}^{fail}}$$

$$C_{t,k}^{bes}=\frac{\Delta E_{t,k}}{2N_{100\%}^{fail}E_{\max}}C^{in,bes}$$

# 2 Problem Formulation: Collaborative Solutions of Wind Power and ESS

- Wind turbines prioritize meeting the frequency regulation demand
- Battery energy storages compensate the remaining regulation demand and regulation error of wind turbines

## Diagram of wind storage cooperation




## Mathematical formulation

$$P_{t,k}^{reg,w} = \begin{cases} P_t^{w,rup} & P_t^{cap} s_{t,k} > P_t^{w,rup} \\ -P_t^{w,rdn} & P_t^{cap} s_{t,k} < -P_t^{w,rdn} \\ P_t^{cap} s_{t,k} & others \end{cases}$$

$$P_{t,k}^{reg,b} = \begin{cases} P_t^{cap} s_{t,k} - P_t^{w,rup} + \varepsilon_{t,k} & P_t^{cap} s_{t,k} > P_t^{w,rup} \\ P_t^{cap} s_{t,k} + P_t^{w,rdn} + \varepsilon_{t,k} & P_t^{cap} s_{t,k} < -P_t^{w,rdn} \\ \varepsilon_{t,k} & others \end{cases}$$

# 2 Problem Formulation: Mathematical Model of Optimal Daily Revenue

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□ **Objective:** Maximize daily returns in the joint energy and frequency regulation market

**Objective Function:**
$$\max_{P_t^{eng,w}\ P_t^{eng,b}\ P_t^{cap}} \sum_{t=0}^{23}\left(r_t^{eng}+r_t^{reg}-\sum_{k\in K}C_{t,k}^{bes}\right)$$

### Power limitations for wind turbines and ESSs

$$0 \leqslant P_t^{eng,w} \leqslant W_t = \min\left(W_{t,k}, W_{t,k+1}, \ldots\right)$$
$$-P^{\max,b} \leqslant P_t^{eng,b} \leqslant P^{\max,b}$$

### Constraints on reserved regulation capacity

$$P_t^{w,rup} = \min\left(W_t - P_t^{eng,w}, \Delta P^{\max,w}\right)$$
$$P_t^{w,rdn} = \min\left(P_t^{eng,w}, \Delta P^{\max,w}\right)$$
$$P_t^{b,rup} = P^{\max,b} - P_t^{eng,b}$$
$$P_t^{b,rdn} = P^{\max,b} + P_t^{eng,b}$$

### Frequency regulation demand

$$P_t^{b,rup} + P_t^{w,rup} \geqslant P_t^{cap}$$
$$P_t^{b,rdn} + P_t^{w,rdn} \geqslant P_t^{cap}$$
$$P_{t,k}^{reg,w} = \begin{cases} P_t^{w,rup} & P_t^{cap} s_{t,k} > P_t^{w,rup} \\ -P_t^{w,rdn} & P_t^{cap} s_{t,k} < -P_t^{w,rdn} \\ P_t^{cap} s_{t,k} & others \end{cases}$$
$$P_{t,k}^{reg,w} = \begin{cases} P_t^{w,rup} & P_t^{cap} s_{t,k} > P_t^{w,rup} \\ -P_t^{w,rdn} & P_t^{cap} s_{t,k} < -P_t^{w,rdn} \\ P_t^{cap} s_{t,k} & others \end{cases}$$

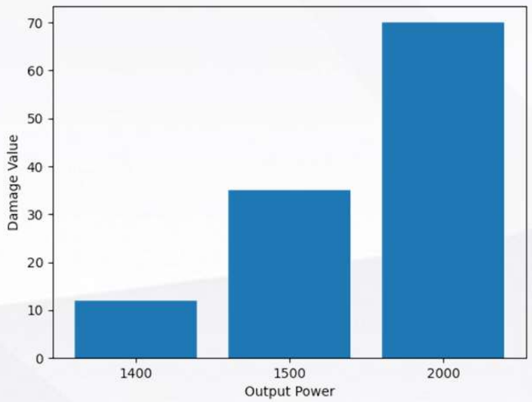
# 2 Problem Formulation: Power Distribution of Wind Turbines

**Subproblem:** Optimal power distribution among different wind turbines in wind farm

**Objective Function:**

$$\min_{P^{w}_{i,\tau,k},\, u_{i,\tau}} \sum_{i\in I}\sum_{\tau=0}^{2}\sum_{k\in K} c^{ope}_{i,\tau,k} + \sum_{i\in I}\sum_{\tau=0}^{2}\left(c^{start}_{i,\tau} + c^{stop}_{i,\tau}\right)$$

**Damage value of wind turbines per second**




**Equivalent cost of wind turbines**

$$c^{ope}_{i,\tau,k} = f_1\left(P^{w}_{i,\tau,k}\right) u_{i,\tau} \Delta k$$

$$c^{start}_{i,\tau} = x_i u_\tau \left(1 - u_{\tau-1}\right)$$

$$c^{stop}_{i,\tau} = y_i u_{\tau-1} \left(1 - u_\tau\right)$$

**Power limitation of wind turbines**

$$\sum_{\substack{i\in I \\ \tau\in(t,t+1)}} P^{w}_{i,\tau,k} = P^{eng,w}_{t} + P^{reg,w}_{t,\tau,k}$$

$$\left|P^{w}_{i,\tau} - P^{w}_{i,\tau-1}\right| \leqslant \Delta P^{\tau\max}_{i}$$

$$P^{w}_{i,\tau,k} \leqslant W_{i,\tau,k} \quad \tau\in(t,t+1)$$

## 3 Solution : Markov Decision Process

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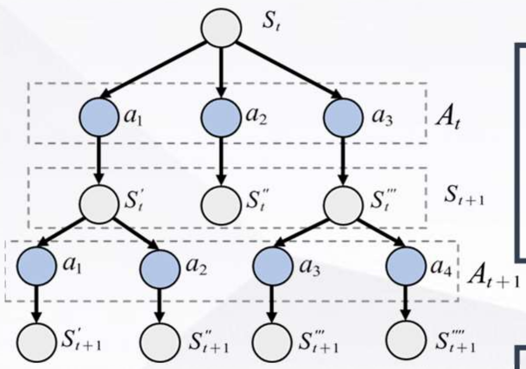
- **Sequential decision-making:** MDP are designed for sequential decision-making problems, enabling the modeling of the dynamic nature of ESS control and operation.
- **Scalability and flexibility:** provide online control framework for ESS

Joint energy and frequency regulation market

Wind turbines-ESS co-generation system




### Reward

$$r_t(s,a)=\begin{cases} r_t^{eng}+r_t^{reg}-\sum\limits_{k\in K} C_{t,k}^{bes} & if\ (s,a_t)\notin F(S,A) \\ -\infty & others \end{cases}$$

### State Transition

$$\Delta E_{t,k}=\begin{cases} \eta^{ch}\left(P_t^{eng,b}+P_{t,k}^{reg,b}\right)\cdot\dfrac{\Delta k}{3600} & if\ P_t^{eng,b}+P_{t,k}^{reg,b}<0 \\ \dfrac{P_t^{eng,b}+P_t^{reg,b}}{\eta^{dch}}\cdot\dfrac{\Delta k}{3600} & if\ P_t^{eng,b}+P_{t,k}^{reg,b}\leqslant 0 \end{cases}$$

### State and state value

$$s=\{t,e\}$$

$$V(s)=E\left[R_{t+1}+\gamma R_{t+2}+\gamma^2 R_{t+3}+\cdots|s\right]\ \ s\in S$$

### Action

$$a_t=\{P_t^{eng,w},P_t^{eng,b},P_t^{cap}\}$$

# 3 Solution : Offline Strategy Formulated in the Day-ahead Stage

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### 1~24h Scene prediction

1. Maximum wind power output
2. Frequency fluctuation

### Bellman equation

$$V(s) = \max_{\pi} \sum_{a \in A} \pi(a|s) \left[ r(s,a) + \gamma \sum_{s'} p(s'|s,a) V(s') \right]$$

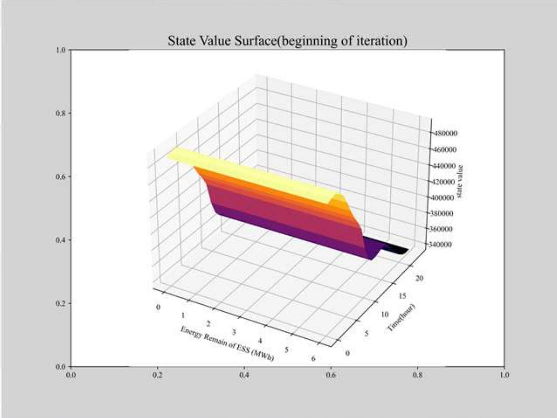
### Value iteration

**Pseudocode: Value iteration algorithm**

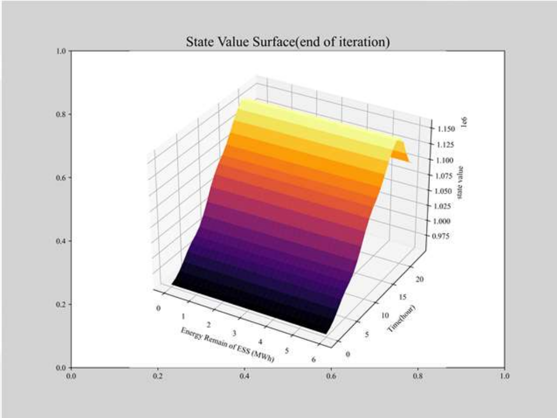
**Initialization:** The probability model $p(r|s,a)$ and $p(s'|s,a)$ for all $(s,a)$ are known. Initial guess $v_0$.

**Aim:** Search for the optimal state value and an optimal policy solving the Bellman optimality equation.

While the state value has not converged, for the $k$th iteration, do
- For every state $s \in \mathcal{S}$, do
  - For every action $a \in \mathcal{A}(s)$, do
    - q-value: $q_k(s,a) = \sum_r p(r|s,a)r + \gamma \sum_{s'} p(s'|s,a) v_k(s')$
  - Maximum action value: $a_k^*(s) = \arg\max_a q_k(a,s)$
  - *Policy update:* $\pi_{k+1}(a|s) = 1$ if $a = a_k^*$, and $\pi_{k+1}(a|s) = 0$ otherwise
  - *Value update:* $v_{k+1}(s) = \max_a q_k(a,s)$



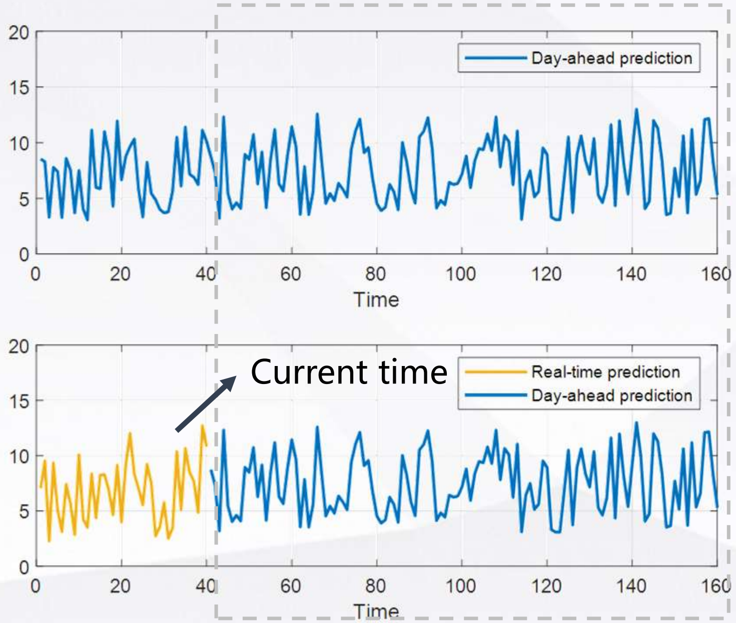

**Initial state value**




**Optimal state value**

# 3 Solution : Online Policy Modification

- Hourly short-term forecast results in real-time stage deviate from day-ahead forecast results
- Optimize real-time strategies based on **Rolling Horizon** methods




**Algorithm: Rolling Programming**

Input: optimal state value $V^*$ obtained by DP.

Aim: based on the short-term forecast information, find the best action $a_t^*$ in $t$th hour in the real-time market.

For every action $a \in A$ ,do

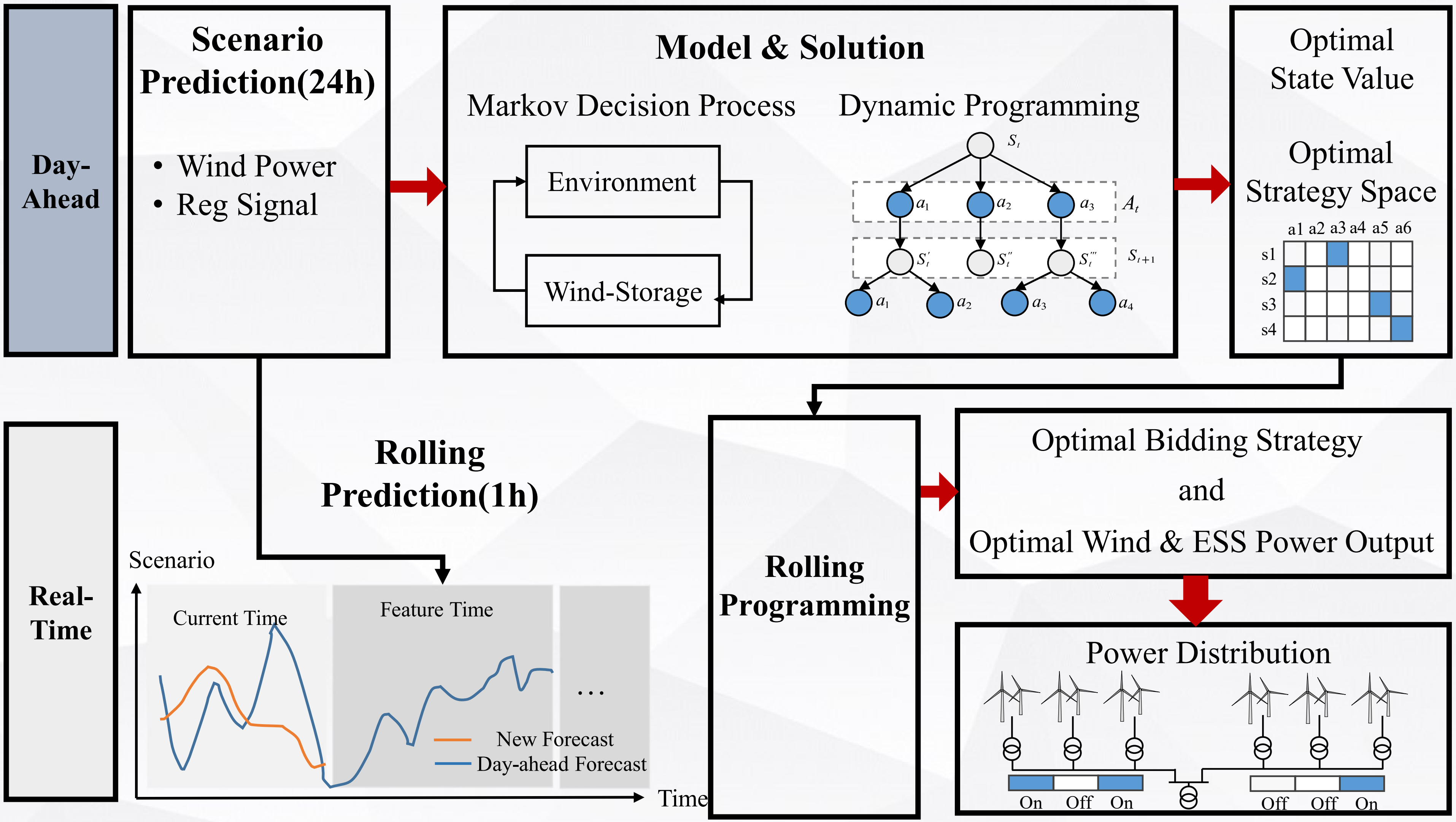
  Calculate new immediate reward $r_{new}(s,a)$

  Do State Transition: $s' \leftarrow s,a$

  $$a_t^* = \arg\max_a Q = [r_{new}(s,a) + V(s')]$$

V(t+1,e), V(t+2,e),...V(24,e) can still reflect the optimal solution when the future scene after t+1 is consistent with the predicted scenario day-ahead

## 3 Solution : Two Stage Coordination Framework



## 4 Case Study: Parameters

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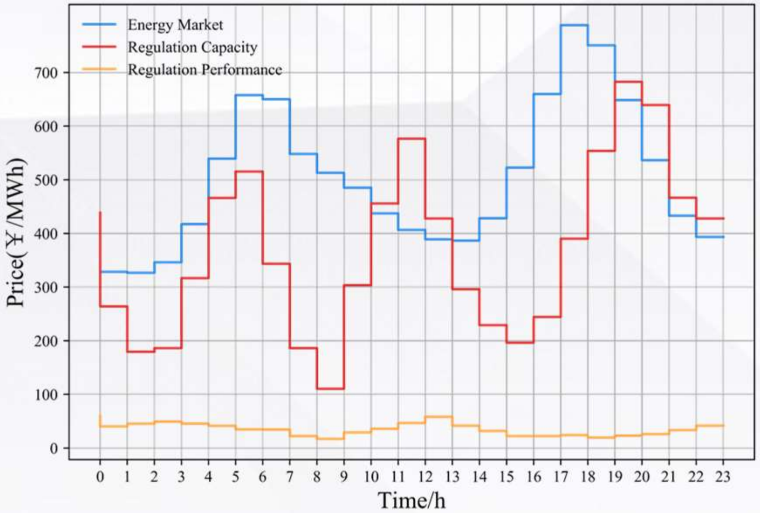
### Market price




### Wind Farm

**Rated capacity:** 30MW (1.5MW*20)

**Climbing rate:** 20% uphill/h, 15% downhill/h

**Purchase cost:** 8,000,000 RMB

**Maximum power of wind power:**from the 2015-01-14 data of wind farm in the western United States.

### Cost of wind turbines

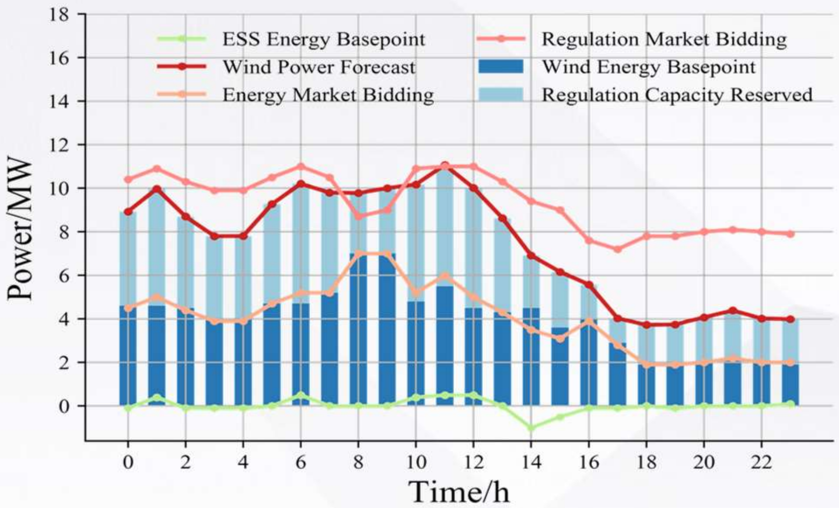
| Work Conditions | Cost (RMB) |
|---|---|
| 0~1400 kW | 0.012/s |
| 1400~1500 kW | 0.025/s |
| Start-up | 0.738/time |
| Shut-down | 0.154/time |

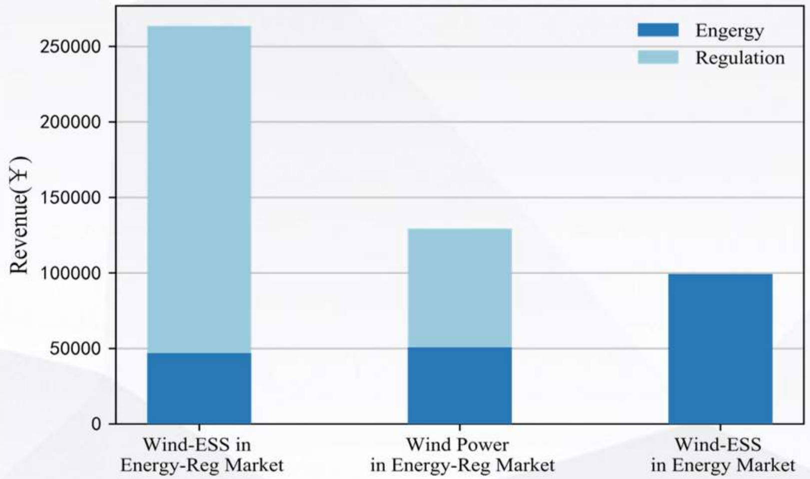
### Energy Storages

**Rated capacity:** 6MW
**Maximum charge-discharge times in 100% DoD:** 5000
**Purchase cost:** 10.8 million RMB
**Efficiency:** 95%

## 4 Case Study: Simulation Results of Daily Revenue

- Wind farm will achieves the **highest revenue** (265717￥) when coupled with ESSs and taking part in this joint energy and frequency regulation market.

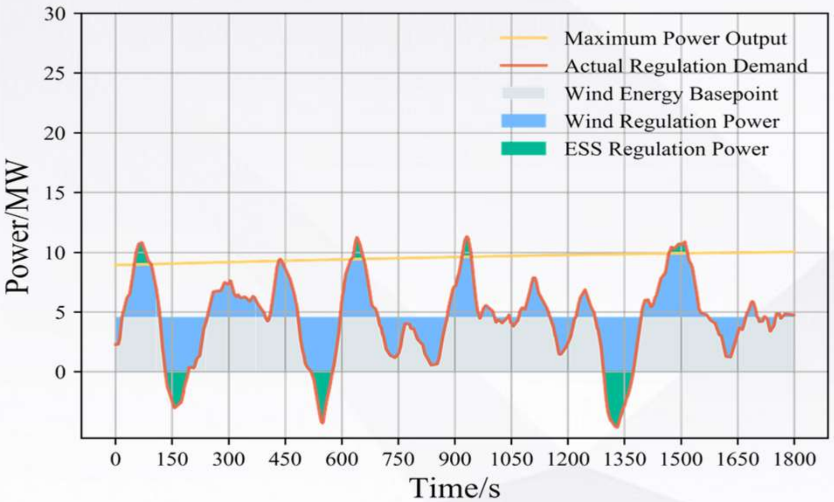


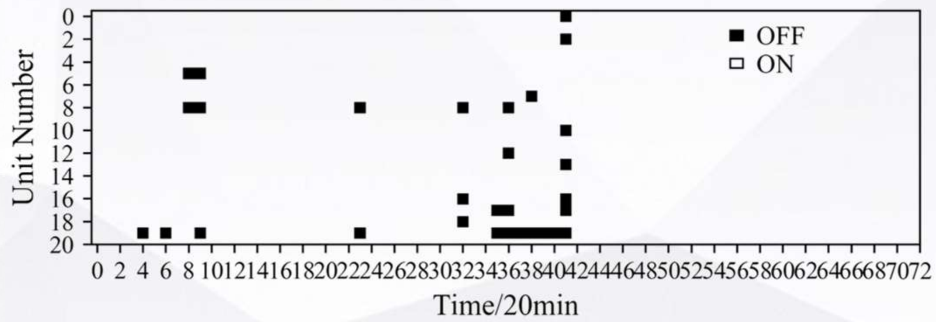

| | Wind-ESSs(￥) | Wind (￥) |
|---|---|---|
| Energy Market | 46830.41 | 50685.96 |
| Regulation Market | 216879.12 | 78597.51 |
| ESSs Cost | 2008.11 | / |
| Total | 265717.64 | 129283.47 |

# 4 Case Study: Simulation Results of Daily Revenue

- By properly shutting down some wind turbines when the full power output is not necessary, the life depreciation and its corresponding costs of these wind turbines can be effectively reduced




Cooperative scheme between wind generators and ESSs to track the regulation signal in one operating hour




The optimized results of the wind turbine start-stop status

# Case Study: Simulation Results of Daily Revenue



- Under the acceleration of jit compiler (Numba) on Python code, the time used by Rolling Programming is only **in seconds**

## Algorithm performance comparison

| Dynamic Programming | Heuristic Algorithm | Rolling Programming |
|---|---|---|
| 24887.1s | 5 min plus | 2.3s |

## Platforms used for this numerical simulation

**3.2 GHz AMD Ryzen processor** + **SCIP Optimizer** + **Python** + **Numba**

5 **Conclusion**

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- Energy storages can effectively **increase the revenue** of the wind farm in the frequency regulation market, especially in terms of regulation capacity revenue
- The Rolling Programming algorithm proposed in this paper provides an effective solution for real-time operation with **reduced computational requirements**, addressing the impact of errors between day-ahead and real-time prediction
- The power allocation and start-stop control scheme proposed for the wind farm can effectively **reduce the wear and tear** on wind turbines, thereby reducing costs.

# THANKS!