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

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Introduction

- Work grew out of an escapee thesis chapter, and some preliminary modelling done for ERANZ in course of producing White Paper on electricity regulation:
  - Disclaimer – this work does not purport to represent the views of ERANZ or its members.
- 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:
  - Potential for wide-spread decentralisation of generation capacity, and/or network bypass – consumers going fully or partially "off-grid".

Prosumerism

- More likely, household-level and "aggregated" DER investments will remain "on-grid":
  - DER owners will at various times either compete with, or complement, existing energy suppliers or transporters.
- Provides important example of "prosumerism":
  - Parties conventionally thought of as "consumers" also, depending on market signals and/or other circumstances, being "producers".

Prosumerism (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:
  - "Lumberjacks" when log prices are high relative to NZU prices, but "carbon farmers" when reverse is true;
  - Example of "real options".

Research Gap

- Very limited research on prosumerism – we know about "household production", but not like this ...
- Very few studies on welfare, regulatory and strategic impacts of DERs – those studies there are make very unsatisfactory assumptions, e.g.:
    - Linear electricity demand – usually dissatisfying, and glaringly deficient here;
    - Electricity consumption directly entering consumer "utility", ...
- No systematic study of how DERs affect both (residual) electricity demand *and* demand for DERs themselves.

This Presentation

- In this presentation I:
  - Background the "household production" model, and stress that electricity demand is both *derived* and *conditional*;
  - Use words to explain how the household production model needs adapting to accommodate DERs;
  - (Mostly) use words to describe what *total* and *residual* electricity demand looks like with DERs, and show how this then affects demand for DERs in the first place; and
  - Discuss what this means for the welfare of prosumers and conventional consumers.
- This work is foundational – can't meaningfully analyse welfare, regulatory or competitive effects of DERs without it!

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

- But penetration of DERs not assured to enhance ("consumer"/social) welfare, e.g.:
  - Risk of inefficient entry – excessive fixed costs;
  - Increased intermittency, providing large-scale generators incentives to reduce peaking capacity (to enjoy greater market power when peaking needed); and
  - "Waterbed effects" – those wealthy enough to own a roof and to make DER investments avoiding shared network costs which are then borne more by the less wealthy:
    - Possibly even induced by regulation intended to protect the latter – e.g. low fixed charge tariff ...

Unclear Welfare Impacts (cont'd)

- Welfare impacts could hinge critically on who owns or controls DERs, with different trade-offs if by:
  - Households;
  - EDBs – do DERs complement or substitute for network services?
  - 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 ...

Household Production

- 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)

- Household production models recognise that many of the things consumers buy are combined with their own resources (e.g. time/labour) to produce the things ultimately consumed:
  - E.g. going to the opera combines the household's commitment of time to the provision of the opera itself;
  - Implies that the things giving households "utility" are not just goods or services themselves, but those goods or services combined with household-level inputs in "production functions" which yield the things ultimately consumed.

Household Production (cont'd)

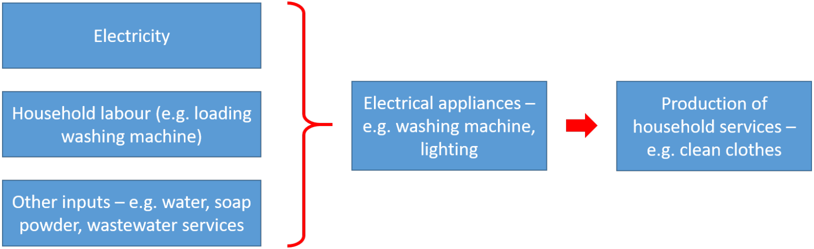
- Kerkhofs and Kooreman (2000, pp 1-2), *Identification and Estimation of a Class of Household Production Models*:

  "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 (cont'd)

- Standard microeconomics tells us that the *demand* for goods or services is obtained by solving the household's problem of choosing the goods and services to consume, subject to the budget constraint.
- Household production theory makes it much clearer why certain goods and services are "grudge purchases" – e.g. electricity:
  - Households don't demand electricity because they inherently desire "electrons";
  - Rather, households inherently desire certain goods or services – e.g. a warm house, entertainment, or clean clothes:
    - Some of which happen to require electricity as an input in their production.

Household Production (cont'd) – 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]

Household Production – DERs vs Appliances

- So what's different about DERs like PV panels, etc?
  - Aren't they just another form of "energy efficiency" – effectively making a household's *given* income go farther?
  - Can't they be modelled just like other electric appliance choices?
- To some extent yes, but in at least one important way, definitely not:
  - At most, an appliance can be 100% energy efficient; but
  - DERs can provide >100% of household electricity demand, providing a *surplus* that can be sold to *increase* available income:
    - This affects optimal DER choice differently to appliance choice.

Modelling DER Prosumers

- So, how should we think about households':
  - Decision to invest in DERs themselves;
  - *Total* electricity demand for own consumption – either self-generated, or purchased from others; and
  - *Residual/Net/Purchased* electricity demand – what households buy – or sell – on the market?
- To simplify, I take the household's set of appliances as given:
  - Ideally I should model this as separate choice, influenced by DER choice ...

Modelling DER Prosumers (cont'd)

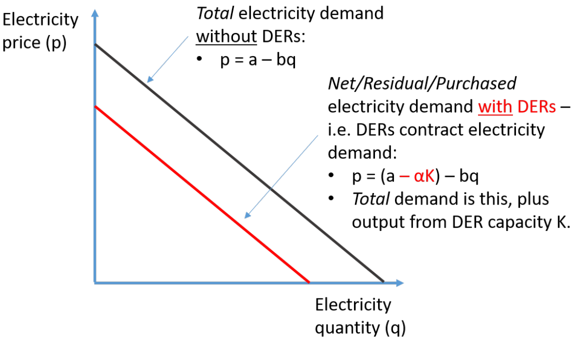
- Household DER choice doesn't just depend on capacity and price, as if DERs were final goods – it also depends on how DERs, as productive inputs:
  - Change the cost of electricity relative to other (input) goods and services:
    - Through substituting for purchased electricity; and
    - Affecting the level electricity-consuming services consumed; and
  - Affect household income – and hence consumption of both electric and *non*-electric goods and services.

Two Stages – DERs First, Consumption Goods Second

- I imagine households making the following sequence of choices:
  1. Some time ago, households chose their electric appliances;
  2. *Given* their appliances, they choose how much to invest in DERs, *anticipating* how this will affect their consumption of electric and non-electric goods and services; and
  3. Finally, *given* their appliance *and* DER choices, households decide what goods and services to consume (e.g. watch TV, put on the dishwasher, read a book, etc):
     - This then determines their total, and net, electricity demand.
- So I need to model the latter two choices, working out (3) before we can work out (2), taking (1) as given in each case:
  - Natural to think of DER investments as "long-term", and real-time consumption decisions as shorter-term.

Why not Simplify Further?

- Why can't we just assume that electricity demand is a (linear) function of electricity price, and allow for DER investment to shift that demand up or down at all price levels in some manner?



Why not Simplify Further? (cont'd)

- Setting aside how arbitrary this would be, how does this deal with demand being negative – i.e. self-produced electricity being sold:
  - And how do we capture DER impacts on household consumption of other goods and services through relative prices, let alone via income effects?
- What if DER capacity is so great that net demand contracts all the way to the origin:
  - If we measure prosumer welfare using consumer surplus (area under the demand curve), has it really vanished – when electricity is still being consumed?

Why not Simplify Further? (cont'd)

- Does this adequately capture the *two-way* relationship between demand for DERs and (net) demand for electricity?
  - How do we aggregate across different consumers – e.g. those who can and can't invest in DERs?
  - How do we model DER demand, given households' discrete choices (DER/not, big/small DER, etc)?
- More generally, prosumer welfare from DERs must account for how DERs:
  - Change the relative price of electricity – e.g. through being able to produce at zero marginal cost;
  - Change income – e.g. *because DERs cost money*, and also if surplus electricity is being sold; and
  - How these combine to affect the bundle of goods and services prosumers ultimately consume, and hence their welfare.

My Approach – Electricity Demand, given DER Choice (and Appliances)

- I assume a given household chooses to consume a *composite good* not requiring electricity, and an *electricity-consuming good or service*:
  - The latter combines electricity with given appliances to produce the good or service actually consumed.
- The household makes this choice subject to its budget constraint – a given DER investment with certain capacity reduces both:
  - The household's per-period income by an assumed DER rental cost – i.e. rental rate, times DER capacity; and
  - Expenditures on purchased electricity – i.e. DER productivity factor, times DER capacity.

My Approach – Conditional Electricity Demand (cont'd)

- I allow expenditures on purchased electricity to be negative – surplus power is sold at retail electricity price ("net metering").
- Maximising the household's "utility" from choosing these two consumption items, subject to its DER-modified budget constraint, tells us the household's *derived conditional total* electricity demand:
  - Purchased electricity is this total demand, less self-produced electricity (i.e. DER productivity factor, times DER capacity);
- *Household* electricity demand depends on electricity *price*, household *income*, DER *capacity*, and existing *appliances*:
  - *Market-level* electricity demand is just a "weighted sum" over all households – recognising that some can't install DERs (e.g. don't have a roof, or are renting).

My Approach – Conditional Welfare

- For antitrust, regulatory or distributional analyses of DERs, it is useful to distinguish DER impacts on welfare of non-uptaking and uptaking households:
  - I do so directly, measuring the "utility" of households that have DERs, and those that don't (or can't);
- In each case I simply take a "weighted sum" of individual households' utility, based on their *optimal* electricity demand, *taking DER choices and appliances as given*:
  - Hence this is *conditional* welfare – given (for now) DER choice, and appliance choice.
- I start with a general derivation, but consider two specific cases that can be explicitly solved:
  - *Cobb-Douglas* (tractably captures DER income effects) and *quasi-linear* (simpler, but no income effects).

DER Choice

- So far I've discussed how:
  - Individual households determine their total/residual electricity demand;
  - To compute their welfare given that demand; and
  - To aggregate these measures across different types of consumer.
- In each case we took DER capacity as given (and appliances) – so these measures were all *conditional*.

DER Choice (cont'd)

- Now, *anticipating* a household's optimal electricity demand as a function of DER capacity, how much DER capacity should they choose?
  - To simplify, I assume households can choose either a given level of DER capacity (e.g. 4kW of PV), or no DERs at all;
  - Can easily be generalised to an arbitrary selection of (discrete) DER capacities – i.e. 4kW, 8kW, etc.
- For antitrust, regulatory or distributional analyses, would be convenient if DER demand from *discrete* household-level choices was a *continuous* function of DER per-period rental rate *and* electricity price:
  - Enables both DER and electricity demands to be incorporated in models of (e.g.) oligopolistic firm behaviour, optimal regulation, etc.

Continuous DER Demand from Discrete DER Choices

- This is a standard feature of "discrete-choice" demand models:
  - Start with individual consumers making choices over discrete bundles of goods or services (here, DER capacity);
  - Allow for consumers to make those choices based on factors that are not fully observed (but which can be described in terms of probability distributions);
  - Work out the *probability* of consumers choosing a given discrete bundle as a function of prices; and
  - Take a "weighted sum" across choice probabilities, for different types of consumers, to arrive at market-level demand.
- Distinct merit of this approach is that it is designed to be taken to data – i.e. *we should be able to use my results to empirically estimate demand, welfare, etc.*

Continuous DER Demand (cont'd)

- I follow this recipe for deriving DER demand as a function of both electricity price, and DER per-period rental rate:
  - DER "price" (i.e. rental rate) enters for obvious reasons – the more costly DERs are, the less they will be purchased;
- Electricity price enters into the equation because households have to anticipate how DERs will affect their ability to consume goods and services:
  - This depends on how much cheaper DER electricity is relative to the alternative of electricity purchased on-market.

Continuous DER Demand (cont'd)

- My resulting DER demand, reassuringly:
    - *Falls* as the DER rental rate rises – households are less likely to buy DERs the more expensive they are; but
    - *Rises* with increases in the *product* of DER productivity and electricity price.
- Latter effect represents the "cost savings" associated with having DERs, and thus not having to buy electricity:
    - If purchased electricity becomes more expensive, or DER productivity rises, then those households who can buy DERs are more likely to do so, because it saves them money.

Unconditional Welfare

- Earlier, I discussed how I derived welfare for households *conditional* on how much DER capacity they had (and appliances):
  - Of course, some consumers will never be able to directly install DERs, e.g. because they don't have a roof, or are renting, ...
- Now that we have derived households' optimal DER investment (probabilities), we are in a position to work out *unconditional* welfare for each household type:
  - We can then take a "weighted sum" over all household types to estimate overall welfare – of prosumers (i.e. DER uptakers) and ordinary consumers (i.e. non-uptakers):
    - Taking into account their respective optimal DER choices.

Conclusions

- This work is a high-level "how to" guide, and develops tools that should pave the way for proper analysis of DER impacts on both uptaking and non-uptaking households:
  - *Critically, incumbent and entrant electricity suppliers' optimal electricity price choices will be affected by DER uptake, and vice versa* – with non-uniform impacts on uptakers and non-uptakers.
- Regulators, antitrust authorities and policymakers need to clearly understand these inter-linkages:
  - Especially if they are to (de)regulate or otherwise intervene in DERs, electricity pricing, housing markets, etc.

Conclusions (cont'd)

- My analysis doesn't tell anyone if DERs are good or bad:
  - Instead, it provides coherent tools, based on solid microeconomic foundations, for analysing both DER demand and the impact of DERs on electricity demand/markets.
- These tools are intended to facilitate both:
  - *Theory modelling* – e.g.:
    - What are the antitrust or regulatory implications of DERs being owned by households, (un)regulated EDBs, gentailers, etc; or
    - How will DER uptake affect the welfare of uptakers and non-uptakers – once firms' electricity price responses are accounted for?
  - *Empirical analysis* – e.g. what is expected DER demand for different types of household, is DER uptake increasing or decreasing overall welfare, etc.

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