Incentive Compatibility for Power System Planning

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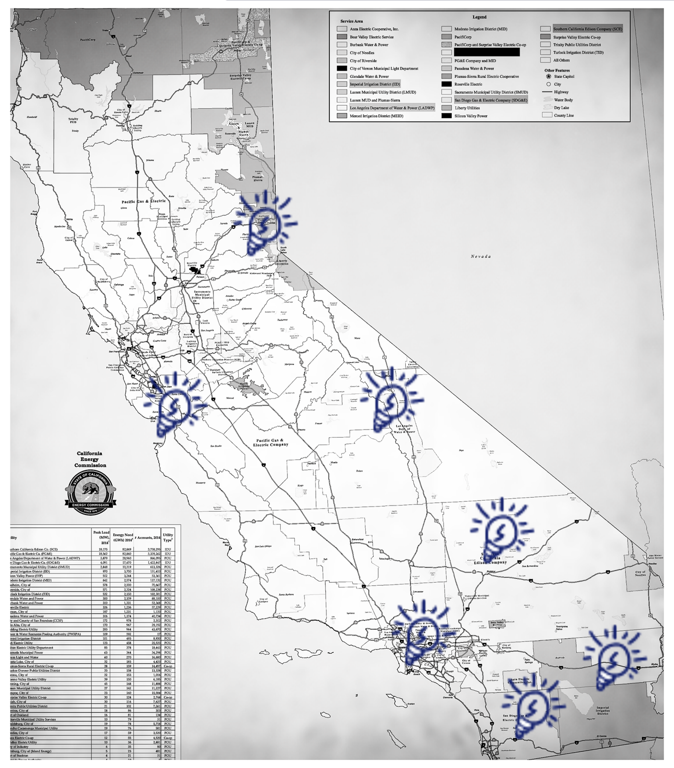
BACKGROUND

Power System Planning

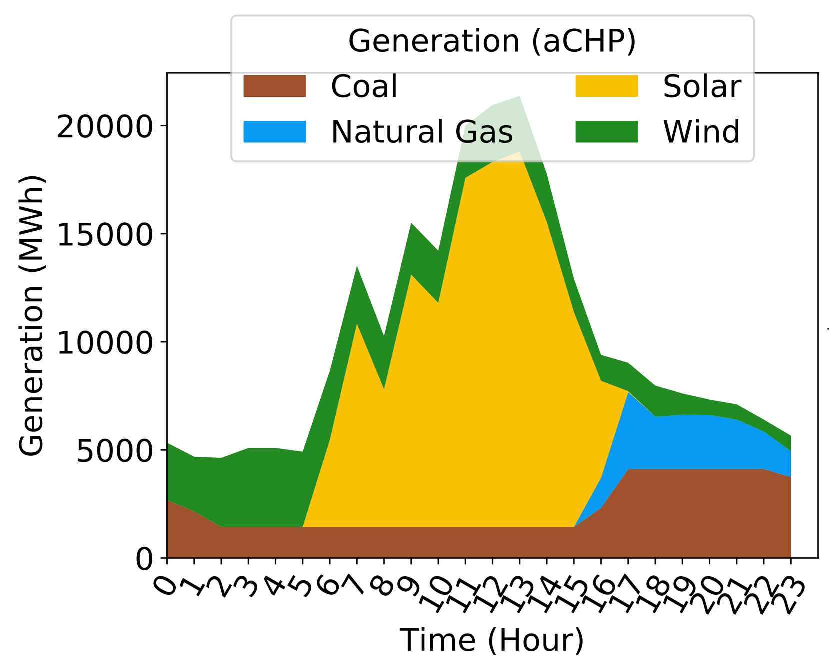


- A power grid is a network connecting producers and consumers
- Power system planning integrates new elements into the power grid
- Our work focuses on new generators

Our Goals

- ✓ Satisfy peak load in a future year
- ✓ Ensure incentive compatibility of generators
  - Produce electricity
  - Invest in new generators

Unit Commitment (UC) Problem



For each hour decide:

- Production unit states
- Production levels

Variables:

- $u_g \rightarrow$ startup decisions
- $p_g \rightarrow$ power output levels
- $d \rightarrow$ electricity load
- $\mathcal{X}_g \rightarrow$ commitment and production constraints

$$\min_{u,p} \sum_{g\in\mathcal{G}} f(u_g, p_g)$$
$$\text{s.t.} \sum_{g\in\mathcal{G}} p_g = d$$
$$(u_g, p_g) \in \mathcal{X}_g \quad \forall g \in \mathcal{G}$$

Electricity Price: aCHP

- We use approximated convex hull price (aCHP)
- Solve LP relaxation of the UC problem $\rightarrow$ obtain the shadow price of the load constraint $\sum_{g\in\mathcal{G}} p_g = d$

Revenue Adequacy In the Literature

- Martin et al. [2010] uses cutting planes to eliminate non-profitable solutions
- Ruiz et al. [2012] derives revenue adequate prices using a primal-dual model
- Dvorkin et al. [2017] uses a two-stage model to ensure profitability of the energy storage investment
- ★ **Our contribution**: Ensuring profitability in generation expansion

MODEL

Overview

Minimize:
- Investment Cost + 2nd Stage Duality Gap

Subject to:
- 1st Stage Constraints (Investment Decisions)
- 2nd Stage MIP Primal Constraints (UC Decisions)
- 2nd Stage LP Dual Constraints (Pricing Decisions)
- 2nd Stage Complementarity Constraints (Profitability Requirements)

▶ In the objective, we minimize the duality gap to be close to the market equilibrium

▶ 2nd stage MIP primal constraints include traditional UC constraints, such as load constraints, reserve constraints, etc.

▶ 2nd stage LP dual constraints contain dual variables for the electricity prices and reserve prices

A Mixed Integer Bilinear Program

Our model is a large-scale Mixed Integer Bilinear Program

- Contain binary variables for investment and commitment decisions
- Both LP dual constraints and complementarity constraints have bilinear terms:

◇ In LP dual constraints:

$$\begin{aligned} DOC = \sum_{d\in\mathcal{D}}\sum_{t\in\mathcal{T}} \Big(& D_{dt}\lambda_{dt} + F^{\text{Spin}} D_{dt}\varrho^{\text{Spin}}_{dt} + F^{\text{Op}} D_{dt}\varrho^{\text{Op}}_{dt} + \sum_{g\in\mathcal{G}^{\text{Ther}}} (-R^{\text{Up}}_g \beta^{\text{RU}}_{gdt} \\ & - R^{\text{Down}}_g \beta^{\text{RD}}_{gdt} - \upsilon_{gdt} - \nu_{gdt}) + \sum_{g\in\mathcal{G}^O\cap\mathcal{G}^{\text{Ther}}} (-\zeta_{gdt} - \xi_{gdt}) \\ & + \sum_{g\in\mathcal{G}^N\cap\mathcal{G}^{\text{Ther}}} (-P^{\max}_g w_g(\pi_{gdt} + \pi^{\text{Spin}}_{gdt} + \pi^{\text{QS}}_{gdt}) - w_g\zeta_{gdt} - w_g\xi_{gdt}) \\ & + \sum_{g\in\mathcal{G}^O\cap\mathcal{G}^{\text{Renew}}} F^{\text{CF}}_{gdt} P^{\max}_g \alpha^{\text{Renew}}_{gdt} + \sum_{g\in\mathcal{G}^N\cap\mathcal{G}^{\text{Renew}}} F^{\text{CF}}_{gdt} p^{\text{Renew}}_g \alpha^{\text{Renew}}_{gdt} \Big) \end{aligned}$$

◇ In complementary constraints:

$$\overbrace{\sum_{d\in\mathcal{D}}\sum_{t\in\mathcal{T}} (\lambda_{dt} p^{Gen}_{gdt} + (\varrho^{\text{Spin}}_{dt} + \varrho^{\text{Op}}_{dt}) p^{\text{Spin}}_{gdt} + \varrho^{\text{Op}}_{dt} p^{\text{QS}}_{gdt})}^{\text{Revenue}} \geq$$
$$\underbrace{\sum_{d\in\mathcal{D}}\sum_{t\in\mathcal{T}} (C^{VOM}_g + C^{\text{Fuel}}_g) p^{Gen}_{gdt} + \sum_{d\in\mathcal{D}}\sum_{t\in\mathcal{T}} C^{\text{Startup}}_{gt} u_{gdt} + \frac{C^{FOM}_g |\mathcal{D}|}{365}}_{\text{Cost}}$$

◇ Definition and type of some variables:

- $w_g \in \{0,1\}$: investment decisions for thermal generators
- $p^{\text{Renew}}_g \geq 0$: investment decisions for renewable generators
- $\pi_{gdt}, \pi^{\text{Spin}}_{gdt}, \pi^{\text{Op}}_{gdt}, \zeta_{gdt}, \xi_{gdt} \geq 0, \alpha^{\text{Renew}}_{gdt}$: dual variables
- $p^{\text{Gen}}_{gdt}, p^{\text{Spin}}_{gdt}, p^{\text{QS}}_{gdt} \geq 0$: production/reserve levels
- $\lambda_{dt}, \varrho^{\text{Spin}}_{dt}, \varrho^{\text{Op}}_{dt} \geq 0$: electricity/reserve prices

SOLUTION METHODS

Discretization

- Similar technique as Dvorkin et al. [2017]
- Linearize by discretizing the dual variables in bilinear terms
- ☹ Restrict the original problem
- ☹ Add many binary variables, size grows very quickly

Other Options

- Generalized Benders decomposition (Geoffrion, 1972)
- Global optimization algorithm (Floudas and Visweswaran, 1993)
- Commercial solvers

PRELIMINARY EXPERIMENTAL RESULTS

Data

☼ Data from California Independent Operator (CAISO)

Instance	nOldTher	nNewTher	nOldRenew	nNewRenew	nDay
SmallInst	4	4	4	4	1
MedInst	52	20	4	4	1

Computational Performance

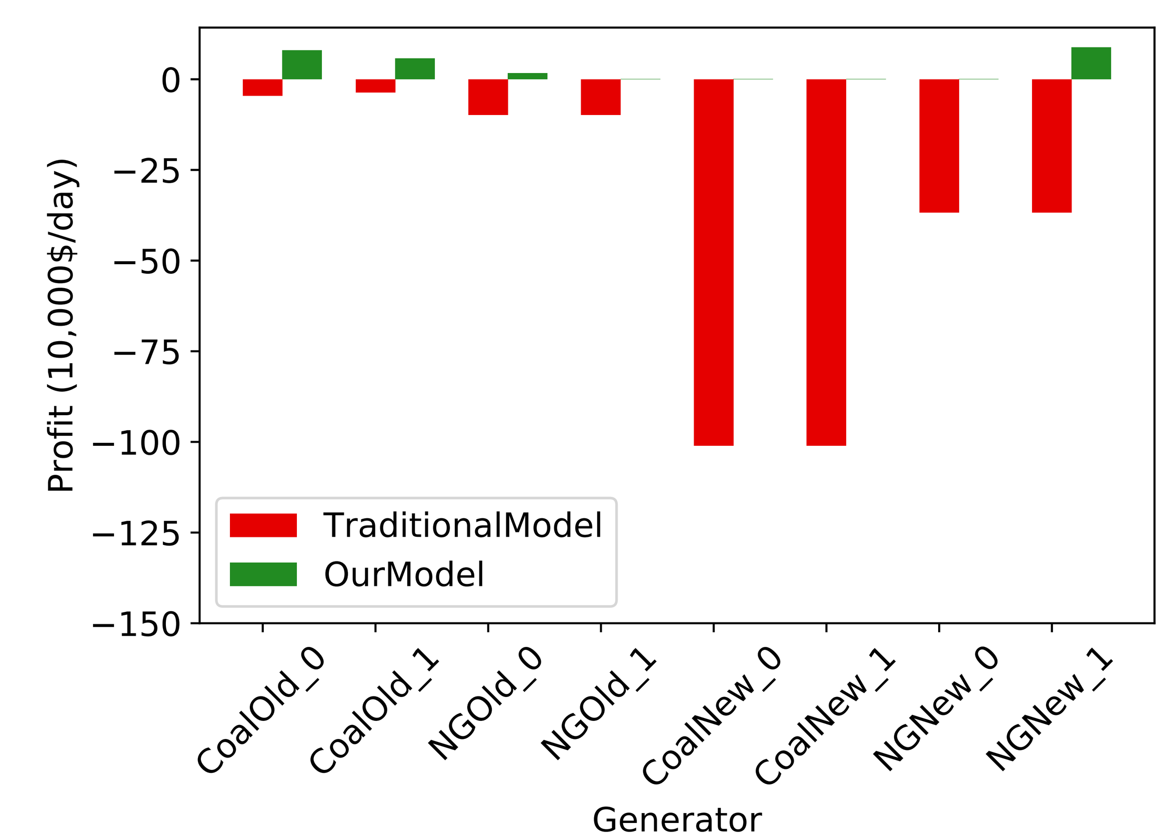
Instance	Time/Gap OurModel	Time/Gap TraditionalModel
SmallInst	11%	0.50 sec
MedInst	-	1.06 sec

- Time Limit: 30 minutes
- - : Fails to find a feasible solution

⇒ Our model is solved via discretization

⇒ Discretization increases the size of our model significantly, making it computationally hard

Profitability of Thermal Generators



⇒ Experimented on SmallInst

⇒ In traditional model all generators are non-profitable

★ Our model is incentive compatible

Ongoing Work

- Looking for better algorithms to make our model practical
- Incorporate energy storage/capacity market