The welfare gains for prosumers

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What we do?

- Mimic the preferences of households
- Focus on their optimal behavior with respect to electricity consumption, storage, and grid purchases/feed-ins, and
- Appraise the welfare gains from installing a solar photovoltaic (PV) system and demand management devices.

Motivation

- Large scientific consensus on global climate change,
  - often asserted that renewable energy (RE), such as wind and solar power, will replace fossil fuels
- Green energy generation, storage and distribution of energy: part of the solutions for more **sustainability**
- Nearly 30% of global electricity consumption comes from residential buildings (EIA, 2016)
  - RE investments at the household level can significantly contribute to the expansion of RE capacity.
- However, ***intermittency*** is a challenge associated with a higher penetration of RE generation (Speer et al., 2015)
- Effective storage capacity and demand management offer new opportunities for flexibility to tackle these challenges (Jeon et al., 2015; De Castro and Dutra, 2011; MITei, 2015)

Related literature

- Even though electricity demand management and smart grids have recently received a lot of attention both in the academic literature (De Castro and Dutra, 2013; Léautier, 2014; Hall and Foxon, 2014; Bigerna et al., 2016; Brown and Sappington, 2017; Stojanovski et al., 2020) and media (Palmer, 2015b,a; Patel, 2018; Peachey, 2019; Shaw, 2019; Rothstaff, 2021; Horton, 2021),
- the focus has mostly been on the additional costs that they lead to instead of the added economic values that they generate (Baker et al., 2013)

Related literature

- Few studies explore the profitability of solar PV and storage (Castillo-Cagigal et al., 2011; Hittinger and Siddiqui, 2017; Fares and Webber, 2017) (not that of smart meter) but they do not consider optimizing households.
  - The load profiles are mainly simulated and the household electricity consumption is assumed not to be affected by the changes in the electricity tariff.
- In the majority of the studies, batteries are mechanically loaded by the PV system when the PV generation exceeds household consumption.
  - the possibility that battery generates economic value through arbitrage is prohibited or very limited

Related literature - some results

- Fares and Webber (2017): economic benefits that the storage system renders to the households are not sufficiently high to justify its installation in Austin, Texas,
- Hoppmann et al. (2014): installation of a solar PV system and a battery are always profitable under various price scenarios in Stuttgart, Germany.
- Grid defection is not beneficial in several locations (in the US) given the electricity tariff rates (Hittinger and Siddiqui, 2017)
- Possible effects that energy storage capacity can have on power flows (in and out of the house) are pointed out when designing new electricity systems (Castillo-Cagigal et al., 2011)
- Limited understanding of how the optimal behavior of the household w.r.t electricity consumption and storage affect the profitability of investments in solar panels, batteries and smart meters.

In this study...

- We investigate how investments in solar panels, storage device and/or smart meters affect the welfare of a household who optimizes with respect to electricity consumption, storage and grid purchase/sale under stochastic intermittency and diurnal and seasonal variations in solar energy.

- Data from a low energy dwelling in South Wales, UK. Its performance was extensively monitored
- The findings of this analysis are therefore based on this particular dwelling and location

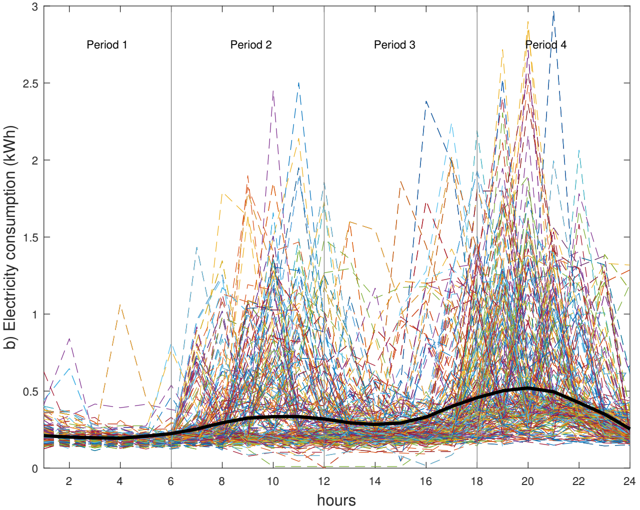
Data (ctd.)

About the dwelling:

- Constructed in 2010
- Floor area: 78 m^2
- Designed to meet the Passive House standard
  - to minimize space heating
  - fitted with a 1.9 kw peak PV installation
- No electricity storage system
- Surplus generated electricity fed to the grid at the same price as the imported electricity
- Extensive monitoring system: The system logged 85 sensors in the dwelling every 5 minutes
- Hourly data May 2012-April 2014

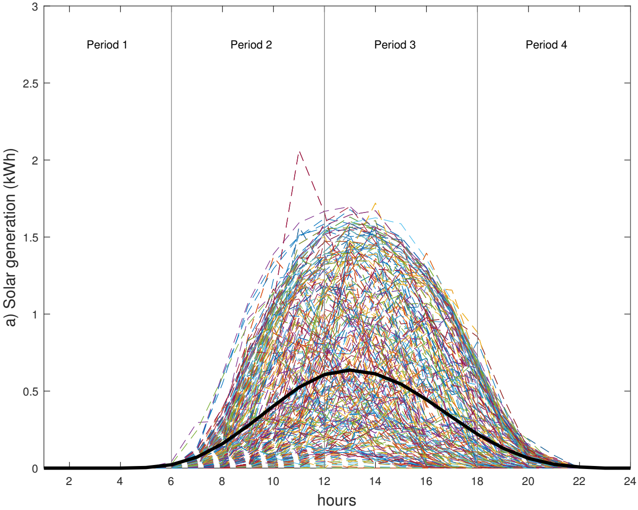
Household electricity consumption

Figure: Electricity consumption. The bold line corresponds to hourly averages of electricity consumption.



Household electricity generation

Figure: Solar energy generation. The bold line corresponds to hourly averages of electricity generation.



Seasonal household electricity consumption and generation

Figure: Averaged values for each meteorological season. The four-period characteristic is preserved in each figure.

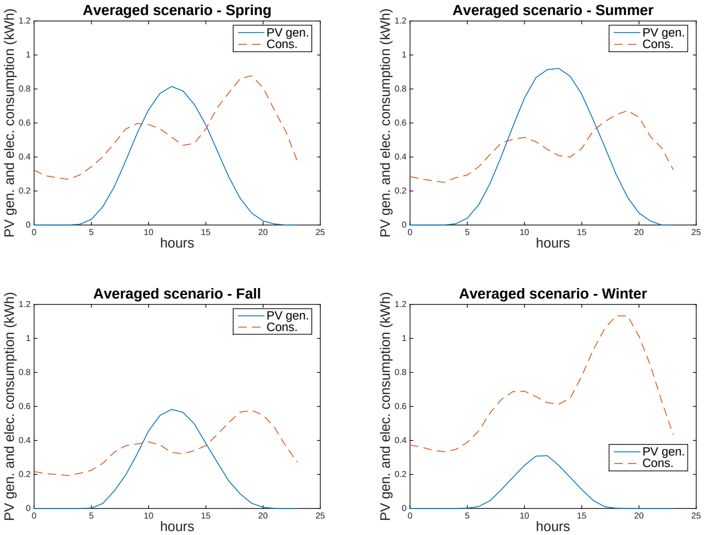
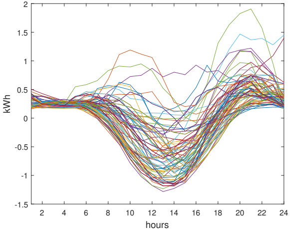
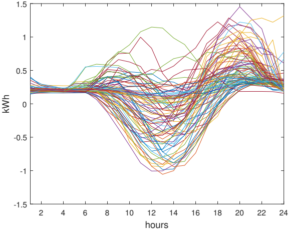


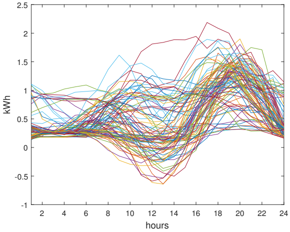
Figure: Electricity purchases from the grid



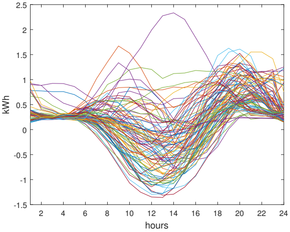
(a) Summer



(b) Fall



(c) Winter



(d) Spring

Model

$$
\begin{aligned}
\max_{\{s_l, g_j\}} \quad & u_1\left(g_1 - s_1\right) - p_1 g_1 \\
& + \int_0^1 \left[u_2\left(x\bar{K} + g_2(x) - s_2(x) + \phi s_1\right) - p_2 g_2(x)\right. \\
& + \int_0^1 \left[u_3\left(y\bar{K} + g_3(x,y) - s_3(x,y) + \phi s_2(x)\right)\right. \\
& \left.\left. + u_4(g_4(x,y) + \phi s_3(x,y)) - \sum_{j=3,4} p_j g_j(x,y)\right] dF^y(y)\right] dF^x(x)
\end{aligned}
$$

$$
\text{s.t.} \quad s_l \leq \bar{s} \text{ and } s_l \geq 0
$$

$u_j(\cdot)$: gross surplus in period j, $x\bar{K}$ and $y\bar{K}$: solar power generation given x and y; p_j: price on the grid in period j; g_j: grid purchases (or sales); s_l: amount of energy storage that is carried to the following period; ϕ: round-trip efficiency parameter.

Calibration - Utility function

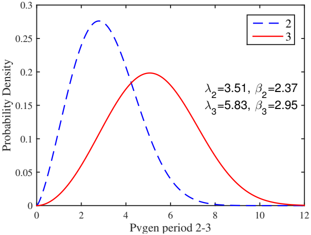
- Using electricity consumption data, we calibrate a Stone-Geary utility function (season i and period j),

$$u_{ij}(c) = \frac{\alpha(c - \bar{c}_{ij})^{1-\gamma}}{1-\gamma}$$

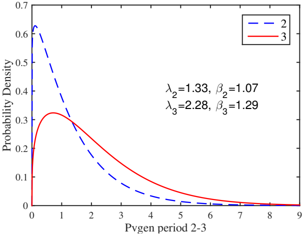
Calibration - Solar power gen. and electricity consumption

- Real-time solar electricity gen. data to generate the PDFs.
- We approximate the PV generation with Weibull distribution, whose scale and shape parameters are estimated using MLE.

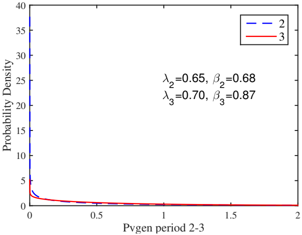
Figure: The pdfs for period 2 and 3 for each season



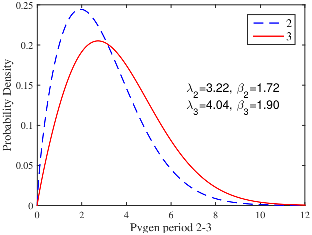
(a) Summer



(b) Fall



(c) Winter



(d) Spring

Calibration - The Storage Device

The Tesla Powerwall has a 92.5% round-trip efficiency: $\phi = 0.925$.

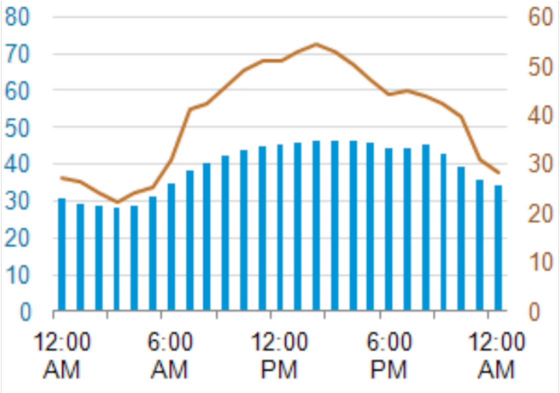
The home battery has a capacity of 6.4 kW and a charge and drain limit of 3.3 kW. As each period in our model consists of 6 hours, this specific type of home storage battery can be fully charged or drained within each period.

Calibration - Time-of-use pricing

- Uniform tariff when the data was collected
- Therefore, we do not have observed time-of-use pricing data concerning the period of interest, nor observed consumption data with time-of-use pricing.
- Nevertheless, conducting the optimization with a price profile like the one in the figure below allows us to compute the optimal electricity consumption levels and welfare gains obtained under a non-uniform tariff rate.

Calibration - Time-of-use pricing

Figure: Example of the variation in hourly electric power demand and price over a single day. The solid line represents the day-ahead power price ($) per MWh while the bars illustrates electricity demand. Source: EIA, http://www.eia.gov/todayinenergy/detail.cfm?id=6350



Calibration - Time-of-use pricing

According to the figure,

- The early morning and night (day-ahead) tariff is the lowest
- The noon power price is the highest
- The prices during the morning and evening peaks are between the former two.
- The observed price of electricity is 15 pence/kWh
  - Then, in line with the figure, we assume $p_3 = \frac{4}{3}p_2 = \frac{4}{3}p_4 = 2p_1$ where the average price, $(p_1 + p_2 + p_4 + p_3)/4$, equals 15 pence/kWh.
  - Consequently, $p_3 = 20$ pence/kWh, $p_2 = p_4 = 15$ pence/kWh, and $p_1 = 10$ pence/kWh.

Calibration - Calculating the present value of the total welfare

- Discount rate: $r = 0.05$
- 20 years of financial lifetime (Arimura et al., 2012; Ossenbrink et al., 2013), which is often the required average period of time for the smart grid equipment (SGCC, 2010).

Results

Focus: the benchmark scenario where no device is installed and two alternative scenarios that are more commonly observed and policy-relevant.

- Scenario A: change in welfare following the installation of a 1.9 kW peak solar PV system. Uniform-pricing both before and after the installation of the PV system.
- Scenario B: Welfare change following the installation of the solar PV system, a battery (Tesla Powerwall), and a smart meter implying time-of-use pricing.
    - The equipment in scenario B allows the household to take advantage of the time-of-use prices through consumption adjustment and storage.

Results

- To calculate the change in surplus coming from the installation of the device(s), we first compare the surplus over 20 years under Scenario A and Scenario B with the surplus under the benchmark case.
- The surplus over 20 years is computed as the discounted sum of the yearly surpluses, the latter being the sum over one year of the expected daily surpluses, differing across seasons.
- Annual surpluses (normalized between 0 and 100) for each scenario presented below:

Results

Figure: Annual surpluses normalized between 0 and 100

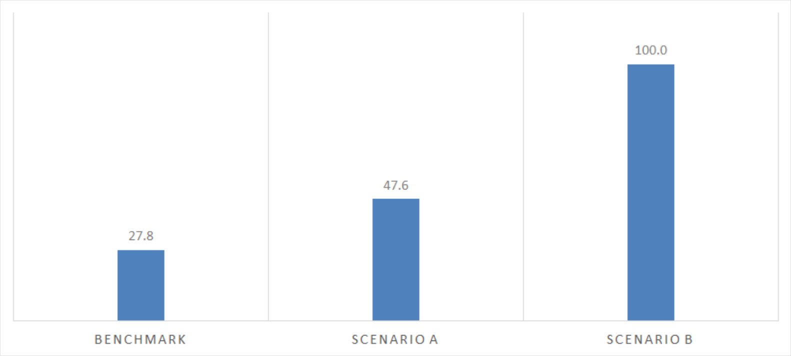


Figure: Annual surpluses normalized between 0 and 100

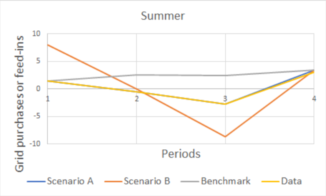
According to the figure,

- Benchmark: The benchmark case with no equipment leads to the lowest welfare.
- Scenario B: the availability of the smart meter and time-of-use pricing alongside the battery allows significant flexibility for the household to tailor its electricity consumption, delivering the highest annual surplus among the scenarios.
- Scenario A: the electric power generated by the solar panels allows for feed-ins of electricity to the grid or reduced consumption from the grid, significantly improving the household's economic welfare relative to the benchmark scenario.

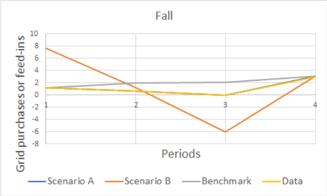
Results

- Household's expected grid purchases/feed-ins over a day in each season:

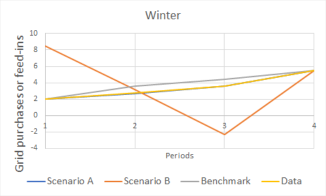
Figure: Grid purchases and feed-ins



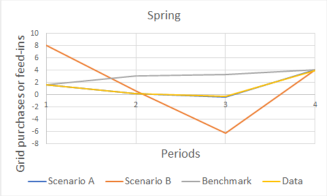
(a)



(b)



(c)



(d)

Results: welfare gains from smart meter installation

- Scenario B provides significant flexibility options
  - the household prefers to purchase and store a significant amount of electricity during the period with the lowest tariff rate (*i.e.*, in the first period)
  - feed a significant amount of electricity to the grid when the tariff rate is the highest (*i.e.*, in the third period).

Maximum investment expenditures

The maximum investment expenditures (the change in the 20-year surplus) the household would make associated with each scenario:

Table: Surplus change over 20 years of financial lifetime

Benchmark	$\rightarrow$	Scenario A	£3662
Benchmark	$\rightarrow$	Scenario B	£6356

- Establishment cost: 1.9 kW peak PV system (the one installed in the passive Welsh house)= £3230.
- The welfare gain for Scenario A and B: £432>0 and £3136>0
- Significantly beneficial to install the solar PV system regardless of the pricing scheme.

Extending for no feed-ins

- While net metering is allowed in some regions and countries, such as the European Union and the United States, a significant number of countries have not yet initiated feed-in policies.
- It can be of practical interest to investigate the welfare gains from the installation of solar panels and smart devices when legislation prohibits net-metering.
- The problem, set out earlier is subject to the no-feed-ins constraint:

$$g_j \geq 0 \text{ for } j = 1, 2, 3, 4$$

- One of the implications of the no feed-ins constraint is that the optimal amount of energy storage can take interior values depending on the amount of previously stored energy and power generated by the solar PV system.
- Hence, we cannot exploit the FOCs to calculate the household's total maximum net surpluses.

Results: No feed-ins

Figure: Annual surpluses in each scenario in percentage

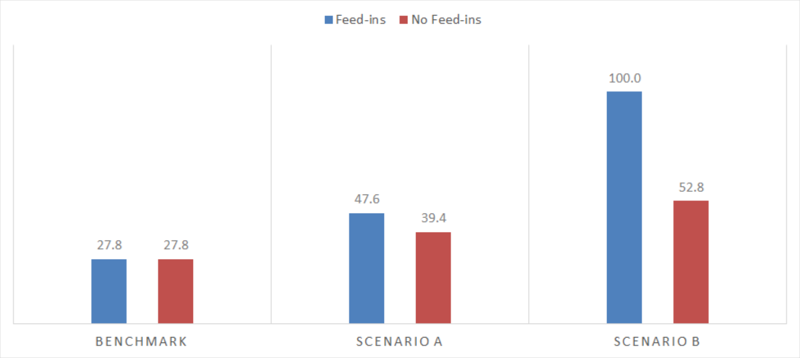


Table: Surplus change over 20 years of financial lifetime (no feed-ins)

Benchmark	$\rightarrow$	Scenario A	£2586
Benchmark	$\rightarrow$	Scenario B	£4167

Table: Scenarios.

Scenario 1:	SM, ST, SP	
Scenario 2:	~~SM~~, ST, SP	- Scenario 2′: ~~SM~~, ~~ST~~, SP
Scenario 3:	SM, ST, SP^{O}	
Scenario 4:	SM, ST, SP^{P}	
Scenario 5:	SM, ST, ~~SP~~	
Scenario 6:	SM, ~~ST~~, SP	
Scenario 7:	SM, ~~ST~~, ~~SP~~	
Scenario 8:	~~SM~~, ST, ~~SP~~	- Scenario 8′: ~~SM~~, ~~ST~~, ~~SP~~

Note: Scenarios 1, 2', and 8' correspond to Scenario B, A, and the benchmark scenario, respectively, in the previous section.

Surplus change - No feed-ins

Table: Surplus changes over 20 years and installation costs.

Equipment				Surplus change (£)
Smart meter (cost: £214.50)	Scenario 8 $(\cancel{SM}+ST+\cancel{SP})$	$\rightarrow$	Scenario 5 $(SM+ST+\cancel{SP})$	1974
	Scenario 2 $(\cancel{SM}+ST+SP)$	$\rightarrow$	Scenario 1 $(SM+ST+SP)$	2694
	Scenario 2′ $(\cancel{SM}+\cancel{ST}+SP)$	$\rightarrow$	Scenario 6 $(SM+\cancel{ST}+SP)$	-374
	Scenario 8′ $(\cancel{SM}+\cancel{ST}+\cancel{SP})$	$\rightarrow$	Scenario 7 $(SM+\cancel{ST}+\cancel{SP})$	-345
Solar panel (cost: £3230)	Scenario 5 $(SM+ST+\cancel{SP})$	$\rightarrow$	Scenario 1 $(SM+ST+SP)$	4382
	Scenario 7 $(SM+\cancel{ST}+\cancel{SP})$	$\rightarrow$	Scenario 6 $(SM+\cancel{ST}+SP)$	4382
Storage (cost: $>$ £8000)	Scenario 6 $(SM+\cancel{ST}+SP)$	$\rightarrow$	Scenario 1 $(SM+ST+SP)$	2319
	Scenario 7 $(SM+\cancel{ST}+\cancel{SP})$	$\rightarrow$	Scenario 5 $(SM+ST+\cancel{SP})$	2319
	Scenario 6 $(SM+\cancel{ST}+SP)$	$\rightarrow$	Scenario 3 $(SM+ST+SP^{O})$	347
	Scenario 6 $(SM+\cancel{ST}+SP)$	$\rightarrow$	Scenario 4 $(SM+ST+SP^{P})$	-869

No feed-ins - results in a nutshell

Considering the case with net-metering,

- Solar panels are profitable: no need for public support
- What matters for smart meters: storage
- What matters for storage
  - the cost of the device
  - dynamic pricing

Policy recommendations (sharing the characteristics of the passive Welsh house)

- To encourage the adoption of RE, the public policy should concern the possibility of net-metering.
  - In countries where it is already possible, solar panels seem profitable already, and do not require any public policy support.
- Many countries have started introducing feed-in-premiums, leaving feed-in-tariffs. Our conclusion, which indicates that subsidies in the form of feed-in-tariffs are unnecessary concerning our particular case, also applies to the feed-in-premium policy.
- Hence, public policy can focus on storage and smart devices.

When feed-ins are prohibited,

- the first public policy to be implemented should concern the possibility of **net metering**
- If net-metering will not be easily implemented soon, the most efficient public policy should focus on solar panels

To the best of our knowledge...

- First time in the literature, data on real-time electricity consumption and real-time electricity generation are used to calibrate such an optimizing model of electricity.
- Because the weather in Wales is generally mild, cloudy, and wet (ASC, 2016), appraising the welfare effects of solar power under such climatic conditions is a valuable contribution to the literature.
- Our contribution is essentially **methodological** and **very general**.
    - This approach can be used in a generic way to analyze and assess the welfare gains for prosumers in any other locations and for any additional equipment characteristics.

Extensions/Further Research

- Our methodology can easily be applied to another type of dwelling in another location.
- Compute Levelized Cost of Electricity (LCOE) of electric systems that account for both intermittent generation and the complementary technologies such as smart meters and batteries $\rightarrow$ would enable better assessment of competitiveness at the household level.
  - LCOCE (Levelized Cost of Consumed Electricity), a new measure of the cost of a unit of electricity consumption
- Endogenous prices: Results obtained under the assumptions that the household takes grid electricity prices as given and has free access to the grid provided by the electricity utilities.
  - Should investments in solar panels and grid feed-ins become prevalent among households, the grid electricity price may be altered and the utilities may no longer be willing to let households freely take advantage of their network (In progress)

Thank you for your patience!

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