Empirical Methods for the Analysis of the Energy Transition

Slide Set 9

Prof. Mar Reguant

2025/2026

Barcelona School of Economics

Roadmap

Inequity of energy climate policies

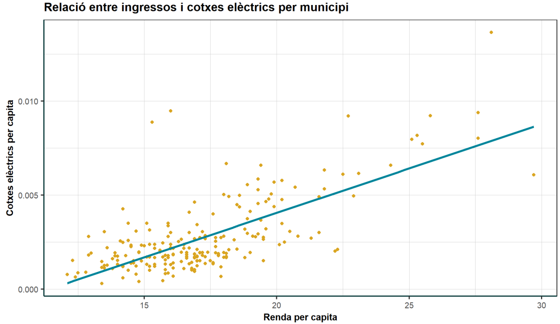
The case of rooftop solar

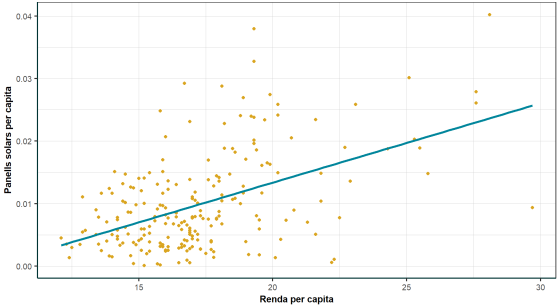
Practicum: net-metering and rooftop solar

The energy transition and its equity impacts

- The energy transition can have substantial impacts on households that can be highly heterogeneous.
- Example: Rich households have easier access to solar and batteries. Net-metering of solar can leave poorer households stranded without policy action.
- Uneven impacts combined with climate change impacts:
  - Households most exposed to extreme events tend to have the lowest income (poor building construction and insulation, heat islands).
  - Also least able to adapt and upgrade with resilience equipment (solar + backup battery, solar + EV as battery).

Example: adoption of EV and solar in Catalonia





Source: Enrich and Reguant, 2023. "Efectes distributius de la transició energètica: reptes i oportunitats per a una transformació justa." Nota d'Economia.

Equity impacts can be substantial

The energy crisis is unprecedented and is driving the cost of living crisis. Last October, 4.5 million UK households were in fuel poverty. Now National Energy Action estimates there are 6.7 million. Come April, we are expecting there to be 8.4 million.

Read the latest policy briefing here

Across the UK, **cold homes are already damaging the lives of the poorest households**.

After Days Of Mass Outages, Some Texas Residents Now Face Huge Electricity Bills

February 21, 2021 · 12:01 PM ET

REBECCA HERSHER

Equity impacts can be devastating

Excess deaths could rise as vulnerable skimp on heating, UK charities warn

Freezing temperatures and high energy costs lead to fears that more people will die this year without action

WINTER STORM 2021

At least 111 people died in Texas during winter storm, most from hypothermia

> The newly revised number is nearly twice the 57 that state health officials estimated last week and will likely continue to grow.

BY SHAWN MULCAHY MARCH 25, 2021 4 PM CENTRAL

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Many energy/climate policies tend to be regressive

- Energy policies tend to favor the **highest income quintiles**.
- Electric vehicles and rooftop solar panels are key examples, but this pattern applies more generally.
- While energy expenditure as a share is higher for low-income households, energy expenditure in levels grows with income.
- Additionally: credit constraints, tax credits, real estate ownership, etc.

Many open questions to address efficiency and equity

- Critical need to think about open topics concerning the energy transition that seem highly suited for economists and that touch distributional issues:
  - Equity impacts of non-linear and dynamic pricing during energy transition.
  - Stranded assets and design of tariffs for fixed costs.
  - Competition with dynamic prices and heterogeneous inattentive consumers.
  - Solar panel and battery adoption with credit constraints.
  - Transportation electrification and combustion car phase out.
  - Heterogeneous ability to engage in reliability and resilience.
  - Etc.

Examples of tools/topics in the literature

- Studies focus on different policies/tools and data:
  - Quantification of impacts via detailed tax/purchase data (Davis and Borenstein, 2016 – US energy tax credits; Borenstein, 2017 – solar PV).
  - Comparisons of pricing impacts with micro data and aggregate income/demographic data (Borenstein, 2012 – non-linear pricing; Leslie et al, 2021 – RTP pricing using substation data; Cahana et al, 2022 – RTP pricing using household data).
  - Counterfactual equilibrium model of demand and supply based on household data (Wolak, 2016 – water; Feger et al., 2021, DeGroote and Verboven, 2022 – solar panels).
  - Responses to uneven impacts of energy policies using survey/voting data (Fabre and Douenne, 2022 – Yellow Vests) and electoral data (DeGroote, Gautier and Verboven, 2022 – solar PV).
  - Quantification of the impacts of a carbon tax, looking at the entire system (Metcalf, 2019; Cronin et al., 2019; Paoli and van der Ploeg, 2021),...

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Inequity of energy climate policies

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Practicum: net-metering and rooftop solar

Today: uneven participation to policies meets rooftop solar

- Rooftop solar is a textbook case where climate policy, tariff design, and inequality interact.
- Access to subsidies for renewable power tends to be uneven.
- Additionally, renewable power tends to get favorable electricity tariffs.

- The two create an **advantage to high-income households**.
- It can potentially unravel, the so-called "death spiral": low income households are left behind with the older infrastructure, which becomes more and more costly to maintain per person.

- We will first establish some of these facts and then build the intuition in the model.
- Note: not all papers are strictly about solar.

Inequity channels

- Three elements favor high-income households:
  - **Access channel**: who can adopt
  - **Tariff channel**: who benefits more conditional on adoption
  - **System channel**: who pays when many adopt (”death spiral”)

Borenstein and Davis (2016) - Access channel

- Borenstein and Davis (2016) document tax credits.
- They use tax return data (IRS) to examine characteristics of recipients.
- Results suggest these are highly regressive.
- Plausably more regressive than carbon taxes, although much more popular (to a certain extent).

6

The Distributional Effects of US Clean Energy Tax Credits

Severin Borenstein, *University of California at Berkeley and NBER*
Lucas W. Davis, *University of California at Berkeley and NBER*

Executive Summary

Since 2006, US households have received more than $18 billion in federal income tax credits for weatherizing their homes, installing solar panels, buying hybrid and electric vehicles, and other "clean energy" investments. We use tax return data to examine the socioeconomic characteristics of program recipients. We find that these tax expenditures have gone predominantly to higher-income Americans. The bottom three income quintiles have received about 10% of all credits, while the top quintile has received about 60%. The most extreme is the program aimed at electric vehicles, where we find that the top income quintile has received about 90% of all credits. By comparing to previous work on the distributional consequences of pricing greenhouse gas emissions, we conclude that tax credits are likely to be much less attractive on distributional grounds than market mechanisms to reduce greenhouse gases (GHGs).

Energy tax credits for EVs and solar in the US

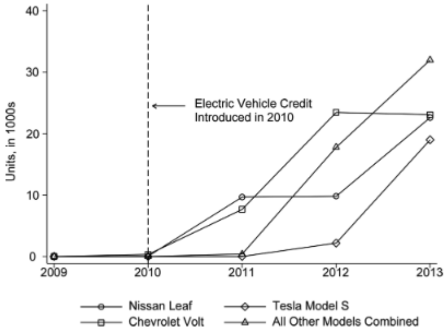


Fig. 4. US Sales of Electric and Plug-In Hybrid Vehicles

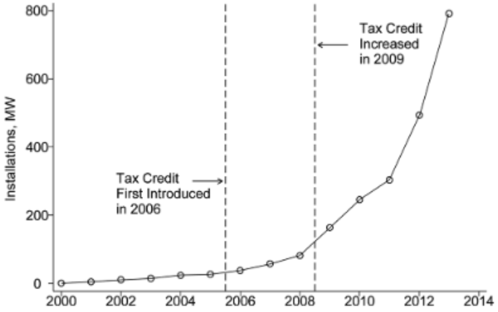


Fig. 2. US Residential Installations of Solar Panels by Year

Evolution of overall spending

- Paper focuses on a period of large energy programs via the American Recovery and Reinvestment Act (Recovery Act).
- Large programs to **subsidize energy efficiency** (windows, furnances, heat pumps), solar panels and alternative vehicles.
- Over $18 billion over the period of study on residential-focused subsidies alone.

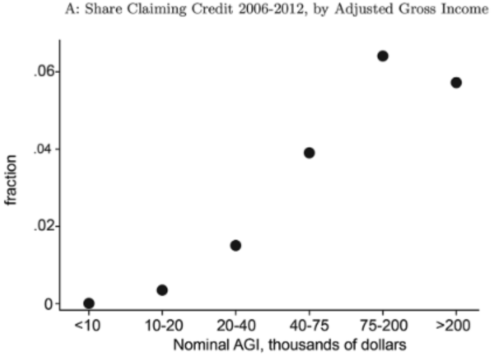
Table 1
Annual Expenditures on US Clean Energy Tax Credits, in Millions

Year	Windows and Other Energy-Efficiency Investments (NEPC) ($)	Solar Panels and Other Residential Renewables (REEPC) ($)	Hybrids and Other Alternative Fuel Vehicles (AMVC) ($)	Electric and Plug-In Hybrid Vehicles (PEDVC) ($)
2005	0	0	0	0
2006	957	43	50	0
2007	938	69	185	0
2008	0	217	49	0
2009	5,177	645	137	129
2010	5,420	754	93	1
2011	755	921	14	76
2012	449	818	20	139
Total	13,696	3,467	549	346

Sources: This table was constructed by the authors using US Department of the Treasury, Internal Revenue Service, "Statistics of Income, Individual Tax Returns," 2005–2012 and US Department of the Treasury, Internal Revenue Service, "Individual Income Tax Returns Line Item Estimates," 2005–2012.
Notes: See appendix for details. Tax credits across all four categories totaled $18.1 billion between 2005 and 2012.

Distributional analysis: access

- Thanks to the very **detailed micro data** from the US Treasury (IRS), authors can document that adoption of energy tax credits is very low by low income households.
- Due to the nature of these tax credits, some of these tax credits cannot be accessed by low income households.
- This is in addition to several other barriers (credit constraints, renter status, etc.).



Distributional analysis: concentration curves

- Authors also compute concentration curves of transfers of energy tax credits.
- x-axis: income / y-axis: transfers.
- Concentration is very large, and much larger than the distribution of income (annual gross income or AGI).
- Figure: example from EVs.

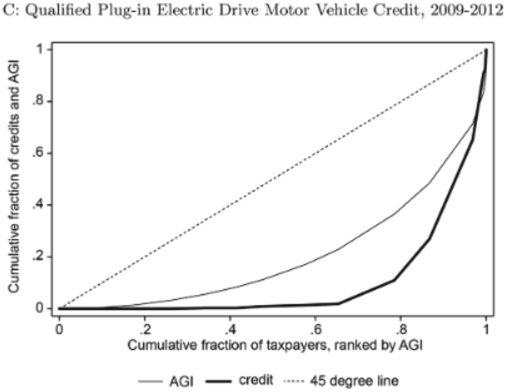
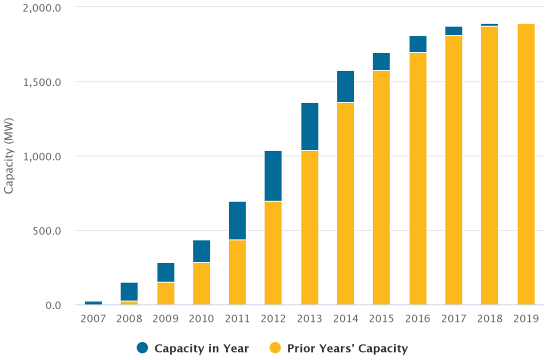


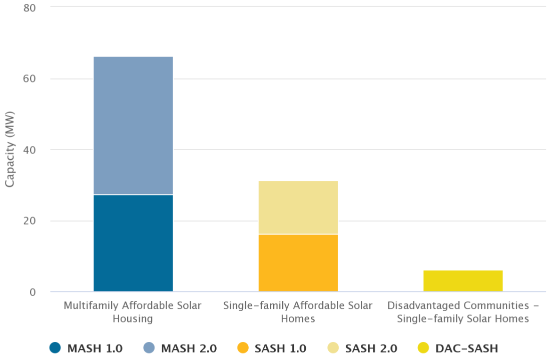
Fig. 7. Concentration Curves

How to deal with uneven access?

- Many policies try to now explicitly **target low-income households**.
- Example: weatherization assistance program (WAP), community solar programs.
- In practice, difficult to implement in low-income neighborhoods with high participation costs and limits on ability to directly benefit from program (e.g., renters).
- Need to pool across several housing units also makes practical implementation harder (e.g., community solar rooftop: problems with community agreements, also with bureaucracy, limits on property tax credits, etc.).

Solar PV in California: low-income focus?





Source: California Distributed Generation Statistics, https://www.californiadgstats.ca.gov/.

Access remains an important channel in rooftop solar equity concerns.

Borenstein (2017) - Tariff channel

- Paper studies the distributional impacts of solar PV in the PG&E territory.
- It uses detailed billing data with solar panel installation and production data to quantify adoption and winning by income quintiles (Census block group). Also, limited hourly consumption data for a sample of households.
- Paper computes the relevance of rate design in effective solar PV adoption.

Private Net Benefits of Residential Solar PV: The Role of Electricity Tariffs, Tax Incentives, and Rebates

Severin Borenstein

Abstract: With dramatic declines in the cost of solar PV technology since 2010, the electricity industry is in the midst of debates about whether to use this low-polluting renewable energy source in grid-scale generation or in distributed rooftop generation (DG). California has led the growth in DG solar in the United States. I use 2007 to early 2014 residential data from Pacific Gas & Electric—the utility with the largest number of residential solar customers in the United States—to examine the full range of private incentives for installing residential solar, from direct rebates and tax credits to indirect incentives that result from the residential tariff design and the crediting of solar production under "net energy metering." I then study the income distribution of solar adopters and how that has changed over time. I find the skew to wealthy households adopting solar is still significant but began to lessen after 2011. Adoption continued to be dominated by the heaviest electricity-consuming households, probably because the steeply tiered tariff structure greatly increased the private value of solar to such customers while reducing the incentive for consumers who are below median consumption. In fact, the financial incentive for those who actually adopted solar over the sample period may have been due nearly as much to California's tiered tariff structure as to the 30% federal tax credit. The California experience suggests that rate design can greatly influence the economic incentives for residential solar adoption and which customers receive those benefits.

JEL Codes: L94, Q42, Q58

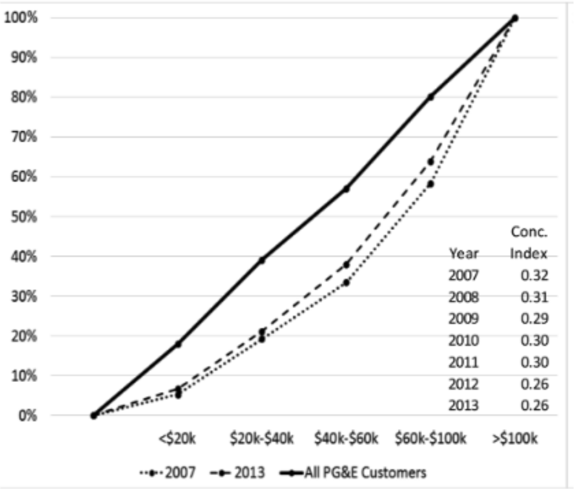
Keywords: Alternative energy, Distributed generation, Energy subsidies

What does the paper do?

- **Question**: To which extent is net-metering a subsidy to solar adoption? How does it relate to income?
- **Data**: Monthly billing data for the three largest utilities in California (PG&E, SCE, SDG&E), social bonus status (CARE), median and mean income at the Census block group level (precise, small neighborhood area, but not individually).
- **Method**: Ecological methods to bound redistributive impacts under assumption of perfect sorting (higher consumption $\rightarrow$ higher income) vs. no sorting vs. weighted based on survey data (most realistic).
- **Findings**: Net-metering can be as large of a subsidy as the subsidies themselves!

Concentration indices

- Concentration curves show a higher concentration of adoption in high-income categories.



CSI Customers

Factors making solar very attractive in California

- Federal tax credit
- Accelerated Depreciation Value (if under lease)
- State subsidies (CSI program)
- Good solar radiation
- High electricity prices
- Rate structure (net-metering)

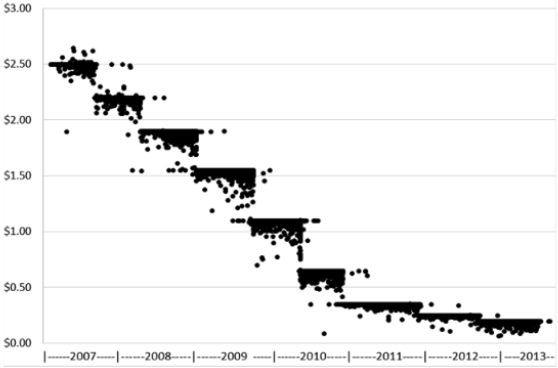


Figure 1. CSI rebate (per Watt of rated capacity) paid under PG&E program

What is net-metering (NEM)?

- Under NEM, households will get the energy produced from their solar panels subtracted from their demand.
- They are only charged for their net demand, e.g., at the monthly level.
- Traditionally, energy-based, so the implicit price for solar power is the **retail price.**
- Due to non-linear pricing, net-metering is more attractive to high energy users, which on average, are higher income.

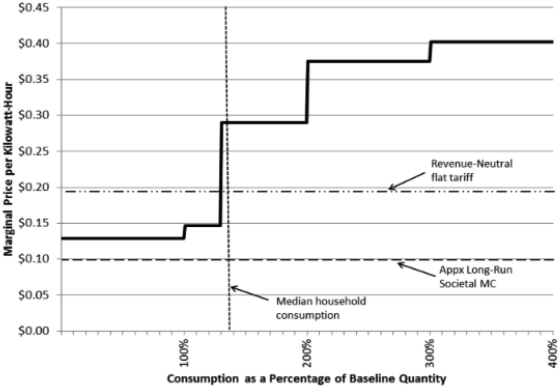


Figure 2. Average PG&E increasing block pricing tariff during 2007–13

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NEM can be a substantial subsidy

- Under traditional NEM expected the net present value (NPV) of solar panels can be much larger.
- This is due to the fact that the retail energy prices can be much larger than the marginal cost of electricity.
- In California, there were **no fixed fees**: all the distribution network is paid via retail prices that are proportional to electricity consumption.

Table 2. Average Bill Savings under Alternative Tariffs for All PG&E Residential Solar

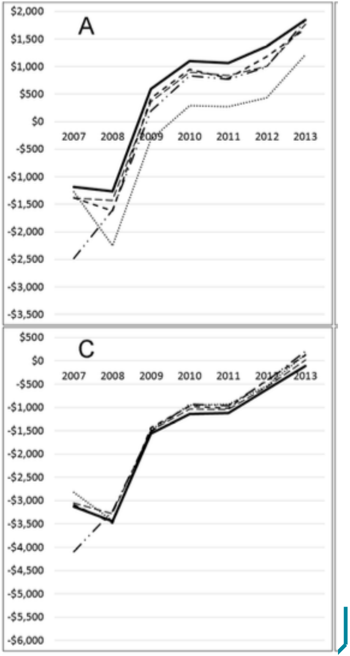
			NPV of 25-Year Electricity Bill Savings ($)			
Year	Obs.	Capacity (kW)	IBP with Monthly NEM	IBP with Hourly NEM	Flat Rate ($.19/kWh)	MC ($.10/kWh)
2007	5,601	3.67	20,965	18,223	14,576	7,650
2008	5,701	3.73	21,628	18,612	14,829	7,783
2009	8,393	4.00	23,338	19,794	15,943	8,368
2010	9,110	4.42	26,270	22,167	17,634	9,255
2011	11,827	4.02	23,321	19,972	16,017	8,407
2012	15,182	4.17	23,556	20,074	16,630	8,728
2013	25,654	4.46	24,726	21,024	17,793	9,339
2014*	8,411	4.65	25,729	21,789	18,600	9,762

IBP = Increasing block pricing

NEM interacts with income

- Going from traditional NEM to a flat rate per solar output reduces benefits of households.
- It also reduces benefits to higher income households disproportionately more, making differences across households much smaller.

Note: A - Monthly IBP. C - flat tariff. Solid line denotes higher income.



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Feger, Pavanini & Radulescu (2022) - System channel

- Estimates a **structural model** of:
  - household electricity demand, and
  - dynamic rooftop solar adoption.
- Households respond to:
  - volumetric electricity tariffs,
  - fixed grid fees, and
  - solar installation subsidies.
- Uses the model to simulate equilibrium outcomes as solar adoption increases:
  - tariff adjustments needed to recover grid costs,
  - adoption responses,
  - welfare and distributional effects.
- Why a model? Tariff incidence and adoption decisions interact, so partial-equilibrium accounting is no longer sufficient.

Welfare and Redistribution in Residential Electricity Markets with Solar Power

FABIAN FEGER
University of Bern
NICOLA PAVANINI
Tilburg University and CEPR
and
DOINA RADULESCU
University of Bern, KPM, CESifo and Oeschger Center for Climate Change Research

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An increasing number of households installing solar panels and consuming the energy thus produced raises two challenges for regulators: network financing and vertical equity. We propose alternative tariff and subsidy designs for policymakers to incentivize solar panel adoptions and guarantee that network costs are recovered, while trading off efficiency, equity, and welfare motives. We estimate a structural model of energy demand and solar panel adoption, using a unique matched dataset on energy consumption, prices, income, wealth, solar panel installations, and building characteristics for 165,000 households in Switzerland from 2008 to 2014. Our counterfactuals recommend the optimal solar panel installation cost subsidies and two-part energy tariffs to achieve a solar energy target. We show that, relative to installation cost subsidies, relying on marginal prices to incentivize solar panel adoptions is more cost efficient and progressive across the income distribution, but generates a larger aggregate welfare loss.

Key words: Energy, Photovoltaics, Income distribution, Welfare, RDD, Structural estimation

JEL Codes: D12, D31, L94, L98, Q42, Q52

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FPR - When solar adoption scales up: the “death spiral”

- Rooftop solar adoption reduces households’ purchases from the grid.
- But electricity networks have **largely fixed costs**.
- When fewer kWh are sold, **volumetric tariffs must rise** to recover largely fixed network costs.
- Higher retail prices make solar adoption even more attractive.
- This feedback loop is often referred to as the utility **“death spiral”**.

FPR - Data

- Administrative panel data for 135,000 households in the Canton of Bern (Switzerland).
- Annual electricity consumption, prices, and fixed fees from local utilities.
- Matched income and wealth data from tax records.
- Detailed information on rooftop solar adoption and building characteristics.
- Simulated household-level solar production to evaluate counterfactual adoption.

FPR - Main results

- Solar adopters save substantially on electricity bills.
- Non-adopters face rising tariffs as grid costs are reallocated.
- Because adoption is concentrated among higher-income households:
  - the **access channel** is regressive across adopters vs. non-adopters;
  - the **system channel** can appear progressive across income groups on average, since higher-income households consume more electricity and adoption remains limited in the Swiss context.

- Equity conclusions depend on **which margin** we focus on and on the institutional context.
- In settings with higher solar potential and faster uptake, both margins are likely to become regressive (e.g. Spain, California), where death spiral is already playing a major role.

Roadmap

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Practicum: net-metering and rooftop solar

System channel: In vs. out

- Net metering has implications for other households, due to the high cost of this *implicit* subsidy.
- This has led to an evolution of net metering policies in many states and countries.
- We will create a baby simulation of the death spiral.

The New York Times

Nevada's Solar Bait-and-Switch

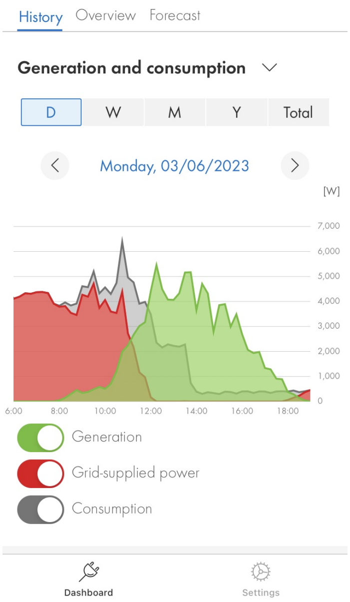
By Jacques Leslie

Feb. 1, 2016

Give this article

A growing challenge

- Demand of electricity is not always well timed with solar production.
- Net-metering is equivalent to assuming that we produce electricity when we need it.
- With few customers, this might be manageable.
- However, with more and more households, one needs to properly incentivize consumption at the right time (or promote battery adoption).



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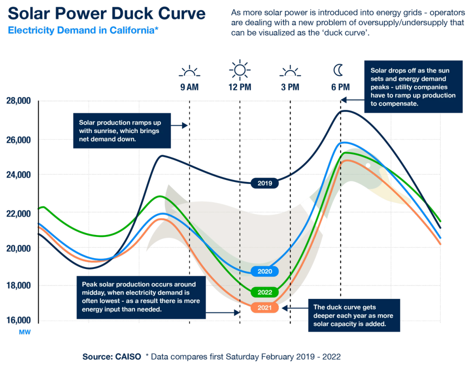
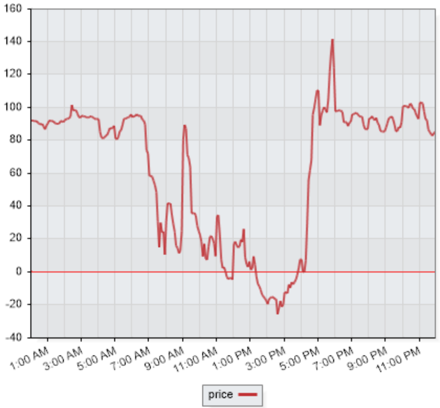
The duck curve and wholesale market prices





What is the “correct” NEM policy?

- With the duck-curve effect, traditional net-metering (NEM) subsidies tend to be even larger (as consumer retail prices are typically not real-time).
- More and more, NEM policies tend to separate self-consumption of solar power vs. “mismatched” consumption of solar power.
- This distinction is enabled by smart meters, as traditionally the old-fashioned NEM was the easiest.
- **Updated NEM**:
  - If self-consumption, it cancels demand and it tends to cancel retail price obligation (or something close to it).
  - If pouring it into the grid (“mismatched”), household receives a different price, based on retail competitive offers, wholesale day-ahead or real-time prices, or regulated “avoided cost.”

NEM payoffs

- **1.0**
  - Pay and receive a constant high retail price p^r for consumption or generation.

$$Bill = p^r \sum_t (d_t - q_t),$$

  where d_t is demand, q_t is solar output.

- **2.0**
  - Receive retail price only if consumption is coincidental.
  - Receive wholesale price p^w for non-coincidental demand if they produce in excess.

$$Bill = \sum_t \Big((1(d_t - q_t \geq 0)p^r + 1(d_t - q_t < 0)p^w \Big)(d_t - q_t)$$

  - Households receive high p^w if they are net-producing: an incentive to consumption shifting or battery adoption.

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Practicum goals

- We will model self-consumption and solar output of residential households.
- We will add grid costs to the model
- We will examine the value of solar power with different forms of NEM.

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Let's practice.

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