DER UNDER NET ENERGY METERING X

PROSUMER DECISIONS, SOCIAL WELFARE, CROSS-SUBSIDIES, AND MARKET POTENTIAL

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Joint work with Ahmed S. Alahmed

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Net energy metering (NEM) and retail tariff

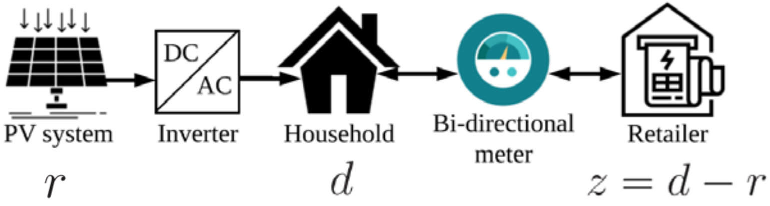
Steven J. Strong

1981

1979

1999

http://solardesign.com/history-of-sda/



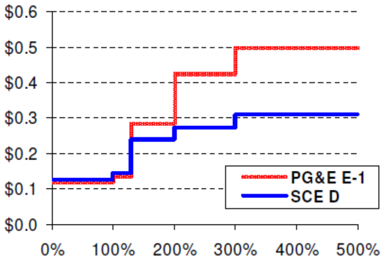
r Renewable (DER) d Demand $z = d - r$ Net demand

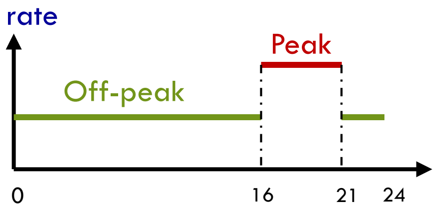
NEM 1.0 tariff model:

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

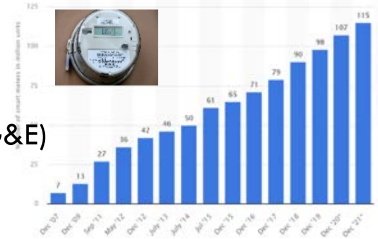
Volumetric charge (0.03, 0.46) \$/kWh

Fixed (connection) charge (-20, 75) \$/month

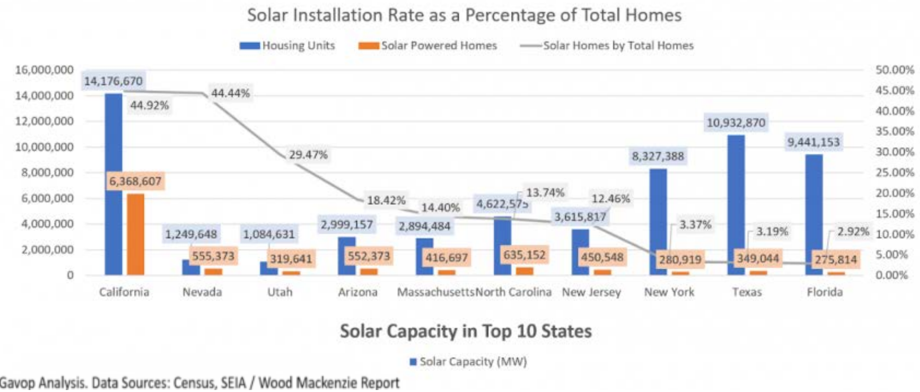


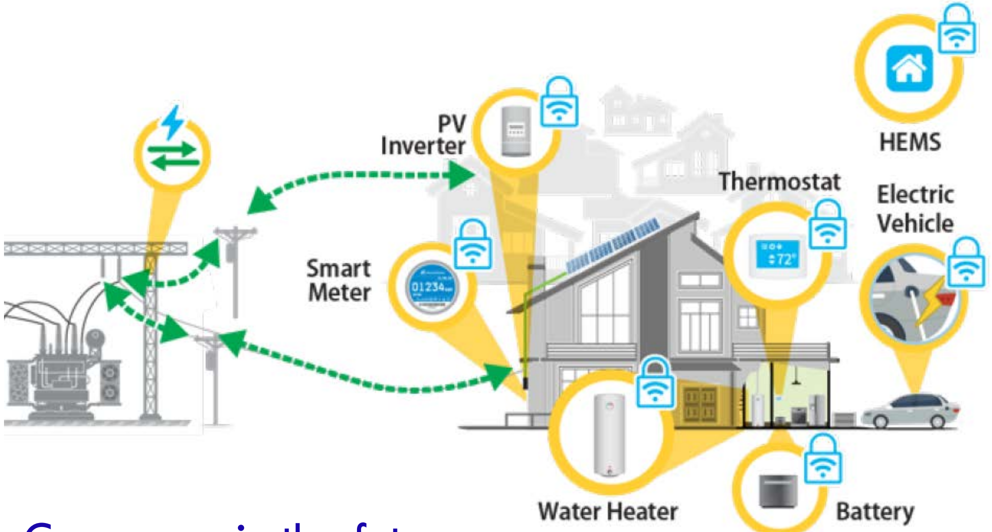


From 1970's to 2020's



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





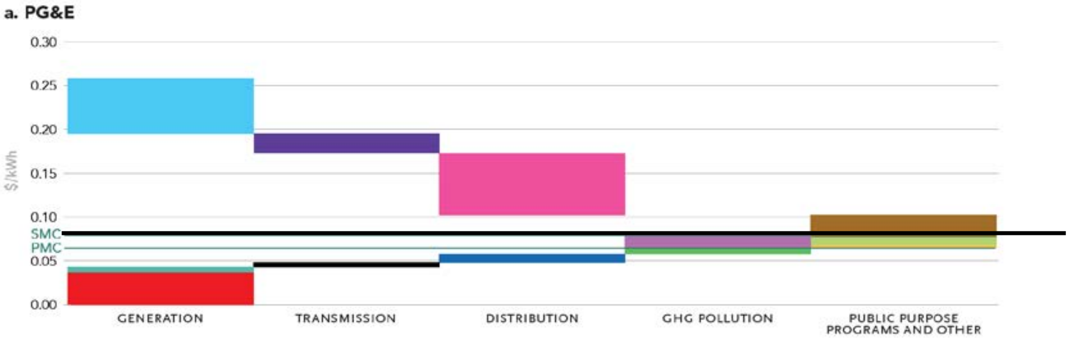
Consumers in the future

- 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 d $z = d - r$

BTM DER Demand Net demand



Borenstein-Fowlie-Sallee, "Designing electricity rates for an equitable energy transition, Energy Institute WP 314, Feb. 2021

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

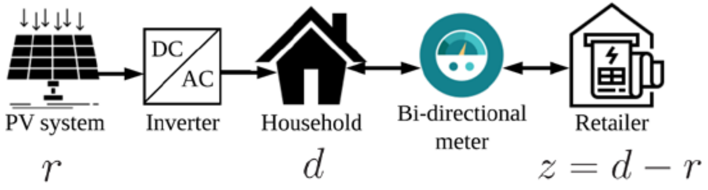
Bonbright principles:

Cost recovery, efficiency, equity, stability.

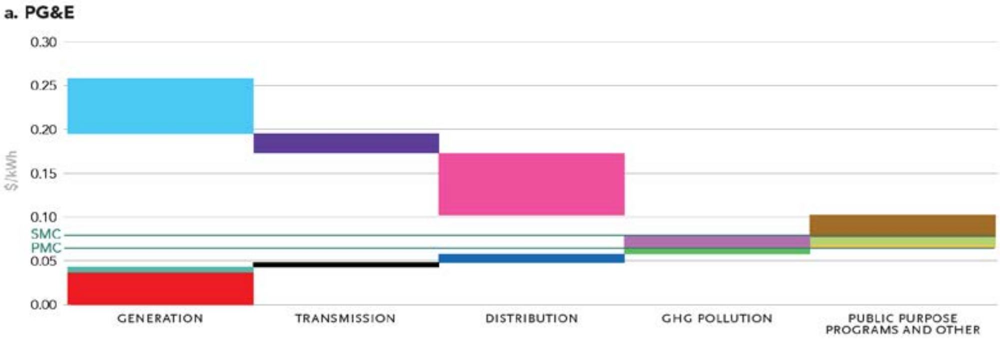
J.C. Bonbright, "Principles of public utility rates," 1961.

- 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



BTM DER | Demand | Net demand



Borenstein-Fowlie-Sallee, "Designing electricity rates for an equitable energy transition, Energy Institute WP 314, Feb. 2021

NEM 1.0 tariff model:

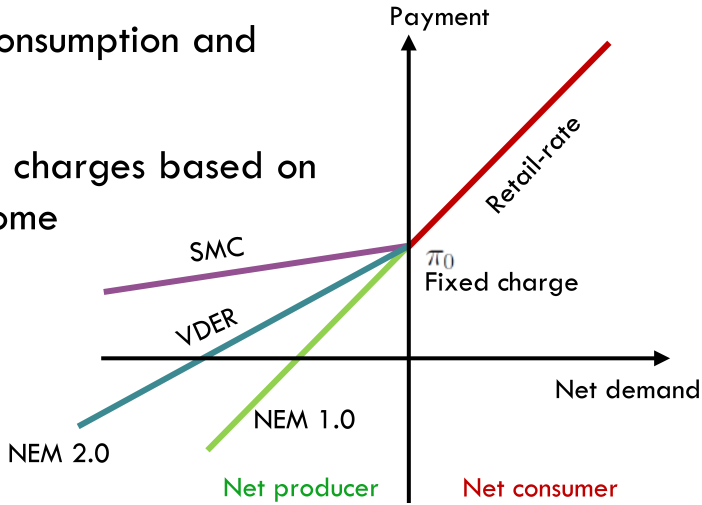
$$P_{1.0}(d, r) = \pi(d - r) + \pi_0$$

Volumetric charge π: (0.03, 0.46) \$/kWh

Fixed charge π_0: (-20, 75) \$/month

Features of NEM 2.0 and proposed successors

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



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Efficiency, cost recovery, equity, stability.

J.C. Bonbright, "Principles of public utility rates," 1961.

Objectives and main results:

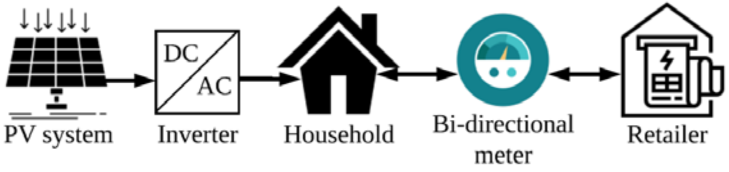
- Objectives: (i) Obtain optimal price- and DER-elastic prosumer consumptions; (ii) gain analytical insights into prosumer behavior under NEM.
- Results: Formalize an inclusive parametric model—NEM X—that captures key features of the existing and proposed NEM tariff models.
- Results: Characterize optimal (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.

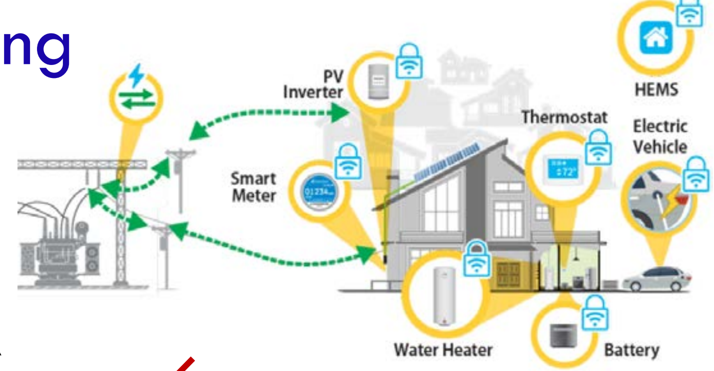
Some limitations:

- Stylized theoretical models and idealized assumptions.
- Numerical evaluations used extrapolated parameters from on-line data.

Ahmed S. Alahmed and Lang Tong, "On Net Energy Meeting X: Optimal Prosumer Decisions, Social Welfare, Cross-subsidies," arxiv https://arxiv.org/abs/2109.09977, Oct. 2021

Timescales of sensing, control, and pricing

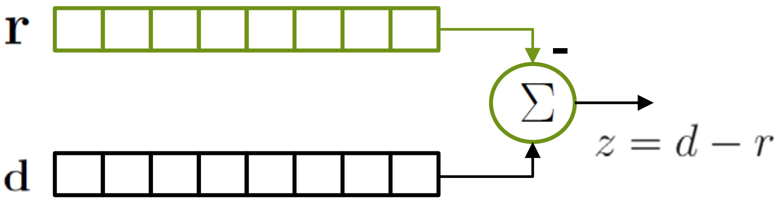




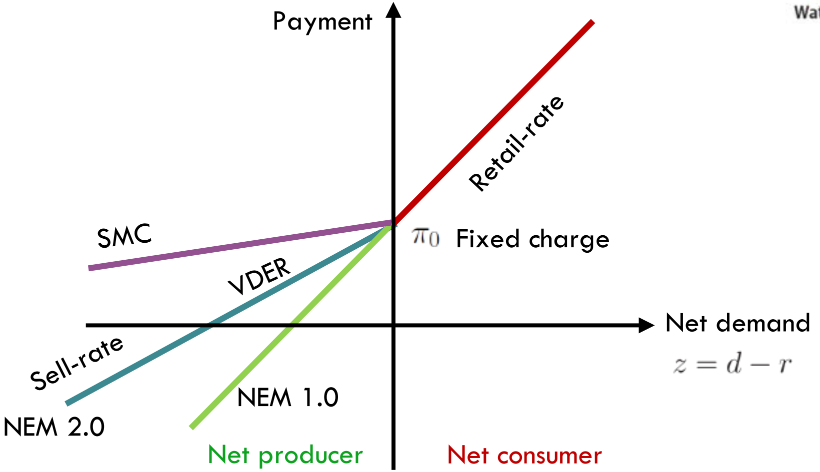
BTM DER $\mathbf{r}$

Demand $\mathbf{d}$

Net demand $z = d - r$



Billing (netting) period



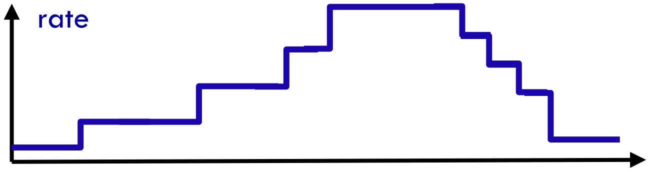
NEM 1.0 tariff model:

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

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



$$P^{\boldsymbol{\pi}}_{\text{NEM-X}}(d,r) = \begin{cases} \pi_i^+(d-r) + \pi_j, & d \geq r \\ \pi_i^-(d-r) + \pi_j, & d < r \end{cases}$$

$i \in \{1, \cdots, N\}$ Time-dependent: (dynamic) price

$j \in \{1, \cdots, K\}$ Class-dependent charge: (income, capacity)

$$\boldsymbol{\pi} = (\boldsymbol{\pi}^+, \boldsymbol{\pi}^-, \boldsymbol{\pi}_0)$$

$\boldsymbol{\pi}^+ = (\pi_1^+, \cdots, \pi_N^+)$ Retail (consumption) rate

$\boldsymbol{\pi}^- = (\pi_1^-, \cdots, \pi_N^-)$ Sell (generation) rate

$\boldsymbol{\pi}_0 = (\pi_0^1, \cdots, \pi_0^k)$ Fixed charge

Net billing period:

minutes, hours, days,…

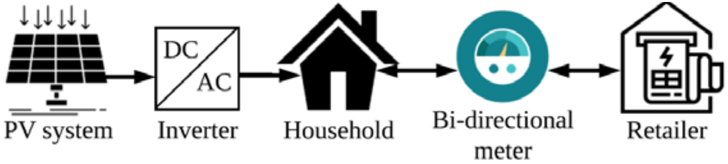
Consumer and prosumer responses

Surplus maximization:

$$\max_{d} \Big(\underbrace{U(d)}_{\text{Utility}} - \underbrace{P(d-r)}_{\text{Payment}}\Big)$$

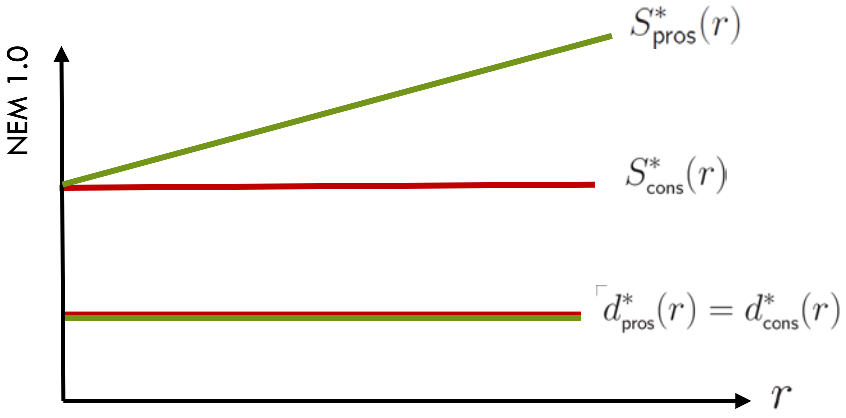
$$d^*(r) := \arg\max_{d} \Big(U(d) - P(d-r)\Big)$$

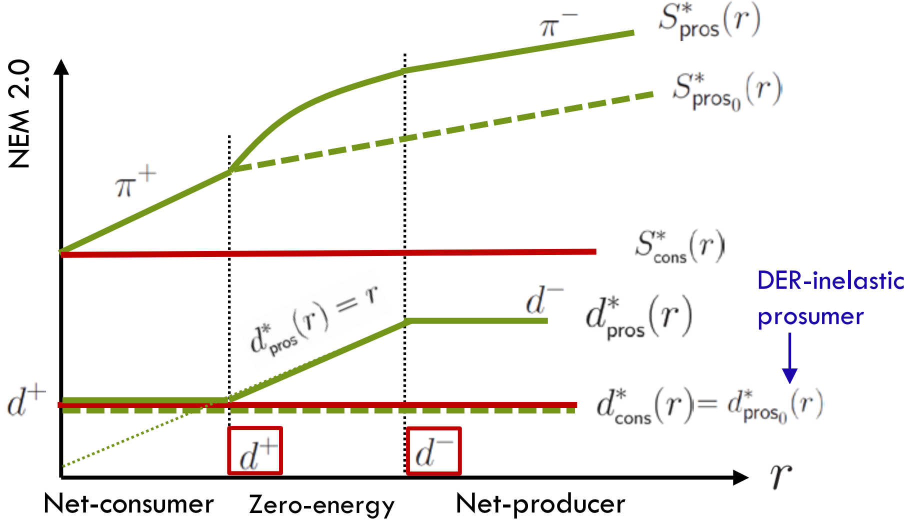
$$S^*(r) := U(d^*) - P(d^* - r)$$



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?

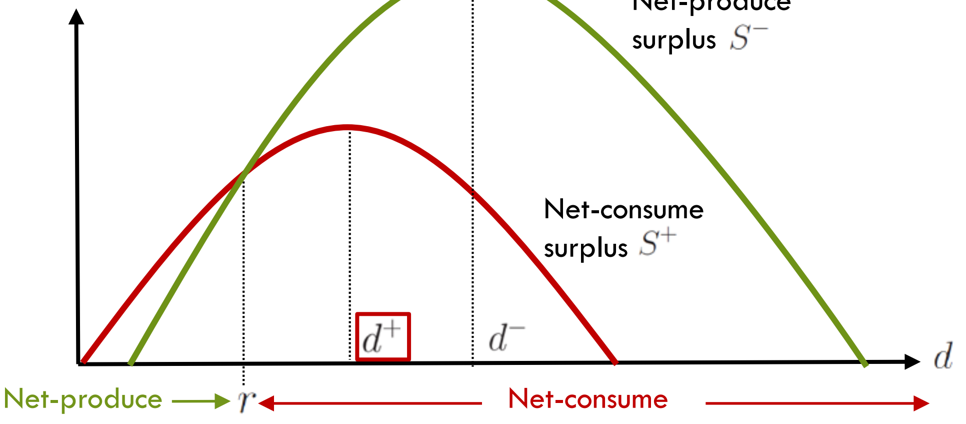
$$S_r^+(d) = U(d) - \pi^+(d-r) = U(d) - \pi^+ d + \boxed{\pi^+ r}$$

$$d^+ := \arg\max_d S_r^+(d) \quad \text{(Independent of } r\text{)}$$

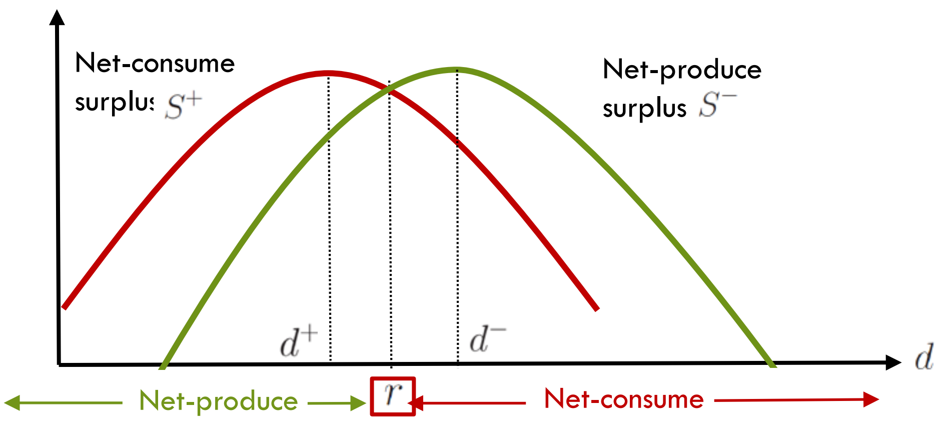
$$S_r^-(d) = U(d) - \pi^-(d-r) = U(d) - \pi^- d + \boxed{\pi^- r}$$

$$d^- := \arg\max_d S_r^-(d) \quad \text{(Independent of } r\text{)}$$

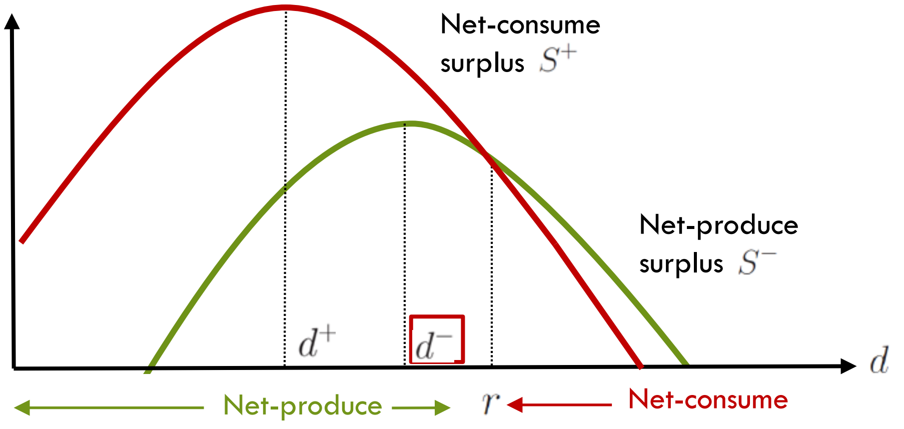
$r < d^+$ Net-consume



$d^+ < r < d^-$ Net-zero



$r > d^-$ Net-produce



Prosumer with multiple devices under NEM X

Theorem 1 (Prosumer decision under NEM X). *Given NEM parameter $\pi = (\pi^+, \pi^-, \pi^o)$ and marginal utility $(V_1, \cdots, V_M)$ of consumption devices, under A1-A4, the optimal prosumer consumption policy is given by two thresholds*

$$\begin{aligned} d^+ &:= \textstyle\sum_i \max\{0, V_i^{-1}(\pi^+)\}, \\ d^- &:= \textstyle\sum_i \max\{0, V_i^{-1}(\pi^-)\} \geq r^+ \end{aligned} \tag{3}$$

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*

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

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

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

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

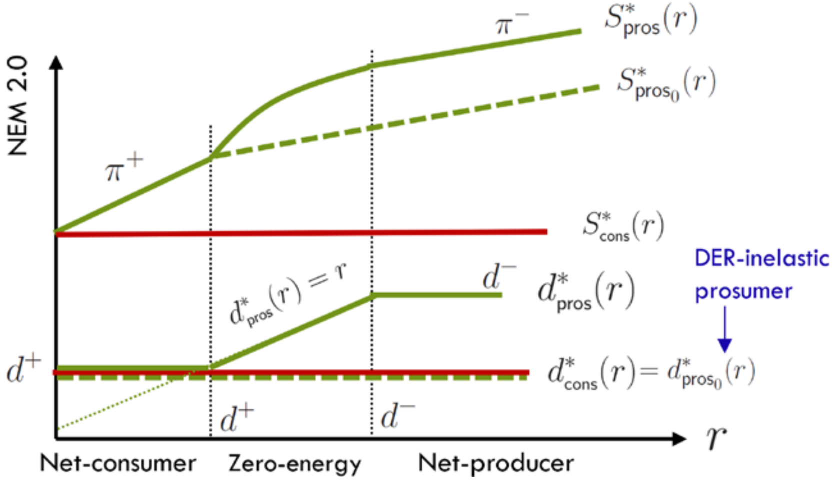
$$d_i^o(r) = \max\{0, V_i^{-1}(\mu^*(r))\} \in [d_i^+, d_i^-], \forall i \tag{6}$$

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

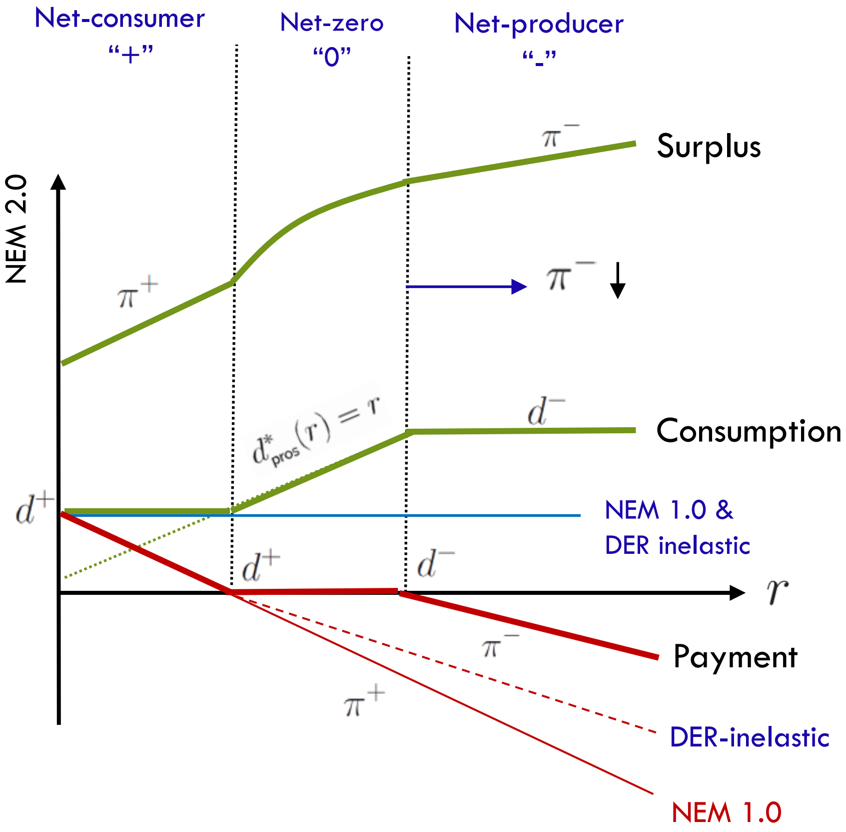
$$\sum_{i=1}^{M} \max\{0, V_i^{-1}(\mu)\} = r, \tag{7}$$

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

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



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 STATIC ANALYSIS

	$r\uparrow$			$\pi^+\uparrow$			$\pi^-\uparrow$			$\pi^0\uparrow$		
Zone	+	-	0	+	-	0	+	-	0	+	-	0
$d_i^\pi(r)$	—	—	↑	↓	—	—	—	↓	—	—	—	—
$S^\pi(r)$	↑	↑	↑	↓	—	—	—	↑	—	↓	↓	↓
$P^\pi(r)$	↓	↓	—	X	—	—	—	↓	—	↑	↑	↑

↑: increasing ↓: decreasing —: unchanged X: indeterminant

Key take-aways:

- 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).

Rate-setting under NEM X

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

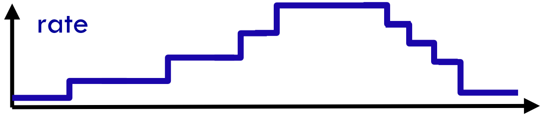
$$P_{2.0}(d,r) = \begin{cases} \pi^+(d-r) + \pi_0, & d \geq r \\ \pi^-(d-r) + \pi_0, & d < r \end{cases}$$

$$P^{\boldsymbol{\pi}}_{\text{NEM-X}}(d,r) = \begin{cases} \pi_i^+(d-r) + \pi_j, & d \geq r \\ \pi_i^-(d-r) + \pi_j, & d < r \end{cases}$$

$i \in \{1, \cdots, N\}$ Time-dependent prices

$j \in \{1, \cdots, K\}$ Class-dependent charge: (income, capacity)

$(\pi_i^+, \pi_i^-, \pi_0^j)$



Ramsey pricing

Customer surplus

Fraction of prosumers

Environmental benefits

$$\begin{aligned} &\underset{\pi}{\text{maximize}} && \textstyle\sum_{n=1}^N \mathbb{E}\Big(S_c^\pi(\mathbf{d}^*(r_n),\gamma) + \gamma\mathcal{E}(r_n)\Big) \\ &\text{subject to} && \textstyle\sum_{n=1}^N \mathbb{E}(S_u^\pi(\mathbf{d}^*(r_n),\gamma)) = 0. \end{aligned}$$

Utility surplus

Break-even condition

$$S_c^\pi(d^*(r_n),\gamma) := \gamma S^\pi_{\text{pros}}(d^*_{\text{pros}}(r_n)) + (1-\gamma) S^\pi_{\text{cons}}(d^*_{\text{cons}}(r_n))$$

Prosumer surplus

Consumer surplus

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.

DESCRIPTION OF CASE STUDIES

#	Name	Tariff	Rate	Compensation ($/kWh)	Fixed Charges	Discrimination‡
1	NEM 1.0	one-part	IBR*	$\pi^- = \pi^+$	–	No
2	NEM 2.0	one-part	ToU§	$\pi^- = \pi^+ - 0.03$	–	No
3	NEM SMC	one-part	ToU	$\pi^- = \pi^{smc}$	–	No

* Similar to PG&E, IBR has two blocks, with a 20% higher price for above baseline usage.
§ 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.

Performance measures

- Social welfare:

$$\sum_{n=1}^{N} \mathbb{E}\Big(\underset{\text{\% of prosumers}}{\gamma} \underbrace{S^{\pi}_{\text{pros}}(d^*_{\text{pros}}(r_n))}_{\text{Prosumer surplus}} + (1-\gamma) \underbrace{S^{\pi}_{\text{cons}}(d^*_{\text{cons}}(r_n))}_{\text{Consumer surplus}} + \gamma \underbrace{\mathcal{E}(r_n)}_{\text{Environmental surplus}} \Big)$$

- Cost shifts:

$$\psi^{\pi}_{\gamma} = \sum_{n} \gamma \mathbb{E}\big(\underbrace{\Delta P^{\pi}(r_n)}_{\text{Prosumer bill saving}} - \pi^{\text{SMC}} r_n \big) \qquad \Delta P^{\pi}(r_n) := P^{\pi}(1^{\intercal}\mathbf{d}^*_c) - P^{\pi}(1^{\intercal}\mathbf{d}^*_p(r_n) - r_n).$$

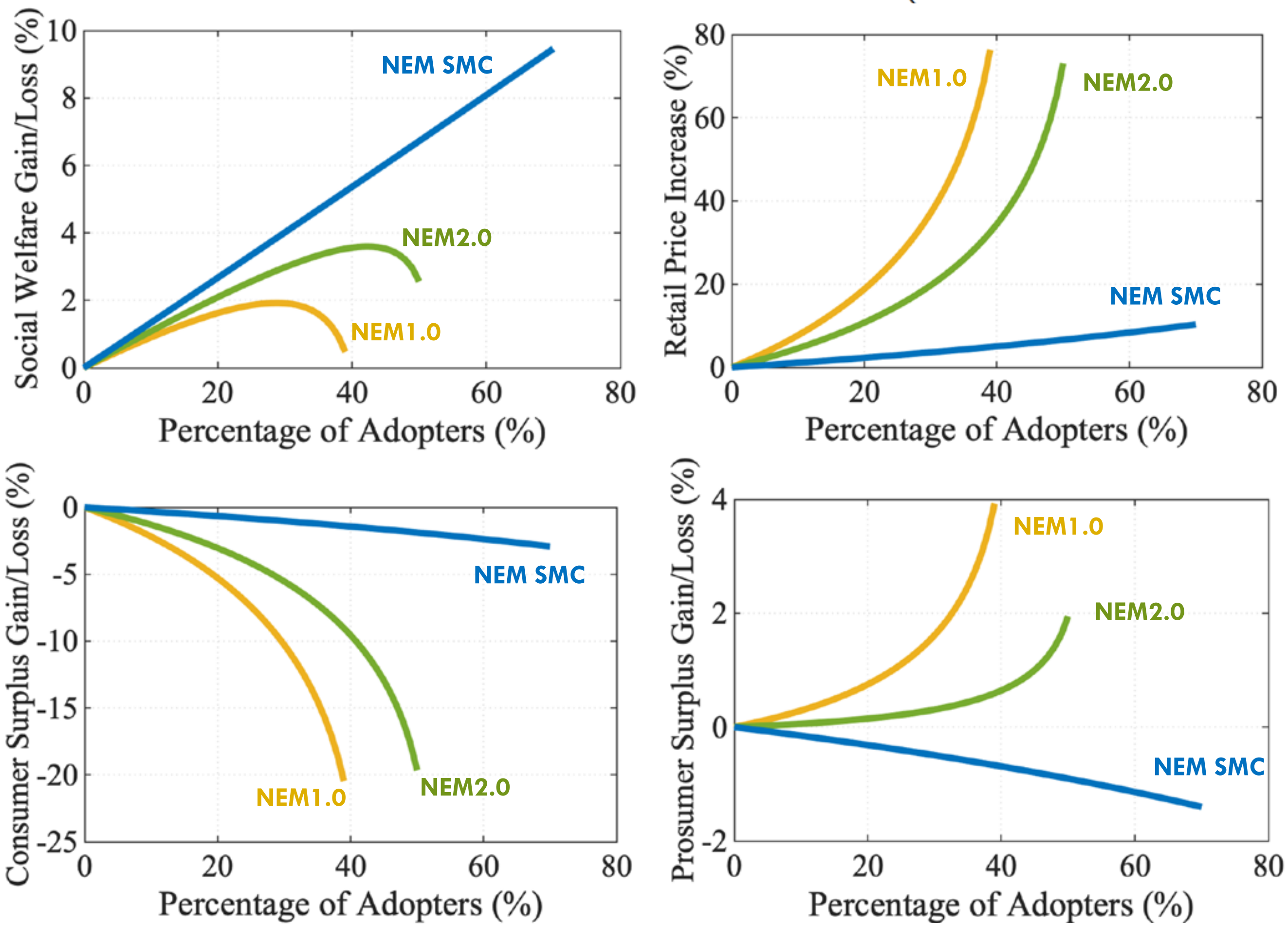
- Payback time:

$$t^{\pi}_{\text{PB}}(r,\xi) = \min_{t^*} \Big\{ t^* : \sum_{t=0}^{t^*} \Big(\frac{1-\nu}{1+\zeta} \Big)^{t} \mathbb{E}(\Delta P^{\pi}_t(r_t)) \geq \underbrace{\xi}_{\text{DER costs}} \Big\}$$

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

Short-run social welfare

$$\sum_{n=1}^{N} \mathbb{E}\Big(\gamma \underbrace{S^{\pi}_{\text{pros}}(d^{*}_{\text{pros}}(r_n))}^{\text{Prosumer surplus}} + (1-\gamma) \underbrace{S^{\pi}_{\text{cons}}(d^{*}_{\text{cons}}(r_n))}^{\text{Consumer surplus}} + \gamma \underbrace{\mathcal{E}(r_n)}^{\text{Environmental/health}} \Big)$$



Key parameters:

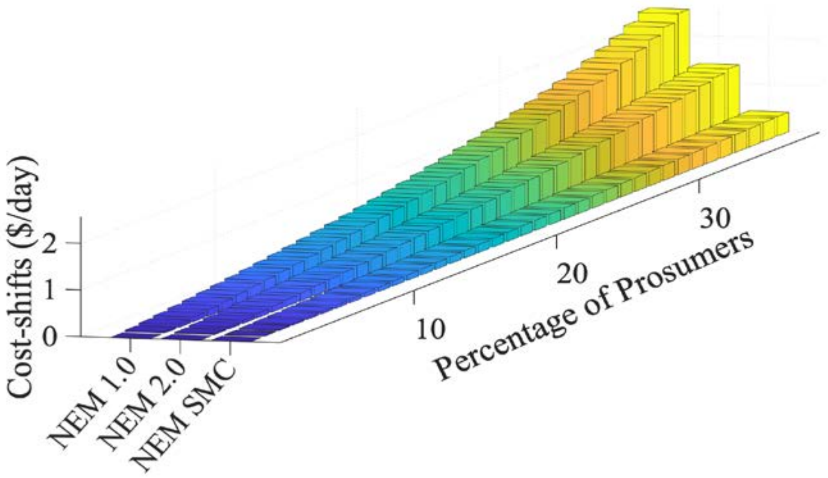
- SMC: \$0.08/kWh

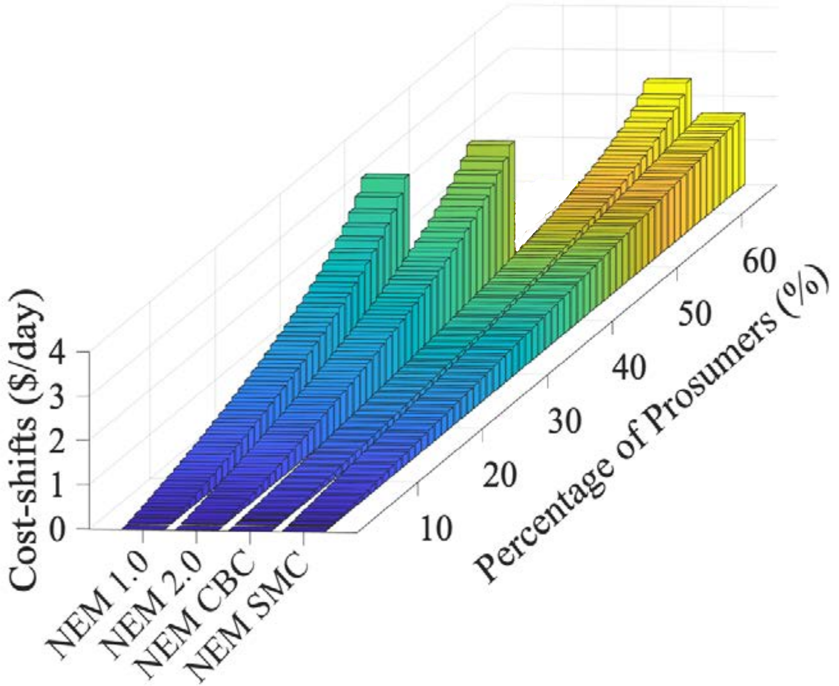
Borenstein-Fowlie-Sallee, "Designing electricity rates for an equitable energy transition, Energy Institute WP 314, Feb. 2021

- 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

Short-run cost shifts





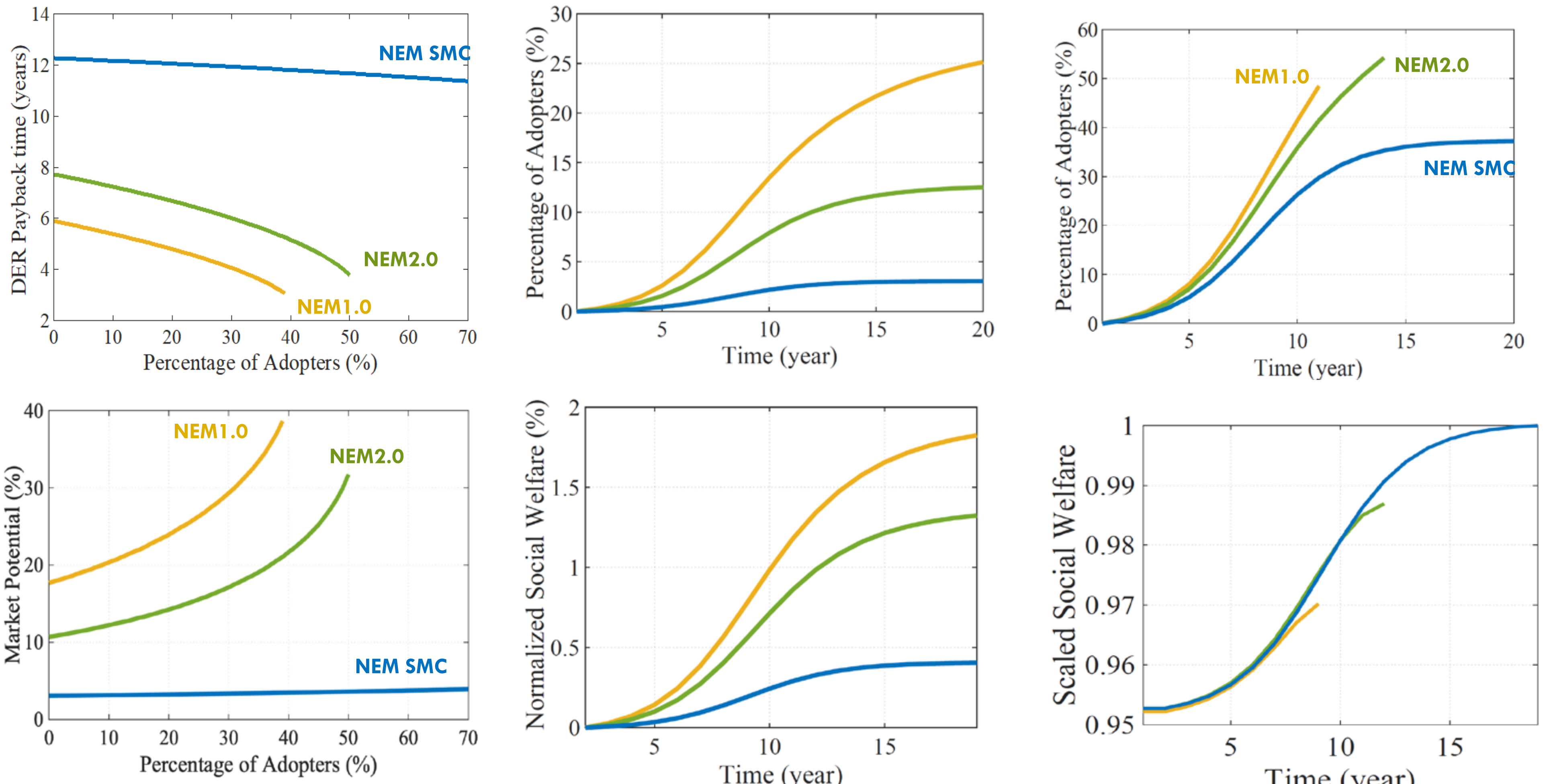
Prosumer bill saving

- Cost shifts: $\psi_\gamma^\pi = \sum_n \gamma \mathbb{E}\left(\Delta P^\pi(r_n) - \pi^{\text{SMC}} r_n\right)$

$$\Delta P^\pi(r_n) := P^\pi(\mathbf{1}^\intercal \mathbf{d}_c^*) - P^\pi(\mathbf{1}^\intercal \mathbf{d}_p^*(r_n) - r_n).$$

Prosumer population	5%	15%	25%	35%	45%	55%	65%
NEM 1.0	0.18	0.72	1.46	2.71	–	–	–
NEM 2.0	0.14	0.54	1.04	1.74	3.01	–	–
NEM CBC	0.06	0.22	0.40	0.62	0.89	1.31	2.37
NEM SMC	0.09	0.30	0.53	0.78	1.03	1.31	1.6

Payback time, market potential, and long run DER adoption



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.