DER UNDER NET ENERGY METERING X PROSUMER DECISIONS, SOCIAL WELFARE, CROSS-SUBSIDIES, AND MARKET POTENTIAL

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Net energy metering (NEM) and retail tariff

NEM 1.0 tariff model:

\[ P_{1.0}(d, r) = \pi(d - r) + \pi_0 \]

- Volumetric charge: \((0.03, 0.46)\) $/kWh
- Fixed (connection) charge: \((-20, 75)\) $/month

\[ z = d - r \]

Rate structure:

- Off-peak
- Peak

Steven J. Strong

1979

1981

1999

http://solardesign.com/history-of-sda/
From 1970’s to 2020’s

- 10% customers are under NEM (PG&E)
- 24% total gen. from solar.

Consumers in the future

- Distributed energy resources and flexible demand
- Smart home: intelligent HEMS with IoT sensors. Data analytics and ML to adapt to DER supply and pricing signals from the utility and DERA.
- Stratified consumer groups:
  - Price and DER elastic prosumers with AI/ML hardened HEMS
  - Still, conventional consumers are always significant customer population.
Retail rate of electricity

\[ r \]  
BTM DER  
\[ d \]  
Demand  
\[ z = d - r \]  
Net demand

NEM 1.0 tariff model:

\[ P_{1.0}(d, r) = \pi(d - r) + \pi_0 \]

Volumetric charge  
(0.03, 0.46) $/kWh  
Fixed charge  
(-20, 75) $/month

Bonbright principles:
Cost recovery, efficiency, equity, stability.


- High volumetric charges above SMC send distorted signal that inhibits electrification.
- High (uniform) fixed charges discourage conservation and discriminate low consumption customers.
- Ramsey pricing maximizes social welfare subject to cost recovery constraints.
- BTM DER impacts:
  - **Equity**: cost shifts and cross subsidies.
  - **Stability**: death spiral hypothesis.
Retail rate of electricity

\[ r \quad d \quad z = d - r \]

BTM DER
Demand
Net demand

NEM 1.0 tariff model:

\[ P_{1.0}(d, r) = \pi(d - r) + \pi_0 \]

Volumetric charge
(0.03, 0.46) $/kWh

Fixed charge
(-20, 75) $/month


Bonbright principles:
Efficiency, cost recovery, equity, stability.


Features of NEM 2.0 and proposed successors

- Discriminating via consumption and production prices
- Discriminating fixed charges based on DER capacity & income
- TOU pricing
Objectives and main results:

- **Objectives:** (i) Obtain optimal price- and DER-elastic prosumer consumptions; (ii) gain analytical insights into prosumer behavior under NEM.

- **Results:** Formalize an inclusive parametric model—**NEM X**—that captures key features of the existing and proposed NEM tariff models.

- **Results:** Characterize optimal (elastic) prosumer decisions under NEM X:
  - The optimal consumption policy is a three-zone two-threshold (predetermined) policy based on BTM generation.

- **Results:** Under (stochastic) Ramsey pricing model, provide comparative statics with respect to NEM parameters and performance evaluation of social welfare, cost shifts (cross subsidies), and market potentials.

Some limitations:

- Stylized theoretical models and idealized assumptions.

- Numerical evaluations used extrapolated parameters from on-line data.

Timescales of sensing, control, and pricing

**BTM DER Demand**

$r$  
$d$  
$z = d - r$

**Net demand**

$z = d - r$

**Billing (netting) period**

**NEM 1.0 tariff model:**

$$P_{1.0}(d, r) = \pi(d - r) + \pi_0$$

**NEM 2.0 tariff model:**

$$P_{2.0}(z) = \begin{cases} 
\pi^+ z + \pi_0, & z \geq 0; \\
\pi^- z + \pi_0, & z < 0. \quad \pi^+ > \pi^- 
\end{cases}$$
Net metering X tariff model

\[ P_{\text{NEM-X}}(d, r) = \begin{cases} \pi^+_i(d - r) + \pi_j, & d \geq r \\ \pi^-_i(d - r) + \pi_j, & d < r \end{cases} \]

\( i \in \{1, \cdots, N\} \) Time-dependent: (dynamic) price
\( j \in \{1, \cdots, K\} \) Class-dependent charge: (income, capacity)

\[ \pi = (\pi^+, \pi^-, \pi_0) \]
\[ \pi^+ = (\pi^+_1, \cdots, \pi^+_N) \] Retail (consumption) rate
\[ \pi^- = (\pi^-_1, \cdots, \pi^-_N) \] Sell (generation) rate
\[ \pi_0 = (\pi^1_0, \cdots, \pi^k_0) \] Fixed charge

Net billing period: minutes, hours, days, …
Consumer and prosumer responses

Surplus maximization:

\[
\max_d \left( U(d) - P(d - r) \right)
\]

\[
d^*(r) := \arg \max_d \left( U(d) - P(d - r) \right)
\]

\[
S^*(r) := U(d^*) - P(d^* - r)
\]

**NEM 1.0:**  
\[
P_{1.0}(d, r) = \pi(d - r) + \pi_0
\]

**NEM 2.0:**  
\[
P_{2.0}(d, r) = \begin{cases} 
\pi^+(d - r) + \pi_0, & d \geq r \\
\pi^-(d - r) + \pi_0, & d < r
\end{cases}
\]
Why three operation zones?

\[
S_r^+(d) = U(d) - \pi^+(d - r) = U(d) - \pi^+ d + \frac{\pi^+}{r} d^+ := \arg \max_d S_r^+(d) \quad \text{(Independent of } r) \\
S_r^-(d) = U(d) - \pi^-(d - r) = U(d) - \pi^- d + \frac{\pi^-}{r} d^- := \arg \max_d S_r^-(d) \quad \text{(Independent of } r)
\]

\[d^+ < r < d^- \quad \text{Net-zero}\]

\[r < d^+ \quad \text{Net-consume}\]

\[r > d^- \quad \text{Net-produce}\]

\[r = d^+ \quad \text{Net-consume surplus } S^-\]

\[r = d^- \quad \text{Net-produce surplus } S^+\]
Theorem 1 (Prosumer decision under NEM X). Given NEM parameter $\pi = (\pi^+, \pi^-, \pi^0)$ and marginal utility $(V_1, \cdots, V_M)$ of consumption devices, under A1-A4, the optimal prosumer consumption policy is given by two thresholds

$$d^+ := \sum_i \max\{0, V_i^{-1}(\pi^+)\},$$
$$d^- := \sum_i \max\{0, V_i^{-1}(\pi^-)\} \geq r^+$$

that partitions the range of DER production into three zones:

1) **Net consumption zone**: $r < d^+$: Be a net-consumer when $r < d^+$ with consumption

$$d_i^+ = \max\{0, V_i^{-1}(\pi^+)\} \geq 0, \ \forall i.$$  \hspace{1cm} (4)

3) **Net-zero energy zone**: $d^+ \leq r \leq d^-$. Be a net-zero consumer when $d^+ \leq r \leq d^-$ with consumption:

$$d_i^0(r) = \max\{0, V_i^{-1}(\mu^*(r))\} \in [d_i^+, d_i^-], \forall i$$

where $\mu^*(r) \in [\pi^-, \pi^+]$ is a solution of

$$\sum_{i=1}^M \max\{0, V_i^{-1}(\mu)\} = r,$$

and $d_i^0(\cdot)$ is continuous and monotonically increasing in $[d_i^+, d_i^-]$.

2) **Net production zone**: $r > d^-$. Be a net-producer when $r > d^-$ with consumption

$$d_i^- = \max\{0, V_i^{-1}(\pi^-)\} \geq d_i^+, \ \forall i.$$  \hspace{1cm} (5)

NEM 2.0: $P_{2.0}(d, r) = \begin{cases} \pi^+(d - r) + \pi_0, & d \geq r \\ \pi^-(d - r) + \pi_0, & d < r \end{cases}$
Comparative statics

Key take-away:

- **Prosumer maximizes its surplus and improves system efficiency by consuming more using BTM DER in the net-zero and net-producing zones.**
- **Reducing sell rate narrows the net-production zone and enlarges the net-zero zone.**
- **Optimal consumption reduces negative payment (cost shifts).**

**NEM 2.0:**

\[ P_{2.0}(d, r) = \begin{cases} 
\pi^+(d - r) + \pi_0, & d \geq r \\
\pi^-(d - r) + \pi_0, & d < r
\end{cases} \]
Rate-setting under NEM X

\[ P_{1.0}(d, r) = \pi(d - r) + \pi_0 \]
\[ P_{2.0}(d, r) = \begin{cases} 
\pi^+(d - r) + \pi_0, & d \geq r \\
\pi^-(d - r) + \pi_0, & d < r 
\end{cases} \]

\[ P_{\text{NEM-X}}(d, r) = \begin{cases} 
\pi_{i}^+(d - r) + \pi_j, & d \geq r \\
\pi_{i}^-(d - r) + \pi_j, & d < r 
\end{cases} \quad i \in \{1, \cdots, N\} \quad \text{Time-dependent prices} \\
\text{Class-dependent charge:} \quad \text{(income, capacity)} \\
\quad j \in \{1, \cdots, K\} 

\text{Ramsey pricing}

\text{maximize} \quad \sum_{n=1}^{N} \mathbb{E}\left( S_c^\pi(d^*(r_n), \gamma) + \gamma \mathcal{E}(r_n) \right) \\
\text{subject to} \quad \sum_{n=1}^{N} \mathbb{E}(S_u^\pi(d^*(r_n), \gamma)) = 0. \\

\[ S_{c}^{\pi}(d^*(r_n), \gamma) := \gamma S_{\text{pros}}^{\pi}(d_{\text{pros}}^*(r_n)) + (1 - \gamma) S_{\text{cons}}^{\pi}(d_{\text{cons}}^*(r_n)) \]

\[ \text{Prosumer surplus} \quad \text{Consumer surplus} \]

Customer surplus \quad Fraction of prosumers \quad Environmental benefits

Utility surplus \quad Break-even condition
Performance evaluation

NEM X tariff cases

- NEM 1.0 (CA)
- NEM 2.0 w. TOU (CA)
- NEM 2.0 w. SMC sell rate at 8 cents/kWh.

Performance measures

- Social welfare: $$\sum_{n=1}^{N} \gamma_\pi \left[ E \left( \gamma S_{\text{pros}}^{\pi} (d^*_{\text{pros}} (r_n)) + (1 - \gamma) S_{\text{cons}}^{\pi} (d^*_{\text{cons}} (r_n)) + \gamma E (r_n) \right) \right]$$

- Cost shifts: $$\psi_\gamma = \sum_{n} \gamma_\pi E (\Delta P^{\pi} (r_n) - \pi^{\text{SMC}} r_n)$$

- Payback time: $$t^{\pi}_{PB} (r, \xi) = \min_{t^*} \left\{ t^* : \sum_{i=0}^{t^*} \left( \frac{1 - \nu}{1 + \zeta} \right)^t E (\Delta P^{\pi}_i (r)) \geq \xi \right\}$$

- Market potential: $$\rho (\pi, \xi) = \gamma^{\max} \exp (-\epsilon t^{\pi}_{PB} (r, \xi))$$

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**Description of Case Studies**

| # | Name     | Tariff | Rate  | Compensation (S/kWh) | Fixed Charges | Discrimination
|---|----------|--------|-------|----------------------|---------------|----------------
| 1 | NEM 1.0  | one-part | IBR$^*$ | $\pi^- = \pi^+$     | -             | No
| 2 | NEM 2.0  | one-part | ToU$^{\text{w. TOU}}$ | $\pi^- = \pi^++0.03$ | -             | No
| 3 | NEM SMC  | one-part | ToU$^{\text{w. SMC}}$ | $\pi^- = \pi^{\text{SMC}}$ | -             | No

$^*$ Similar to PG&E, IBR has two blocks, with a 20% higher price for above baseline usage.
$^{\text{w.}}$ ToU parameters for all case studies are similar to PG&E ToU-B, i.e. 1.5 peak ratio and a 16 – 21 peak period.
Short-run social welfare

\[ \sum_{n=1}^{N} \mathbb{E} \left( \gamma S_{\text{pros}}^n \left( d_{\text{pros}}^* (r_n) \right) + (1 - \gamma) S_{\text{cons}}^n \left( d_{\text{cons}}^* (r_n) \right) + \gamma \mathcal{E}(r_n) \right) \]

Key parameters:

- **SMC**: $0.08/\text{kWh}
  

- **Utility fixed cost**: $2.35/day
  
  California Public Utility Commission, “Prepared testimony for a successor tariff to the current net energy metering tariffs,” June 18, 2021
Cost shifts: \( \psi_\gamma^{\pi} = \sum_n \gamma \mathbb{E}(\Delta P^\pi(r_n) - \pi^{\text{SMC}} r_n) \)

\[ \Delta P^\pi(r_n) := P^\pi(1^T d_c^*) - P^\pi(1^T d_p^*(r_n) - r_n). \]
Payback time, market potential, and long run DER adoption

[Graphs showing the payback time, percentage of adopters, market potential, normalized social welfare, and scaled social welfare for NEM SMC, NEM1.0, and NEM2.0 over time.]
Conclusions

- NEM X is a convenient and natural model for existing NEM policies and the proposed successor tariffs. It can also be extended to include feed-in tariff.

- The optimal prosumer consumption has a simple two-threshold three-zone structure that lends itself to a highly scalable scheduling solution.

- Optimal prosumer consumption not only maximizes its surplus but also improves overall system efficiency and reduces cost-shifts (cross subsidies).

- Significant insights can be gained into characteristics of the optimal prosumer consumption, and how it is affected by NEM tariff parameters.

- NEM 2.0 and its successors aim to address three of the four Bonbright principles, leaving out the long-run stability of NEM policies.