A principal-agent model of aggregators and prosumers

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Distributed energy resources

How should distributed energy resources (DERs) be incorporated into electricity markets?

DERs: Small-scale resources located at end-consumer level

- Rooftop solar
- Electric vehicles
- Batteries

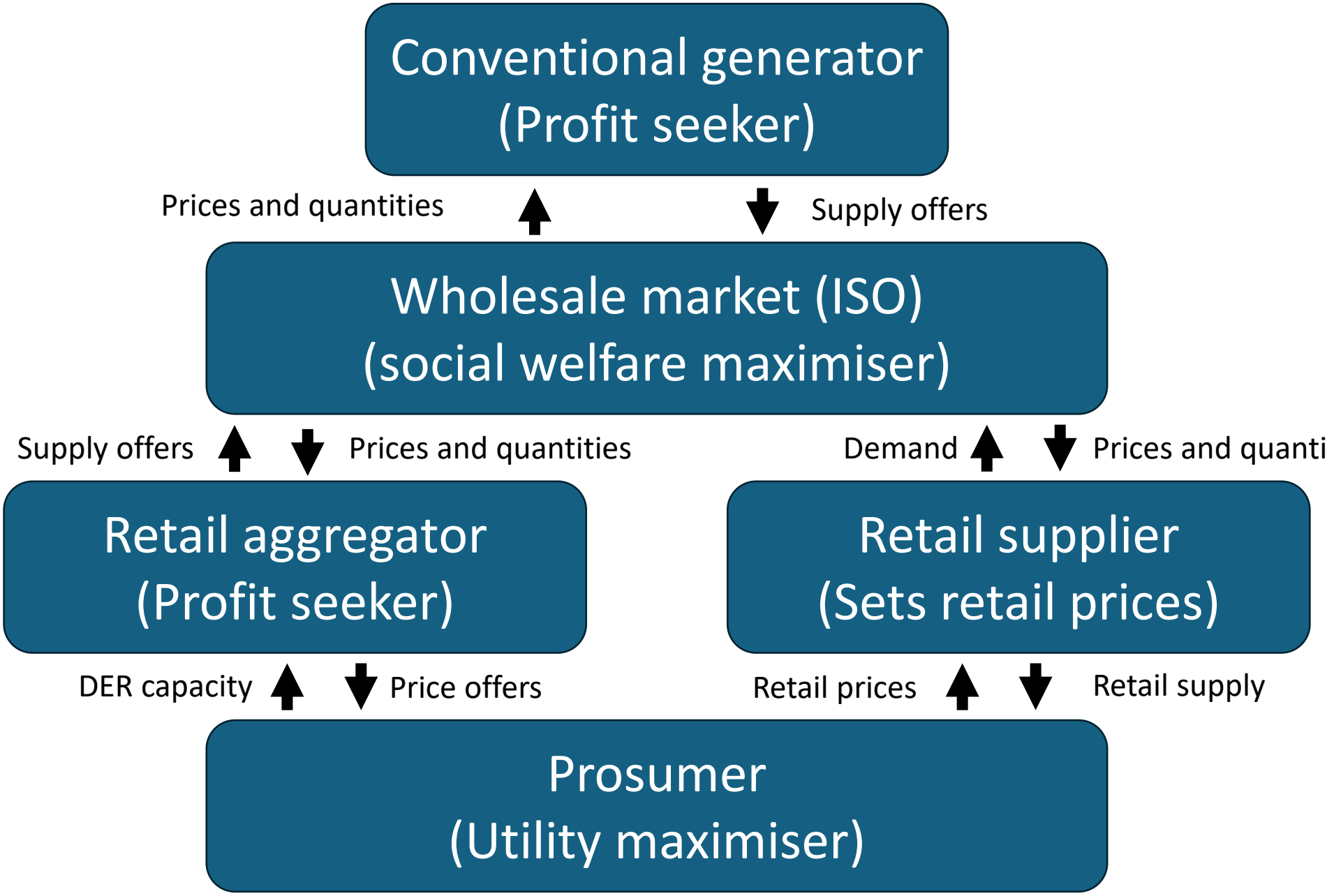
DERs mean end consumers are both producers and consumers or **prosumers**

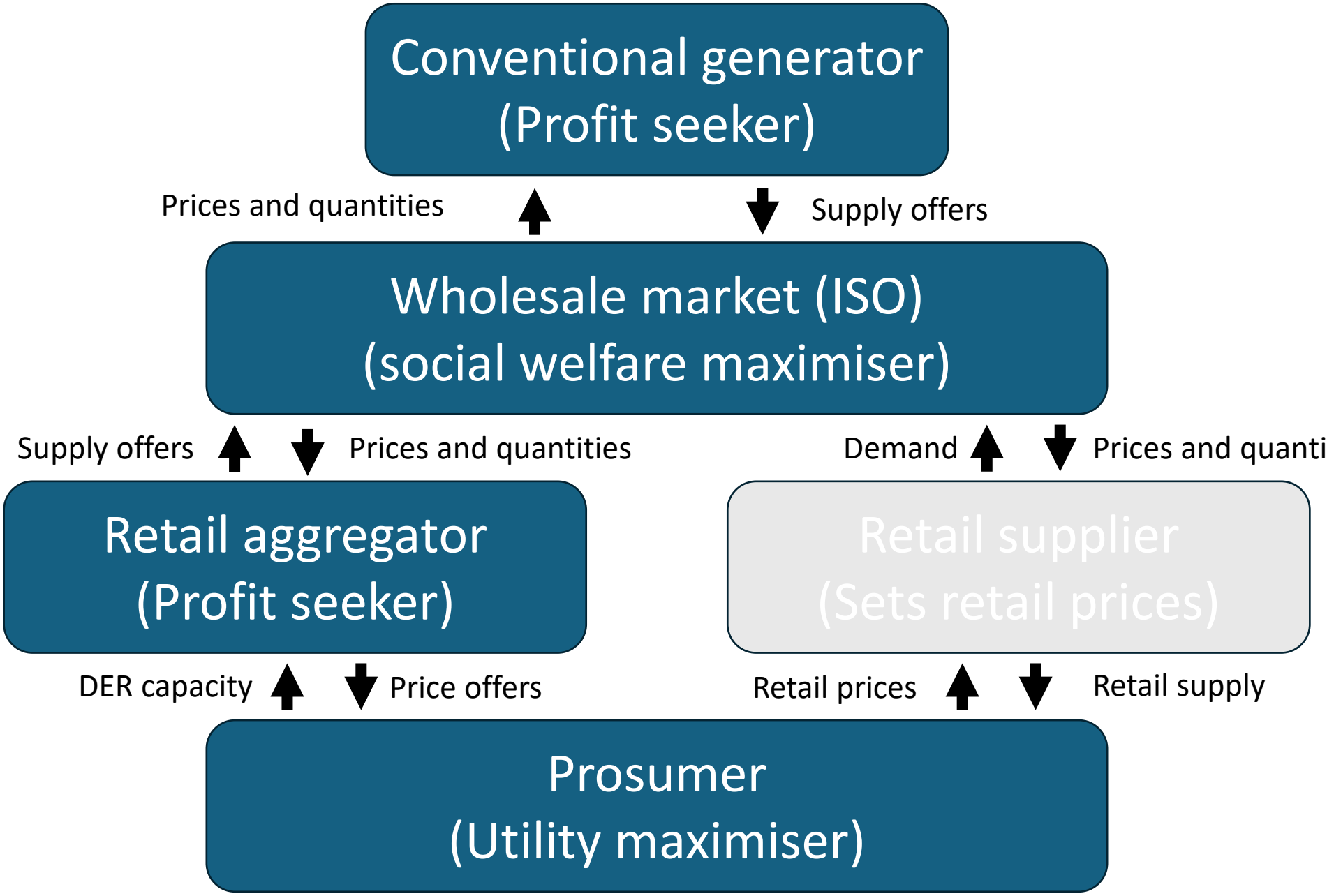
Integrating DERs

1. Net energy metering, where prosumers receive credit from their utility for excess energy production
2. Prosumers directly participate in wholesale market
3. Distribution system operator (DSO) finds socially optimal dispatch similar to an ISO
4. Fully distributed electricity market where end-consumers trade among themselves
5. **Aggregators purchase energy from DER owners, and then participate in the wholesale market as a supplier**

Aggregators

- DER aggregation via profit-seeking intermediaries has been adopted in California and New York
- California currently has 7 DER aggregators, including 4 that are not conventional utilities


Conventional generator
(Profit seeker)
Prices and quantities
Supply offers
Wholesale market (ISO)
(social welfare maximiser)
Supply offers
Prices and quantities
Demand
Prices and quanti
Retail aggregator
(Profit seeker)
Retail supplier
(Sets retail prices)
DER capacity
Price offers
Retail prices
Retail supply
Prosumer
(Utility maximiser)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This talk

- How should aggregators design contracts with prosumers when there is a single time period?
  - Based on Gao et al 2024

- What we're working on now: How should aggregators design contracts with prosumers when there are multiple time periods, and prosumers have batteries

Single period problem

Benchmark model

- What is the total social welfare when prosumers can sell energy directly to the wholesale market?

Prosumer's problem

- Prosumers have some fixed generation capacity C
- Prosumers gain some utility from consuming energy
- Prosumers can sell excess capacity back to the market at the wholesale price
- Prosumers can buy additional energy at a retail price

$$\pi(z) = u(z) + \lambda[C - z]^+ - \zeta[z - C]^+$$
$$\pi(z) = u(C - x + d) + \lambda x - \zeta d$$

Generator's problem

- Generator submits (truthful) cost functions to the ISO
- Given a wholesale price, generators will choose a supply amount that will maximise their own profit

$$\hat{\pi}(y) = \lambda y - c(y)$$

ISO

- ISO is managing an electricity network of multiple nodes
- Each node has prosumers and generators
- ISO solves an Economic Dispatch Problem to set wholesale prices at each node

ISO

- The ISO will set wholesale prices to maximise social welfare

- Prosumer surplus (PS)

$$\pi(z) = u(C - x + d) + \lambda x - \zeta d$$

- Generator surplus (GS)

$$\hat{\pi}(y) = \lambda y - c(y)$$

- Merchandising surplus

$$\sum_k \lambda^k h^k$$

Social welfare

Social welfare = prosumer consumption utility
- retail markup
- generation cost

$$W_b = \sum_k \left[\sum_i \left(u_i^k \left(z_i^k \right) - \kappa^k d_i^k \right) - \sum_j c_j^k \left(y_j^k \right) \right]$$

Profit-seeking aggregator

- A profit-seeking aggregator (principal) first sets prices to the prosumers
- Prosumers (agents) then decide how much energy to consume, how much energy to buy, and how much energy to sell to the aggregators

- Result: A profit-seeking aggregator setting a two-price tariff will maximise social welfare
  - Prosumers must pay a fixed participation fee to sell to the aggregator
  - Prosumers receive a per unit price for energy sold to the aggregator

Two-part tariff

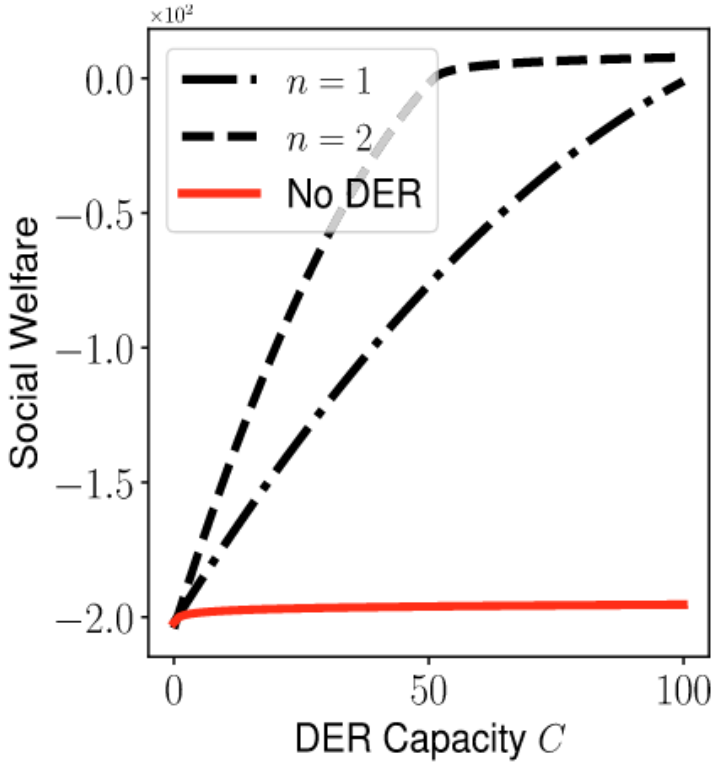
- The aggregator can pay an individual marginal price p_i^k to each prosumer, and charge an individual participation P_i^k fee to each prosumer

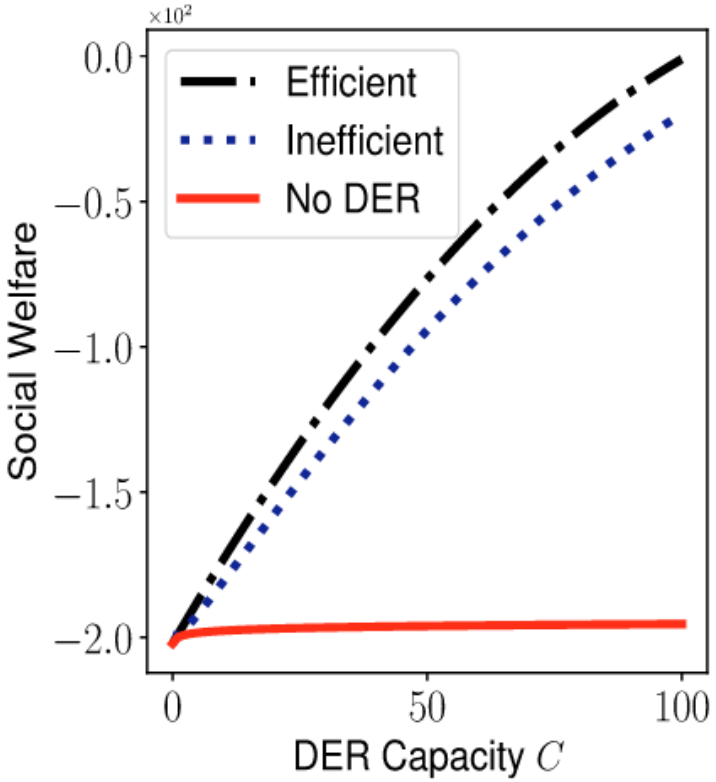
- The profit-maximising pricing strategy is to buy from the prosumers at the marginal wholesale price λ_k, and extract all prosumer surplus using participation fees

$$P_k^i = \lambda^k\left(C_k - z_i^k\right) + u_i^k\left(z_i^k\right) - u_i^k\left(C_i^k\right)$$

- Prosumers consume, buy, and sell energy at the same quantities as if they were selling to the wholesale market directly

Numerical example





Regulated aggregator

- Option 1: Aggregator is required to set uniform fees for all prosumers at the same location
  - Reduces total social welfare
  - Social welfare can be arbitrarily close to no DER participation
- Option 2: Aggregator is bound to a two-part pricing policy determined by a regulator, but is guaranteed non-negative (and potentially positive) profits
  - Maximum social welfare can be achieved
  - Uses the same per-unit price as the unregulated aggregator, but participation fees are reduced

Multiple time periods with batteries

Prosumer decisions

Assume: Prosumer knows the prices (for both buying and selling) they will observe throughout the day, and how much energy they will produce each time period

- Each time period, the prosumer decides:
  - How much they consume
  - How much they buy
  - How much they sell
  - How much they charge to or discharge from the battery
- We assume the prosumer will end the day with the same battery charge they started with

Prosumer behaviour

- When generation capacity is large, prosumers will use the battery to sell when prices are high
- When generation capacity is small, prosumers will use the battery to buy when prices are low

Conjectures

- Two-part tariff will maximise social welfare

- Regulated two-part tariff can maximise social welfare while guaranteeing the aggregator non-negative (and possibly positive) profits

Suspicious modelling choices

- Generation each period is deterministic
- Prices each period are known
- Prosumers are utility maximisers

$$\pi(z) = u(C - x + d) + \lambda x - \zeta d$$

- Others?