An Energy Market with Carbon Emission Allocation Enabling Real-Time Energy Storage Participation

Rui Xie

Postdoctoral Fellow

The Chinese University of Hong Kong

Oct 17, 2023

- Rui Xie, Yue Chen, “Low-carbon operation of power systems with energy storage via electricity-emission prices,” *arXiv preprint arXiv:2307.00207*, 2023.

informs.

Background

Reduce carbon dioxide emissions → mitigate global climate change

However...

- Carbon emissions are produced by fossil fuel power plants, but it is the consumers that create the electricity demand.
- Energy storage (ES) has a near-zero net energy consumption, but it can help reduce system emissions by shifting green energy.

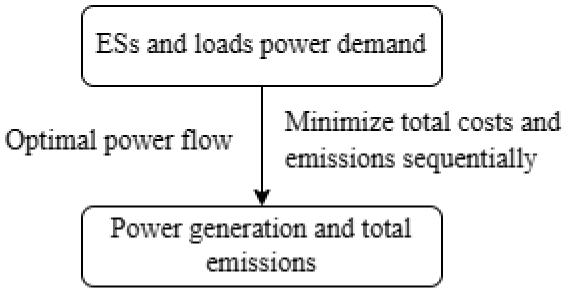
Conventionally…

- Carbon responsibilities are allocated among electric demands by the carbon emission flow (CEF) method.
- CEF may change if virtual buses are added; CEF only depends on the inflows but not outflows, which weakens its ability to encourage ESs to shift green energy.

Hence, a new emission allocation method is needed.

Emission Allocation Based on Aumann-Shapley prices

Power plants take responsibility for half of the emissions.
The other half is allocated to the ESs and loads.



Regard total emission $\mathcal{E}$ as a function of demand vector D

$$\mathcal{E}(D) = \frac{1}{2} \sum_{i \in S_G} \kappa \Psi_i p_i^*(D) \tau$$

Use Aumann-Shapley prices to allocate $\mathcal{E}(D)$

$$\mathcal{E}_i(D^*) = \int_0^{D_i^*} \frac{\partial \mathcal{E}}{\partial D_i} \left(\frac{y}{D_i^*} D^* \right) dy$$

$$\sum_{i \in S_B} \mathcal{E}_i(D^*) = \mathcal{E}(D^*) - \mathcal{E}(0)$$

Impact of demand on total emission

Cost-sharing property

Proposed Algorithm

Every bus has an emission price:

$$\psi_i(D^*) = \frac{\mathcal{E}_i(D^*)}{D_i^* \tau} = \frac{1}{\tau}\int_0^1 \frac{\partial \mathcal{E}}{\partial D_i}(yD^*)\, dy$$

$\mathcal{E}(D) = K^T x$ with x optimal in the linear OPF:

$$\min_{x \geq 0} C^T x$$
$$\text{s.t. } Ax = GD + H$$

Multi-parametric LP

Idea: Along the segment from 0 to D^*, use the optimal basis to calculate $\partial\mathcal{E}/\partial D_i$ and the range of D where this basis remains optimal.

Algorithm 1 Emission Price Calculation

Input: Parameters in (6) and (7); a step paramter $\delta > 0$.

Output: Emission prices $\psi_i, i \in S_B$.

1: Initiation: Calculate A, C, G, H, and K in (11) and $\tilde{D}^*$ by (10). Let $\psi_i \leftarrow 0, \forall i \in S_B$, $m \leftarrow 0$, $y_m \leftarrow 0$.

2: Let $m \leftarrow m+1$. Solve the linear program in (11) with $\tilde{D} = (y_{m-1}+\delta)\tilde{D}^*$ to obtain the optimal basis $A_{B_{m-1}}$ and the corresponding $K_{B_{m-1}}$. Solve (13) and obtain an interval $[y', y'']$. Let $y_m \leftarrow \min\{y'', 1\}$ and

$$\psi_i \leftarrow \psi_i + \frac{1}{\tau}(y_m - y_{m-1})K_{B_{m-1}}^\top A_{B_{m-1}}^{-1} G\omega_i, \; i \in S_B.$$

3: If $y'' \geq 1$, terminate and output $\psi_i, i \in S_B$; otherwise, go to Step 2.

Real-Time ES Bidding

In the proposed energy market with emission allocation, ESs make profits by shifting energy and making use of the fluctuating combined electricity and emission prices.

$$\max_{p_{st}^c, p_{st}^d, e_{st}, \forall t} \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} \mathbb{E}[(\lambda_{st} + \psi_{st})(p_{st}^d - p_{st}^c)\tau]$$

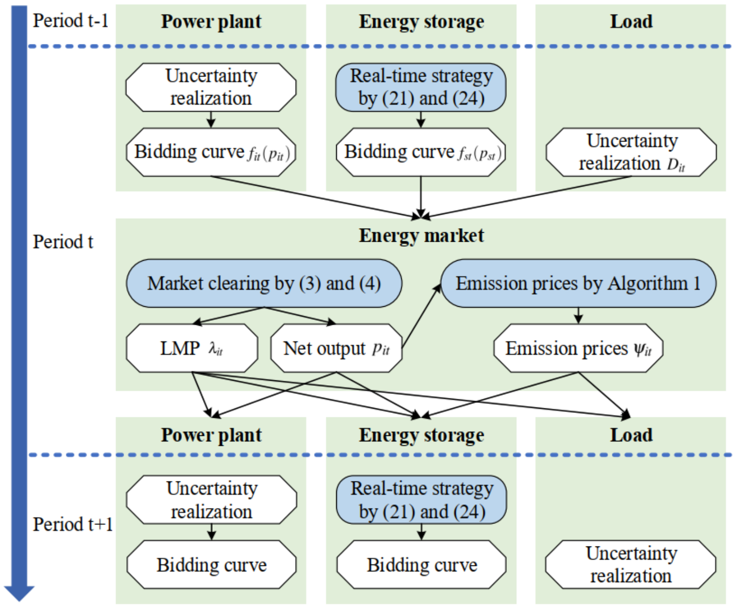
$$\text{s.t. } 0 \le p_{st}^c \le P_s^{max}, 0 \le p_{st}^d \le P_s^{max}, p_{st}^c p_{st}^d = 0, \forall t$$

$$e_{s(t+1)} = e_{st} + p_{st}^c \tau \eta_s^c - \frac{p_{st}^d \tau}{\eta_s^d}, \forall t$$

$$\underline{E}_s \le e_{st} \le \bar{E}_s, \forall t$$

Lyapunov optimization

Minimize drift + one period cost
Feasibility & performance guarantees



Overall procedure

Operation strategy: $p_{st} = h(\lambda_{st} + \psi_{st}, e_{st})$ Future uncertainties are unknown

Power Price SoC

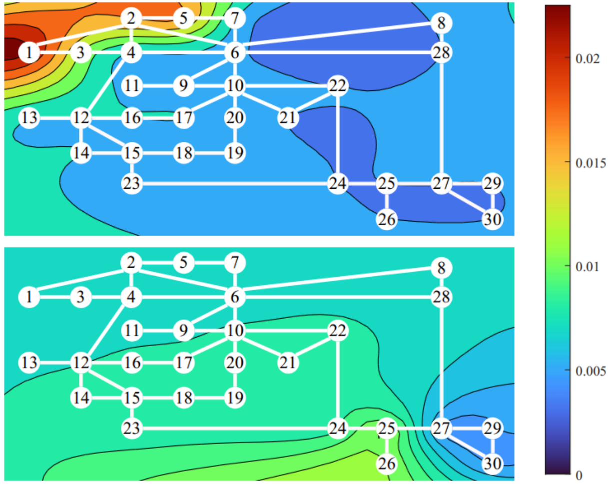
Bidding cost curve: $f_{st}(p_{st}) \triangleq \int_0^{p_{st}} \lambda_{st} dp_{st}$

Then the market clearing result coincides with the operation strategy.

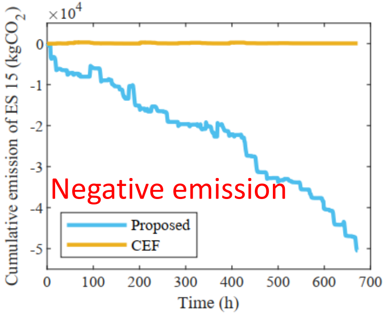
Simulations – vs Conventional Allocation Methods

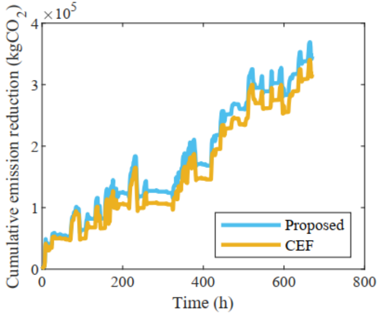
CEF

Proposed



Emission price





The proposed method can measure the impacts of ESs on system emission and then better encourage ESs to help reduce the emissions than the CEF method.

TABLE III
COMPARISON OF DIFFERENT CARBON EMISSION ALLOCATION CALCULATION METHODS

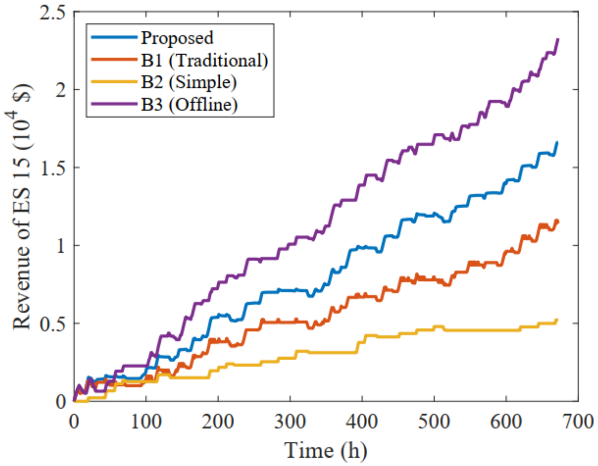
Method	Sample number	Cost-sharing error	Computation Time (s)
C1	100	4.64%	159
C1	1000	3.19%	1680
C2	100	2.74%	6.91
C2	1000	0.02%	107
Proposed	4	0.00%	0.37

The proposed algorithm is faster and more accurate than numerical estimation methods.

Simulations – Impacts of ESs

TABLE II
RESULTS WITH/WITHOUT ESs AND CARBON EMISSION ALLOCATION

Case	Proposed	A1	A2	A3
ESs	✓	✓	×	×
Carbon emission allocation	✓	×	✓	×
Total generation cost ($/h)	3387	3121	3443	3173
Total emission (kgCO_2/h)	30546	53701	31063	54457
Renewable curtailment	1.84%	1.84%	3.25%	3.25%



ESs participation reduces the total cost, emission, and renewable curtailment.
The proposed method decreases the total emissions by 43%.

The proposed real-time ES operation strategy achieves 71% of the offline revenue rate, which is much higher than the traditional Lyapunov optimization-based real-time method.

Thank you!

Email: yuechen@mae.cuhk.edu.hk