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.

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 if 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

- Very few studies on welfare, regulatory and strategic impacts of DERs – those studies there are 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 that 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 – 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.

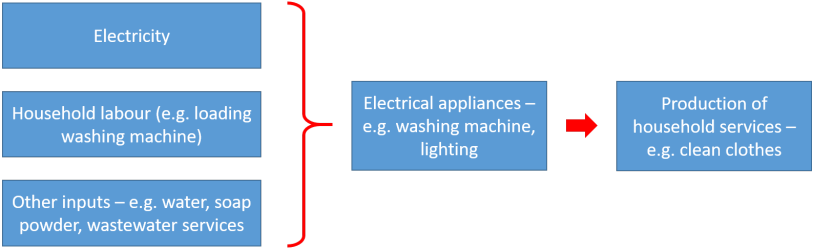
Contribution

- 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 – Example



Electricity

Household labour (e.g. loading washing machine)

Other inputs – e.g. water, soap powder, wastewater services

Electrical appliances – e.g. washing machine, lighting

Production of household services – e.g. clean clothes

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 preferred DER capacity K;
  3. Conditional on K (and Φ), household chooses its utility-maximising mix of:
     - 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:

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

- 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 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:

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

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:

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

and

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

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

Cobb-Douglas Case – Demand

- Conditional derived demand for electricity is then:

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

- 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:

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

- 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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