Time Is Money: The Social Benefits of Time-of-use Tariffs

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Introduction

- Efficiency loss in the electricity retail market:
  - Generation cost changes in real time with varying demand and renewables.
  - Consumers (mostly) pay a flat rate.
- First-best option: real-time electricity price
  - Price reflects generation cost.
  - Cognitively costly.
- Second-best option: time-of-use tariff (TOU tariff)
  - Prices varying in different periods of the day.
  - Prices are the same in the same periods across days.

Background and Research Questions

▶ China's time-of-use tariffs started in 2003, since then:

- Coverage: from large I&C users to all I&C users
- Peak/shoulder/off-peak ratio: becoming wider
- Pricing periods: re-designed based upon (residual) load

▶ Research questions

I. Do I&C users respond to TOU tariff?

II. What's the social benefits of TOU tariff?

III. How to design the optimal TOU tariff?

Contributions

I. Do I&C users respond to TOU tariff?

- Conventional econometric estimation vs Machine learning counterfactual predict estimation
- Consistent results and precisely identified

II. What's the social benefits of TOU tariff?

- We develop a generic method to assess the social benefits from policy, technological, climate shocks.
- Using this method, we estimate the social benefits of TOU tariffs

III. How to design the optimal TOU tariffs?

- 98% of social benefits of TOU tariff come from the saved capacity investment
- Low policy costs, high social benefits

TOU Tariff in Guangdong, China

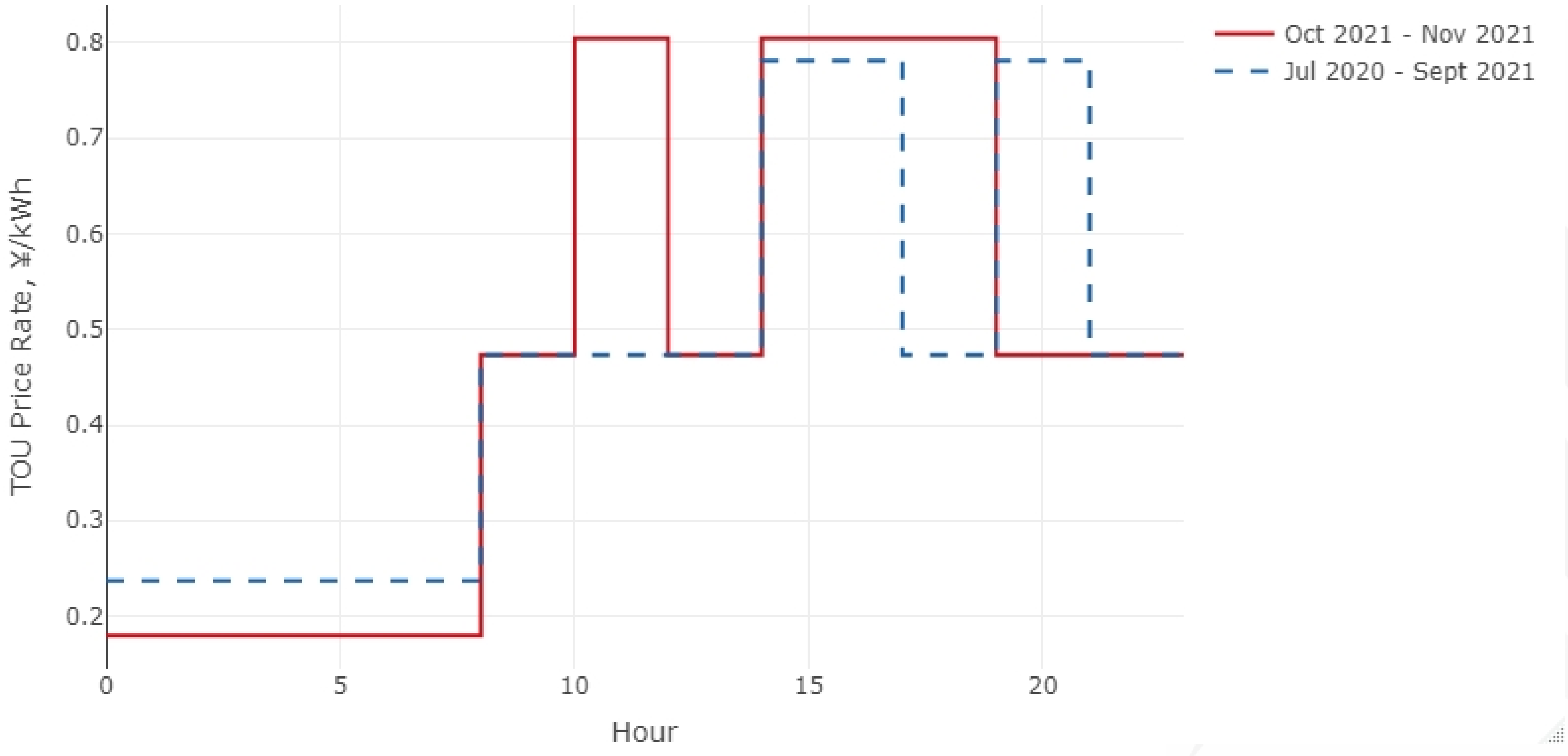

Figure 1: TOU periods and rates in Guangzhou

I. Do I&C users respond to TOU tariff?

- Guangdong as an example: substitution effect *v.s.* conservation effect

- Estimation substitution effect using conventional econometric method:

$$\frac{q_{d,i,m}}{\bar{q}_{d,\mathrm{BM}}} = \beta_{0,i} + \beta_{1,i}\frac{p_{d,i,m}}{\bar{p}_{d,\mathrm{BM}}} + \sum_{k=2}^{K} \beta_{k,i} X_{k,d,i,m} + \varepsilon_{d,i,m}, \quad \forall i.$$

  - Baseline regression: excluding control variables
  - Robust check 1: *add* time fixed effect
  - Robust check 2: *add* time fixed effect *add* weather and Covid variables
  - Robust check 3: *add* time fixed effect *add* weather and Covid variables *remove* first year data

I. Do I&C users respond to TOU tariff?

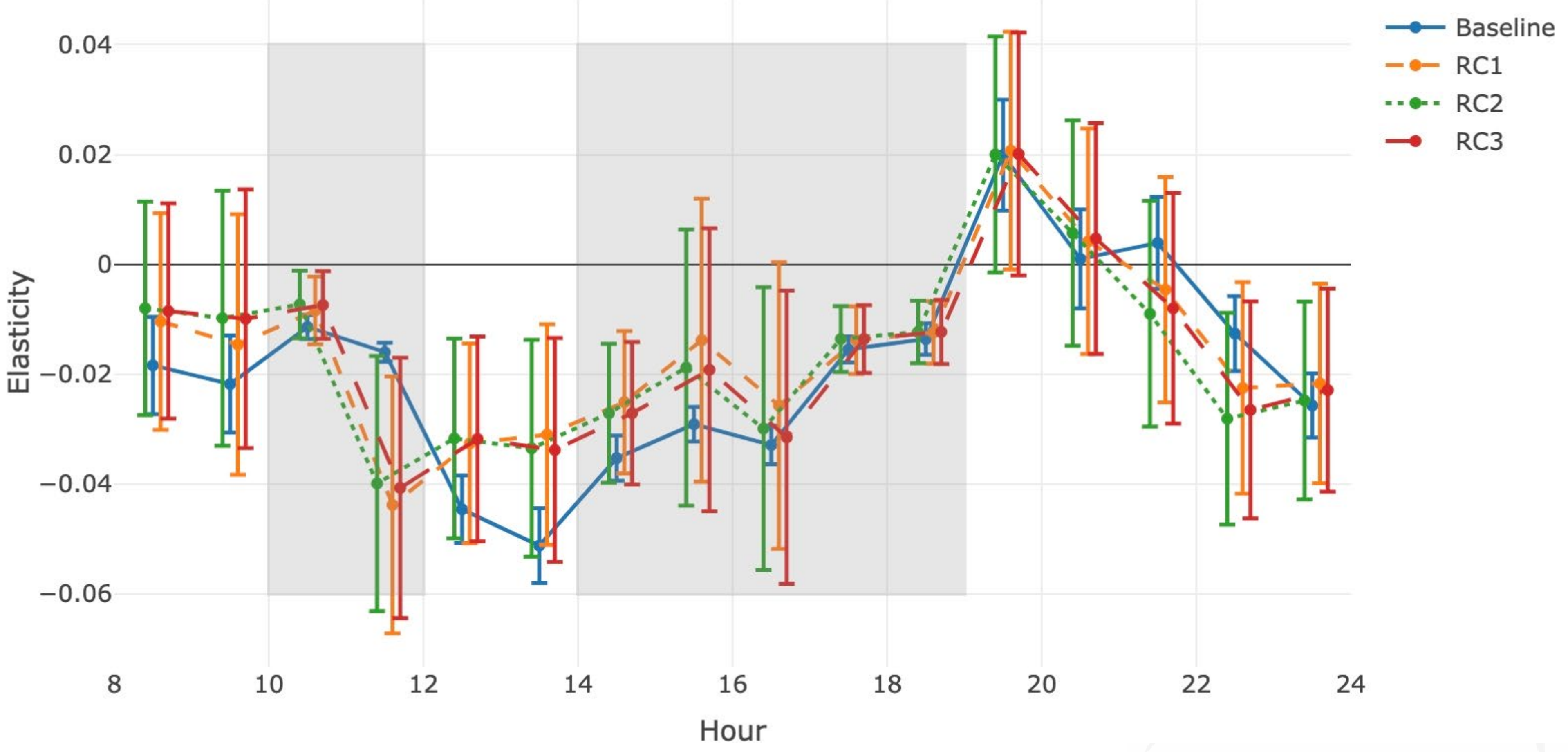

Figure 2: Estimation Result of Substitution Effect (Econometric Method)

I. Do I&C users respond to TOU tariff?

- Estimation substitution effect using ML CF Pred. Est. :
  - XGBoost
  - Using electricity load before the policy change (Oct 2019-Sep 2021) to
  - Predict the counterfactual load if there was no policy change — the pseudo control group (Oct. 2021-Sep. 2022)
  - Use the actual electricity load following the policy change as the treatment group (Oct. 2021-Sep. 2022)
  - Estimation the treatment effect between the treatment group and the pseudo control group using econometric method

I. Do I&C users respond to TOU tariff?

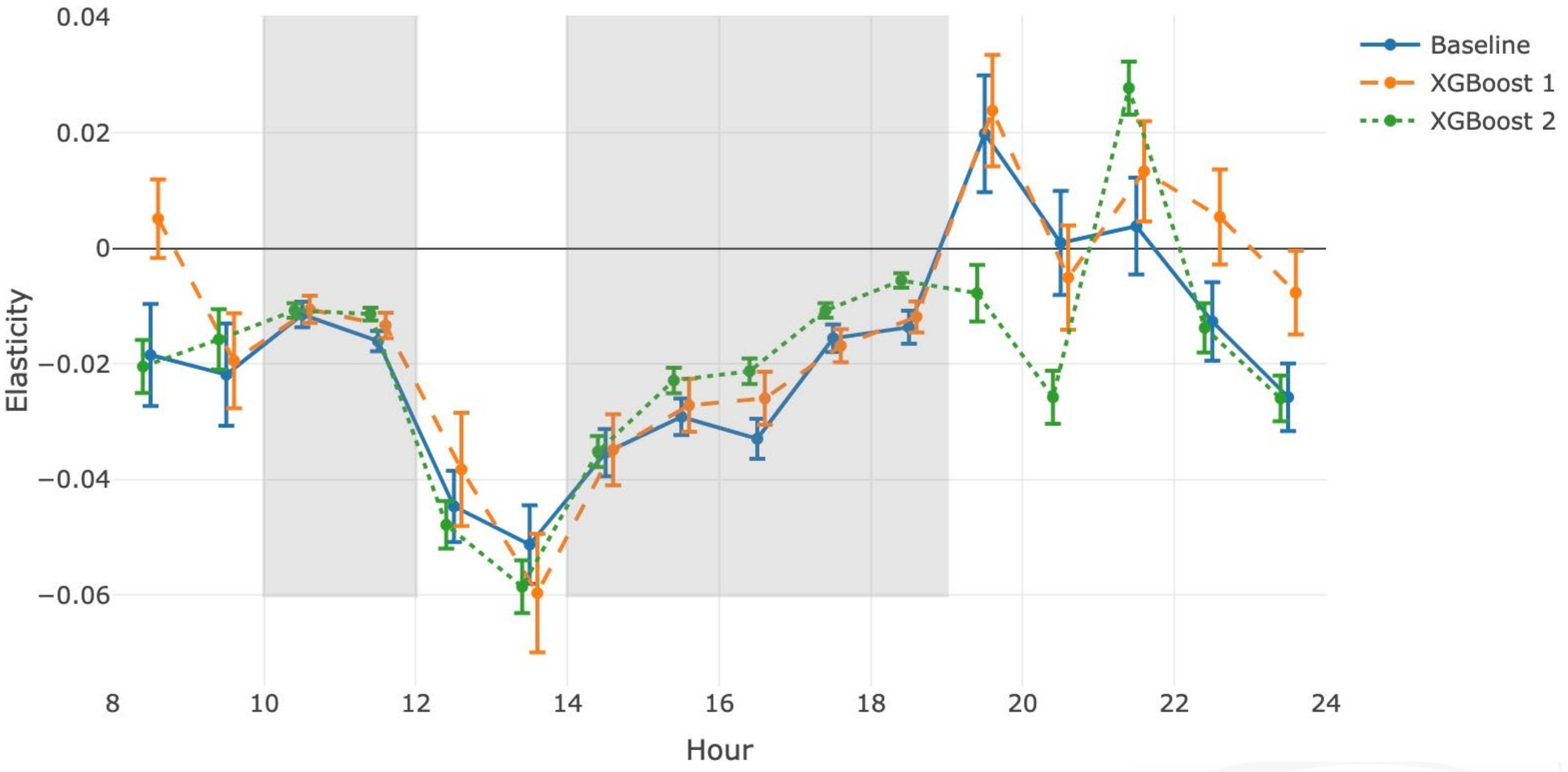

Figure 3: Estimation Result of Substitution Effect (ML Method)

I. Do I&C users respond to TOU tariff?

- Estimating conservation effect using traditional econometric method:

$$\ln Q_d = \theta_0 + \theta_1 \ln \bar{p}_d + \sum_{j=1}^{J} \theta_j X_{j,d} + e_d.$$

Table 1: Estimation Results of Conservation Effect (Econometric Method)

	(1)	**(2)**	**(3)**	**(4)**
	OLS	IV	IV	IV
$\ln\bar{P}_d$	-0.276*	0.293	0.129	0.145
	(0.111)	(0.434)	(0.287)	(0.285)
Instrument		MCP	Coal	MCP+Coal
Weak Instrument		0.000	0.000	0.000
Wu-Hausman		0.093	0.033	0.026
Over-identification				0.636

I. Do I&C users respond to TOU tariff?

- Estimating conservation effect using traditional ML method:

Table 2: Estimation Results of Conservation Effect (ML Method)

	XGBoost 1		XGBoost 2	
	(5)	(6)	(7)	(8)
	OLS	IV	OLS	IV
$\ln\bar{P}_d$	0.073	0.007	-0.063	0.483
	(0.152)	(0.396)	(0.157)	(0.416)
Instrument		MCP+Coal		MCP+Coal
Num. obs.	365	365	365	365
R-squared	0.229	0.229	0.033	0.000

II. What's the social benefits of TOU tariff?

- Compare three scenarios: flat tariff, TOU tariff (before policy change) and TOU tariff (after policy change)
  - Using the estimated substitution effect and conservation effect
- Our generic method to estimate the social benefits
  - Generation fuel cost: fuel cost of the marginal plants
  - Emission cost: the marginal emission of electricity generation and the social cost of carbon (SCC)
  - Capacity investment cost: reduction of maximum load and investment cost of capacity
  - Congestion cost: the difference among the nodal prices
  - Ancillary cost: the price and load differences between day-ahead and real-time markets
- Sensitivity analysis: assuming all estimates follow normal distributions, repeated 500 times

II. What's the social benefits of TOU tariff?

Table 3: The Social Benefits of TOU Tariff (Compared to Flat Tariff) , Billion RMB

Saved costs	**10/2019-09/2020**		**10/2020-09/2021**		**10/2021-09/2022**	
	PRE	POST	PRE	POST	PRE	POST
Generation	0.043	0.091	0.080	0.169	0.108	0.229
	(0.010)	(0.013)	(0.017)	(0.022)	(0.022)	(0.031)
Emission	-0.002	-0.004	-0.004	-0.009	-0.005	-0.010
	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Investment	6.813	9.269	7.334	9.386	7.060	10.123
	(0.649)	(0.770)	(0.706)	(0.736)	(0.701)	(0.838)
Congestion	0.050	0.069	0.047	0.123	0.016	0.072
	(0.003)	(0.004)	(0.004)	(0.006)	(0.005)	(0.005)
Ancillary Service	0.030	0.041	0.027	0.065	-0.002	0.024
	(0.002)	(0.002)	(0.004)	(0.007)	(0.003)	(0.003)
Total	6.934	9.466	7.484	9.734	7.177	10.438
	(0.652)	(0.774)	(0.709)	(0.741)	(0.699)	(0.844)

III. How to design the optimal TOU tariff?

- The “optimal” pricing periods

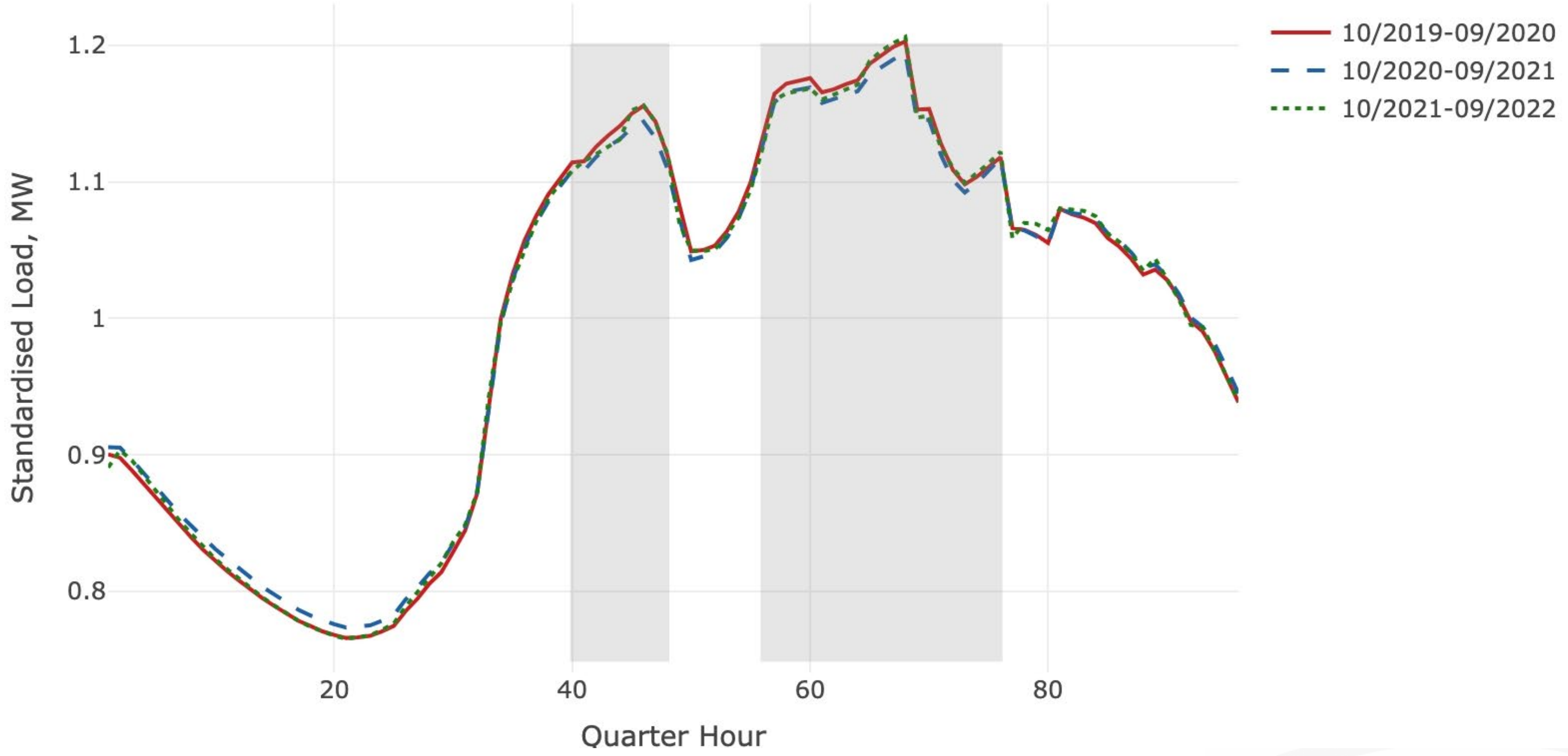

Figure 4: The Electricity Load Curve under Flat Tariff

III. How to design the optimal TOU tariff?

- The "optimal" PSO Ratios: calculate the social benefits under all possible combinations.
- The Optimal PSO ratios simulated by maximizing total social benefits is exactly the same as by simply minimizing capacity investment costs.
- Low policy costs, high social benefits

Table 4: The Social Benefits under the "Optimal" TOU rate, Billion RMB

	1st Year	2nd Year	3rd Year	3-year Ave.
Optimal PSO Ratios	2:1:0.27	1.83:1:0.27	1.96:1:0.27	1.96:1:0.27
Optimal Social Benefits	12.772	13.210	16.650	14.062
Actual Social Benefits	6.934	7.484	10.438	8.285
Potential Improvements	84.2%	76.5%	59.5%	69.7%

Conclusions

- The substitution effect of TOU tariffs is significant while the conservation effect is not.
- From 10/2019 to 09/2022, the social benefits of TOU tariffs equal to 4.5% of generation costs in Guangdong, China.
- The social benefits can be raised to 7.6% from the "optimal" PSO ratios.
- 98% of the benefits come from the saved capacity investment.
- Our methodology is generic to a variety types of shocks in the electricity industry — especially when shock changes the (residual) electricity load.