Gaming on Coincident Peak Shaving: Equilibrium and Strategic Behavior

------- 6th EEE Graduate Student Symposium

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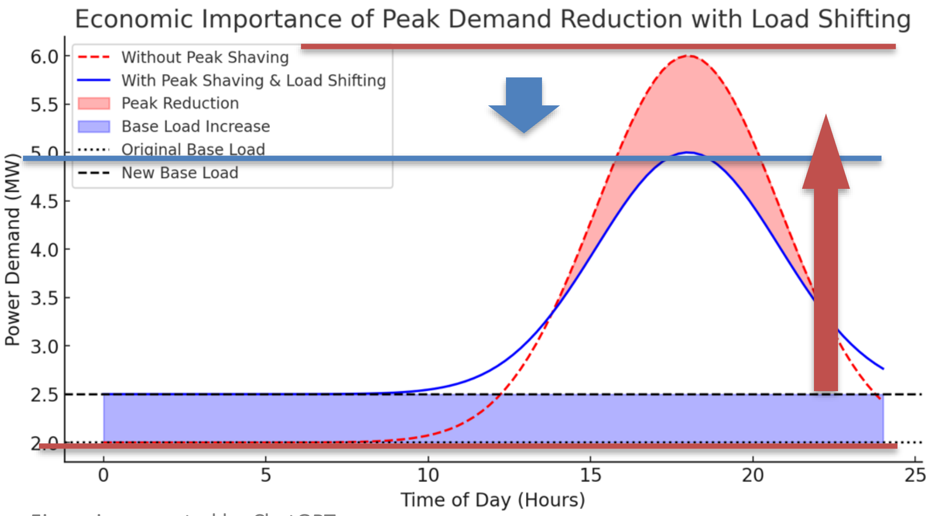
Feb. 7. 2025

What is Coincident Peak Shaving?

Coincident Peak

Why peak demand is important

- Real-time supply-demand balance
- infrastructure investment due to high peak demand
- The largest share of electricity prices comes from infrastructure investment (investment costs, energy generation costs, operational costs, and ancillary services)
- Voltage and frequency instability



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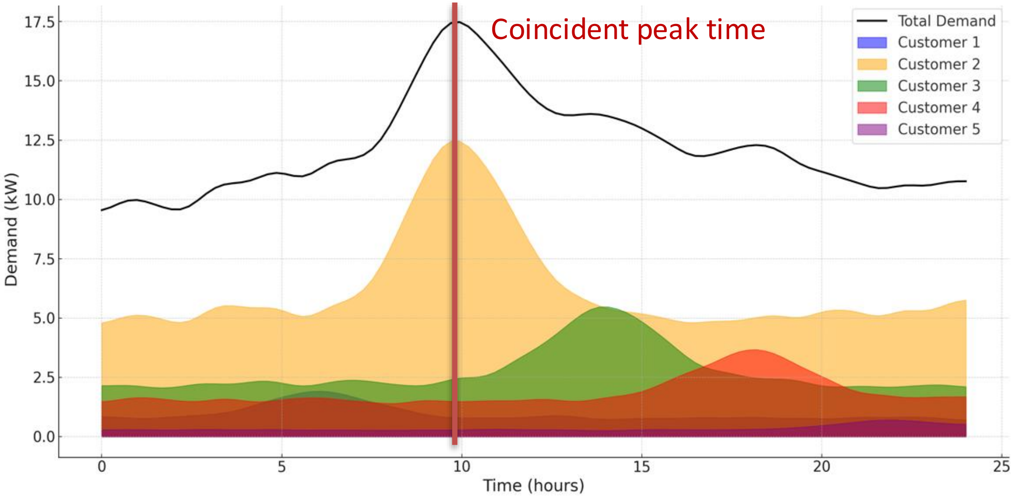
Coincident Peak

Coincident peak (CP) demand charge



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Electricity bill: Energy Charge + peak demand charge

$$C_{\text{energy},i} = \int_{t_1}^{t_2} P(t) \cdot q(i,t)\, dt \;+\; C_{\text{peak},i} = P_{\text{peak}} \cdot \max_t q(i,t)$$

$q(i,t)$ is the demand of customer i at time t

$P(t)$ is the electricity price at time t

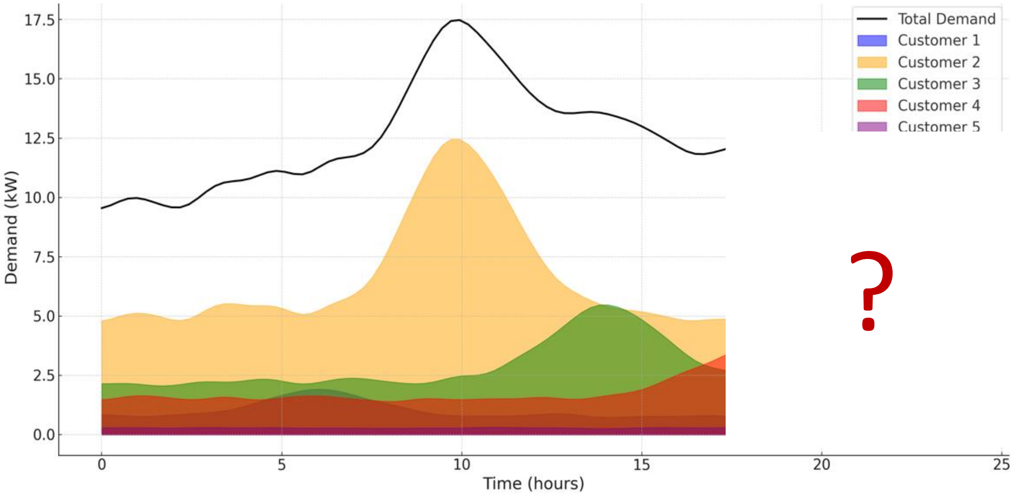
P_{peak} is the peak price at time t

4CP program in Texas: hourly peak in each month over Jun. – Sep., adding the charge to next year's electricity bill

https://www.ercot.com/mktinfo/data_agg/4cp

Research Gap & Motivation

Research gap



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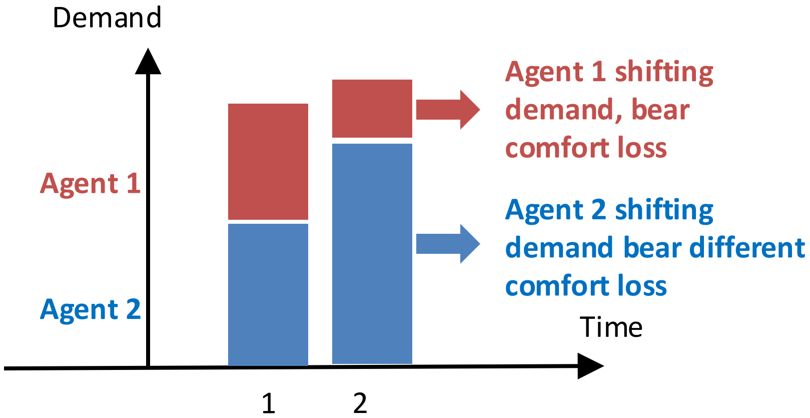
- CP time realized posterior.
- Predicting the CP time individually based on historical data
- Missing the interaction between customers – system peak time depends on all customers' demand consumption
- Motivate a game formulation – never been studied before

- R. Carmona, X. Yang, and C. Zeng, "Coincident peak prediction for capacity and transmission charge reduction," arXiv preprint arXiv:2407.04081, 2024
- C. P. Dowling, D. Kirschen, and B. Zhang, "Coincident peak prediction using a feed-forward neural network," in 2018 IEEE Global Conference on Signal and Information Processing (GlobalSIP). IEEE, 2018, pp. 912–916
- Z. Liu, A. Wierman, Y. Chen, B. Razon, and N. Chen, "Data center demand response: Avoiding the coincident peak via workload shifting and local generation," in Proceedings of the ACM SIGMETRICS/international conference on Measurement and modeling of computer systems, 2013, pp. 341–342

Research Gap & Motivation

Motivation – intuitive analysis



System peak time = 2
Agent 1 peak time = 1
Agent 2 peak time = 2

- Each agent shifts demand between two time periods.
- Variant shifting capacities – different comfort loss and baseline demand conditions.
- Peak time may or may not change during the game
- Peak time change – discrete problem
- Peak time stay– continuous problem.

Research Questions

1

Whether the game-based framework workable for the CP shaving problem?

2

How do gaming consumers' strategic behavior affect the system efficiency

Formulation

Two-agent two-period peak shaving model

Agent *1 - game*

CP charge at period 1

CP charge at period 2

$$\max_x f_x(x,y) = -\pi(X_1+x)I(S_1(x,y)-S_2(x,y)) - \pi(X_2-x)I(S_2(x,y)-S_1(x,y)) - \alpha_x x^2$$

System peak time determination

Shifting penalty

$$I(x) = \begin{cases} 1 & x \geq 0 \\ 0 & x < 0 \end{cases},$$

$$S_1(x,y) = X_1 + Y_1 + x + y = S_{1,0} + x + y,$$

$$S_2(x,y) = X_2 + Y_2 - x - y = S_{2,0} - x - y.$$

X_1, Y_1 is the baseline demand at period 1

x, y is the demand shifting

S_1 is the system demand at period 1

α is the shifting penalty parameter

Centralized

$$\{x^*, y^*\} \in \arg\max_{x,y} f_x(x,y) + f_y(x,y),$$

Main results

Does the game framework workable?

Does Nash Equilibrium exist, unique, stable, and reachable?

Theorem – NE under two-agent two-period setting (informal)

Under two agent settings, the CP game could be concave, quasiconcave/discontinuous, non-concave/discontinuous (determined by parameters), all types of game have unique pure-strategy NE

Theorem – Stable NE (informal)

The CP game system is global uniform asymptotically stable if all agents' demand shifting is within the baseline limit. (Denoting system dynamics following the gradient of each agent's payoff function)

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Main results

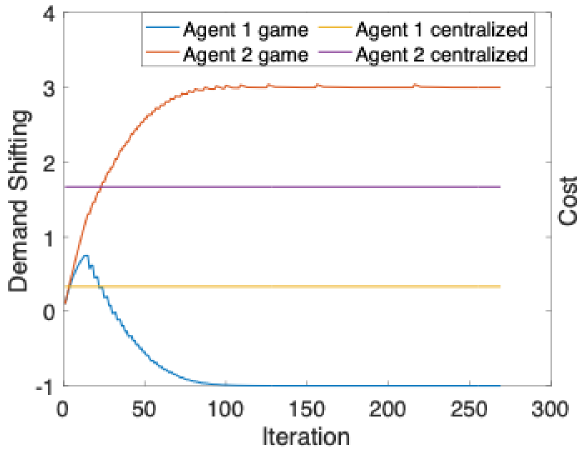
Does the game framework workable?

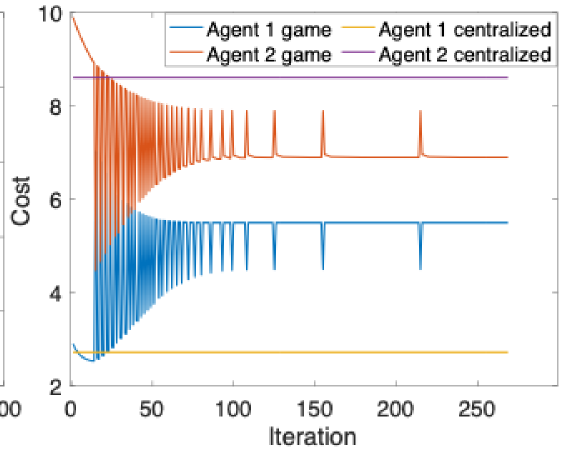
Does Nash Equilibrium exist, unique, stable, reachable?

Theorem – algorithm convergence (informal)

Gradient-based algorithms can converge, if use an updating rule from the finite difference approximation to the system dynamics. (learning rate chosen from backtracking line search)

$$x_{h+1} = x_h + \tau_h F_j(x_h), j = 1, 2,$$





The results can also be extended to a multi-agent setting, two agents need to change to two sets of agents

Game framework is workable

Main results

What is the performance of the game model?

Price of anarchy (PoA) vs. peak shaving effectiveness

Theorem – peak shaving effectiveness (informal)

In all conditions (two-agent, multi-agent, all types of game), the peak shaving effectiveness of the game model is always the same as the centralized model.

Key takeaway

Helpful for operators when applying the game model, care more about peak shaving, and the costs are collected from the consumers 😅.

What is the cost performance?

Hint: both centralized and game models flatten the demand or shift the same amount of demand

$$\{x^*, y^*\} \in \arg\max_{x,y} f_{\mathrm{x}}(x, y) + f_{\mathrm{y}}(x, y),$$

Main results

What is the performance of the game model?

$$P = \frac{\text{Game payment}}{\text{Centralized payment}} = \frac{f_x(x^*, y^*) + f_y(x^*, y^*)}{f_x(x^*_{cen}, y^*_{cen}) + f_y(x^*_{cen}, y^*_{cen})}$$

Price of anarchy (PoA) vs. peak shaving effectiveness

Theorem – PoA with agent equity (informal)

Under two-agent settings, the PoA (*P*) increases with inequity among agents, as measured by the marginal shifting cost

$$\frac{\partial P}{\partial[(\alpha_x x^* - \alpha_y y^*)^2]} > 0$$

Marginal shifting cost

Theorem – PoA with game type (informal)

Under two-agent settings, fixed system conditions (system total demand, peak charge price)

$$P(\text{Quasiconcave game}) \geq P(\text{Non-concave game}) \geq P(\text{Concave game}) = 1$$

Agent flexibility reduce
- Higher shifting penalty parameter
- Less demand

Key takeaway

- **CP shaving mechanisms can consider effectiveness and fairness together – balance agents' marginal shifting cost.**
- **Greater agent flexibility amplifies system inefficiency.**
- **Concave game equivalent to centralized model**

Main results

Extension to multi-agent two-period setting

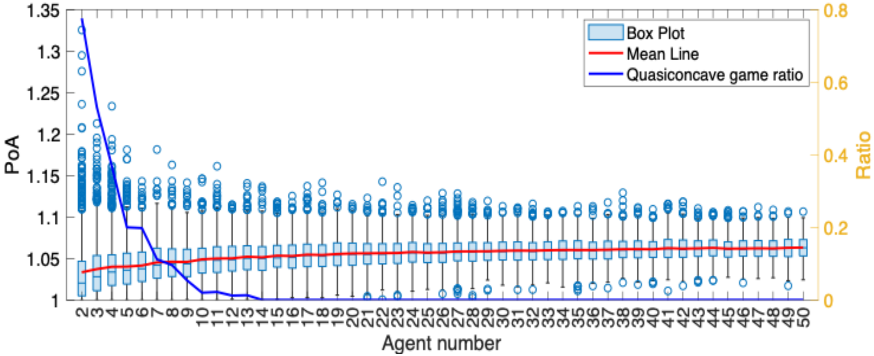
Price of anarchy (PoA) vs. peak shaving effectiveness

Remark – PoA with agent number (informal)

With agent number increase, game types are more likely to be non-concave games, and PoA becomes stable.

Key takeaway

- **PoA of a small system is more sensitive to the agents' flexibility (game type);**
- **PoA of a large system is stable and can diminish flexible agent's influence**



Interpretation and Conclusion

Implications

- We formulate a new game framework for the CP shaving problem
- We analytically show the game's properties, including NE existence, uniqueness, stability, and convergence under the two-agent two-period setting
- We analyze gaming agents ' strategic behavior regarding system economic performance and peak shaving effectiveness.
- We also generalized our finding to the multi-agent setting.

Takeaway

For industry practitioners and policymakers

- One can adopt the game model without concerns about its impact on CP shaving effectiveness.
- One can design targeted incentive mechanisms aimed at balancing flexibility across agents.
- One can build larger gaming systems for flexible agents while leaving inflexible agents to form small gaming systems.

Thanks!

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Q&A

For all details, please reference to - https://arxiv.org/abs/2501.02792