Measuring Prosumer Welfare: Modelling Household Demand for Distributed Energy Resources and Residual Electricity Supply

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Introduction

- New technologies like photovoltaic (PV) solar panels and home-scale batteries (including electric vehicles, EVs) – collectively, "distributed energy resources" (DERs) – have the potential to transform electricity systems:
  - Increasingly wide-spread decentralisation of generation capacity, and/or network bypass;
  - La Nauze (2018) – Germany and California PV penetration at 5% of dwellings, Australia at 15%.
- Households with DERs might optimally remain "on-grid":
  - DER owners could become "prosumers" – buying from existing energy suppliers or transporters, or competing with or complementing them.

Introduction (cont'd) – California Solar Share

Table A1: California Generation by Fuel

	Year			
Fuel	2013	2014	2015	2016
Coal	0.4%	0.4%	0.2%	0.2%
Large Hydro	10.2%	6.9%	5.9%	12.3%
Natural Gas	60.6%	61.1%	59.7%	49.9%
Nuclear	8.9%	8.5%	9.4%	9.6%
Oil	0.02%	0.02%	0.03%	0.02%
Petroleum Coke	0.1%	0.1%	0.1%	0.1%
Waste Heat	0.1%	0.1%	0.1%	0.1%
Biomass	3.3%	3.4%	3.2%	3.0%
Geothermal	6.3%	6.1%	6.1%	5.8%
Small Hydro	1.9%	1.4%	1.2%	2.3%
Solar PV	1.9%	4.6%	6.6%	8.7%
Solar Thermal	0.3%	0.8%	1.2%	1.3%
Wind	6.0%	6.6%	6.2%	6.8%

Annual California generation by fuel source is provided by the California Energy Commission (`http://www.energy.ca.gov/almanac/electricity_data`).

From Bushnell and Novan (2018), *Setting with the Sun: The Impacts of Renewable Energy on Wholesale Power Markets*.

Introduction (cont'd)

- Example – *self-consuming* from PV generation or batteries/EVs if power prices are low:
  - But *selling* energy – e.g. on P2P platforms to other households – when prices are high, during network outages, etc.
- Parallel – forest-owners operating in an ETS environment (i.e. facing carbon prices):
  - "Lumberjacks" when log prices are "high" relative to NZU prices; and
  - "Carbon farmers" when reverse is true.

Motivation – Possible Competition/Regulation Benefits

- DER penetration might relieve/resolve historical competition or regulatory issues, e.g. *uptaking* households:
  - Becoming less reliant on network services – less exposed to excessive pricing or inadequate quality;
  - Providing network reliability services or otherwise reducing peak network demands – potentially an uncompensated positive externality;
  - Introducing downstream competition that *offsets* competition losses from upstream mergers – or *induces* such mergers ...

Unclear Welfare Impacts

- Welfare impacts could hinge critically on who owns or controls DERs, with different trade-offs depending on whether they are owned by:
  - Households – inefficient entry and/or failure to internalise positive/negative externalities?
  - "Monopoly" lines companies – do DERs complement or substitute for network services, does existing price regulation over/under-induce uptake, incentives for strategic "blocking"?
  - Generators or retailers – distinguishing vertically-integrated from stand-alone in each case:
    - Do DERs complement networks but substitute for generation, or complement peaking capacity, ...;
  - Telcos, Amazon ...

Research Gap

- Studies on welfare, regulatory and strategic impacts of DERs are few, and make limiting assumptions, e.g.:
  - Sioshansi (2014) – assumes linear electricity demand;
  - Munoz-Alvarez et al. (2017) – model welfare effects of different assignments of DER ownership, but limited micro foundations;
  - Feger et al. (2017) – examine redistribution effects of DERs, but assume electricity consumption directly enters utility; and
  - De Groote and Verboven (2018) – model DER choice in terms of present value of cost savings, but without jointly modelling DER impact on energy demand and DER uptake.
- La Nauze (2018) shows DER income impacts valued differently to general income changes – provides behavioural interpretations.

Research Gap (cont'd)

- Very limited research on *prosumerism* per se – we know about "household production", but not like this ...
- Dubin and McFadden (1984) and Davis (2008) analyse households' choices of electric appliances, and the resulting demand for electricity:
  - However, they consider only energy-*consuming* appliances;
  - What changes when "appliances" can increase income, not just affect unit costs through changing efficiency?
- No systematic study of how DERs affect both (residual) electricity demand *and* demand for DERs themselves.

Contribution

- I systematically model a household's choice to invest in DERs, anticipating how DERs affect *derived* electricity demand:
  - I also derive expressions for gross and net (i.e. of self-generation) electricity demand – at household and market level – conditional on such DER investments.
- Using these expressions, I directly derive un/conditional welfare – allowing for some electricity consumers to never invest in DERs:
  - Useful for assessing redistributive impacts of regulation or policy, including climate change policy, ...
- These provide the necessary foundations for proper, micro-founded theoretical IO analyses of DERs, and in ways that can also be taken to data ...

Framework – Household Production

- I extend the seminal "household production" models of Becker (1965) and Lancaster (1966):
  - Treat electricity demand as a *derived* demand – i.e. derived from households' demand for good or services requiring electricity as an input.
- I also extend the "discrete-continuous" approach of Dubin and McFadden (1984) and Davis (2008):
  - *Discrete* choice re DERs, then *continuous* choice re how much to use them; and
  - Allow for DERs to relax the household's budget constraint, as well as change relative prices.

Household Production (cont'd)

- Standard microeconomics tells us that consumers (e.g. households) consume the bundle of goods or services:
  - That gives them the most satisfaction ("utility"); and
  - Which they can afford, given their income and the prices of those items (i.e. their "budget constraint").

Household Production (cont'd)

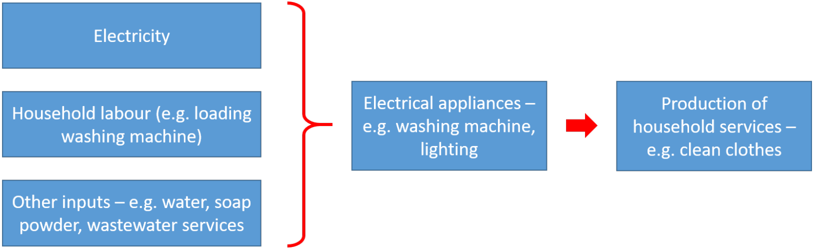
- Seminal "household production" models take a different approach:
  - Becker (1965), *A Theory of the Allocation of Time* – general theory for how households allocate non-work time, including time constraint as well as budget constraint;
  - Lancaster, (1966), *A New Approach to Consumer Theory* – supposes households' "utility" derives from "characteristics" produced by underlying goods and services:
    - Conceives of consumer durables (e.g. electrical appliances) as producing a stream of time-specific "characteristics".

Household Production (cont'd)

- Kerkhofs and Kooreman (2000, pp 1-2), *Identification and Estimation of a Class of Household Production Models*:

  "preferences of a household are not defined in terms of quantities of goods and non-labour time, but rather in terms of activities or household products that are produced with the aid of these goods and time endowments."

Household Production – Example



Household Production – Electric Appliances

- The demand for electricity is therefore a *derived* demand – i.e. derived from households' demand for these other goods or services.
- Dubin and McFadden (1984), *An Econometric Analysis of Residential Electric Appliance Holdings and Consumption*, formally analyse households' choice of electric appliances (form of consumer durables), and the resulting demand for electricity:

  "Economic analysis of the demand for consumer durables suggests that such demand arises from the flow of services provided by durables ownership. The utility associated with a consumer durable is then best characterized as indirect."

Household Production – Electric Appliances (cont'd)

- Households face a "discrete-continuous" choice:
  - Firstly, the *discrete* number and types of appliances to purchase;
  - Secondly, the *continuous* consumption of electricity-consuming services (e.g. hours of TV to watch), depending on their appliance choices:
- Reflects not just their preferences for electricity-consuming services, but also appliance characteristics – e.g. efficiency, size/output rating, etc.
- Electricity demand is therefore not just a derived demand, it is also *conditional* – i.e. conditional on the household's choice of which appliances to buy/install, as well as how to use them.

Household Production – Electric Appliances (cont'd)

- Davis (2008, p. 530), *Durable Goods and Residential Demand for Energy and Water: Evidence from a Field Trial*, notes the risk of "rebound effects" with efficiency-enhancing investments:

  "Between 1972 and 2001, average gasoline consumption per mile for new automobiles decreased 49% and average electricity consumption of central air conditioners and refrigerators decreased 44% and 56%, respectively. Despite these innovations, energy consumption per capita in the United States decreased only 3% during the same period.

  "One reason for the small decrease is that households in 2001 were driving more, keeping their homes cooler in the summer, and owning larger refrigerators. In part, these changes in utilization were a reaction to the efficiency improvements. ***Improvements in energy efficiency decrease the price of using durable goods which may lead to higher utilization****." [emphasis added]*

Setup – Timing

- Timing is as follows:
  1. At some point in the past, household (i) chooses its stock of appliances Φ:
     - Hence appliance choices are treated as exogenous;
  2. (Conditional on Φ), household chooses its (discrete) preferred DER capacity K;
  3. Conditional on K (and Φ), household chooses its utility-maximising mix of (continuous):
     - Electricity-consuming household services (z_1); and
     - Other good and services (composite good, z_2).

Household's Problem

- Writing indirect utility as $V(.)$, household chooses DER capacity K_j as follows:

$$\max_{j \in 1,\ldots J} \{V(K_1;\Phi),\ldots,V(K_J;\Phi)\}$$

- In turn, with electricity demand x and price p, DER rental rate r and "productivity" factor γ, and exogenous household income y, $V(.)$ solves:

$$V(K_j;\Phi) = \max_{\{x,z_2\}} U(z_1,z_2)$$

subject to:

$$z_1 = f(x;\Phi)$$

$$p(x-\gamma K_j)+1\cdot z_2 = y - rK_j \quad \text{(i.e. net metering, P2P, ...)}$$

Solution – Electricity Demand

- I start with general case, and then solve two specific cases:
    - *Quasi-linear preferences* – simple, but less informative (since suppresses income effects); and
    - *Cobb-Douglas utility* – preserves income effects, and log-form solution "plays nice" with logit model for K choice.
- First present general case, then focus on Cobb-Douglas.

General Case: Total and Net Demand

- Household's maximisation simplifies after substituting constraints:

$$V(K_j;\Phi) = \max_{x} \; U(f(x;\Phi), y - rK_j - p(x - \gamma K_j))$$

- Household's *total/gross* electricity demand – conditional on K_j (and Φ) – is $x^*(p, y; K_j, \Phi)$ is thus defined implicitly by:

$$U_1'(x; p, r; K_j, \Phi, y, \gamma) f'(x;\Phi) - U_2'(x; p, r; K_j, \Phi, y, \gamma) p = 0$$

- The household's *net* conditional electricity demand X^* from *external* suppliers (i.e. market-facing demand) is:

$$X^*(p, r; K_j, \Phi, y, \gamma) = x^*(p, r; K_j, \Phi, y, \gamma) - \gamma K_j \quad \lesseqgtr 0$$

General Case – Market-Level Net Demand

- With mass M of consumers, proportion θ of whom cannot install DERs, the *market-level* conditional demand for *supplied* electricity $\tilde{X}^*$, as faced by other suppliers, is:

$$\tilde{X}^*(p, r; M, \theta) = M\theta \int x^*(.)\, dF_y(y)\, dF_\Phi(\Phi) + M(1-\theta) \int X^*(.)\, dF_y(.)\, dF_\Phi(.)\, dF_K(.)\, dF_\gamma(.)$$

General Case – Conditional Welfare

- Finally, adopting a standard utilitarian framework, social welfare – conditional on household DER investment – can be defined in terms of the utility provided by total conditional electricity demand as:

$$W(p,r;M,\theta) = M\theta \int U^*(.)\, dF_y(y)\, dF_\Phi(\Phi) + M(1-\theta)\int U^*(.)(p,y;\Phi)\, dF_y(.)\, dF_\Phi(.)\, dF_K(.)\, dF_\gamma(.)$$

where:

$$U^*(.) \equiv U\left(f\left(x^*(.);\Phi\right), y - rK_j - p\left(x^*(.) - \gamma K_j\right)\right)$$

Cobb-Douglas Case

- To operationalise this so we have tractable demand expressions (and can use them to solve for DER demand), suppose:

$$z_1(x;\Phi) = \Phi^{\alpha} x^{1-\alpha}$$

and

$$U(z_1(x;\Phi), z_2(x;K_j)) = \beta \, ln\left(\Phi^{\alpha} x^{1-\alpha}\right) + (1-\beta)\, ln\left((y - rK_j) - p(x - \gamma K_j)\right)$$

- Assume $\alpha, \beta \in [0,1]$.

Cobb-Douglas Case – Demand

- Conditional derived demand for electricity is then:

$$x^*(p, r; K_j, \Phi, y, \gamma) = \frac{\beta(1-\alpha)}{1-\alpha\beta}\left[\gamma K_j + \frac{(y - rK_j)}{p}\right]$$

- K_j plays offsetting roles in a household's utility-maximising conditional derived demand for electricity:
    - Reduces effective purchasing power due to DER rental charge rK_j;
    - But causes demand contraction at all prices, γK_j, due to being able to self-generate that amount at zero marginal cost.
- Find that $x^*(.)$ is increasing in K_j and decreasing in r, but only decreasing in p if $y > rK_j$.

Cobb-Douglas Case – Indirect Utility

- After some algebra, it can be shown that the IUF takes the following convenient form, where A does not depend on K_j:

$$V(p, r; K_j, \Phi, y, \gamma) = A - (\alpha\beta - 1)\, ln((\gamma p - r)\, K_j + y)$$

- This proves useful later, when deriving choice probabilities for K_j:
  - Terms such as A which do not depend on K_j are eliminated when a given household compares indirect utilities from different K_j choices.

DER Choice

- Anticipating household (i's) electricity demand given DER capacity, how do they choose that capacity?
- WLOG, consider the (discrete) choice between $K_{i1} = 0$ and $K_{i2} = \hat{K}$, and write our Cobb-Douglas IUF as:

$$V_{i1} \equiv V_i\left(p, r; K_{i1} = 0, \Phi_i, y_i, \gamma_i\right) = A_i - (\alpha\beta - 1)\, ln\left(y_i\right) + \varepsilon_{i1}$$

$$V_{i2} \equiv V_i\left(p, r; K_{i2} = \hat{K}, \Phi_i, y_i, \gamma_i\right) = A_i - (\alpha\beta - 1)\, ln\left(\left(\gamma_i p - r\right)\hat{K} + y_i\right) + \varepsilon_{i2}$$

- Assume unobservable (to the econometrician) indirect utility $\varepsilon_{ij} \sim$ Type I Extreme Value, so $\varepsilon_{i1} - \varepsilon_{i2} \sim$ logistic.

DER Choice (cont'd)

- Using standard approach in discrete choice literature (e.g. Train (2009)), the probability that household i chooses $K_{i2} = \hat{K}$ is:

$$P_{i2} = \frac{1}{1 + e^{\alpha\beta - 1}\left(1 + \frac{(\gamma_i p - r)\hat{K}}{y_i}\right)}$$

- Hence, aggregating over those $(1-\theta)$ of mass M of households who can install DERs, total DER demand is:

$$K^*(r; M, \theta) = \int \frac{M(1-\theta)}{1 + e^{\alpha\beta - 1}\left(1 + \frac{(\gamma_i p - r)\hat{K}}{y_i}\right)} dF_y(y)\, dF_\gamma(\gamma)$$

- Find that $K^*(.)$ *increasing* in r, and *decreasing* in p, if $\gamma p > r$ – opposite of quasi-linear case.
- Can use this to now compute *unconditional* welfare, take it to data, or do some applied theory work ...

Example Application – Monopoly DER Supply

- A monopolist DER supplier's profit function writes as:

$$\Pi^{M}_{DER}(r) = K(r)(r-c) - F$$

- Using $K(r)$ for the simpler quasi-linear case, this writes as:

$$\Pi^{M}_{DER}(r) = \int \frac{M(1-\theta)(r-c)}{1+e^{-(\gamma_i p - r)K}} dF_{\gamma}(\gamma) - F$$

- We can now coherently assess the impacts of r, p, γ (etc) on a monopolist DER supplier's strategic choices ...

Conclusions (cont'd)

- This analysis provides micro-founded tools for analysing both DER demand and the impact of DERs on electricity demand/markets.
- These tools are intended to facilitate both empirics and theory, e.g.:
  - What is expected DER demand for different types of household, is welfare increasing or decreasing in DER uptake;
  - How do DERs affect decarbonisation, allowing for endogenous demand and uptake responses;
  - What are the antitrust or regulatory implications of DERs being owned by different parties; and
  - How will DER uptake affect the welfare of uptakers and non-uptakers – once firms' electricity price responses are accounted for?

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