Co-optimizing Distributed Energy Resources for AI-Enabled Prosumers

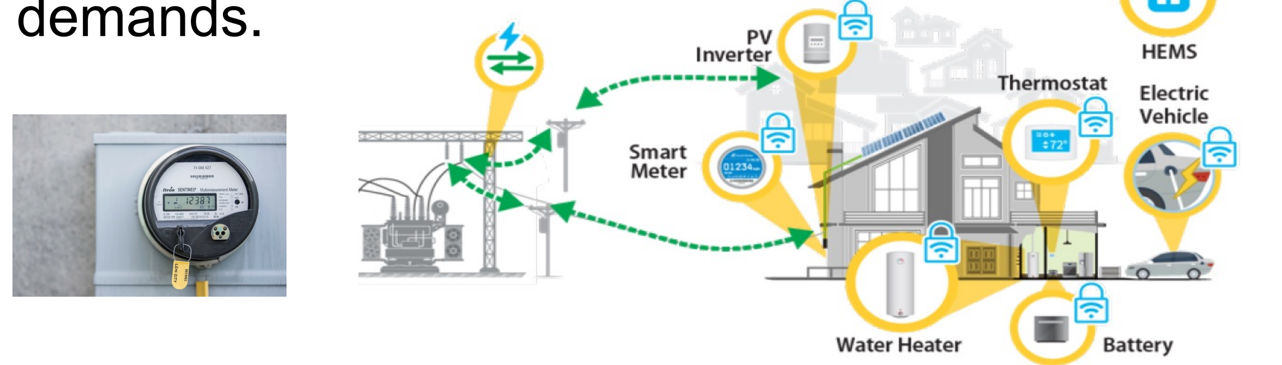
Ahmed S. Alahmed, Cornell University,

KAUST Research Conference:
AI for Energy
6-8 March 2023

DERs, Prosumers and NEM X

Distributed Energy Resources (DER):

Behind-the meter DERs, include rooftop solar, electric vehicles, energy storage and flexible demands.



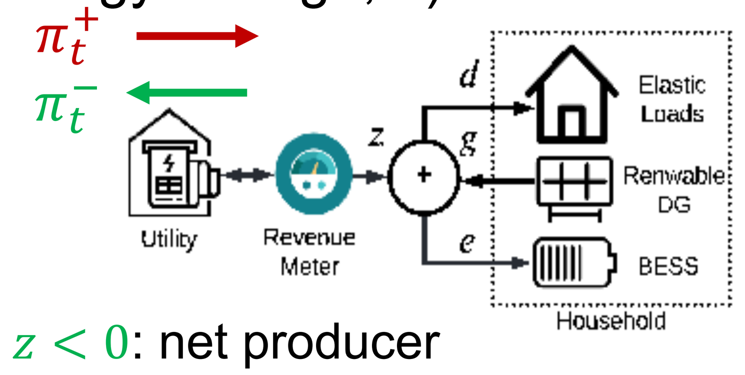
Prosumers: we consider prosumers with 1) solar PV, 2) Battery energy storage, 3) flexible demands.

π_t^+: buy rate

π_t^-: sell rate

z: net-consumption

$z \geq 0$: net consumer, $z < 0$: net producer



Net Energy Metering (NEM) X:

a metering policy that enables prosumers with DER to be billed (payment $P_{\pi_t}^{NEM}$) based on the difference between their gross consumption and BTM generation.

$$P_{\pi_t}^{\text{NEM}}(z_t) := \pi_t^+[z_t]^+ - \pi_t^-[z_t]^- + \pi_t^0$$

$\boldsymbol{\pi} = (\boldsymbol{\pi}^+, \boldsymbol{\pi}^-, \boldsymbol{\pi}^0)$: NEM X parameter

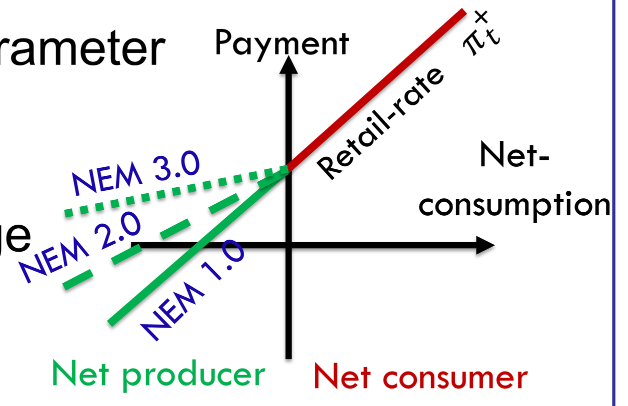
$\boldsymbol{\pi}^+ = (\pi_1^+, \ldots, \pi_T^+)$: retail rate

$\boldsymbol{\pi}^- = (\pi_1^-, \ldots, \pi_T^-)$: sell rate

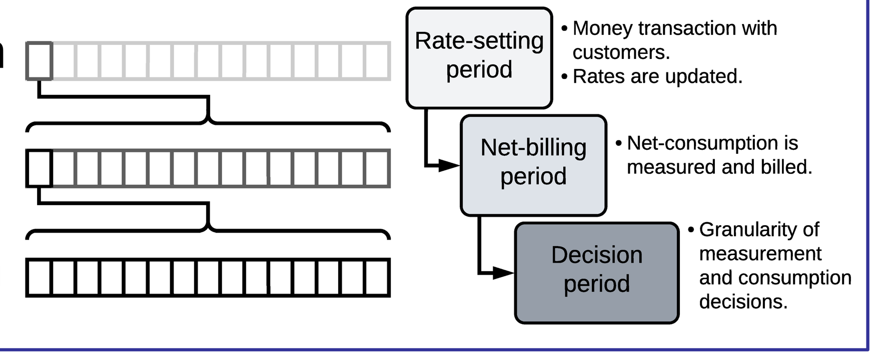
$\boldsymbol{\pi}^0 = (\pi_1^0, \ldots, \pi_T^0)$: fixed charge

$[x]^+ := \max\{0, x\}$,

$[x]^- := -\min\{0, x\}$



Measurements, Sensing and Control



Prosumer Decision Problem

Given the renewable generation g and NEM tariff π, the AI-enabled prosumer solves the following storage-consumption co-optimization:

$$\mathcal{P}: \underset{\mu=(\mu_0,\ldots,\mu_{T-1})}{\text{Maximize}} \ \mathbb{E}_\mu\left\{\gamma(s_T - s) + \sum_{t=0}^{T-1} r_t(x_t, u_t)\right\}$$

Subject to for all $t = 0, \ldots, T-1$,

$$z_t = \mathbf{1}^\top \boldsymbol{d}_t + [e_t]^+ - [e_t]^- - g_t$$
$$s_{t+1} = s_t + \tau[e_t]^+ - [e_t]^-/\rho$$
$$g_{t+1} \sim F_{g_{t+1}|g_t}$$
$$\underline{s} \leq s_t \leq \overline{s}$$
$$0 \leq [e_t]^- \leq \underline{e}$$
$$0 \leq [e_t]^+ \leq \bar{e}$$
$$\mathbf{0} \preceq \boldsymbol{d}_t \preceq \overline{\boldsymbol{d}}$$
$$x_0 = (s, g)$$

Storage control:
$e_t > 0$ charging
$e_t < 0$ discharging

<u>MDP State</u> x_t : $x_t = (s_t, g_t)$, g_t: renewable state (Markov)
s_t: storage SoC, Initial state $x_0 = (s, g)$

<u>Control Policy</u> μ_t: $x_t \xrightarrow{\mu_t} u_t := (\boldsymbol{d}_t, e_t)$,

$$\boldsymbol{d}_t = (d_{t1}, \ldots, d_{tK}) \in \mathcal{D} := \{\boldsymbol{d}: \mathbf{0} \preccurlyeq \boldsymbol{d} \preccurlyeq \overline{\boldsymbol{d}}\} \subseteq \mathbb{R}_+^K$$

<u>Stage Reward</u> r_t :

$$r_t(x_t, u_t) := \begin{cases} S_{\pi_t}^{NEM}, t \in [0, T-1] \\ \gamma(s_T - s), t = T \end{cases}$$

γ: salvage value of energy in the storage

<u>Prosumer Surplus</u> $S_{\pi_t}^{NEM}$:

$$S_{\pi_t}^{NEM}(u_t; g_t) := U_t(\boldsymbol{d}_t) - P_{\pi_t}^{NEM}(\mathbf{1}^\top \boldsymbol{d}_t + e_t - g_t)$$

<u>Utility</u> $\mathrm{U_t}$ <u>and marginal utility</u> L_t <u>functions</u>:

$$U_t(\boldsymbol{d}_t) := \sum_{k=1}^{K} U_{tk}(d_{tk}), \ \boldsymbol{L}_t := \nabla U_t = (L_{t1}, \ldots, L_{tK})$$

Assumption 1: Sandwiched salvage value:

$$\frac{1}{\tau}\max\{(\pi_t^-)\} \leq \gamma \leq \rho \min\{(\pi_t^+)\}$$

Assumption 2: Large capacity regime (non-binding SoC)

Optimal Prosumer Decision:

Proposition 1 (Marginal value of storage): $\frac{\partial}{\partial s} V_t(x_t) = \gamma$

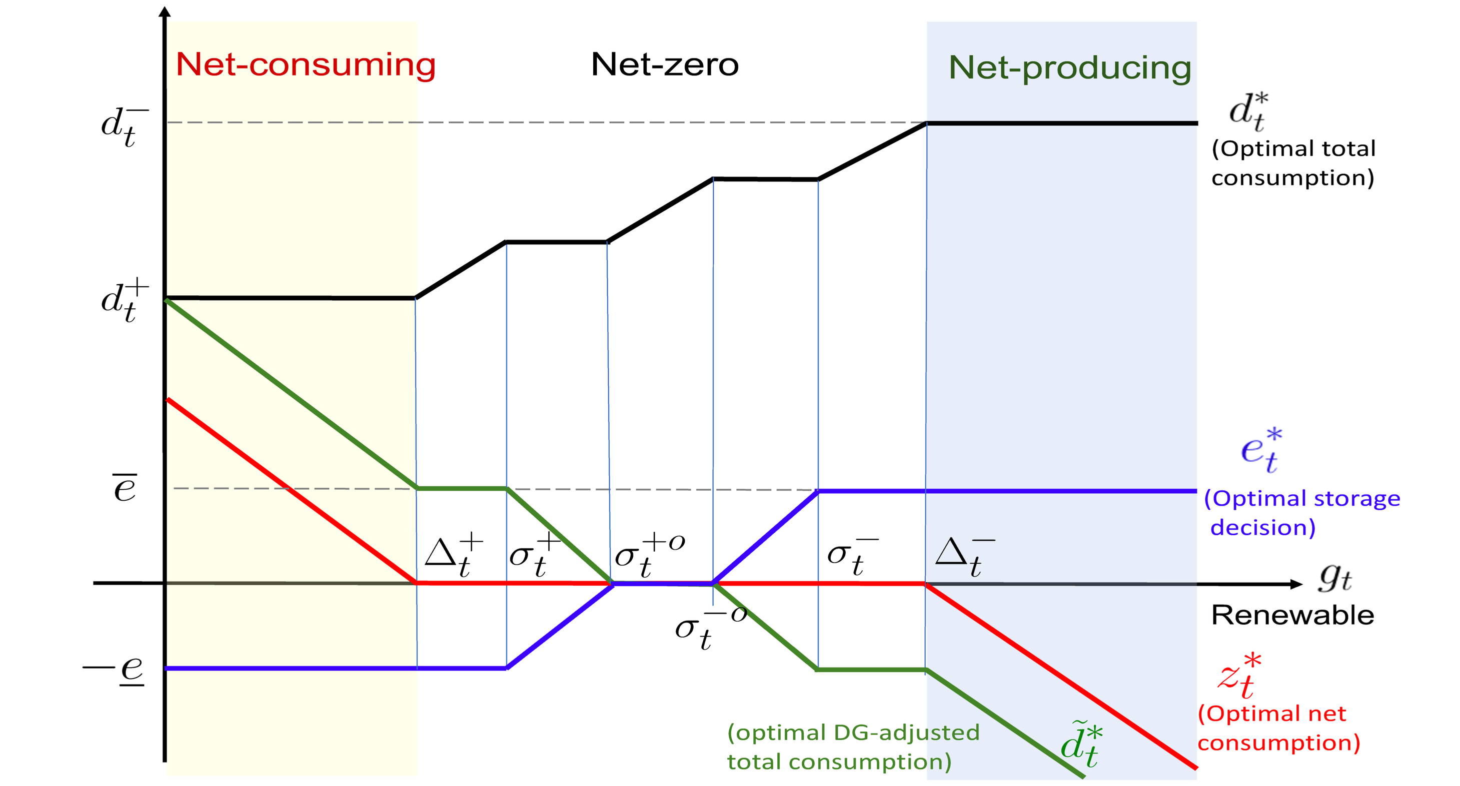
Proposition 2 (Storage-consumption complementarity):

- Charge only locally. $(i) \quad e_t^* z_t^* \leq 0$, $(ii) \quad e_t^*(d_t^* - g_t) \leq 0$
  - Grid power is never used to charge the storage.
- No discharging to grid.
- Storage is charged only after consumption is completely met by renewables.

Proposition 3 (Optimal storage operation):

$$e_t^* = \begin{cases} \max\{r_t - d_t^*, -\underline{e}\}, & g_t \leq d_t^* \\ \min\{r_t - d_t^*, \overline{e}\}, & g_t \geq d_t^* \end{cases}$$

Optimal Co-optimization Policy



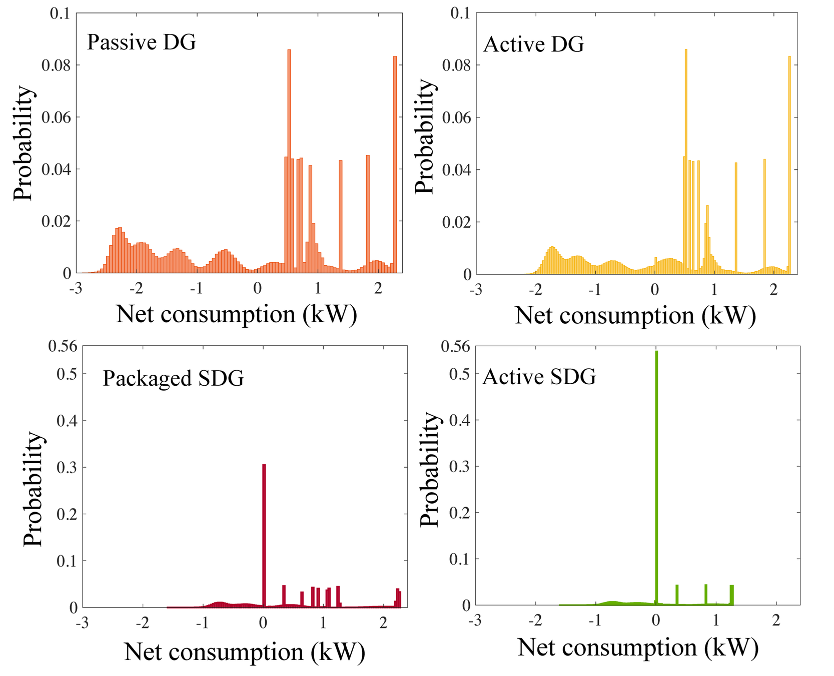
Simulation Results

Cumulative reward Gain (%) over consumer reward

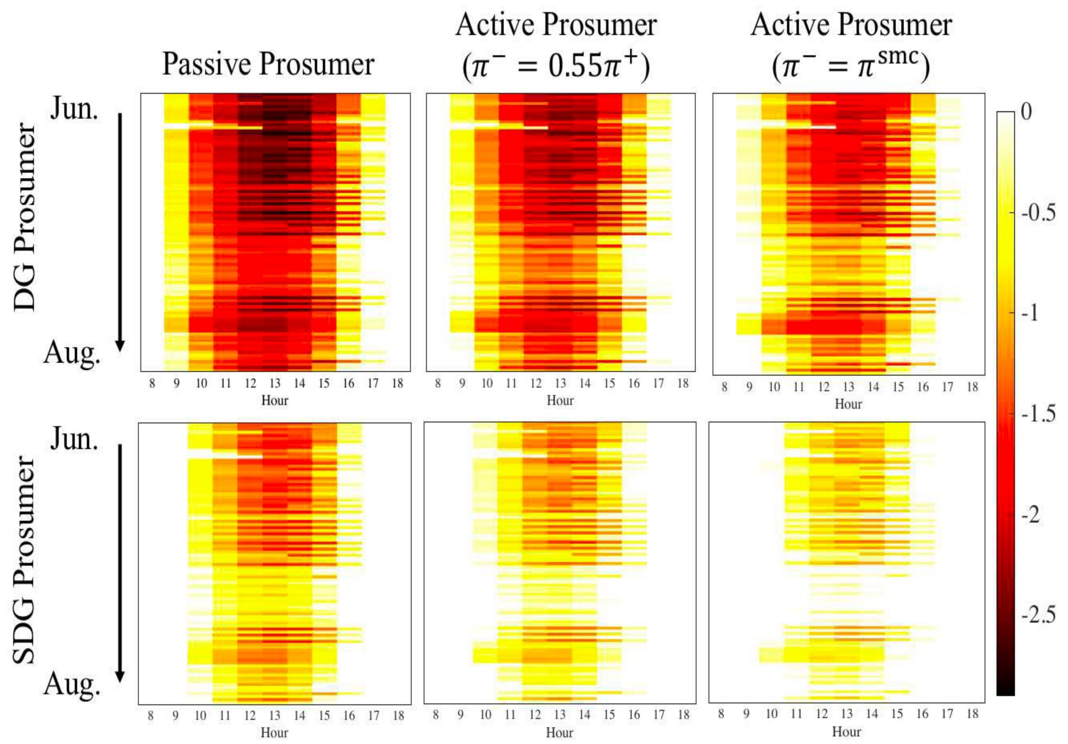
π^- ($/kWh)	$\bar{e} = \underline{e}$ (kW)	Customer Type: Consumer	Passive DG	Active DG	Packaged SDG	Active SDG
π^{SMC}	1	0%	42.3%	48.7%	58.4%	69.5%
	1.5	0%	42.3%	48.7%	60.0%	75.0%
	2	0%	42.3%	48.7%	59.2%	78.2%
$0.5\pi^+$	1	0%	55.6%	57.9%	61.5%	72.5%
	1.5	0%	55.6%	57.9%	61.0%	75.9%
	2	0%	55.6%	57.9%	59.2%	78.2%

<u>Terminology</u>:
Passive prosumer: renewable-inelastic consumption.
Active prosumer: renewable-aware consumption.
SDG: Storage + DG prosumer, Consumer: no DER customer.

Net-consumption distribution



Reverse power flows



Summary

- Optimal prosumers have renewable-generation-aware schedules for their resources.
- The optimal DER co-optimization policy, under large capacity regime, can schedule a large number of flexible demands and storage decisions as closed-form functions of BTM renewables.
- Reducing NEM export rate increases the value of co-optimizing the BTM resources.
- Optimal prosumer consumption not only maximizes its surplus but also improves overall system efficiency and reduces cost-shifts (cross subsidies).