Willingness to pay for solar panels and smart grids*

Tunç Durmaz[†], Aude Pommeret[‡], Ian Ridley[§]

May 2, 2017

Abstract

It is expected that the renewable share of energy generation will rise considerably in the near future. The intermittent and uncertain nature of renewable energy (RE) calls for storage and grid management technologies that can allow for increased power system flexibility. To assist policy makers in designing public policies that incentivize RE generation and a flexible power system based on energy storage and demand-side management, better knowledge as to the willingness to pay for the corresponding devices is required. In this paper, we appraise the willingness of a household (HH) to pay for a 1.9 kW peak photovoltaic (PV) system and smart grid devices, namely, a smart meter and a home storage battery. Results indicate that having access to a storage device is key for the HH decision to install a smart meter. We also find that it is beneficial for the HH to install the PV system regardless of the pricing scheme and the ownership of the battery pack. It is, nevertheless, barely desirable to install the battery pack regardless of the presence of the PV system; an outcome pointing to the fact that the high cost of storage is a drawback for the wider use of these systems. When storage is constrained in such a way that only the generated power can be stored, the willingness to install the battery pack reduces even further. The investment decisions made when legislation prohibits net-metering are also analyzed.

Keywords: *Renewable Energy; Intermittency; Distributed generation; Smart solutions; Energy Storage; Demand response; Willingness to pay*
JEL codes: *D12; D24; D61; Q41; Q42*

*We thank the ANR (project REVE, ANR-14-CE05-0008), French Ministry of Research, for financial support.

[†]School of Energy and Environment, City University of Hong Kong, E-mail: tdurmaz@cityu.edu.hk.
[‡]School of Energy and Environment, City University of Hong Kong, E-mail: aude.pommeret@cityu.edu.hk.
[§]School of Energy and Environment, City University of Hong Kong, E-mail: ian.ridley@cityu.edu.hk.

1 Introduction

Given all the climate change related issues, it is often asserted that renewable energy (RE), such as wind and solar power, will replace fossil fuels, therefore justifying public policies that promote RE technologies (Van Benthem et al., 2008; Hirth, 2015). The fact that approximately 28% of global electricity consumption comes from residential buildings, RE investments at the household (HH) level can significantly contribute to the expansion of RE capacity in several regions of the world.[1] However, because the amount of RE generated depends heavily on prevailing weather conditions, and, hence, is intermittent and unpredictable, there are challenges associated with a higher penetration of RE sources (Speer et al., 2015); e.g., decrease in system efficiency, and mismatches between supply and demand.

Much progress to date in solar photovoltaic (PV) installations has been achieved with a combination of policy incentives and improvements in the technology. Nevertheless, the upfront costs of solar PV are still high (Reichelstein and Yorston, 2013; Hagerman et al., 2016; IER, 2016; Sivaram and Kann, 2016), and distributed solar energy investments are mainly driven by regionally-tailored incentive programs (Haegel et al., 2017). For example, in Germany, annual installations since 2013 fell significantly with the challenges associated with the incentive programs (Haegel et al., 2017). In the UK, following the cut in subsidies for HHS to fit solar panels (and phased-out subsidies for large-scale solar farms), the amount of solar power installed in 2016 fell by about half when compared to the year before (The Guardian, 2017). Furthermore, repeated tariff cuts are also contributing to the deflation of Japan's investment in solar PVs(Watanabe, Chisaki and Stapczynski, Stephen, 2016; Haegel et al., 2017).

Such developments call for grid-integration technologies and flexibility options that can enable a smooth integration of intermittent and uncertain RE, with feasible cost and stability. Effective storage capacity and demand management are some of the ways to accommodate intermittent RE (Jeon et al., 2015; De Castro and Dutra, 2011). Motivated by the fact that there is a lack of economic analysis of a decentralized clean energy investment and provision (Baker et al., 2013), we investigate the willingness to pay (WTP) of an HH for solar PV, storage devices and smart meters. We are particularly interested with how and whether the WTP for one of these technologies is affected by the complementary technologies. For instance, how do smart meters and batteries affect solar PV installations or how do solar PV and smart meters affect batteries installation. Better knowledge, in this regard, will help policy makers to design public policy that is aimed at providing incentives for RE generation.

In the literature, some papers study the optimal energy source mix for electricity generation (fossil fuels and renewables) when intermittency is taken into account (see

[1] The share of the global electricity consumption is calculated from the data provided in Table F1 in EIA (2016).

Ambec and Crampes, 2012, 2015). There is also another strand of literature examining the energy dispatch problem when storage can take care of peak electricity or excess nuclear energy production (see Jackson, 1973; Gravelle, 1976; Crampes and Moreaux, 2010). Furthermore, some more technical studies have been conducted showing, for instance, that with a PV size below 5 kW peak, electricity consumption in UK passive houses needs to be reduced by 70% to reach a zero-energy targets (Ridley et al., 2014). Nevertheless, even though electricity demand management and smart grids have recently received a lot of attention both in the academic literature (see De Castro and Dutra, 2013 or Hall and Foxon, 2014 and Bigerna et al., 2016) and in the media (see The Economist, 2009; The Telegraph, 2015b,a), not much work has been done that investigates the WTP of HHs for solar PV systems and smart devices.

In this paper, we account for two levels of equipment in smart grids. The first one concerns the installation of smart meters, which are relatively widely used in Europe (e.g., Linky in France). Smart meters allow end-use consumers in electricity markets to monitor and change their electricity consumption in response to changes in the electricity price at different times of day (Durmaz, 2016, Borenstein and Holland, 2005 and Joskow and Tirole, 2007).[2] The second level relates to energy storage. The costs of implementing the smart grid devices is usually assumed to be borne by consumers who may, therefore, oppose strong resistance to the adoption of these devices (Madigan, 2011). Nevertheless, the cost of dedicated storage is high and Jeon et al. (2015) argue that deferrable demand would be a cheaper way to tackle RE intermittency. In this study, we appraise the WTP of an HH for RE systems and smart grid devices, and attempt to identify the focus of public policy that can allow for a smooth transition towards more RE generation. These WTPs are likely to differ, depending on whether the legislation allows grid feed-ins from RE sources or energy storage devices. Feed-ins of power can simply be achieved by net metering, as long as this is not in conflict with the country's legislation. While the European Union and the United States allow net metering, Hong Kong and some African countries do not. Accordingly, we investigate the sensitivity of the HHs' WTPs for a solar PV system and smart grid devices with respect to the legislation on grid feed-ins.

We generalize Durmaz et al (2017) and calibrate it on observed HH behaviors to derive WTP for solar panels and smart grid devices. Accounting for RE generation intermittency and grid price uncertainty, Durmaz et al (2017) analyze the efficient mix of investments in intermittent RE (namely, solar panels) and smart grids (namely, smart meters and batteries). In this model, the HH can choose at each period whether to feed (resp. purchase) electricity to (resp. from) the grid or to store energy (or to use stored energy) upon RE installations. Results point out that smart grid devices do not automatically imply less reliance on the electric grid and that curtailment measures to avoid grid congestion can discourage investment in RE generating and energy storage capacities. We generalize the aforementioned study by accounting for more periods within a day (i.e., four periods instead of two) and by considering a whole distribution for

[2]Do note that the export of PV generated electricity to grid can be merely be achieved with the installation of an extra dumb meter that measures generation. Accordingly, it does not necessarily have to be smart.

PV generation instead of two possible realizations. In calibrating the model, we use the electricity consumption and PV generation of an HH living in a passive house that is located in Wales, UK and equipped with a solar PV system (see Table 1 in Ridley et al., 2014).[3] Following the calibration, we compute the WTPs for a 1.9k W peak PV system, a smart meter, and a home storage battery (Tesla Powerwall), depending on which other equipment is already installed and whether the HH can sell electricity to the grid. Throughout the paper, Tesla Powerwall, home storage battery, and battery pack are used interchangeably.

Results indicate that having access to a storage device can allow a HH to take a better advantage of a smart meter. For instance, when the HH can generate electricity through the PV system but cannot store energy, the installation of a smart meter would not be justified. Considering a 1.9kW peak PV system, we find that it would significantly be beneficial for the HH to install the PV system regardless of the pricing scheme and the possession of the storage device. Furthermore, our results indicate that it is barely advantageous to install the battery pack regardless of the presence of the PV system. This outcome points to the fact that the current high cost of energy storage is a drawback for the wider use of these systems. When storage is constrained in such a way that only solar power generation can be stored (not the electricity from the power grid), the willingness to install the battery pack reduces even further. Things become even worse when the generated solar power first fills the battery. Moreover, when legislation prohibits net-metering, our results indicate the WTP for the smart meter is the highest when the HH owns only the battery pack. This is mainly due to the fact that the HH would not be able to provide electricity to the grid had it owned the PV system.[4] Lastly, and interestingly, it is never beneficial to install the home storage battery, and the solar PV system is only profitable in the absence of smart meters.

The remainder of this paper is structured as follows. Next section presents the data that motivated the research and that are used to calibrate the model. Section 3 presents the model and analyzes the optimal electricity purchases/sales and energy storage decisions. Calibration strategy is explained in Section 4. We calculate the different WTPs in Section 5 under the assumption that the HH can freely feed the grid. We explore the consequences of the alternative assumption in Section 6. Finally, Section 7 concludes.

[3]"A passive house is a building in which a comfortable indoor climate can be obtained without a traditional heating or cooling system. Compared to traditional building they use far less energy. For most countries these demands are 70–90% reduced compared to the actual energy efficiency requirements for heating and cooling, but this depends on the actual energy standards. For countries with high energy efficiency requirements it is less" (p. 66, Laustsen, 2008).

[4]A similar result would be obtained if we assumed grid constraints such as the ones recently implemented in Japan, where the country encountered such constraints because of the accelerated deployment of PVs (Haegel et al., 2017). See Section 6 in Durmaz et al (2017) for the analytical details.

2 Data

In this example, data from a low energy dwelling, the performance of which was extensively monitored, is used (Ridley et al., 2014). This case study was chosen due to the availability of a high quality monitored data. The findings of this analysis are therefore based on this particular dwelling and location. The methodology outlined and tested here could of course be applied to any data from other regions and dwelling types of interest or indeed to data produced by simulation exercises.

The case study is in many ways typical of the type of new low energy dwellings that are currently being built throughout northern Europe (reference), incorporating passive techniques to reduce space heating demands and modest sized PV systems that can offset approximately 40-60% of electricity consumption. As the data is "real monitored" data it represents the behaviour and consumption patterns of occupants whose dwellings do include PV generation with a feed in tariff to the grid but no storage capability, and hence will reflect any modified behaviour due to the reduced electricity bill due to the installed system. As the dwelling was being monitored and part of a research project the occupants were aware of the energy saving potential of the dwelling and could be considered to be well-informed building users. The property was rented, and the occupants were not necessarily motivated to recoup any investment that had been made on their behalf, but they were responsible for paying all utility bills. Therefore any savings due to their energy consumption behaviour did accrue to them.

The house was constructed in 2010 in South Wales, and monitored for 24 months to evaluate the energy and environmental performance. The two bedroom detached dwelling has a floor area 78 m^2, is owned and constructed by a social housing provider and rented and occupied by a 3 person family. The low energy dwelling was designed to meet the Passive House standard to minimise space heating and was fitted with a 1.9 KW peak PV installation on the south facing pitched roof. The PV system was designed with the aspiration to produce enough electricity to offset the carbon emissions from heating, lighting and hot water consumption of the dwelling. The dwelling has no electricity storage system, but could sell surplus generated electricity to the grid, at the same price as imported electricity it bought from the grid. The extensive monitoring system logged 85 sensors, including a weather station, in the dwelling every 5 minutes for 2 years, including all electricity sub circuits and the quantity of electricity exported to and imported from the grid. Hourly data from May 2012 to April 2014 was used in this study.

It is noted that the dwelling is not representative of a typical UK Home, in that it has a much lower space heating demand due to the high level of thermal insulation. However in the future When the offset of the PV system is considered the dwelling emits 75% less carbon annually than a typical UK home. Space heating and domestic hot water was provided by a gas boiler with additional input to domestic hot water from a solar thermal system but a further data set was constructed from the monitored data to represent an all-electric case study, in which the space heating and domestic hot water were also provided by electricity instead of gas. The monitored gas consumption of the heating and domestic hot water system were converted to an additional electricity consumption by assuming that they were now met by a heat pump system with an average coefficient of performance of 4 (i.e., very efficient) for both heating and hot water.

One motivation for choosing the all-electric case is due to is the trend in low energy housing design to the transition from gas fueled heating and hot water systems to all electric solutions thus taking advantage of the growing percentage of renewable in the electric supply grid (Feist, 2014). However, the electricity consumption and consumption profile (for non heating and hot water uses) of the house is typical for a UK dwelling of this size and occupancy (Owen and Foreman, 2012). The appliances in the dwelling were not particularly energy efficient, being installed and owned by the occupants rather than being the highly energy efficient appliances originally specified by the project designers. The main difference in the dwelling (apart from the PV system) which slightly reduced electricity consumption was the lighting system which included energy efficient LED bulbs.[5] Conversely, being a passive house the dwelling had a mechanical ventilation system that was in continual operation which slightly increased electricity consumption.

Using the data, we produce three figures (Figure 1). The first figure from the left presents the 2x365x24 observations for solar power generation and electricity consumption for the passive and low carbon Welsch house. While the second figure demonstrates the expected values for solar power generation and electricity consumption each hour, the last figure presents a smoothed version of the second one. As is also indicated in the last figure with the dashed-green line, the first period is the late-night and early-morning period. While the first peak from the left, that is, morning peak load, covers the second period, the midday does this for the third period. Lastly, the second peak, which is the evening peak load, is incorporated in the fourth period. For a constant price of electricity (15pence/kWh during the period in consideration) and for a given amount of consumption, c, the electricity is relatively valued the most on the margin in the evening-peak period. While the electricity is valued relatively less on the margin in the morning-peak period, it is valued the least in the first and third periods. Accordingly, let $u'_{i2}(c) > u'_{i4}(c) > u'_{i3}(c) > u'_{i1}(c)$, where $u_{ij}(x)$ and $u'_{ij}(x)$ are the periodic surplus and marginal surplus functions in season i (i=summer, fall, winter, spring), respectively.

[5]LED lighting is now widely available and increasingly replacing less efficient forms of lighting.

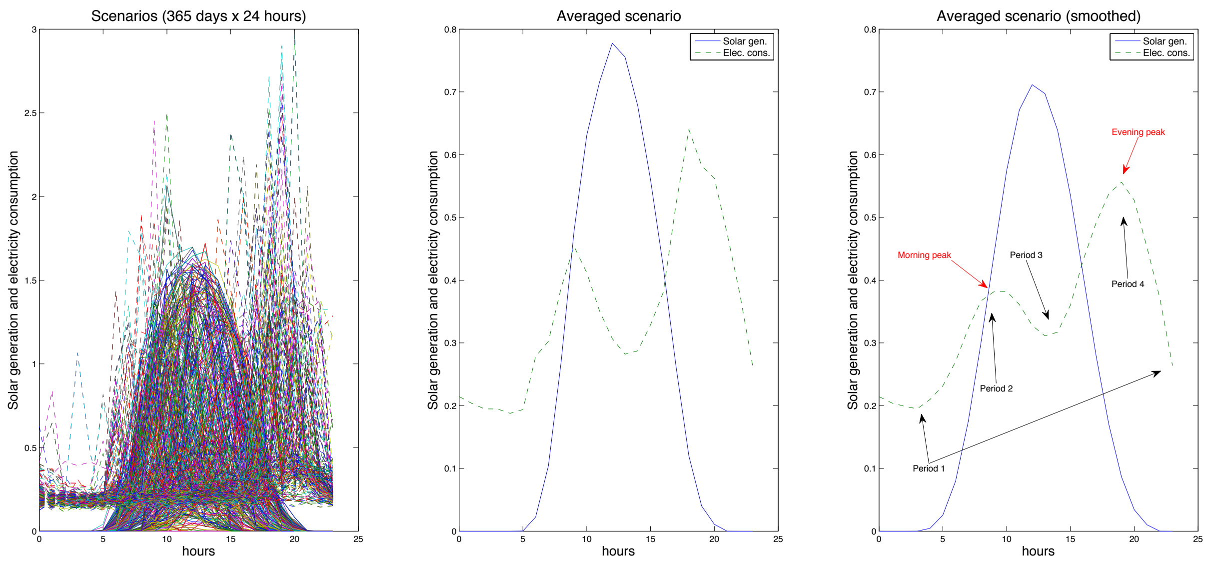

Figure 1: *Solar power generation and electricity consumption.*

3 Model

At each period the HH has a gross surplus over electricity consumption. Let $u_{ji}(\cdot)$ denote this surplus, where j and i denote the season of the year and the period within the day, respectively. It is assumed that $u' > 0$ and $u'' < 0$ where u' and u'' are the first- and second-order derivatives of the surplus function, respectively.

Let $p_3 > p_2 = p_4 > p_3$, where p_j denote the electricity price in period j $(j = 1, 2, 3, 4)$. This inequality follows naturally from the data. Figure 2 presents variation in hourly electric power demand and price over a single day. As the figure shows, the early morning and night (day-ahead) price is the lowest. While the noon power price is the highest, the prices during the morning and evening peaks are somewhere between the former two.

Assuming that each period is of equal length and that the decision to store energy can be taken at every period, the problem then is the following:

$$\max_{\{s_i, g_i\}} \quad u_1\left(g_1 - s_1 + s_0\right) - p_1 g_1 + \int_0^1 \Big[u_2\left(x\bar{K} + g_2(x) - s_2(x) + \phi s_1\right) - p_2 g_2(x)$$
$$+ \int_0^1 \left[u_3\left(y\bar{K} + g_3(y) - s_3(y) + \phi s_2(x)\right) + u_4(g_4(y) + \phi s_3(y)) - \sum_{i=3,4} p_i g_i(y)\right] dF^y(y)\Big] dF^x(x)$$
$$\text{s.t.} \quad s_i \leq \bar{s}, s_i \geq 0, \text{ and } p_3 > p_4 \geq p_2 > p_1. \tag{1}$$

In the optimization problem, $x\bar{K}$ and $y\bar{K}$ denote the solar power generation given the weather conditions represented by x and y in periods 2 and 3, respectively. For $j = 1, 2, 3, 4$, g_j denote the grid purchases (or sales). Furthermore, s_l ($l = 1, 2, 3$) denotes the amount of energy storage that is carried to the following period. Lastly, ϕ is the round-trip efficiency parameter.

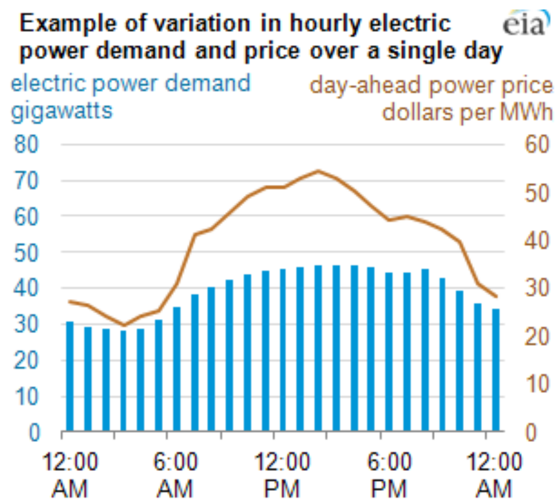

Figure 2: *Example of variation in hourly electric power demand and price over a single day. Source: EIA, http://www.eia.gov/todayinenergy/detail.cfm?id=6350*

3.1 Solving the model

We solve the problem recursively. In the last period, the HH solves the following problem:

$$\max_{\{g_4\}} \quad u_4\left(g_4 + \phi s_3\right) - p_4 g_4$$

The optimal level of the grid activity, g_4^*, solves $u_4'\left(g_4^* + \phi s_3\right) = p_4$, and therefore, will be calculated from $g_4^* = u_4'^{-1}\left(p_4\right) - \phi s_3$. When $u_4'\left(\phi s_3\right) > p_4$, then $g_4^* > 0$. Otherwise, (i.e., $u_4'\left(\phi s_3\right) \leq p_4$), $g_4^* \leq 0$. The optimality conditions dictate that the electricity will be purchased from (resp. fed to) the grid when it is sufficiently cheap (resp. expensive). In particular, given $s_3 > 0$, when the amount of stored energy is sufficiently low such that the marginal gross surplus is greater than the unit cost of electricity in the last period, electricity will be purchased and the other way around.

In the third period, the problem is as follows:

$$\max_{\{s_3, g_3\}} u_3\left(y\bar{K} + g_3 - s_3 + \phi s_2\right) - p_3 g_3 + u_4\left(g_4^* + \phi s_3\right) - p_4 g_4^*$$

$$\text{s.t.} \quad s_3 \leq \bar{s}, \text{ and } s_3 \geq 0.$$

The first order conditions with respect to the grid activity and energy storage are

$$u'\left(y\bar{K}+g_3-s_3+\phi s_2\right)=p_3, \tag{2a}$$
$$-u'\left(y\bar{K}+g_3-s_3+\phi s_2\right)+\phi u_4'(g_4^*+\phi s_3)+\eta_3-\nu_3=0, \tag{2b}$$

respectively. Substituting the prior into the latter equation yields

$$-p_3+\phi p_4+\eta_3-\nu_3=0. \tag{3}$$

The willingness to store energy is determined by the marginal surplus from energy consumption today and in the next period. Given that the prices are fixed and that the HH has the option to feed its electricity to the grid, storage decision reduces to the difference between the electricity price in the third and fourth periods after accounting for the round-trip efficiency parameter. For $-p_3+\phi p_4>0$, $\nu_3>0$, and therefore, the storage device will be charged up to its capacity: $s_3^*=\bar{s}$. On the other hand, if $-p_3+\phi p_4<0$, $\eta_3>0$ and $s_3^*=0$. Given s_3^*, g_3^* can be calculated from Eq. (2a): $g_3^*=u'^{-1}(p_3)-y\bar{K}+s_3-\phi s_2$.

The problem in the second period is

$$\max_{\{s_2,g_2\}} \; u_2\left(x\bar{K}+g_2-s_2+\phi s_1\right)-p_2g_2 + \mathbb{E}\left[u_3\left(y\bar{K}+g_3^*-s_3^*+\phi s_2\right)-p_3g_3^*+u_4\left(g_4^*+\phi s_3^*\right)-c_4^*g_4\right]$$
$$\text{s.t. } s_2\leq\bar{s}, \text{ and } s_2\geq 0.$$

The first order conditions are

$$u_2'\left(x\bar{K}+g_2-s_2+\phi s_1\right)=p_2, \tag{4a}$$
$$-u_2'\left(x\bar{K}+g_2-s_2+\phi s_1\right)+\phi\mathbb{E}[u_3'(y\bar{K}+g_3^*-s_3^*+\phi s_2)]+\eta_2-\nu_2=0. \tag{4b}$$

Energy storage decision is now determined by the marginal surplus from energy consumption today and the expected marginal surplus in the next period (adjusted for the round-trip efficiency) as RE generation in third period is uncertain. Substituting Eqs. (2a) and (4a) in Eq. (4b), if $-p_2+\phi p_3>0$, $\nu_2>0$ and the optimal amount of energy storage in the second period will be $s_2^*=\bar{s}$. Otherwise, that is, if $-p_2+\phi p_3<0$, $\eta_2>0$ and $s_2^*=0$. Given s_2^*, the second-period optimal grid activity, g_2^*, is obtained by solving Eq. (4a) for g_2.

Lastly, the problem in the first period is

$$\max_{\{s_1,g_1\}} \; u_1\left(g_1-s_1+s_0\right)-p_1g_1+\mathbb{E}_2\Big[u_2\left(x\bar{K}+g_2^*-s_2^*+\phi s_1\right)-p_2g_2 + \mathbb{E}\left[u_3\left(y\bar{K}+g_3^*-s_3^*+\phi s_2\right)-p_3g_3^*+u_4\left(g_4^*+\phi s_3^*\right)-p_4g_4^*\right]\Big]$$
$$\text{s.t. } s_1\leq\bar{s} \text{ and } s_1\geq 0.$$

The first order conditions for the final problem are

$$u'_1(g_1 - s_1 + s_0) = p_1, \tag{5a}$$

$$-u'_1(g_1 - s_1 + s_0) + \phi\mathbb{E}[u'_2(x\bar{K} + g^*_2 - s^*_2 + \phi s_1)] + \eta_1 - \nu_1 = 0. \tag{5b}$$

In a similar fashion, if $-p_1 + \phi p_2 > 0$, $\nu_1 > 0$ and $s^*_1 = \bar{s}$. Otherwise, that is, if $-p_1 + \phi p_2 < 0$, $\eta_1 > 0$ and $s^*_1 = 0$. Given s^*_1, g^*_1 is calculated from Eq. (5a).

Due to technical constraints, if it would only be possible to store electricity from the solar PV system, the storage capacity at period t would become $\bar{s}_t = \min(\bar{s}, k\bar{K} + \phi s^*_{t-1})$ ($k = x, y$ for period 2 and 3, respectively). Notice that given a fixed pricing scheme, that is, for $p_1 = p_2 = p_4 = p_3$, which is the case for the passive and low carbon Welsch house in Ridley et al. (2014), it would never be optimal to store energy.

4 Calibration

We consider a CRRA utility function,

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

where $\bar{c}_{ij}$ denotes required/desired access to a minimum level of electricity (similar, to some extent, to subsistence level of consumption) for season i and period j and α is a scale parameter. We consider different subsistence levels depending on the seasons of the year (summer, fall, winter and spring) and the periods of the day (12-6am, 6am-12pm, 12pm-6pm and 6pm-12am) while keeping γ and α constant.

In calibrating the model, we use the observation from our data set that correspond to the minimum consumption level at night during the summer season (1.059kWh) as an approximation of the subsistence level of summer consumption at night. Given $\gamma = 5$ (sensitivity analysis), the average level of night summer consumption (1.5241 kWh), the corresponding subsistence level of consumption and the observed constant price of electricity (15pence/kWh), we calculate $\alpha = 0.3263$, which we take as fixed for all other periods. The subsistence consumption levels in all other seasons and periods are computed by equating the marginal utilities as the price of electricity is constant in the data.[6] Based on the fact that the Tesla Powerwall has a 92.5% round trip efficiency when charged or discharged (by a 400–450 V system at 2 kW with a temperature of 25 degrees, and when the product is brand new) we take $\phi = 0.925$. Furthermore, the Tesla Powerwall has a capacity of 6.4 kW and a charge and drain limit of 3.3kW. 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.

[6] The average per season per period consumption and subsistence level of consumption are provided in Table 3 in the Appendix.

In obtaining the probability density functions for period 2 and 3 PV generation (that is, when there is sun) at each season, we approximate the data with Weibull distribution whose scale and shape parameters are estimated using maximum likelihood estimation. After generating a row vector of linearly equally spaced points, which correspond to PV generation, we construct the pdf of the Weibull distribution with the estimated scale and shape parameters evaluated at each PV generation level.[7] The probability density functions for PV generation in the second and third periods are demonstrated in Figure 3.

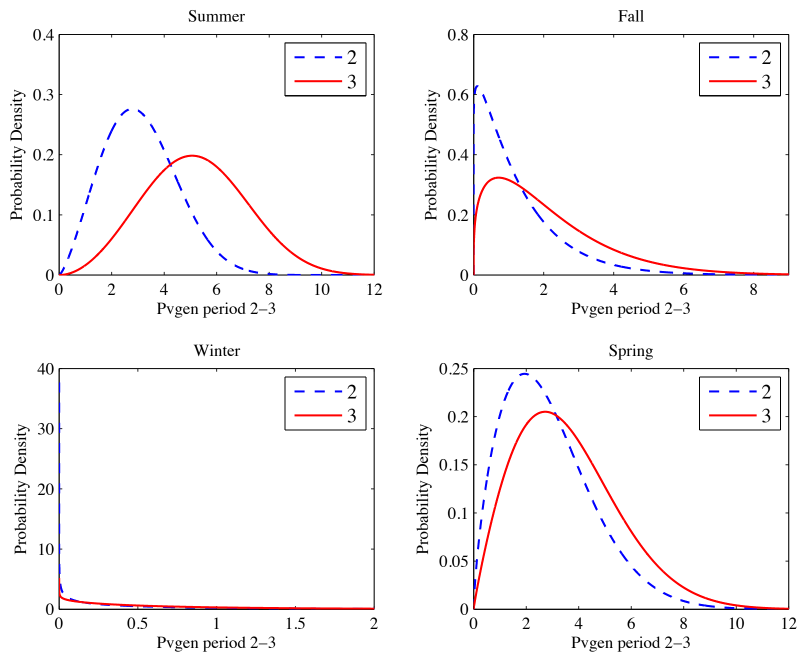

Figure 3: *The pdfs for period 2 and 3 at each season*

Given that the observed price of electricity is 15pence/kWh and in line with Figure 2, we assume that $p_3 = \frac{4}{3}p_2 = \frac{4}{3}p_4 = 2p_1$ where the average price, $(p_1+p_2+p_4+p_3)/4$, equals 15 pence/kWh.

5 Results

We consider 8 different scenarios/cases and demonstrate the results of our calculations in Table 1. In the table, *welfare1*, the total daily welfare in a season, corresponds to the case where the HH can store electricity from both the solar PV system and the grid when the

[7]On the one hand, we obtain the variance and the mean of the Weibull distribution using the estimated shape and scale parameters. On the other hand, we compute the variance and the mean of the simulated levels of PV generation and verify that these values match. Furthermore, using the simulated levels of PV generation, we compute the expected consumption and ensure that they correspond to the ones computed analytically; e.g., $c_{ij} = u'^{-1}(p_j) + \bar{c}_{ij}$.

prices are dynamic.[8] When electricity price is fixed ($p_1 = p_2 = p_4 = p_3 = 15$ pence/kWh) and, therefore, storage is suboptimal, the daily welfare is represented by *welfare2*. When electricity can only be stored using the PV system, *welfare3* and *welfare4* represent the daily welfare when energy is stored optimally and when any electricity produced by the PV system first goes to the battery, respectively.[9] Furthermore, *welfare5* is the daily welfare when no solar panels are installed and the prices are dynamic. Thus, energy can only be stored by electricity purchases from the grid. In the absence of an energy storage system, *welfare6* represents the daily welfare when the HH owns a PV system. Finally, *welfare7* and *welfare8* represent the daily welfare when prices are dynamic and fixed and when no solar panels and storage systems are installed, respectively, .

	welfare1	**welfare2**	**welfare3**	**welfare4**	**welfare5**	**welfare6**	**welfare7**	**welfare8**
Summer	36.0538	-32.6881	-0.28232	-37.63	-114.777	-11.1462	-161.977	-157.485
Fall	-28.8519	-83.6289	-71.5298	-91.0664	-90.4215	-76.0519	-137.622	-134.672
Winter	-171.066	-208.058	-215.4	-224.66	-198.927	-218.266	-246.127	-232.13
Spring	-35.1898	-92.2241	-72.4916	-104.975	-150.008	-82.3898	-197.208	-189.09
Total	-17942	-37827.4	-32590.4	-41626	-50492	-35170	-67720	-65031.7

Table 1: *Welfares - 8 cases. (Welfare values measured in pence.)*

A few comments are in order. One can notice that the total daily welfare in the summer season in the first case (i.e., *welfare1*) is positive. This figure is mainly related to the relatively higher amount of feed-ins to the grid in the second and third periods in the day (see Table 4 in the appendix). Moreover, while in the majority of cases the summer welfare is the highest, in cases 5, 7 and 8, the daily welfare in the fall season is the highest. This is mainly related to the fact that the HH does not have the solar PV. Accordingly, it cannot benefit from the rather higher solar radiation, and in turn, solar power generation, in the summer. Sustaining the desired level of consumption then leads to a relatively higher amount of payments to purchase electricity in the summer.

[8]The annual data that we employ consists of 92, 91, 90 and 92 days of summer, fall, winter and spring, respectively.

[9]The grid activity, and in turn, the value of grid purchases and sales, which one needs to consider when calculating the net surplus may not be constant in these two cases. This is due to the fact that energy can only be stored from the energy generated by the solar PV system. Consequently, a low level of RE generation, which will not fill the storage device up to its capacity, will expose the optimal grid activity to RE generation. A two level of uncertainty, that is, uncertain RE generation in the second and third periods, will lead to a dimension that is too large to compute when one works with the probability density functions. To circumvent this problem, we restrict ourselves to a manageable number of realizations within the same range. A further and detailed explanation of this procedure is provided in Section 6.

5.1 Willingness to pay for smart meters

To find out whether there is any room for investment in smart meters, we compare the welfare under dynamic pricing net of the usage cost of a smart meter device with the welfare under fixed pricing. This allows us to identify the maximum investment expenditure the HH would be willing to make for the smart meter. In this subsection, we make different computations depending on whether the HH owns, and therefore, have access to the solar PV system or the home storage battery or both. In particular, we compare the welfares in cases 1 and 2, 7 and 8, 2 and 6, and 5 and 8, respectively.

In calculating the present value of the total welfare, we employ a discount rate, r, of 5% (thus, a discount factor, $\beta = 1/(1+r)$, of 0.95). We, further, consider a 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 (CSWG, 2010). In the case where the HH has access to solar panels and the battery pack, the comparison between the discounted sum of the welfares can be written as in the following:

$$W_1 - \hat{r}k_m \geq W_2 \equiv k_m \leq \frac{W_1 - W_2}{\hat{r}} \tag{6}$$

where

$$\hat{r} \equiv (1-\beta)/(1-\beta^{21})$$

and k_m is the cost of installing a smart meter. With the interest rate being equal to 5%, the WTP is £2677, corresponding to £198.85 change in welfare. The latter figure is indeed the difference between *welfare2* and *welfare1*. Note that even if there is a storage device, it is not optimal to store energy under a fixed pricing scheme. This may explain the big discrepancy between *welfare1* and *welfare2*.

When the HH has access neither to the home storage battery nor the solar panels, the annual welfare would decrease by £27 (this corresponds to *welfare7*-*welfare8*). Therefore, -£362 is the willingness to pay of the HH for the smart meter. By comparing *welfare2* and *welfare6*, we obtain nearly the same result (-£358) when the HH owns the PV system but not the storage device. Having access to the battery pack but not to the PV system would increase the welfare change to £145 (this corresponds to welfare5-welfare8). This corresponds to £1957 WTP for a smart meter.

Based on the pricing scheme we used, the results show that having access to a storage device allows the HH to take a significantly better advantage of a smart meter. While having the PV system in addition to the home storage battery makes smart meters even more beneficial for the HH, using only the solar panels (and therefore, having no access to the home storage battery) would not justify the installation of a smart meter.

The Department of Energy and Climate Change (DECC) puts the cost per HH of installing smart meters at £214.50.[10] Consequently, regardless of whether the HH has access to the energy generated by the solar panels or not, it should install a smart meter if and only if it can store electricity using the battery pack.

5.2 Willingness to pay for solar panels

In this subsection we compare scenarios with and without the PV system to deduce the WTP for its installation. In particular, we compare the welfares in cases 1 and 5, 6 and 7, and 2 and 8 respectively. When the pricing scheme is dynamic, installing the PV system increases the annual welfare approximately by £325, regardless of the installation of the battery pack (this correspond to both *welfare1*-*welfare5* and *welfare6*-*welfare7*). This result translates into a WTP of £4382. Moreover, for the case where the pricing scheme is fixed (therefore, energy would not be stored), the annual welfare increases by £272 upon the installation of the solar panels (this is obtained by *welfare2*-*welfare8*) corresponding to a WTP of £3662. Considering a 1.9kW peak PV system with an establishment cost of £2755, it is significantly beneficial for the HH to install the solar PV system regardless of the pricing scheme and the presence of the storage device.[11]

5.3 Willingness to pay for energy storage

To deduce the WTP for the installation of the home storage battery, we compare scenarios with and without the storage device in this subsection. Specifically, we compare the welfare in cases 1 and 6, 5 and 7, 3 and 6, and 4 and 6, respectively. The annual welfare rise in case of a dynamic pricing schedule (with or without the solar PV system) is £172.3 when the HH installs a battery pack (this correspond to both *welfare1*-*welfare6* and *welfare5*-*welfare7*). The WTP, accordingly, equals £2319. Considering that the specific home storage battery solution costs approximately £2300 (3000 USD), it is optimal for the HH to install the Tesla Powerwall home battery. Yet, the small difference between the WTP and the cost of storage may be taken as inconsequential and point to the fact that the high cost of storage is a drawback for the wider use of these systems (Durmaz, 2016; IEA, 2016).[12]

As is seen from the results, having access to solar PV does not have a significant impact on the welfare rise following the installation of the battery pack. The argument runs as follows. The HH has the discretion to sell to the grid when its valuation of the electricity on the margin gets lower than the electricity price. For instance, in case of a sufficiently large solar generation and high electricity price, the HH will provide electricity to the grid

[10]This gets passed indirectly on to consumers, along with other network costs. Link: http://www.telegraph.co.uk/finance/personalfinance/energy-bills/11975065/Smart-meters-will-cost-11bn-but-youll-be-lucky-if-yours-saves-you-30.html.

[11]1.9kW peak PV system is the one that is installed in the aforedescribed passive house.

[12]It is, however, expected that the cost of energy storage systems will fall by 40% by 2020 (Ortiz, 2016).

instead of storing in the battery pack. Therefore, what matters for the storage decision of the HH is the pricing dynamics.

Nonetheless, when storage is constrained in such a way that only solar power generation can be stored (not the electricity from the power grid), the WTP reduces to £347 (this corresponds to *welfare3*-*welfare6*). This makes it suboptimal to install the storage device. Things get even worse when the generated solar power first fills the battery. This is because the HH is not able to optimally allocate the generated electricity for storage, and with it, electricity consumption and feed-ins to the grid. Subsequently, the welfare decreases by £64.56 (*welfare4*-*welfare6*) when the storage device is installed.

6 No feed-ins to the grid

While in some regions and countries, such as the European Union and the U.S., net metering is allowed, it is not in some others like Hong Kong and some African countries. Therefore, it can be of practical interest to investigate the WTP for smart meters, solar panels and storage devices when legislation prohibits the net-metering practice.

When net metering is not allowed, we solve the problem given by Eq. (1) by also imposing the no-feed-ins constraint; that is,

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

In this case, we will not be able to exploit the FOCs as we did in the previous section where selling to or buying from the grid was at the discretion of the HH. The current problem, accordingly, exhibits a dimension that is too large to derive all the potential FOCs (except, possibly, if we restrict the number of realizations for solar power generation to two (e.g., solar power generation at the capacity or no solar power generation at all). We, therefore, turn to fully solving the problem numerically. Nevertheless, this is subject to the curse of dimensionality when one wants to work with the density functions we constructed earlier (see p. 11). To circumvent this problem, we restrict ourselves to 11 realizations within the same range for solar power generation.

Restricting the number of the realizations to 11, and therefore, working with 10 probability mass functions, will lead to overestimation of the true expected value. Let $\mathbf{\Pi} \equiv \pi_1, ..., \pi_{11}$ denote the probabilities that solar power generation will be less than $\mathbf{X} \equiv x_1, ..., x_{11}$, respectively.[13]. To avoid this problem, we discretize each interval (e.g., $x_{11}, ..., x_{1z}$ where z is the number of elements within interval $[0, x_1]$) and assign a weight (ω_{ij}, $i = 1, ..., n$ and $j = 1, ..., z$) to each member within. To calculate the weights, we use the densities from the Weibull distribution given the scale and shape parameters that we calculated earlier:

$$\omega_{ij} = \frac{f(x_{1j})}{\Sigma_{j=1}^{z} f(x_{1j})}. \tag{7}$$

[13]Calculating the expected value using $\mathbf{\Pi}'\mathbf{X}$ will lead to overestimation

This approach allows us to assign higher weights to the outcomes with higher densities and, in turn, circumvent the aforementioned bias problem. Utilizing the weights, we then construct a new index $\hat{\mathbf{X}} \equiv \hat{x}_1, ..., \hat{x}_{11}$ where $\hat{x}_i \equiv \Sigma_j^z \omega_{ij} x_{ij}$. In the final step, given the reduced number of realizations, we check whether the expected value, $\mathbf{\Omega}'\hat{\mathbf{X}}$ where $\mathbf{\Omega} \equiv \omega_1, ..., \omega_{11}$, matches the mean of the Weibull distribution given λ and k parameters. If not, we increase the number of realizations z until this is achieved. As this approach does not require solving an optimization problem, it can numerically be calculated with ease.

The following table presents the expected welfares for the cases where the HH is not allowed to provide electricity to the electric grid:

	welfare1	welfare2	welfare5	welfare6	welfare7	welfare8
Summer	-38.68	-46.31	-129.32	-76.56	-161.98	-157.48
Fall	-73.09	-85.87	-108.84	-91.63	-137.62	-134.67
Winter	-187.32	-214.06	-204.81	-225.31	-246.13	-232.13
Spring	-83.33	-95.14	-160.02	-107.29	-197.21	-189.09
Total	-34735	-40093	-54956	-45531	-67720	-65032

Table 2: *Welfare - No feed-ins. (Welfare values are measured in pence.)*

6.1 Willingness to pay for smart meters

One can note that in the absence of the solar PV system and the battery pack (*welfare7* and *welfare8*) the no feed-in constraint is not binding and welfares are identical to the ones in Table 1. Therefore, when the HH does not have access to the home storage battery and solar panels, the WTP of the HH for the smart meter (obtained through the discounted difference between *welfare7* and *welfare8*) is identical to the difference we obtained in the previous section. As the outcome is negative (-£362), it is not beneficial for the HH to install a smart meter. In all other cases, the welfare gain obtained from installing a smart meter is smaller than the welfare that would be obtained when the grid could be fed in. This is especially the case when the PV system is installed as the HH can extensively benefit from electricity provisions to the grid. As a result, a smart meter that is accompanied by the PV system would not lead to any welfare gains in the absence of the storage device (this is obtained from *welfare6*-*welfare2*, corresponding to a WTP that equals -£732). This outcome also overlaps with the one where grid could be fed. In case the HH owns the storage device, however, the welfare gain from installing a smart meter is positive even if the stored energy cannot be fed to the grid when the electricity price is sufficiently high. With the PV system the WTP for the smart meter equals £721, which is calculated from *welfare1*-*welfare2*. Without solar panels, it is £1356 (calculated from *welfare5*-*welfare8*). The fact that the WTPs are higher than the cost of the smart meter justifies the installation of the smart meter. Notice, however, that they all are smaller than those when the HH can feed-in the grid.

6.2 Willingness to pay for solar panels

Accounting for the current cost of the PV system installed in the Lime house, it is not obviously profitable for the HH to install them. The WTP for the solar PV system is always smaller than those when it is possible to feed the grid. Furthermore, the WTP is the lowest when the pricing schedule is dynamic. Specifically, it is £2722 (derived from welfare1-welfare5) with storage and £2987 in the absence of storage (derived through welfare6-welfare7). Notice that the additional flexibility brought by solar panel is less valuable when there is a storage device because this device allows taking advantage of the dynamic pricing and generates already high welfares. As the cost of the solar PV system, £2755, is only an approximation, it may well be that installing the PV system is not profitable when the pricing schedule is dynamic, even without the storage system.[14]. The WTP becomes £3357 without a smart meter, i.e., under fixed pricing (derived through welfare2-welfare8), making storage ineffective. In this case only, it is profitable to install the PV system.

6.3 Willingness to pay for energy storage

Interestingly, it is never profitable to install the battery pack. Recall that the cost of this device is approximately £2300 (3000 USD). If the PV system is already installed, the WTP is only £1453 (this is derived from *welfare1-welfare6*). The WTP (£1718, calculated from *welfare5-welfare7*) is still smaller than the cost without the PV system. In any case, the WTP is significantly smaller than the ones calculated when grid feed-ins were possible. This is consistent with the intuition as selling to the grid is a way to take advantage of the storage device.

7 Conclusion

In this paper, we account for solar energy generation as well as for two levels of equipment in smart grids that can allow for additional flexibility in the electricity system. The first one concerns the smart meters, which are rather widely used in Europe. The second level relates to energy storage. We appraise the WTP of a HH for RE systems as well as the smart grid devices in an attempt to identify the focus of public policy that can allow for a smooth transition towards more RE generation.

[14] If the cost is (slightly) overestimated, the PV system may be profitable regardless of the presence of energy storage.

Our results indicate that having access to a storage device can allow a HH to take a better advantage of a smart meter. Complementing the storage device with a PV system induces a further willingness for the HH to install a smart meter. Yet, this impact is rather limited. When the HH cannot store energy but can still generate electricity through the PV system would not justify the installation of the smart meter. Considering a 1.9kW peak PV system, we find that it would significantly be beneficial for the HH to install the PV system regardless of the pricing scheme and the possession of the storage device. Furthermore, having access to solar PV does not contribute significantly to the willingness of the HH to install the battery pack. While in some regions and countries, such as the European Union and the U.S., net metering is allowed, it is not in some others like Hong Kong and some African countries. Therefore, we also investigate the WTP for smart meters, solar panels and storage devices when legislation prohibits net-metering. Consistent with the intuition, our results indicate that the WTPs for solar panels or smart grid devices are always smaller than when the HH can feed-in the grid.

Our results suggest that the first public policy to be implemented to foster the adoption of RE should concern the possibility of net-metering. However, net-metering is already possible in some countries and where it is not, this implies changes in legislations that may be difficult to implement due to the lobbying of some reluctant electric utilities concerned with their market shares. In countries where it is already possible to feed the grid, public policy should be focused on storage and smart devices. On the contrary, solar panels themselves seem to be already profitable and do not require any public policy support. In countries where net-metering will not be easily implemented soon, subsidizing storage would have the joined positive effect of making smart meters profitable as well, even without any targeted policy. However, the most efficient public policy should probably focus on solar panels as their net present value is not very negative. Do note that our model is calibrated on UK households but could easily be applied to any other country of the world. Indeed, it could be interesting to appraise whether public policy recommendations are robust to countries' specificities (for instance climate, insulation or electricity price levels).

References

Ambec, S. and C. Crampes (2012). Electricity provision with intermittent sources of energy. *Resource and Energy Economics 34*(3), 319–336.

Ambec, S. and C. Crampes (2015). Environmental policy with intermittent sources of energy. *Mimeo*.

Arimura, T., S. Li, R. Newell, K. Palmer, et al. (2012). Cost-effectiveness of electricity energy efficiency programs. *Energy Journal 33*(2), 63–99.

Baker, E., M. Fowlie, D. Lemoine, and S. S. Reynolds (2013). The economics of solar electricity. *Annual Review of Resource Economics 5*.

Bigerna, S., C. A. Bollino, and S. Micheli (2016). Socio-economic acceptability for smart grid development–a comprehensive review. *Journal of Cleaner Production*.

Borenstein, S. and S. Holland (2005). On the efficiency of competitive electricity markets with time-invariant retail prices. *RAND Journal of Economics 36*(3), 469–493.

Crampes, C. and M. Moreaux (2010). Pumped storage and cost saving. *Energy Economics 32*(2), 325–333.

CSWG (2010). Guidelines for smart grid cyber security: Vol. 1, smart grid cyber security strategy, architecture, and high-level requirements. Technical Report 7628, National Institute of Standards and Technology Interagency.

De Castro, L. and J. Dutra (2011). The economics of the smart grid. In *Communication, Control, and Computing (Allerton), 2011 49th Annual Allerton Conference on*, pp. 1294–1301. IEEE.

De Castro, L. and J. Dutra (2013). Paying for the smart grid. *Energy Economics 40*, S74–S84.

Durmaz, T. (2016). Precautionary storage in electricity markets. *NHH Dept. of Business and Management Science Discussion Paper* (2016/5).

EIA (2016). International Energy Outlook 2016. Technical report, U.S. Energy Information Administration.

Feist, W. (2014). Passive House - the next decade. In *Proceedings of the 18th International Passive House Conference, Aachen, Germany*.

Gravelle, H. (1976). The peak load problem with feasible storage. *The Economic Journal 86*(342), 256–277.

Haegel, N. M., R. Margolis, T. Buonassisi, D. Feldman, A. Froitzheim, R. Garabedian, M. Green, S. Glunz, H.-M. Henning, B. Holder, et al. (2017). Terawatt-scale photovoltaics: Trajectories and challenges. *Science 356*(6334), 141–143.

Hagerman, S., P. Jaramillo, and M. G. Morgan (2016). Is rooftop solar pv at socket parity without subsidies? *Energy Policy 89*, 84–94.

Hall, S. and T. J. Foxon (2014). Values in the smart grid: The co-evolving political economy of smart distribution. *Energy Policy 74*, 600–609.

Hirth, L. (2015). The optimal share of variable renewables: How the variability of wind and solar power affects their welfare-optimal deployment. *Energy Journal 36*(1).

IEA (2016). Nordic Energy Technology Perspectives 2016: Cities, exibility and pathways to carbon-neutrality. Technical report, International Energy Agency.

IER (2016). The high cost of rooftop solar subsidies: How net metering programs burden the american people. Technical report, Institute for Energy Research.

Jackson, R. (1973). Peak load pricing model of an electric utility using pumped storage. *Water Resources Research 9*(3), 556–562.

Jeon, W., J. Y. Mo, and T. D. Mount (2015). Developing a smart grid that customers can afford: The impact of deferrable demand. *Energy Journal 36*(4).

Joskow, P. and J. Tirole (2007). Reliability and competitive electricity markets. *The Rand Journal of Economics 38*(1), 60–84.

Laustsen, J. (2008). Energy efficiency requirements in building codes, energy efficiency policies for new buildings. *IEA Information Paper*, 1–85.

Madigan, L. (2011). An experiment too expensive for consumers. *Chicago Tribune* (June 21st 2011).

Ortiz, L. (2016). Grid-scale energy storage balance of systems 2015-2020: Architectures, costs and players. Technical report, GTM Research.

Ossenbrink, H., T. Huld, A. J. Waldau, and N. Taylor (2013). Photovoltaic electricity cost maps. *JRC Scientific and Policy Reports - European Commission*.

Owen, P. and R. Foreman (2012). Powering the nation: Household electricity using habits revealed. Technical report, Energy Saving Trust.

Reichelstein, S. and M. Yorston (2013). The prospects for cost competitive solar pv power. *Energy Policy 55*, 117–127.

Ridley, I., J. Bere, A. Clarke, Y. Schwartz, and A. Farr (2014). The side by side in use monitored performance of two passive and low carbon Welsh houses. *Energy and Buildings 82*, 13–26.

Sivaram, V. and S. Kann (2016). Solar power needs a more ambitious cost target. *Nature Energy 1*, 16036.

Speer, B., M. Miller, W. Shaffer, L. Gueran, A. Reuter, B. Jang, and K. Widegren (2015). The role of smart grids in integrating renewable energy. Technical report, National Renewable Energy Laboratory.

The Economist (2009). Building the smart grid. *The Economist* (June 4th 2009).

The Guardian (2017). Solar power growth leaps by 50% worldwide thanks to US and China. *The Guardian* (Mar 7th 2017).

The Telegraph (2015a). My solar power smart meter shaves £250 off energy bills. *The Telegraph* (August 28th 2015).

The Telegraph (2015b). Smart meters: will you pay more for peak electricity? *The Telegraph* (May 24th 2015).

Van Benthem, A., K. Gillingham, and J. Sweeney (2008). Learning-by-doing and the optimal solar policy in california. *The Energy Journal*, 131–151.

Watanabe, Chisaki and Stapczynski, Stephen (2016). Japan?s solar boom showing signs of deflating as subsidies wane. *Bloomberg Technology* (Jul 6th 2016).

Appendices

A Average and subsistence levels of consumption

Table 3 demonstrates the average level of consumption (s_avg, f_avg, w_avg, sp_avg) and the subsistence level of consumption for each season and period.

Given the 8 cases that we consider, Table 4 demonstrates the optimal grid decisions of the HH for each season and period.

B Periodic grid activities and optimal levels of consumption when there are feed ins to the grid

Table 5, where cj ($j = 1, 2, ..., 8$) correspond to the eight different cases that we are considering, demonstrates the optimal level of consumption for each season and period. As expected, even for constant level of pricing in each period, the optimal levels of consumption differ because desired access to the minimum level of electricity $\bar{c}_{ji}$ are not the same.

	s_avg	gbarS	f_avg	gbarF	w_avg	gbarW	sp_avg	gbarSp
Period 1	1.5241	1.059	1.1938	0.968	2.0478	1.085	1.6543	1.1713
Period 2	2.63	2.1649	1.9694	1.5043	3.5626	3.0976	3.0882	2.6232
Period 3	2.4542	1.9892	2.0549	1.5898	4.3813	3.9162	3.2919	2.8268
Period 4	3.4256	2.9606	3.0558	2.5907	5.5163	5.0512	4.1245	3.6594

Table 3: *Periodic average consumption (c) in kWh and cbar (i.e., $\bar{c}_{ij}$) calculated from the data*

	grid1	grid2	grid3	grid4	grid5	grid6	grid7	grid8
Summerd1	7.963	1.524	1.563	1.563	7.963	1.563	1.563	1.524
Falld1	7.872	1.433	1.472	1.472	7.872	1.472	1.472	1.433
Winterd1	7.989	1.55	1.589	1.589	7.989	1.589	1.589	1.55
Springd1	8.076	1.636	1.676	1.676	8.076	1.676	1.676	1.636
Summerd2	−0.003	−0.483	2.621	2.621	3.11	−0.483	2.63	2.63
Falld2	1.152	0.672	1.964	1.964	2.449	0.672	1.969	1.969
Winterd2	3.196	2.716	3.543	3.543	4.043	2.716	3.563	3.563
Springd2	0.701	0.221	3.049	3.049	3.568	0.221	3.088	3.088
Summerd3	−8.699	−2.753	−5.65	0.448	−3.492	−2.779	2.428	2.454
Falld3	−5.997	−0.051	−1.272	1.918	−3.891	−0.077	2.029	2.055
Winterd3	−2.323	3.623	2.834	4.346	−1.565	3.597	4.355	4.381
Springd3	−6.245	−0.299	−2.941	2.363	−2.654	−0.325	3.266	3.292
Summerd4	3.426	3.426	3.426	−2.215	3.426	3.426	3.426	3.426
Falld4	3.056	3.056	3.056	0.105	3.056	3.056	3.056	3.056
Winterd4	5.516	5.516	5.516	4.118	5.516	5.516	5.516	5.516
Springd4	4.124	4.124	4.124	−0.781	4.124	4.124	4.124	4.124

Table 4: *The periodic grid activities. (E.g., grid1 denotes the grid activity for Case 1. Summerd1 denotes the first period of the day in the summer*

	consS	consF	consW	consSp
c1-Period 1	1.5633	1.4723	1.5893	1.6757
c1-Period 2	2.63	1.9693	3.5626	3.0882
c1-Period 3	2.4282	2.0289	4.3553	3.2659
c1-Period 4	3.4256	3.0558	5.5163	4.1245
c2-Period 1	1.5241	1.4331	1.5501	1.6364
c2-Period 2	2.63	1.9693	3.5626	3.0882
c2-Period 3	2.4542	2.0549	4.3813	3.2919
c2-Period 4	3.4256	3.0558	5.5163	4.1245
c3-Period 1	0.50435	1.4723	1.5893	1.6757
c3-Period 2	0.46506	1.9693	3.5626	3.0882
c3-Period 3	0.43906	2.0289	4.3553	3.2659
c3-Period 4	0.46506	3.0558	5.5163	4.1245
c4-Period 1	1.5633	1.4723	1.5893	1.6757
c4-Period 2	2.63	1.9693	3.5626	3.0882
c4-Period 3	2.4282	2.0289	4.3553	3.2659
c4-Period 4	3.4256	3.0558	5.5163	4.1245
c5-Period 1	1.5633	1.4723	1.5893	1.6757
c5-Period 2	2.63	1.9694	3.5626	3.0882
c5-Period 3	2.4282	2.0289	4.3553	3.2659
c5-Period 4	3.4256	3.0558	5.5163	4.1245
c6-Period 1	1.5633	1.4723	1.5893	1.6757
c6-Period 2	2.63	1.9693	3.5626	3.0882
c6-Period 3	2.4282	2.0289	4.3553	3.2659
c6-Period 4	3.4256	3.0558	5.5163	4.1245
c7-Period 1	1.5633	1.4723	1.5893	1.6757
c7-Period 2	2.63	1.9694	3.5626	3.0882
c7-Period 3	2.4282	2.0289	4.3553	3.2659
c7-Period 4	3.4256	3.0558	5.5163	4.1245
c8-Period 1	1.5241	1.4331	1.5501	1.6364
c8-Period 2	2.63	1.9694	3.5626	3.0882
c8-Period 3	2.4542	2.0549	4.3813	3.2919
c8-Period 4	3.4256	3.0558	5.5163	4.1245

Table 5: *Optimal consumption levels*

C Periodic grid activities and optimal levels of consumption when the grid cannot be fed by the HH

	grid1	grid2	grid5	grid6	grid7	grid8
Summerd1	1.63	1.524	7.963	1.563	1.563	1.524
Falld1	4.252	1.433	7.872	1.472	1.472	1.433
Winterd1	7.989	1.55	7.989	1.589	1.589	1.55
Springd1	4.881	1.636	8.076	1.676	1.676	1.636
Summerd2	0.291	0.321	0	0.321	2.63	2.63
Falld2	0	0.926	0	0.926	1.969	1.969
Winterd2	1.512	3.161	2.371	3.161	3.563	3.563
Springd2	0	0.744	0.719	0.744	3.088	3.088
Summerd3	0.016	0.018	0	0.028	2.428	2.454
Falld3	0	0.517	0	0.584	2.029	2.055
Winterd3	0	3.59	0	3.619	4.355	4.381
Springd3	0.08	0.486	0	0.594	3.266	3.292
Summerd4	0.867	0.875	2.9	3.426	3.426	3.426
Falld4	1.673	2.404	1.596	3.056	3.056	3.056
Winterd4	5.215	5.505	5.516	5.516	5.516	5.516
Springd4	1.835	3.035	4.124	4.124	4.124	4.124

Table 6: *Grid - No feed-ins*