The increasing cost of ignoring Coase: inefficient electricity tariffs, welfare loss and distributed energy resources

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Abstract

I show that British electricity tariffs create substantial welfare loss, equivalent to between six and eighteen percent of domestic consumption value. Losses are greater than unpriced distributional and environmental counter effects. Expected technological change will increase this welfare loss. Deployment of distributed energy resources (e.g. solar) benefits adoptees at the expense of non-adoptees as tariffs are recalibrated to recover fixed costs. Reform on Coasian principles avoids these welfare losses and re-distributional effects. In providing these estimates, I combine household-level micro-data with information on utility cost and tariff structure to simulate the welfare effects of tariff reform and technological change.

JEL Codes: K32; L94, L98, Q42, Q48, Q51, Q53, Q54; Q55

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Marginal cost pricing is a fundamental tenet of efficient allocation; consumers buy according to their preferences at prices that reflect the scarcity of supply. If average cost is greater than marginal cost there is an under-recovery of total costs. Two-part 'Coasian' pricing facilitates marginal cost pricing in such circumstances; volumetric tariffs are priced equal to marginal cost and a fixed 'standing charge' recovers fixed costs (Coase, 1946).

While it is known that a departure from marginal cost pricing creates welfare loss[1], there is no clear insight into how welfare will change with approaching technological developments. 'Distributed energy resources' (DERs), generation and storage technologies distributed at the level of the consumer, are on the cusp of widespread deployment (Green et al., 2017; Azarova et al., 2018; Morstyn et al., 2018). These technologies substitute for grid-sourced electricity and bring a change in the revenue structures faced by utilities. If Coasian pricing is not in place, and therefore some fixed costs are recovered via volumetric tariffs, a change in tariff structure will be required for cost recovery. How will these changes affect the level and distribution of consumer welfare? Are there negative spillovers for non-adoptees?

This paper answers these questions and, in so doing, provides two primary contributions. First, I estimate the welfare loss created by British tariffs and compare this to distributional and environmental counter-effects. I combine nationally representative micro-data with information on utility cost and tariff structure to show that volumetric prices exceed marginal cost by more than 50 percent and losses are equivalent to between six and eighteen percent of domestic consumption value, much greater than mispricing inefficiencies observed in the literature. This is the first welfare estimate for the UK, the first to find degrees of mispricing of this magnitude and the first full exploration of electricity welfare loss net of both environmental and distributional counter-effects. This is a crucial insight in a market with multiple distortions (Buchanan, 1969).

Second, I estimate the welfare change due to DER deployment. I show that deployment under current British tariffs redistributes welfare from non-adoptees to adoptees and increases welfare loss in likely circumstances. One may chart the pattern of welfare change by the falling trajectory of DER costs. At retail price parity, deployment leads to welfare loss as grid tariffs are adjusted to ensure fixed cost recovery. Welfare losses arising from these adjustments exceed benefits and adoptees benefit at the expense of non-adoptees. This welfare loss will continue until DER costs reach parity with the marginal cost of grid-sourced electricity. At this point, total welfare does not change but welfare redistribution persists. If DER-sourced electricity is cheaper than the marginal cost of electricity from the grid, there

[1] There is much research in this area. See, for example, Davis and Muehlegger (2010) (US Gas market); Borenstein (2012) (welfare cost of non-linear pricing); Borenstein and Davis (2012) (US retail gas tariffs); Borenstein and Bushnell (2018) (US electricity tariffs); Porcher (2014) (French water tariffs)

is a welfare gain, however, redistribution persists once more. These effects are avoided by a Coasian tariff reform. Welfare costs are substantial; assuming nine percent of households adopt solar, welfare losses of up to £250m per annum can be expected upon retail price parity, with non-adoptees losing up to £55 per annum. This is before any potential subsidy costs are accounted for.

These findings have three primary policy contributions. First, they will inform the ongoing tariff review processes being carried out by the UK regulator Ofgem. The UK Government introduced a Domestic Gas and Electricity (Tariff Cap) Act in July 2018, granting Ofgem power to regulate a default tariff price for domestic consumers. This paper shows that regulation on Coasian principles has potential to increase consumer welfare by up to 18 percent. A Coasian price tariff is estimated to guide such regulation.

Second, this paper informs the correct treatment of distributional counter effects. Ofgem have stated that finding a balance between efficiency, equity and environmental effects is important, particularly in the regulation of network charges[2] (Ofgem, 2017b, 2018b). This paper demonstrates clearly that environmental and social factors do not justify current departures from efficient tariff structures. While there is a considerable number of vulnerable households negatively affected by Coasian reform, the cost of redistribution implicit in the current tariff structure is greater than the marginal cost of public funds. As these distributional impacts are not insignificant, they should not be ignored but rather addressed through adjustments to wider tax and social transfer policy.

Thirdly, this paper shows that not only does Coasian reform lead to immediate benefit for consumers, it safeguards against the additional welfare costs that DER deployment may bring. While the policy discourse is focussed on a 'utility death spiral', the under-recovery of network fixed costs due to a major decrease in the volume of sales, this finding draws attention to a potential 'deadweight death spiral', where growing welfare losses due to increasing distortions outweigh the benefits of technological change.

This paper is structured as follows. Section I reviews the literature, while Section II gives theoretical insight into expected effects. Section III outlines the institutional background while Section IV outlines the data & methodology employed. Results are presented in Sections V-VII. Section V calculates a Coasian tariff reform for Great Britain. Section VI outlines the welfare change and distribution of impacts arising from a Coasian reform. Losses net of environmental and social counter-effects are also considered. Section VII quantifies the welfare change arising from changes at the extensive margin. Section VIII concludes.

[2]Ofgem stated that '[tariff] options that have significant distributional effects between consumers that cannot be justified by a reduction in overall costs (or achieving other objectives) are unlikely to be acceptable' (Ofgem, 2017b). Financial protection for vulnerable consumers is explicitly acknowledged as a policy priority (Ofgem, 2017b).

I Previous research

Many public utilities have high fixed costs and simple marginal cost pricing leads to cost under-recovery. A deep theoretical literature emerged in the early 20th Century to identify the most efficient tariff structure conditional on full cost recovery. Beginning with a discriminatory mark-up (i.e. 'Ramsey-Boiteaux pricing') (Ramsey, 1927; Boiteux, 1956), this literature soon converged on multi-part tariffs to preserve the marginal cost principle. The 'Hotelling-Lerner' solution was the first such attempt, where fixed costs are recovered through additional tax receipts (Hotelling, 1939; Lerner, 1944). Coase (1946) disputed the merits of this solution as it distorts resource allocation and redistributes income. His 'Coasian tariff' solution advocated fixed cost recovery through a standing charge in a two-part tariff. This is often cited as the first-best solution to utility pricing and many utilities have since followed this tariff structure (Borenstein, 2016).

A wide empirical literature has been built on this theoretical foundation, where the (in)efficiency of utility pricing has been estimated in many contexts.[3] Welfare loss due to marginal cost departure has been estimated for water tariffs in Spain and France (Garcia and Reynaud, 2004; Garcia-Valinas, 2005; Porcher, 2014)[4], the US (Swallow and Marin, 1988)[5] and Vancouver, Canada (Renzetti, 1992).[6] Borenstein (2012) quantifies the welfare losses due to non-linear electricity pricing in the US, while Borenstein and Davis (2012) and Davis and Muehlegger (2010) estimate welfare losses for US gas prices.[7] For US electricity, Borenstein and Bushnell (2018) find that the mean of total deadweight loss is USD$0.0024/kWh. This is decomposed to components representing deviations from average marginal cost and time-varying average cost, with the former component comprising 37.66 percent of the total effect, on average. These estimates vary by state as some states have prices much greater, and some much lower, than marginal cost. Inefficiencies are calculated inclusive of environmental

[3]Various degrees of inefficiency have been found and there are many proposed explanations but little empirical evidence as to why this is the case. Cost-reflective pricing should emerge as the profit-maximising tariff structure in a competitive market (Gomez Lobo, 1996; Price and Hancock, 1998) and a lack of cost-reflectivity may be indicative of imperfect competition. Alternatively, fixed charges have a perception of being unfair (Borenstein and Davis, 2012) and it may be the case that utilities avoid this perception by offering lower fixed tariffs in exchange for higher volumetric tariffs.

[4]Garcia and Reynaud (2004) find that marginal water pricing in Bordeaux is less than marginal cost. However, Porcher (2014) find that French marginal prices are 8 percent greater than marginal cost on average.

[5]Using a simulation methodology, Swallow and Marin (1988) find marginal cost pricing would improve welfare by up to 1.5 percent in a typical US city.

[6]Renzetti (1992) use a similar simulation methodology to Swallow and Marin (1988) to show that a switch to marginal cost pricing may increase welfare by up to 4 percent, much greater than welfare benefits of c.1.5 percent cited previously by Swallow and Marin (1988).

[7]Using an econometric specification to regress payments on quantity consumed to identify marginal costs, they find that that volumetric charges are 30 percent (Borenstein and Davis, 2012) to 40 percent (Davis and Muehlegger, 2010) greater than marginal cost.

externalities but the impact net of distributional counter-effects is not considered. While a number of studies exist to estimate the cost of electricity in the UK (Helm, 2017; Rhys, 2018; Ofgem, 2018b), this is the only other study analysing the welfare implications of inefficient electricity tariffs.

Estimating welfare impacts net of social counter-effects facilitates a fully-informed tariff reform as high volumetric tariffs are often tolerated and/or motivated by grounds of equity (Davis and Muehlegger, 2010; Borenstein and Davis, 2012; Porcher, 2014). Should economic costs outweigh social costs, then tariff reform is justified on economic and social grounds. These factors have been considered in the analysis of Borenstein and Davis (2012) who find that US gas pricing schedules are only mildly progressive relative to their welfare costs. They conclude that inefficiencies are not justified on social grounds as a modest social policy of redistribution would be more efficient and progressive than non-Coasian pricing. Similarly, Borenstein (2012) considers the equity and efficiency effects of non-linear pricing in the Californian electricity sector, finding that efficiency losses outweigh equity benefits. Porcher (2014) find inefficiencies of a small magnitude in the French water sector, however, they still outweigh negative distributional effects. Despite this body of work, the social implications of a Coasian electricity tariff reform are unknown. This is especially important insight for a market with multiple distortions (Buchanan, 1969). This paper provides this contribution.

Changes at the extensive margin can have profound welfare impacts (Auerbach and Pellechio, 1978), with this paper providing important insight in this regard. Distributed Energy Resources (DERs) such as solar generation may substitute for grid-sourced electricity. A reduction in volumetric sales affects utility cost recovery if this revenue is required to cover fixed costs (Costello and Hemphill, 2014; Muaafa et al., 2017). This occurs if Coasian pricing is not in place. Tariff recalibration may increase the relative price difference between grid and DER-sourced electricity, increasing the incentive to invest in DER resources, perpetuating a spiral of cost under-recovery. This is known as the 'utility death spiral' (e.g. Costello and Hemphill, 2014; Muaafa et al., 2017).

Related research has examined distortionary investment incentives; Borenstein and Davis (2012) examine how tariff changes may affect the decision to connect a gas network while Smith (2016) find that non-marginal cost electricity pricing leads to air conditioner over-investment. However, welfare impacts do not stop here; a utility response to this behaviour may create further distortions. This paper provides this insight, exploring the utility response to distortionary investment incentives and the resulting welfare effects. This is of considerable policy importance; if negative welfare impacts are sufficiently great, the social good of technological change and any associated public intervention may be compromised.

II Theoretical Predictions

A Welfare change due to non-Coasian pricing

I first provide some theoretical insight into how tariff structure affects consumer welfare, and how this is likely to change with DER deployment. I consider the case of an electricity consumer who does not fully defect from the electricity network and therefore incurs the grid standing charge regardless of DER consumption. DER is assumed to be intermittent, such as Solar PV, and therefore does not respond to demand. DER generation therefore displaces infra-marginal consumption. The decision is considered relative to a representative price of DER-sourced generation. As we are concerned with the decision to invest in DER technology, the average price (incorporating both marginal and fixed costs) is an appropriate metric.

Assume K consumers who consume Q units of electricity. $D_k(p)$ represents the demand function for consumer k, p_c represents the Coasian volumetric price and p_n represents any non-Coasian price where $p_n > p_c$. δ denotes the proportion of fixed cost recovered via the volumetric charge in a non-Coasian tariff (see Appendix A). $q_{k,c}$ denotes the quantity consumed under Coasian pricing for consumer k, whilst $q_{k,n}$ denotes their quantity consumed under non-Coasian pricing. Equation 1 shows the change in consumer surplus for consumer k (ΔCS_k) due to a switch from Coasian to non-Coasian pricing (this is derived in full in Appendix A);

$$\Delta CS_k = \overbrace{\int_0^m D_k(p_c)dp_c - \int_0^{p_n} D_k(p_n)dp_n - m(q_{k,c} - q_{k,n})}^{Consumption\ response} + \overbrace{\delta(\frac{q_{k,n}}{Q} - \frac{1}{K})}^{Tariff\ rebalancing} \qquad (1)$$

Consumer surplus is influenced by two effects. First, utility changes in response to a new consumption level, net of the difference in marginal cost. This change is proportional to the price elasticity of demand. The second effect captures the net change in total cost incidence due to tariff rebalancing, and this is determined by use. If price elasticity is zero, the tariff rebalancing effect dominates. Equation 25 shows that consumer surplus will fall if household k's consumption is low (i.e. $(q_{n,k}/Q) < (1/K)$) and rise if consumption is high (i.e. $(q_{n,k}/Q) > (1/K)$).

If price elasticity is non-zero, households who use a lot of electricity will benefit from both effects. Households who consume less electricity (i.e. those for whom $(q_{n,k}/Q) < (1/K)$) will benefit from the consumption response as prices fall but lose out due to the rebalanced tariff. The extent of the price response will determine whether the net impact is positive or negative and this is calculated in Section VI.

Total consumer surplus is calculated as the sum of each individual consumer's response. Both the magnitude and distribution of winners vs. losers will determine this. I quantify these effects using the simulation of Section VI.

B Welfare effects of DER Adoption

DER deployment will reduce the number of units consumed from the grid, affecting fixed cost recovery if these costs are recovered via the volumetric charge. In this section, I show that adoptees benefit from DER deployment if Coasian pricing is in place. There are no spillover effects for non-adoptees. However, if Coasian pricing is not in place, non-adoptees suffer a welfare loss.

B.1 DER adoption and Coasian pricing

Denote $q_{k,g}$, $q_{k,d}$ and $q_{k,t}$ as the quantity of grid-sourced, DER-sourced and total electricity consumed by consumer k. Under Coasian pricing, consumer surplus for consumer k changes according to the following relationship:

$$\frac{\partial CS_k}{\partial q_d} = m - p_d \tag{2}$$

DER deployment affects adoptees to the extent that the marginal cost of grid-sourced electricity exceeds the price of DER-sourced electricity. If $q_d = 0$, $(\partial CS_k / \partial q_d) = 0$, therefore DER deployment has no effect on the welfare of non-adoptees.

B.2 DER adoption and non-Coasian pricing: volumetric charge adjustment

Equation (3) shows how consumer k's welfare changes if they adopt DER technology:

$$\frac{\partial CS_k}{\partial q_{k,d}} = \overbrace{\left(\frac{\partial}{\partial q_{k,d}} \int_0^{p_v} D(p_v) dp_v\right)}^{Consumption\ response\ (-)} + \overbrace{\left(m - p_d\right)}^{price\ effect\ (+/-)} + \overbrace{\frac{\delta + \frac{\delta}{Q} Q_D}{Q}}^{avoided\ surcharge (+)} - \overbrace{\frac{\delta (q_{k,t} - q_{k,d})}{Q^2}}^{surcharge\ increment\ incurred\ (-)} \tag{3}$$

Welfare changes through four constituent effects. First, there is a negative consumption response; an increase in the volumetric price surcharge reduces consumer welfare. Second, there is a 'price effect'. If DER prices are less than marginal cost, this is positive. This price effect is negative if DER prices are greater than marginal cost. Third, adoptees avoid the surcharge on grid-sourced electricity for the unit of electricity substituted. This gives a positive welfare effect. Finally, the incremental increase in DER-sourced generation increases the surcharge for all grid-consumed units. This is negative but less than the avoided surcharge effect.

Assuming the consumption response is small[8], deployment may yield a positive welfare impact for consumer k if either (1) the price effect is positive or (2) the price effect is negative but the avoided fixed costs are sufficiently positive. This may occur if δ is sufficiently large.

It is important to note that non-adoptee surplus also changes. The change in consumer surplus for household k due to a change in $q_{j,d}$ DER capacity at household j is;

$$\frac{\partial CS_k}{\partial q_{j,d}} = \overbrace{\left(\frac{\partial}{\partial q_{k,d}} \int_0^{p_v} D(p_v) dp_v\right)}^{Consumption\ response\ (-)} - \overbrace{\left(\frac{\delta(q_{k,t})}{Q^2}\right)}^{surcharge\ increment\ incurred\ (-)} \tag{4}$$

Household k incurs a welfare loss due to the negative consumption response and due to the surcharge effect, with no countering price effects or avoided surcharge increments.

B.3 DER adoption and non-Coasian pricing: standing charge adjustment

A change in DER deployment leads to the following changes in consumer surplus. If consumer k has a DER installation;

$$\frac{\partial CS_k}{\partial q_{j,d}} = \overbrace{\left(m - p_d\right)}^{price\ effect} + \overbrace{\frac{\delta}{Q}}^{avoided\ mark-up} - \overbrace{\frac{\delta}{QK}}^{fixed\ cost\ surcharge} \tag{5}$$

As with the volumetric price adjustment, a standing charge adjustment leads to a number of constituent effects. First, there is no consumption response as volumetric charges remain unaffected. Second, there is a price effect attributable to the difference in cost of DER and grid-sourced generation. This is positive if DER costs are less than the marginal cost of grid-sourced electricity and negative if DER costs are greater. Third, for every DER unit deployed, consumer k avoids the pre-existing (δ/Q) mark-up in excess of marginal costs. Fourth, there is an incurred standing charge increment which is less than the avoided pre-existing surcharge if $K > 1$.

Deployment yields a positive welfare impact for consumer k if either (1) the price effect is positive, or (2) the price effect is negative and δ is sufficiently large such that the avoided volumetric charge mark-up outweighs a negative price effect.

DER deployment creates the following changes in consumer surplus if consumer k does not have a DER installation;

[8] With small installations, tariff rebalancing may have a relatively small additional mark-up per consumer with an even smaller consumption response expected.

$$\frac{\partial CS_k}{\partial q_{j,d}} = - \overbrace{\frac{\delta}{QK}}^{fixed\ cost\ surcharge} \tag{6}$$

As such, DER deployment also has spillover negative welfare impacts for non-adoptees if Coasian pricing is not in place and a standing charge adjustment is implemented. These effects are quantified in Section VII.

III Institutional Background

This section briefly describes the features of the UK electricity market that are relevant for this analysis. For more information about the organization and regulatory history of the UK electricity market, see Joskow (2008) and Grubb and Newbery (2018).

Britain has a liberalized, 'unbundled' electricity market which separates the constituent activities of generation, supply and network operation. The UK is dominated by six suppliers (the Big Six) who cover 95 percent of domestic supply; Centrica, EDF Energy, RWE, E.ON UK, Scottish Power and Scottish and Southern Energy (SSE). Consumers obtain their electricity from one of these suppliers who contracts with generators in the wholesale market. Electricity is then transported over national transmission (high volume) and local distribution (low volume) networks to the point of consumption. Each of these sectors comprise a cost component that must be recovered through electricity tariffs.

Generation costs are the largest single component of total electricity cost. Many of the generation and supply companies are vertically integrated and contract internally to procure power. These trades generally take the form of bilateral contracts with a lesser amount comprising spot, forward or balancing market transactions to account for under/over-procurement ahead of time. The cost of this contracting activity is passed onto suppliers through direct energy costs.

Suppliers also pass distribution and transmission costs to consumers through tariffs. Both the Distribution Network Operators (DNOs) and the Transmission System Operator (TSO), National Grid, operate as regulated monopolies. Their annual revenue is capped and recovered through system charges on generators and suppliers. Transmission Network Use of System (TNUoS) and Distribution Use of System Charges (DUoS) (Ofgem, 2018a) are levied on suppliers in accordance with consumer burden. Suppliers pass this cost to consumers through the tariff.

Suppliers are also responsible for social and environmental policy cost recovery; Renewable Obligations Certificates (ROCs), Energy Company Obligation (ECO) and Feed in Tariff

(FiT) costs. These are subsidy programs financed by the electricity consumer.[9] Finally, there are sundry direct and indirect supply-related costs that must also be recovered.

As UK electricity supply is liberalized, suppliers are free to specify their preferred tariff schedules. While two-part tariffs are offered, it is unknown whether these follow Coasian principles. The liberalization of the UK electricity market was expected to bring competition and, with that, a cost-reflective tariff structure (Gomez Lobo, 1996; Price and Hancock, 1998). Whether competition has been sufficient to create cost-reflectivity is still unknown, however, recent policy intervention suggests that this is unlikely. The UK Government introduced a Domestic Gas and Electricity (Tariff Cap) Act in July 2018, granting the regulator, Ofgem, power to regulate a default tariff price for domestic consumers (Ofgem, 2018b). The aim of the default tariff is to provide a more competitive price for consumers who are not active switchers in the market. Estimating a Coasian tariff and understanding the impacts of a departure from marginal cost pricing may guide regulation towards less distortionary tariff structure. This is an empirical question which will now be addressed.

IV Data and Methodology

A Methodology

This paper employs a simulation-based estimation procedure, expanding on the methods of Borenstein (2012). Household-level micro-data provide a representative sample of electricity expenditures, income and other socio-economic data. This provides the foundation with which a counter factual Coasian tariff may be simulated. The welfare effects of reform are then estimated in total, on average and by income group. The second stage of analysis concerns DER deployment. Adoption is simulated amongst a subset of households. Utility revenues are calculated relative to costs and recalibrated to ensure full cost recovery, if required. This is carried out for both current British tariffs and the Coasian counterfactual. The welfare effects of this process are then calculated in total and on average amongst adoptees and non-adoptees.

A number of datasets are used in this analysis. The Living Cost and Food Survey (LCF) provides a representative sample of UK households' income and expenditures and is the foundation upon which welfare effects are simulated. LCF data contain electricity expenditure information which must be converted to units consumed by matching each

[9]The Renewables Obligation (RO) scheme was the predecessor to the current Contracts-for-Difference renewable energy support. The FiT scheme offered a price guarantee for small scale (¡5MW) renewable generation. The Energy Company Obligation (ECO) is a government energy efficiency scheme, where deployment is facilitated through supplier obligation.

household with a representative tariff schedule, using data collected from the UK Department for Business, Energy and Industrial Strategy (BEIS, 2016). To simulate a Coasian reform, I must identify the cost breakdown in fixed vs. marginal components. I use data collected by Ofgem (2017a), the utility regulator in the UK. A revenue-neutral restructuring of tariffs is then carried out based on this proportional breakdown.[10] I do this using a bottom-up approach, similar to the methodology taken by Ofgem in their price cap calculation (Ofgem, 2018b). I observe each cost component, identify whether it is a marginal or non-marginal cost, and apportion accordingly to the volumetric or standing charge. Welfare change is then estimated using an appropriate demand model. These data and methods will now be outlined in detail.

B Household-level micro-data: Living Cost and Food Survey (LCF)

The Living Cost and Food Survey (LCF) of 2015/16 provides is a cross-sectional survey of private households, collecting information on purchasing at both the household and individual level. There are 4,912 weighted households in the dataset. Household expenses, including utility bills, are recorded via face-to-face interview. Electricity data include payment format (prepay, credit, debit), household region, and whether there is electric heating installed. This dataset also contains a rich set of socio-economic information, such as income and expenditure data. Table 1 reports the distribution of pertinent economic and social variables. These are reported in total and, to give insight into the importance of distributional factors, by income quintile. One can see that while electricity consumption is correlated with income, the burden is much greater for low-income households. Distributional concerns therefore warrant further investigation.

A number of steps have been taken when preparing the data. One household who consumes in excess of £350 per week and a small number of households that spend less than zero pounds per week are excluded. This analysis focuses on Great Britain (England, Scotland and Wales); Northern Ireland is part of the Irish Single Electricity Market and so is excluded.

C Electricity tariff data

I match each household with an appropriate tariff to calculate units consumed from expenditure data. Electricity tariffs in the UK vary by tariff type, region, payment method and year. The LCF contains information on payment method, household location (region) and year of survey. This information is used to match households to the average tariff for their

[10]Therefore, welfare change should be interpreted as welfare loss due to non-Coasian structure, not due to supplier rent-seeking.

Table 1: Descriptive statistics by income quintile

	First	Second	Third	Fourth	Fifth	Total
Household disposable income	192.51	365.13	541.70	778.62	1273.15	630.11
	(2.29)	(1.58)	(2.02)	(2.81)	(9.12)	(6.28)
Household expenditure	222.95	334.05	494.25	615.61	943.88	522.07
	(6.92)	(5.87)	(9.53)	(10.75)	(21.04)	(6.67)
Elec. exp as proportion of income	0.08	0.03	0.02	0.01	0.01	0.03
	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Children	0.18	0.38	0.49	0.59	0.59	0.45
	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.01)
Adults	1.24	1.58	1.90	2.13	2.41	1.85
	(0.02)	(0.02)	(0.03)	(0.02)	(0.03)	(0.01)
Prop HRP retired	0.72	0.50	0.32	0.20	0.12	0.37
	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)
Prop working	0.23	0.48	0.67	0.80	0.88	0.61
	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)
Prop home-owner	0.42	0.55	0.65	0.74	0.85	0.64
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)
Electricity expenditure	9.90	10.76	11.26	11.54	13.79	11.45
	(0.25)	(0.23)	(0.22)	(0.22)	(0.27)	(0.11)
Washing machine	4.68	5.11	5.50	5.93	6.80	5.60
	(0.05)	(0.05)	(0.05)	(0.06)	(0.07)	(0.03)
Dishwasher	0.19	0.29	0.43	0.56	0.74	0.44
	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)
Tumble dryer	0.39	0.51	0.59	0.62	0.71	0.56
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)
Observations	910	973	972	954	934	4743

Note: Standard errors in parentheses. The data are from the 2015/2016 Living Cost and Food (LCF) survey. The sample presented excludes households from Northern Ireland. All values are calculated using sample weights. Income and expenditure data represent weekly averages per income quintile.

category. The LCF does not contain information on tariff type and this must be estimated. Households in the UK may choose between two primary tariff types; a standard tariff where all consumption is subject to the same price, or an 'Economy 7' tariff where day and night consumption is subject to differing tariffs. In the UK, electric heating is a primary determinant of adopting an Economy 7 tariff (Centre for Sustainable Energy, 2016). I follow the precedent set by the Centre for Sustainable Energy (2016) and assume all households with electric heating take Economy 7 tariffs. The Centre for Sustainable Energy (2016) precedent is also followed when calculating units consumed, with the typical breakdown of 58 percent peak and 42 percent off-peak use assumed for all households. A sensitivity analysis on the assumptions employed is also carried out in Appendix B. As these calculations demonstrate, the conclusions of this paper are insensitive to variations to these assumptions.

The final step is to match each household to a tariff. I match each household in the LCF with the average tariff for their tariff type (standard or economy 7, proxied by heating type), region, payment method (credit, debit, prepay) and year (2015 or 2016) using average tariff data collected by the Department of Business, Energy and Industrial Strategy (BEIS, 2016). Region-specific tariffs are used in the matching procedure. These are presented in Appendix C. For illustration, national average tariffs are displayed in Table 4.

Table 2: Average UK tariffs by payment method

		Standard Tariff		Economy 7		
		Unit (£/kWh)	Fixed (£/wk)	Day unit (£/kWh)	Night unit (£/kWh)	Fixed (£/wk)
Credit	2015	0.144	1.51	0.18	0.08	1.70
	2016	0.14	1.52	0.18	0.08	1.70
Direct Debit	2015	0.134	1.2	0.16	0.07	1.36
	2016	0.13	1.21	0.16	0.07	1.35
Prepayment	2015	0.146	1.46	0.18	0.08	1.67
	2016	0.14	1.46	0.18	0.07	1.68
Overall	2015	0.139	1.33	0.17	0.07	1.52
	2016	0.14	1.33	0.17	0.07	1.51

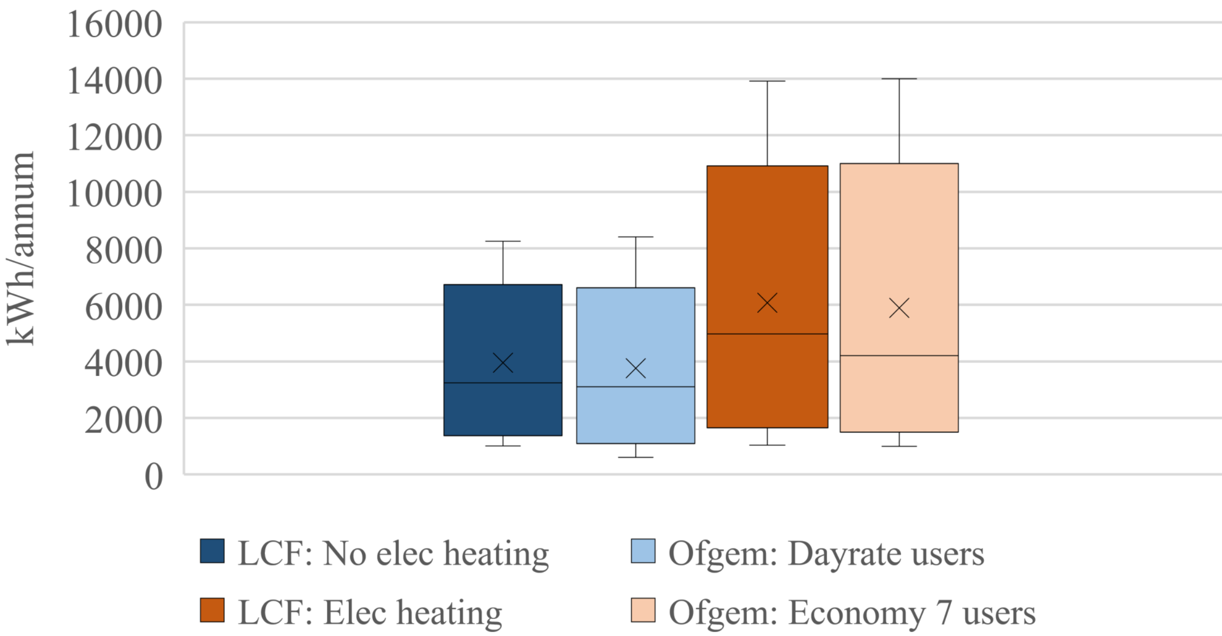
Data Source: (BEIS, 2016)

I validate this matching procedure by comparing the distribution of use against an external source in Figure 1.[11] The distribution of use within the data is very closely matched

[11]Figure 1 compares the distribution of electricity use from the procedure outlined with that calculated

with that observed in the validation procedure and there is confidence that the assumed consumption patterns yield a representative sample of British electricity use.

Figure 1: Validating consumption calculation: LCF data distribution vs. Ofgem Typical Domestic Consumption Values



Note: The sample presented includes all observations excluding households from Northern Ireland. LCF values are calculated using sample weights. All observations are included in this calculation. Ofgem Typical Domestic Consumption Values data source: Ofgem (2017c)

D Utility cost structure: Consolidated Segmental Statements (CSS)

To calculate a Coasian tariff, total revenues must be broken down into fixed and marginal components. Since 2009, the market regulator, Ofgem, has obliged the Big Six energy suppliers to produce annual Consolidated Segmental Statements (CSS) (Ofgem, 2017a). CSS data outline the annual costs of domestic and non-domestic electricity supply. In this paper, I focus on domestic consumers. Total cost is broken down into the components of direct energy costs, supplier margin, network costs, environmental and social obligation costs, other direct costs and other indirect costs. Quantifying welfare change requires a reference marginal cost value. In the short-run, the marginal cost of generation fluctuates by time-of-use and these short run marginal costs aggregate to form an average wholesale marginal cost. This is the

by Ofgem in their periodical 'Typical Domestic Consumption Values' publication. Economy 7 users are assumed to correspond to households with electric central heating in the LCF data reference value assessed by Borenstein (2012) and used for this analysis.[12] Costs will now be categorized into marginal and non-marginal components.

D.1 Marginal Costs

Direct energy costs, supplier margin and balancing services use of system (BSUoS) charges are marginal costs. Direct energy costs comprise the costs of wholesale electricity, transmission and distribution losses and the costs associated with balancing supply and demand (Scottish Power, 2015). These costs vary directly with consumption and are thus marginal. Supplier margin is a marginal cost; the supplier provides a hedge against market price risk for the consumer and any margin earned above cost may be considered as the remuneration for this service.[13]

Transportation costs comprise Distribution Use of System (DUoS) costs, Transmission Network Use of System (TNUoS) costs and Balancing Services Use of System (BSUoS) costs. BSUoS charges are levied by National Grid to balance the electricity system and recover the costs incurred as the System Operator. BSUoS charges are levied at a uniform rate on generators and suppliers according to the amount of electricity they put into, or take out of the grid, adjusted for transmission losses.[14] As this requirement varies with consumption BSUoS costs comprise part of the volumetric charge in a Coasian price schedule. Other direct costs include brokers costs, sales commission, and Elexon/Xoserve market participation (Centrica, 2016). These are costs which have directly given rise to a sale and are therefore marginal.

D.2 Non-Marginal Costs

Distribution costs, transmission costs, environmental/social policy costs and sundry indirect costs do not vary with the decision to consume an additional unit of electricity and are therefore non-marginal. Sundry additional costs include overheads such as sales and marketing,

[12] As Borenstein and Bushnell (2018) outline, total welfare loss may be split into average welfare loss, the difference between the retail price and average marginal costs, and the time-of-use welfare loss, the difference between the average marginal cost and the time-specific marginal cost. To concentrate on the distortions created by non-Coasian pricing in the context of the predominant uniform tariff context, this paper will focus on the former metric.

[13] In 2015 and 2016, the supply margin was very small or zero. There are a number of potential reasons for this. This may be due to inter-annual variability in the hedging activity of the supplier. Furthermore, as many Big 6 firms have a vertically integrated supply and generation structure, much of their profits may be recovered from generating activity, with inter-annual variability in supplier margin covered by cross-subsidies from generating activity.

[14] For the 2015/2016 financial year, the total BSUoS charge was £1,077m. This cost is recovered by levying generators and suppliers. For 2015/16, the average supplier tariff was £2.18/MWh (National Grid plc, 2016). This translates into a supplier burden of £192m or around two percent of transportation costs when apportioned amongst the 88TWh served by the 'Big 6' surveyed (2016 data).

bad debt costs, costs to serve, IT, HR, finance, property, staffing and billing and metering costs (Centrica, 2016). Environmental and social policy costs do not vary with consumption and should also form part of the fixed charge.[15]

Total cost categorization on marginal and non-marginal terms is outlined in Table 3, where we see that marginal costs of supply (direct energy/other costs and supplier margin) are less than half of total costs in both years.

Table 3: Breakdown of UK electricity supply by cost component

Cost	Percent of total (2016)	(2015)	Marginal/non-marginal
Direct energy costs	39.2	42.1	Marginal
Network costs	28.4	26.4	Non-marginal
Env. & Soc. Obligation Costs	15.2	13.4	Non-marginal
Other direct costs	1.1	0.7	Marginal
Other indirect costs	15.8	14.7	Non-marginal
Supplier margin	0	2.7	Marginal

Source: Data calculated by consolidating total costs for each of the Big 6 energy suppliers in the UK for 2015 and 2016 (Ofgem, 2017a). While 5 companies report data by calendar year, SSE report data by financial year. We assume 2014/15 data represent SSE costs for the 2015 calendar year, whilst 2015/16 pertains to SSE costs for the 2016 calendar year.

V Coasian tariff reform

In this section, I show that a Coasian volumetric tariff is less than half the current average volumetric tariff, while the standing charge must increase by up to five times to ensure a revenue-neutral reform. I present Coasian tariffs calculated for each of the 11 UK Governmental office regions in Great Britain for both 2015 and 2016.

The cost of supply varies by region (see Table C in the Appendix) and is primarily driven by regional variation in DUoS charges (see Scottish Power, 2015). Therefore, the preferred estimates assume that spatial variation is attributable to network charges which do not vary with marginal consumption. This approach also carries an implicit assumption that losses are allocated uniformly to all households, following the methodology of cost apportionment to suppliers (Scottish Power, 2015).[16]

[15]Technically, these costs are unrelated to electricity generation and should not form part of the electricity tariff, as Helm (2017) advocates. However, under current UK legislation, these costs are levied on suppliers and are therefore considered as an overhead cost that must be recovered

[16]It may be the case, of course, that a portion (or, in a less likely scenario, all) of this these cost sources vary

A Coasian volumetric tariff is calculated by summing total tariff revenue recovered from the entire LCF population and dividing this into marginal and non-marginal components. The marginal component is then divided by the total number of units consumed. This is carried out for each year. The residual revenue to be recovered for each region represents the regional fixed charge. I assume that costs do not vary by payment method.

Table 4 shows that Coasian volumetric tariffs are over 50 percent less than 2015/16 UK tariffs. A Coasian tariff is in the region of £0.06/kWh, compared with current tariffs in the region of £0.14/kWh. UK households paid £1.14 to £1.60 per week in 2015/16 in standing charges. A Coasian tariff for this period requires that standing charges increase to between £4.98 to £7.40 per week to ensure a revenue-neutral reform. This is an increase of around 350 to 450 percent.

The implications for users across the consumption spectrum are demonstrated in Figure 2, assuming no price response. There is a clear point of consumption, above which a switch to a Coasian tariff yields a lower electricity bill. Electricity expenditure falls for households with an average weekly consumption of 80kWh (c.£10) or above. As the median consumption is 64kWh per week, there are more losers than winners. The welfare effects of such a tariff switch, including the impacts of a consumption response, will be explored in greater detail in Section VI.

VI Welfare change due to Coasian tariff reform

In this section, I show that current British electricity tariffs create substantial welfare losses, experienced across all income groups. Uninternalized environmental and social externalities do not justify currently inefficient tariffs. Distributional effects are shown to be of concern but are more efficiently addressed via tax-benefit policy. Welfare losses are many times greater than the cost of potentially under-priced environmental externalities.

A Total welfare effect

The welfare change of a Coasian tariff reform is predicated on consumers price elasticity of demand. The long-run price elasticity of demand is the appropriate metric in this context (Borenstein, 2012; Borenstein and Davis, 2012; Davis, 2014). As there may be uncertainty surrounding the 'true' price elasticity of demand, I consider welfare change under a range of assumed values. The empirical literature has found that long-run price elasticities are in the

with consumption. In Appendix B, I provide a sensitivity analysis where all regional variation is reflected in the volumetric price. Both tariffs and welfare cost estimates vary by a negligible degree and therefore the conclusions of this analysis are insensitive to this assumption.

Table 4: Coasian tariff reform

	2015		2016		
	Coasian	Original	Coasian	Original	Percent change
Vol. tariff (£/kWh)					
	0.066	0.135	0.0621	0.133	-52 percent
Fixed tariff by region (£/wk)					
North East	6.076	1.240	4.986	1.209	+351 percent
North West	6.785	1.321	6.557	1.332	+403 percent
Yorkshire	6.094	1.236	6.243	1.218	+403 percent
East Midlands	6.258	1.279	6.970	1.324	+408 percent
West Midlands	6.452	1.242	6.876	1.210	+444 percent
East	6.435	1.271	6.571	1.285	+409 percent
London	6.708	1.324	6.708	1.324	+407 percent
South East	6.716	1.303	6.649	1.315	+411 percent
South West	6.991	1.285	7.031	1.317	+439 percent
Wales	7.474	1.391	7.406	1.384	+436 percent
Scotland	7.211	1.438	7.074	1.475	+391 percent

Note: DNO regions and Government office regions do not overlap perfectly and aggregation is required. The average tariff for Scotland is calculated as the average of North Scotland and South Scotland. Wales tariff calculated as average of Merseyside & North Wales and South Wales tariffs, respectively. Percent change calculated as the average of 2015 and 2016 tariff change. Tariffs calculated based on 2015/2016 Living Cost and Food (LCF) survey consumption profile, excluding households from Northern Ireland.

Figure 2: Electricity expenditure due to tariff rebalancing for households across the electricity consumption spectrum

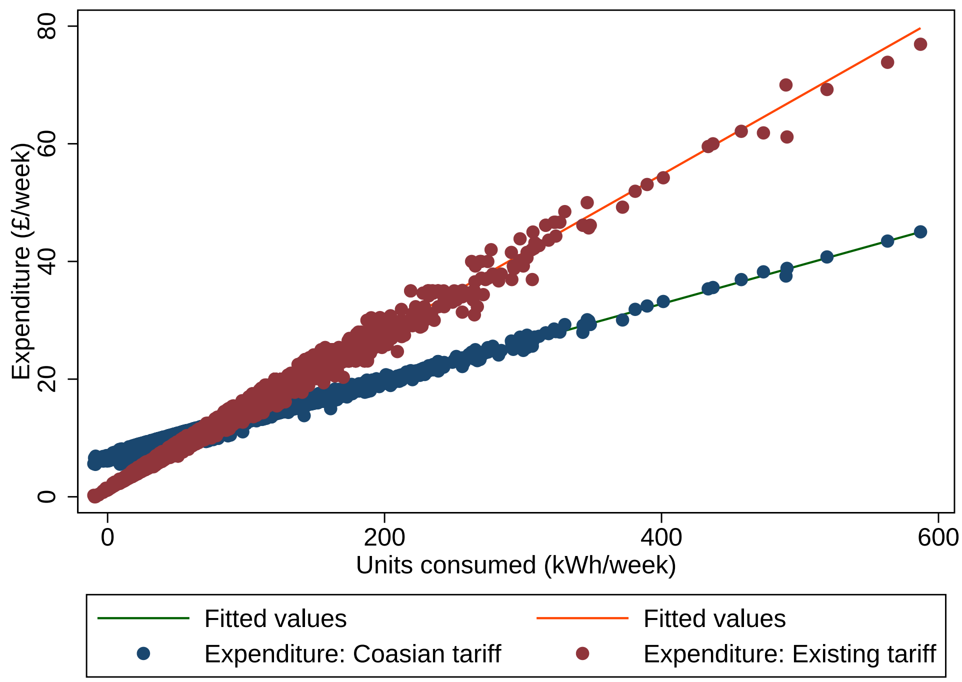


Figure shows consumption profiles based on 2015/2016 Living Cost and Food (LCF) survey and revenue-neutral consumption calculations under a zero price elasticity of demand outlined in Section IV. The sample presented excludes households from Northern Ireland. All values are calculated using sample weights.

range of -0.3 to -0.8, with many studies converging on the upper end of this spectrum.[17] Results extending from $e = 0$ to $e = -0.8$ are presented for completeness. Furthermore, this methodology makes the conventional assumption that consumers respond to the marginal (volumetric) price.[18]

As the Coasian reform is revenue-neutral, producer revenue (and therefore producer surplus) remains constant and welfare change is determined by changes in consumer surplus. Following Borenstein (2012), Borenstein and Davis (2012) and Davis (2014), I calculate a change in consumer surplus using a constant elasticity of demand function: $D(p) = A_k p^e$. Welfare changes are calculated as the area to the left of the demand curve, bounded by the original and Coasian volumetric price, less the change in the standing charge. Each household has an individual A_k parameter calibrated according to $A_k = (q_k/p^e)$, where p is the original volumetric price faced by household k and q_k is the quantity of electricity originally consumed by household k (Davis, 2014).

Average and total welfare change is presented in Table 5, with standard errors presented in parenthesis, calculated using bootstrap re-sampling which respects micro-data sampling weights. While results for a range of assumed elasticities are presented, the true long run price elasticity is expected to be between -0.3 and -0.8. The average welfare cost of current British tariffs is therefore likely to be between £28 to £86 per household, per annum. These household-level welfare losses aggregate to average population-level losses of between £729m to £2,235m per annum. This is a considerable portion of total electricity cost. The total cost of UK residential electricity supply in 2015/16 amounted to £12bn (Ofgem, 2017a). Welfare losses therefore comprise between 6 and 18 percent of domestic consumption value.

[17] In a meta-analysis of international research, Labandeira et al. (2017) find a global long-run average of -0.365. Historically, national studies have reported estimates for residential use in the range of -0.21 to -0.7 (Fan and Hyndman, 2011; Filippini, 1999; Bohi and Zimmerman, 1984). There are very few recent empirical estimates for the UK. Baker et al. (1989) find an own-price elasticity of demand of -0.75 for residential consumers. In a global meta-analysis, Espey and Espey (2004) find long-run elasticity estimates of -0.8. This value is used by recent UK policy analyses, such as that of Advani et al. (2013). Ros (2017) find a long-run price elasticity of electricity demand of -0.4 for residences, whilst Burke (2017) find much higher values, in the region of -1.

[18] When faced with a steep incremental block pricing (IBP) structure, Ito (2014) found that consumers respond to average rather than marginal prices. In the UK, there is no IBP tariff. Standard tariff consumers have one marginal price. Economy 7 users have separate volumetric tariffs for day and night usage. I calculate welfare loss relative to a an average of day and night rates, weighted by assumed usage. This most closely corresponds to a response to average pricing. However, it is also a very close approximation to a marginal response under the correct delineation of day and night usage. As Appendix B.2 shows, the welfare estimates are insensitive to many alternative plausible calculations.

Table 5: Welfare change due to Coasian price reform

Price elasticity	Average welfare change (£/annum)	Total welfare change (£m /annum)
$e = -0.1$	8.609	219.8
	(1.243)	(76.62)
$e = -0.2$	18.22	468.5
	(1.285)	(79.22)
$e = -0.3$	28.28	729.1
	(1.329)	(81.98)
$e = -0.4$	38.83	1,002.2
	(1.376)	(84.90)
$e = -0.5$	49.90	1,288.6
	(1.424)	(87.98)
$e = -0.6$	61.50	1,588.9
	(1.476)	(91.24)
$e = -0.7$	73.67	1,904.1
	(1.529)	(94.69)
$e = -0.8$	86.45	2,234.8
	(1.586)	(98.33)

Note: Standard errors reported in parantheses are calculated from 1,000 bootstrap replications using LCF sampling weights. Tariffs calculated excluding households from Northern Ireland and those that spend less than £0/week or greater than £300/week.

B Distributional impact of Coasian tariff reform

As discussed in the introduction, tariff reform has counteracting distributional consequences that must also be considered for a comprehensive welfare analysis. If the implicit redistribution of welfare to the less well-off is less costly than that achieved by the tax-benefit system, then there may be an economic argument for a non-Coasian tariff. This section presents a comprehensive analysis of these distributional effects.

First, the welfare change by consumption group is assessed. Table 6 presents the average household welfare change by disposable income quintile, while Table 7 presents the distribution of total welfare cost. The distributional impact is determined by the assumed price elasticity of demand[19]. If the true elasticity of demand lies in the upper range of potential values, as estimated by the empirical literature, all income groups benefit from tariff reform on average. 2015/16 tariffs are entirely unjustified on distributional grounds.

Lower income groups lose out if price elasticity is less than that estimated in the empirical literature. If demand is perfectly inelastic, households in the three poorest income quintiles lose out on average. If the price elasticity of demand is between $e = -0.1$ and $e = -0.3$, households in the first income quintile lose between £6 and £32 per annum on average, with households in the second quintile also incurring an average loss.

Second, I explore the implicit cost of redistribution associated with the current tariff schedule. If the welfare loss is less than the implicit cost of redistribution through the tax system, then the distortion may be justified. The marginal cost of public funds, the cost of distortions associated with raising taxes, is the appropriate metric in this regard. Barrios et al. (2013) estimate the marginal cost of public funds for energy and labour taxes. These values provide an expected value and an upper bound for the distortionary effect. For every £1 raised through energy taxes in the UK, £1.13 is lost through economic distortion. For labour taxes, every £1 raised costs £1.81 Barrios et al. (2013). Table 8 shows that the implicit welfare cost of redistribution through 2015/16 tariffs is greater than both of these estimates; every £1 distributed via current tariffs costs between £2.02 to £5.98.

The magnitude of the inefficiency in British electricity tariffs leads to distributional consequences that are somewhat in contrast to much of the literature. To understand why this is the case, we must recall that a change in price has two effects; the consumption response effect and the tariff rebalancing effect. Section II has shown how this will benefit households that consume a lot of electricity or those for whom there is a large price response. Previous studies have found that the negative tariff rebalancing effect dominates for low-income households, reducing average welfare, whilst the consumption response dominates for high-income households on average, increasing welfare Borenstein and Davis (2012); Borenstein (2012); Porcher (2014). Indeed, this prevails in the present analysis if there is a very low consumption response. However, for our preferred range of e = -0.4 to e = -0.8, the positive consumption effect dominates across the income spectrum. This is due to considerable inefficiency in British electricity prices. While it is true that wealthier households benefit from Coasian reform to a greater extent than those less well-off, poorer households also benefit on average.

This is not to say that distributional impacts are irrelevant, but rather more nuanced. There are losers of tariff reform and Tables 21 to 23 in Appendix D show that households

[19] Representative degrees of assumed price response are presented. A full range of results is offered in Tables 19 and 20 in the Appendix

generally considered more vulnerable, those containing old-age pensioners (OAPs), children and those who are not home-owners, suffer greater welfare losses due to non-Coasian tariffs. In particular, households with children experience welfare losses many times greater than households without children. Table 9 shows that, assuming a high price response, there slightly more winners than losers. Therefore, a not-insignificant portion of the population lose out and whilst current tariffs cannot be justified on distributional grounds, these distributional effects are likely to be of policy concern. The findings of this analysis indicate strongly that these are more efficiently addressed via the tax-benefit system.

Table 6: Average welfare change by income quintile

	$e = 0$	$e = -0.2$	$e = -0.3$	$e = -0.5$	$e = -0.7$	$e = -0.8$
First quintile	-32.60	-15.83	-6.826	12.55	33.91	45.41
	(2.571)	(2.753)	(2.851)	(3.061)	(3.295)	(3.421)
Second quintile	-19.37	-1.827	7.583	27.80	50.07	62.04
	(2.635)	(2.815)	(2.912)	(3.120)	(3.351)	(3.475)
Third quintile	-6.952	11.50	21.40	42.65	66.04	78.61
	(2.495)	(2.666)	(2.758)	(2.956)	(3.176)	(3.294)
Fourth quintile	0.976	19.80	29.89	51.53	75.30	88.07
	(2.281)	(2.432)	(2.514)	(2.688)	(2.881)	(2.984)
Fifth quintile	54.98	77.28	89.21	114.8	142.9	157.9
	(2.759)	(2.941)	(3.038)	(3.246)	(3.475)	(3.598)

Note: Standard errors reported in parantheses are calculated from 1,000 bootstrap replications using LCF sampling weights. Tariffs calculated excluding households from Northern Ireland and those that spend less than £0/week or greater than £300/week on electricity. Welfare change is calculated according to disposable income quintile.

Table 7: Total welfare change by income quintile

	$e=0$	$e=-0.2$	$e=-0.3$	$e=-0.5$	$e=-0.7$	$e=-0.8$
First quintile	-168.4	-81.79	-35.27	64.81	175.2	234.6
	(13.53)	(14.30)	(14.75)	(15.81)	(17.08)	(17.80)
Second quintile	-100.5	-9.480	39.34	144.2	259.8	321.9
	(13.74)	(14.61)	(15.12)	(16.28)	(17.66)	(18.44)
Third quintile	-35.95	59.49	110.7	220.6	341.5	406.5
	(12.91)	(13.78)	(14.28)	(15.45)	(16.83)	(17.62)
Fourth quintile	5.059	102.7	155.0	267.2	390.5	456.7
	(11.84)	(12.67)	(13.16)	(14.28)	(15.62)	(16.38)
Fifth quintile	285.2	400.9	462.7	595.4	741.0	819.1
	(14.81)	(16.15)	(16.90)	(18.56)	(20.46)	(21.51)

Note: Standard errors reported in parantheses are calculated from 1,000 bootstrap replications using LCF sampling weights. Tariffs calculated excluding households from Northern Ireland and those that spend less than £0/week or greater than £300/week on electricity. Welfare change is calculated according to disposable income quintile

Table 8: Marginal cost of redistribution under current British tariffs

	$e=0$	$e=$ -0.2	$e=$ -0.3	$e=$ -0.5	$e=$ -0.7	$e=$ -0.8
Welfare cost (£'000)	1,703	2,012	2,186	2,584	3,046	3,304
Welfare redistributed (£'000)	842	765	727	654	585	552
Cost per £ redistributed (£)	2.02	2.63	3.01	3.95	5.21	5.98

Welfare cost is loss of welfare across all quintiles due to non-Coasian pricing. Welfare redistributed is welfare gain for quintiles 1 and 2.

Table 9: Winners and losers due to Coasian tariff reform

	e = -0.1	e = -0.2	e = -0.4	e = -0.5	e = -0.7	e = -0.8
Winners	0.403	0.43	0.488	0.507	0.551	0.574
	(0.00718)	(0.00720)	(0.00724)	(0.00721)	(0.00714)	(0.00716)
Losers	0.597	0.57	0.512	0.493	0.449	0.426
	(0.00706)	(0.00726)	(0.00733)	(0.00731)	(0.00724)	(0.00721)

Table presents proportion of all households that are winners and losers due to Coasian tariff reform. Standard errors reported in parantheses are calculated from 1,000 bootstrap replications using LCF sampling weights. Calculations exclude households from Northern Ireland and those that spend less than £0/week or greater than £300/week.

C Environmental externalities

Thus far, welfare loss has been considered net of private marginal cost and internalized environmental externalities. In Great Britain, environmental costs are internalized by the EU ETS and the UK Carbon price floor. During the period of study, the carbon price floor stood at £18/tCO_2. However, this is lower than current estimates of the social cost of carbon. Nordhaus (2017) provide a suitable lower bound, suggesting that the global cost of carbon may be in the region of £22.15 (\$30)/tCO_2. The UK Committee on Climate Change state that current target-consistent carbon prices are in the region of £50/tCO_2 (Committee on Climate Change, 2015). By restricting consumption, non-Coasian tariffs inadvertently mitigate emissions which may compensate for an under-internalized externality. This section identifies the extent to which this has occurred.

Unlike a carbon tax, non-Coasian pricing does not incentivize the substitution of carbon intensive generation sources for less carbon intensive alternatives. Estimates of foregone external costs should focus solely on avoided emissions through differing consumption patterns. I quantify the foregone environmental cost as welfare loss per ton of CO_2 avoided. The cost of avoided carbon emissions is approximately equivalent across assumed degrees of price elasticity. This is because a higher price elasticity leads to a more positive welfare change when a Coasian price reform is implemented. On average, this cancels out the increased welfare cost of emissions. This results in a similar welfare cost per unit of emissions avoided across elasticity levels.

The welfare cost of emissions avoided is not the same as the carbon price that yields equivalence between the Coasian volumetric price and 2015/16 average price. This is because welfare cost is calculated net of changes to the standing charge. So while a household may incur a welfare benefit due to a lower volumetric price, this is partially offset by a higher standing charge. As Table 10 shows, the implicit cost of emissions avoided is in the region of £119/tCO_2.[20]

Table 10: Implicit cost of emissions avoided

Variable		Value
Benchmark cost of emissions		
2016 UK carbon budget-consistent carbon price		<£50/tCO_2
2030 UK carbon budget-consistent carbon price		£78/tCO_2
2015/16 Implicit cost of emissions avoided		
2015/16 Welfare loss (£)	729m	
2015/16 Emissions avoided (t/CO_2)	7.22m	
Welfare loss/tCO_2 avoided		£101/tCO_2
2015/16 Carbon price floor		£18/tCO_2
Total implicit cost of emissions avoided		**£119/tCO_2**

Note: These calculations are carried out using the emissions intensity of Great British electricity in 2016. This was 286 gCO_2/kWh. Welfare cost avoided calculated by dividing value for total welfare loss by the tonnes of emissions avoided. Values shown assume price elasticity of -0.3, with results consistent across all assumed price elasticities

The welfare loss per ton of CO2 avoided is approximately £101/tCO_2 (Table 10). As electricity generation in the UK currently faces a carbon price floor to the value of £18/tCO_2, the total implicit cost of carbon due to current inefficiencies amounts to £119/tCO_2. This is in excess of current estimates of the social cost of carbon. Indeed, the UK Committee on Climate Change state that current target-consistent carbon prices do not rise above £100/tCO_2 before 2030 (Committee on Climate Change, 2015). Existing tariffs therefore induce a welfare loss that is many times greater than the foregone environmental cost.

VII The welfare effects of distributed energy resource (DER) deployment

This section assesses the welfare effects of distributed energy resource (DER) deployment and compares the welfare change under different tariff structures. I find that DER investment increases the welfare losses estimated in Section VI unless either a Coasian tariff is in place or DER costs are less than the marginal cost of grid-sourced electricity. Furthermore, DER

[20]For information, the equivalising carbon price is £250/tCO_2. This is the carbon price that brings the Coasian volumetric price to parity with current prices and does not take into account the offsetting welfare effect of the standing charge adjustment)

investment redistributes wealth from non-adoptees to adoptees unless a Coasian reform has taken place.

A Simulating DER adoption

As no suitable ex-post data exist, I employ a simulation-based methodology to estimate welfare change ex-ante. This is an implementation of the model outlined in Section II and Appendix A and proceeds as follows. Similar to Borenstein (2012) and Davis (2014), a constant elasticity of demand is assumed;

$$D_k(p_g) = A_k p_g^e \tag{7}$$

where D_k is total electricity demand for household k, p_g is the price of grid-sourced electricity and A_k is a constant. As Section II outlined, DER-sourced generation is assumed to be infra-marginal due to its intermittency[21], and consumption is determined relative to the price of grid-sourced generation. Therefore;

$$q_{k,g} = D_k(p_g) - q_{k,d} \tag{8}$$

where $q_{k,g}$ is grid-sourced electricity for consumer k and $q_{k,d}$ is their DER-sourced electricity. K adoptees are chosen at random, respecting sampling weights. While certain households are more likely to adopt in reality (see Crago and Chernyakhovskiy, 2017), Appendix F shows that the welfare estimates vary little with respect to who is chosen as an adoptee.[22] A pre-determined q_d amount of DER-sourced electricity is specified and substituted for grid-sourced electricity for each adoptee. If a Coasian tariff is not in place, the $(\delta/Q)Q_D$ tariff surcharge is calculated and tariffs are recalibrated via standing or volumetric tariff recalibration, as appropriate. Finally, CS_k is calculated for each household k according to equations (3)-(6). A single representative price elasticity of demand is assumed for these calculations (e = -0.6), chosen as the midpoint of the likely range (See Section VI)[23].

[21] It may be the case that DER-sourced electricity is marginal during periods of low consumption and high output, and non-marginal otherwise. Ito (2014) suggest that consumers may respond to average price when faced with complex non-linear price schedules such as this. As such, a more representative marginal price may be a weighted mean of DER and grid-sourced costs. Unfortunately the LCF data precludes such calculation. However, given the relatively small proportion of consumption substituted in this analysis, and the subset of this that may be marginal, the difference in welfare estimates is likely to be negligible.

[22] This is because household-level welfare change varies little given the small price change assessed in this section. Therefore, the price response differs between households. This is in accordance with the uniform rate of consumption response assumed between households in studies such as that by Borenstein and Bushnell (2018). However, this approach limits distributional analysis to adoptees vs. non-adoptees.

[23] However, there is an insensitivity to elasticity, as Appendix G shows, as the price response effect outlined in Section II is too small to warrant any meaningful consumption response

Simulation parameters are shown in Table 11. I explore low and moderate deployment rates of 2.5 million (approximately 9 percent) and 10 million (33 percent) adoptee households, respectively. A DER unit may displace grid-sourced electricity to varying degrees. I explore a range centred around the expected displacement of solar deployment in the UK; McKenna et al. (2018) find that solar displaces 18.5 +/- 12kWh per week, on average.[24]

The range of cost values analysed extends from twice marginal cost (current UK retail rates) to half the current marginal cost value. A wide range is chosen to accommodate the rapid cost reduction experienced in recent times.[25] I focus on the case where adoptees do not fully defect from the grid and therefore must still pay the standing charge. This is most relevant for the UK and other contexts where full defection is unlikely in the medium term, at least.

When assessing the costs of DER deployment, I consider the scenarios where it is cost-effective to invest (i.e. the cost of DER-sourced electricity is less than or equal to the foregone volumetric cost of grid sourced electricity). Under Coasian pricing, this is the marginal cost of grid-sourced electricity. Under non-Coasian pricing, this is the retail price of electricity. Furthermore, I do not consider any potential subsidy costs that may be introduced to support DER deployment. These costs would be additional to the welfare losses estimated in this analysis.

Table 11: Simulation parameters

Variable	Parameter values
No. adoptee households (K)	2.5 to 10 million (9 to 37 percent adoption)
Electricity displaced per adoptee ($q_{k,d}$)	0 to 30kWh/week
Price of DER-sourced electricity (p_d)	50 to 200 percent of grid-sourced electricity
Elasticity of demand (e)	-0.6

B DER deployment and Coasian price

Coasian pricing brings simplicity to the welfare effects of DER deployment. First of all, adoption only occurs under circumstances that are welfare-improving. Second, there are no negative distributional impacts; adoptees benefit only and in proportion to DER electricity consumed and the price differential, as predicted by Section II. There are no knock-on

[24]McKenna et al. (2018) find that solar displaces 966 +/- 38 kWh/year for UK households with solar installations. This is equivalent to 18.5 +/- 12kWh per week.

[25]The average price of solar PV has dropped by 20 percent with every doubling of installed capacity over the past two decades (de La Tour et al., 2013; Agnew and Dargusch, 2015). Cost parity with retail prices has been reached in many countries (Karneyeva and Wstenhagen, 2017).

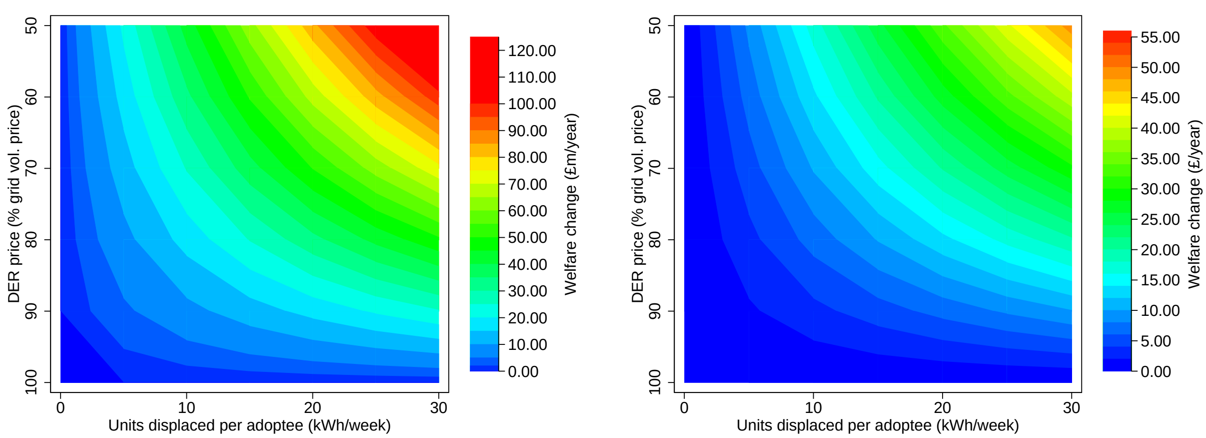
effects for grid-sourced electricity, removing worries of a 'utility death spiral'. Figure 3a charts the change in aggregate welfare as a function of electricity displaced and price differential, assuming 2.5 million British households adopt. Deployment is welfare-enhancing in all circumstances, growing predictably with the relative cost reduction and the quantity of displaced electricity. Under a 2.5 million adoptee scenario, Figure 3b shows that households benefit by up to £55/annum under the most optimistic cost and displacement scenarios. Non-adoptees are unaffected.

It is interesting to note the rates of deployment and cost reduction required to yield relatively small welfare benefits. For example, Figure 3a shows that cost reductions in excess of £80 million per annum requires that DER prices are at least 30 percent cheaper than the marginal cost of grid-sourced electricity. This is a considerable cost reduction, considering current DER costs are in excess of retail prices in many cases. Appendix G.1 shows how a 10 percent reduction below marginal cost would yield similar welfare benefits if 10 million households adopt. This is still a considerable hurdle to yield a modest welfare benefit.

Figure 3: DER deployment and Coasian pricing

(a) Total welfare change

(b) Average welfare change: DER adoptees



Note: Figures display total and average welfare change (adoptees) under Coasian pricing assuming 2.5m households adopt DER-sourced generation. Welfare change for all non-adoptees is zero and this is illustrated in Figure 10 in Appendix G

C DER deployment and non-Coasian pricing

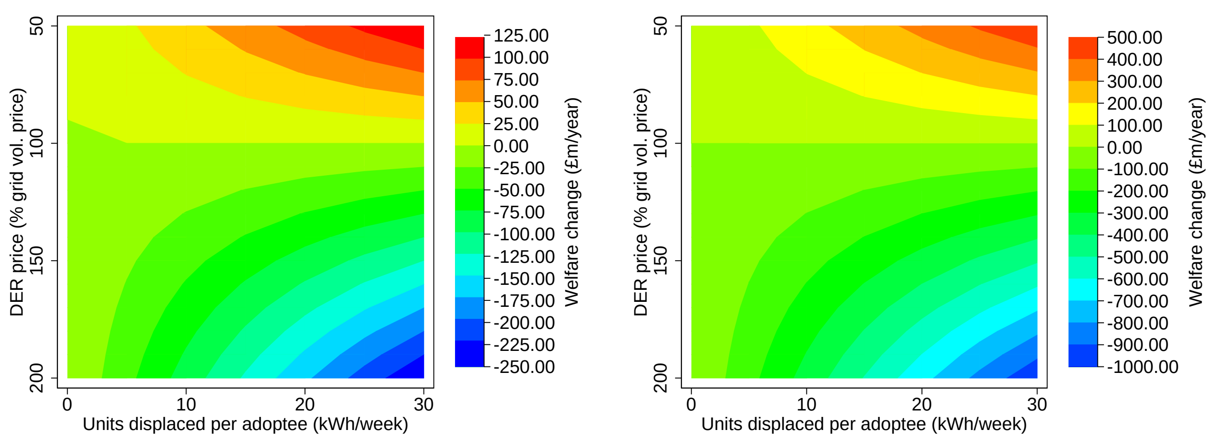
When Coasian pricing is not in place, it is cost-effective to adopt once the DER price reaches parity with the retail price. In Great Britain, this is approximately twice marginal cost. DER deployment creates welfare loss in many circumstances and a redistribution of income from non-adoptees to adoptees, predicted by Section II.

Figure 4 presents total welfare cost as a function of marginal cost and one may chart the pattern of welfare impact by the falling trajectory of DER costs. At retail price parity (200 percent of marginal cost), deployment leads to welfare loss as grid tariffs are adjusted to ensure cost recovery. This grows to £1,000 million per annum, or 10 percent of the value of residential electricity consumption, with 10 million adoptees. Welfare losses to non-adoptees exceed benefits to adoptees; total welfare falls by up to £250 million per annum if 2.5 million households adopt. Non-adoptees, on average, lose up to £55 per annum.

This welfare loss will continue until DER costs reach parity with the marginal cost of grid-sourced electricity. At this point, total welfare does not change but welfare redistribution persists. If DER-sourced electricity is cheaper than the marginal cost of electricity from the grid, there is a welfare gain. If there are 2.5 million adoptees, welfare increases by up to £125 million per annum once DER cost reaches fifty percent of grid-sourced electricity, growing to up to £500 million per annum if there are 10 million adoptees. However, redistribution from non-adoptees to adoptees persists once more.

Figure 4: Total change with no Coase price

(a) 2.5 million adoptees (b) 10 million adoptees



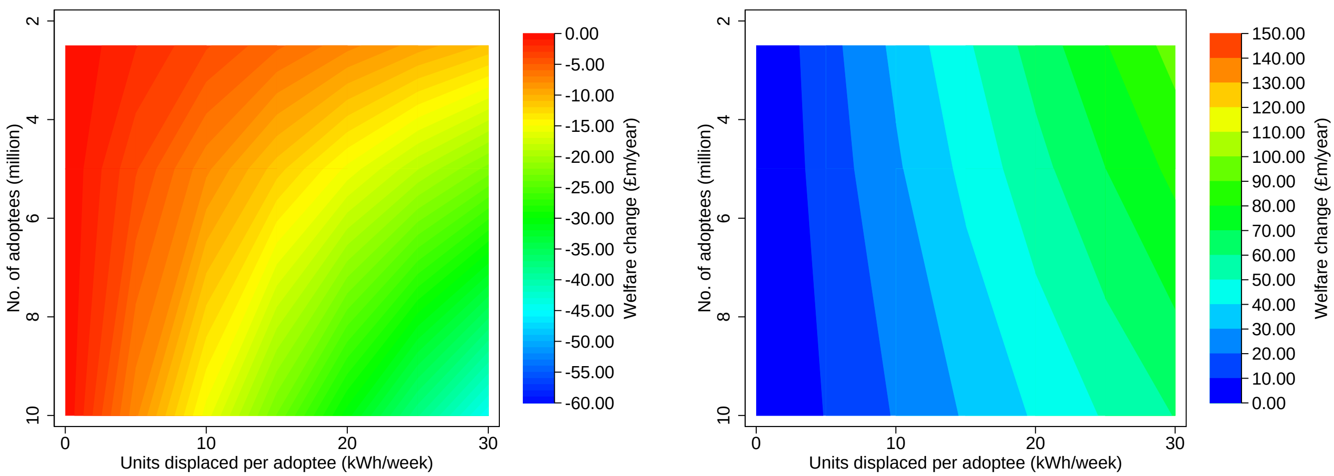
Note: Figures display total welfare change without Coasian pricing according to volumetric charge adjustment.

An interesting special case occurs when the cost of DER-sourced electricity is equal to the marginal cost of grid-sourced electricity, highlighting the redistributional effects at play. Figure 5 shows the distributional effects among adoptees and non-adoptees if cost recovery is facilitated by a standing charge adjustment. If 10 million households adopt and each displaces 30kWh per week, non-adoptees lose out by around £45 per annum. Appendix G shows that this increases to £60 per annum under volumetric charge adjustment. This disparity between adoptees and non-adoptees, and the sensitivity to deployment volume, will be explored in the next section.

Figure 5: Average welfare change with DER grid parity and no Coase price

(a) Standing charge adjustment: non-adoptees

(b) Standing charge adjustment: adoptees



Note: Figures display average welfare change under Coasian pricing where average DER cost is equal to marginal cost of grid sourced electricity

D Distributional implications of DER adoption without Coasian pricing

To fully understand the welfare implications of non-Coasian pricing, the redistribution between adoptees and non-adoptees deserves further attention. This is influenced by two important and interacting dynamics; (1) the magnitude of deployment and (2) the choice of tariff adjustment.

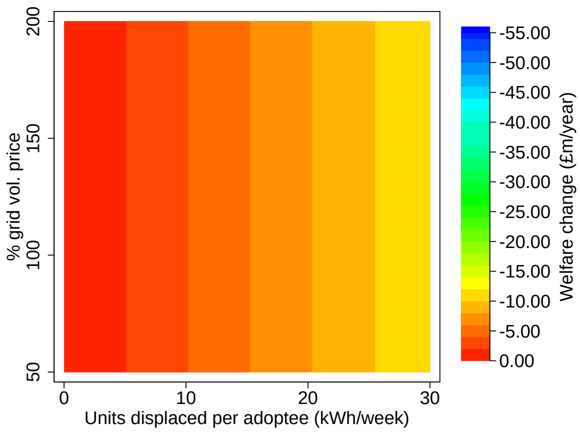
Figure 6 shows the distribution of welfare change between adoptees and non-adoptees when 2.5 million households adopt. At this small scale of deployment, there is little difference in magnitude between standing charge and volumetric charge adjustment. However, the redistribution from non-adoptees to adoptees is apparent. Welfare change for non-adoptees is invariant to DER cost, as expected, and losses are up to £10 per annum for the average household. Adoptees benefit to the extent that DER costs are less than the retail price. For instance, assuming DER costs are 1.5 times the grid cost, adoptees benefit by up to £25 per annum.

These redistributional effects grow with added deployment, but the pattern of this growth is predicated on the choice of tariff adjustment. First of all, a volumetric tariff adjustment has a more burdensome impact than standing charge adjustment due to two effects; a greater shift towards non-adoptees paying the shortfall (as they consume more grid electricity on average) and added distortions due to a greater departure from marginal cost pricing. This latter effect was predicted in Section II.

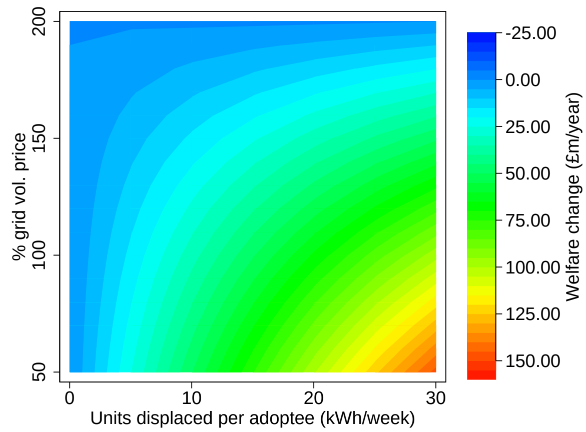
These effects are demonstrated in Figure 7. We see a welfare loss for non-adoptees in the region of £40 per annum under a standing charge adjustment, rising to £55 per annum under a volumetric charge adjustment. Gains for adoptees are also increase under a volumetric charge adjustment, as they shirk a greater proportion of the recalibration payment. For example, adoptees benefit by up to £25 per annum under a volumetric charge adjustment and this falls to c. £5 per annum under a standing charge adjustment, assuming 2.5 million households adopt and DER costs are 1.5 times grid marginal cost. Interestingly, the added negative impact of a standing charge adjustment can outweigh the positive impacts for many adoptees under large-scale deployment. There is a cut-off just below 1.5 times the marginal cost at which point the average adoptee is worse off.

Figure 6: Distribution of welfare change: 2.5 million adoptees

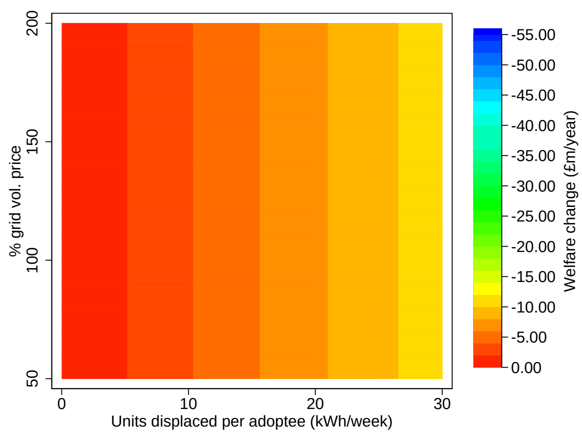
(a) DER non-adoptees: volumetric charge adjustment



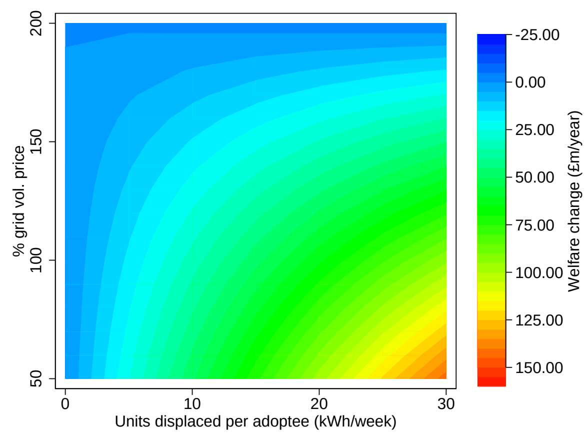
(b) DER adoptees: volumetric charge adjustment



(c) DER non-adoptees: standing charge adjustment



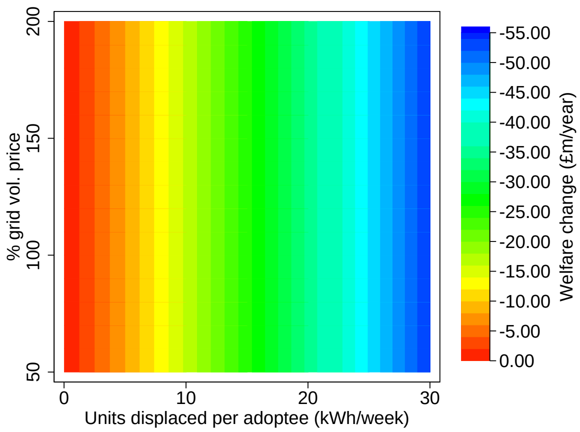
(d) DER adoptees: standing charge adjustment



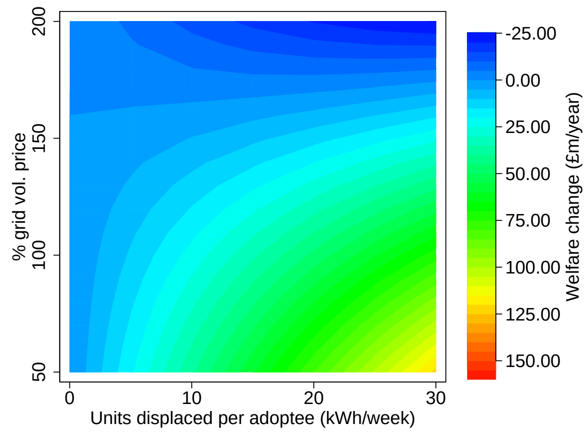
Note: Figures display average welfare change under non-Coasian pricing assuming 2.5 million households adopt DER-sourced generation.

Figure 7: Distribution of welfare change: 10 million adoptees

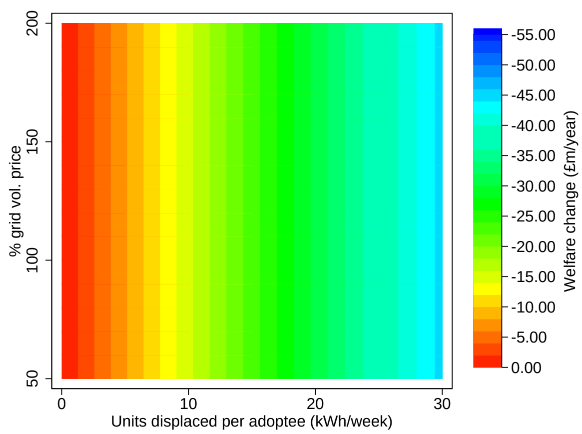
(a) DER non-adoptees: volumetric charge adjustment



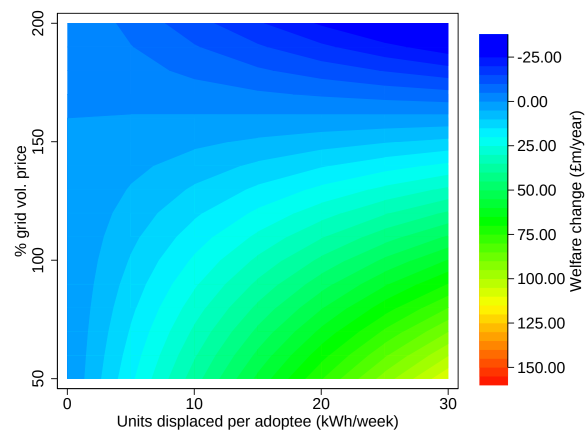
(b) DER adoptees: volumetric charge adjustment



(c) DER non-adoptees: standing charge adjustment



(d) DER non-adoptees: standing charge adjustment



Note: Figures display average welfare change under non-Coasian pricing assuming 10 million households adopt DER-sourced generation.

VIII Discussion and Conclusion

The efficiency of a corrective policy intervention, such as a carbon tax, is predicated on a baseline price structure that reflects the private marginal cost of generation. If the baseline utility price is distortive, additional interventions may interact and serve to exacerbate existing welfare losses. These effects can extend to wider policy interventions and technological change. Fully understanding the influence of these underlying distortions is important for informed policy decision-making.

This paper has examined welfare losses associated with British electricity tariffs, finding that not only do existing tariffs create considerable welfare loss, they present a platform for increasing losses with imminent technological change. Volumetric electricity tariffs in Great Britain are, on average, over 50 percent greater than the marginal cost of generation. Welfare losses are between £729 to £2,234m per annum (6-18 percent of domestic consumption value), depending on the underlying elasticity of demand in the UK. This translates into an annual cost of between £28 to £86 per household. While the current carbon price floor may be lower than that recommended for a sustainable de-carbonization trajectory, this welfare loss is greater than the implicit cost of avoided emissions.

Coasian tariff reform creates negative distributional effects that are concentrated on vulnerable households. However, the implicit cost of redistribution through current distortionary tariffs is many times greater than the marginal cost of public funds. Therefore, while negative distributional implications do no justify current distortionary tariffs, they are not insignificant and warrant attention through adjustments to taxes or benefits.

Distributed Energy Resource (DER; e.g. solar) deployment increases welfare losses and these may be avoided with Coasian tariff reform. As DER prices fall, they will first reach parity with retail prices, inducing adoption. While adoptees benefit, non-adoptees will lose out due to necessary tariff recalibration. These losses will grow with deployment until marginal cost parity. These costs are not insignificant; at retail price parity, a small adoption profile of 2.5 million households leads to an expected welfare loss of £250 million per annum.

These findings have a number of important policy implications. Retail price caps have recently been introduced in the UK and policy that guides tariffs towards a Coasian structure can increase consumer welfare by up to 18 percent. Doing so is a pre-requisite to avoid further welfare loss as DER deployment advances. Environmental and social concerns should not impede such reform.

The findings of this paper are provided by an ex-ante microsimulation methodology. This is shown to give stable and robust welfare estimates for small adoption scenarios. However, this analysis is lacking insight into the socio-economic profile of DER adoptees. This insight will be increasingly important to fully understand the redistribution of rents between different socio-economic groups. Furthermore, this paper is limited to inference relative to the average marginal cost. Welfare losses attributable to time-varying marginal cost are in addition to the welfare losses addressed here and likely to be of comparable magnitude. Further research is required to estimate these effects.

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Supplementary information for online publication only

A Model

Using a simple model, this section demonstrates the potential sources of lost welfare due to non-Coasian tariff structures and how this may change with DER deployment. A deviation from Coasian tariffs leads to a loss in consumer surplus commensurate with the elasticity of demand, a standard result in the economics literature. Similarly, DER adoption under Coasian pricing increases consumer welfare commensurate with displaced electricity. However, the welfare effects of DER adoption under non-Coasian pricing are determined by who bears the cost of tariff rebalancing, and the structure of that rebalancing.

A.1 Coasian tariff formation

Consider an electricity market where a utility must put a tariff structure in place such that total revenue R is equal to total cost C;

$$R = C \tag{9}$$

Total costs consist of fixed costs (network infrastructure, administration, etc.), f, and marginal costs (fuel, operation, market participation, etc.), m. Denoting total market demand as Q, C may be expressed as;

$$C = f + mQ \tag{10}$$

Assume a two-part electricity tariff, comprised of volumetric (i.e. £/kWh) and fixed (£/household) portions. α denotes the portion of total costs to be recovered via the volumetric portion. The volumetric tariff p for each unit consumed may be defined as;

$$p = \frac{\alpha C}{Q} \tag{11}$$

Assuming there are K households, the standing charge, s, per household k is equal to the remaining revenue;

$$s = \frac{C(1-\alpha)}{K} \tag{12}$$

Total Revenue, R, may be rewritten as:

$$R = \frac{\alpha C}{Q} + \frac{C(1-\alpha)}{K} K \tag{13}$$

Each consumer k's consumption is denoted q_k and total consumption is equal to $\sum_{k=1}^{K} q_k = Q$. Each consumer therefore faces the following tariff schedule;

$$t = \frac{\alpha C}{Q} q_k + \frac{C(1-\alpha)}{K}, \tag{14}$$

Coasian pricing dictates that the volumetric price is equal to marginal cost; $p = m$. Assuming each consumer contributes equally towards the standing charge, a Coasian price schedule may be calculated as:

$$p = \frac{C}{Q} = m \tag{15}$$

$$s = \frac{C - mQ}{K} = \frac{f}{K} \tag{16}$$

A.2 Welfare change due to non-Coasian pricing

Welfare is comprised of producer and consumer surplus. Revenue-neutral tariff rebalancing implies that producer surplus remains constant. Therefore, welfare loss is due to a change in consumer surplus alone. For each consumer k, the consumer surplus may be defined as the area under the demand curve bounded by the price charged, less the standing charge.

$$CS_k(p) = \int_0^p D_k(p)dp - pq_k - s \tag{17}$$

For each consumer k, the welfare loss due to non-Coasian pricing may be calculated as the consumer surplus when a Coasian volumetric price (p_c) is in place less the consumer surplus calculated when a non-Coasian (p_n) price is in place;

$$\Delta CS_k = CS_k(p_c) - CS_k(p_n) \tag{18}$$

Equation 18 may be rewritten as;

$$\Delta CS_k = \left(\int_0^{p_c} D_k(p_c)dp - p_c q_{k,c} - s(p_c) \right) - \left(\int_0^{p_n} D_k(p_n)dp - p_n q_{k,n} - s(p_n) \right) \tag{19}$$

As Section A.1 points out, p_c and $s(p_c)$ may be defined as:

$$p_c = m \tag{20}$$
$$s(p_c) = \frac{f}{K} \tag{21}$$

I consider the case of a non-Coasian tariff where the volumetric price is greater than marginal cost and a δ portion of grid fixed costs are recovered via the volumetric charge. Therefore, p_n and $s(p_n)$ may be defined as:

$$p_n = m + \frac{\delta}{Q} \tag{22}$$
$$s(p_n) = \frac{f-\delta}{K} \tag{23}$$

Subbing these values for p_n, $s(p_n)$, p_c and $s(p_c)$ into equation 19, gives;

$$\Delta CS_k = \left(\int_0^m D_k(m)dp_c - mq_{k,c} - \frac{f}{I} \right) - \left(\int_0^{p_n} D_k(p_n)dp_n - (m + \frac{\delta}{Q})q_{k,n} - \frac{f-\delta}{K} \right) \tag{24}$$

which may be simplified to:

$$\Delta CS_k = \overbrace{\int_0^m D_k(p_c)dp_c - \int_0^{p_n} D_k(p_n)dp_n - m(q_{k,c} - q_{k,n})}^{Consumption\ response} + \overbrace{\delta(\frac{q_{k,n}}{Q} - \frac{1}{K})}^{Tariff\ rebalancing} \tag{25}$$

Consumer surplus is affected by two effects. First, utility changes in response to a new consumption level. This change is proportional to the price elasticity of demand. The second effect captures the net change in total cost incidence due to tariff rebalancing, and this is determined by use.

If price elasticity is zero, the tariff rebalancing effect dominates. Equation 25 shows that consumer surplus will fall if household k's consumption is low (i.e. $(q_{n,k}/Q) < (1/K)$) and rise if consumption is high (i.e. $(q_{n,k}/Q) > (1/K)$).

If price elasticity is non-zero, households who use a lot of electricity will benefit from both effects. Households who consume less electricity (i.e. those for whom $(q_{n,k}/Q) < (1/K)$) will benefit from the consumption response as prices fall but lose out due to the rebalanced tariff. The extent of the price response will determine whether the net impact is positive or negative and this effect is demonstrated in Section VI.

Total consumer surplus is calculated as the sum of each individual consumer's response. Both the magnitude and distribution of winners vs. losers will determine this; if there are more individuals for which $(q_{n,k}/Q) < (1/K)$, then losers will outnumber winners. I quantify these effects using the simulation of Section VI.

A.3 Welfare effects of DER Adoption

DER deployment will reduce the number of units consumed from the grid, affecting fixed cost recovery if these are recovered via the volumetric charge. In this section, I show that consumer surplus is unaffected by DER deployment if Coasian pricing is in place. If Coasian pricing is not in place, the welfare of both adoptees and non-adoptees changes.

A.3.1 DER adoption and cost recovery

The constraint $R = C$, representing grid revenue and grid costs, must hold in utility tariff formation. Assume there is a total demand Q, from which Q_g units are sourced from the grid and Q_D units are sourced from DER units.

$$Q = Q_g + Q_D \tag{26}$$

System costs when Q_D DER units are deployed are as follows:

$$C = m(Q - Q_D) + F \tag{27}$$

Whilst revenue recovery may be characterized as:

$$R = (m + \frac{\delta}{Q_g})(Q - Q_D) + \frac{f - \delta}{K}K \tag{28}$$

where δ denotes the proportion of grid fixed costs recovered via the volumetric tariff. A change in DER-sourced electricity has the following effects on cost and revenues:

$$\frac{\partial C}{\partial Q_d} = -m \tag{29}$$

$$\frac{\partial R}{\partial Q_d} = -(m + \frac{\delta}{Q}) \tag{30}$$

With each additional unit of DER-generated electricity deployed, total cost falls by m whilst revenue falls by $m + (\delta/Q)$, therefore there is a loss in revenue that exceeds the loss in cost, with potential under-recovery of fixed costs. Should δ be equal to zero, Coasian pricing is in place. Otherwise, remedial action is required to ensure full cost recovery for the utility.

Either the standing charge or volumetric tariff must be altered such that the (δ/Q) portion may be recovered. I will now explore the welfare implications of these adjustments.

A.3.2 DER adoption and Coasian pricing

Denote $q_{k,g}$, $q_{k,d}$ and $q_{k,t}$ as the quantity of grid-sourced, DER-sourced and total electricity consumed by consumer k. Q_D may be further disaggregated to:

$$Q_D = q_{k,d} + \sum_{j}^{J} q_{j,d}, \tag{31}$$

where $j \neq k$. Under Coasian pricing, consumer surplus may be calculated by:

$$CS_k = \int_0^{p_c} D(p_c)dp_c - m(q_{k,t} - q_{k,d}) - p_d q_d - \frac{f}{K} \tag{32}$$

With DER deployment, consumer surplus for consumer k changes according to the following relationship:

$$\frac{\partial CS_k}{\partial q_d} = m - p_d \tag{33}$$

DER deployment affects adoptees to the extent that the marginal cost of grid-sourced electricity exceeds the price of DER-sourced electricity. If $q_d = 0$, $(\partial CS_k/\partial q_d) = 0$, therefore DER deployment has no effect on the welfare of non-adoptees under Coasian pricing.

A.3.3 DER adoption and non-Coasian pricing: volumetric charge adjustment

For every Q_D units of DER-sourced generation on the system, the regulator must adjust tariffs to compensate for (δ/Q) units of foregone revenue required to recover fixed costs. Therefore, tariffs must be adjusted by $(\delta/Q)Q_D$.

First, I examine consumer welfare change under volumetric charge adjustment. Volumetric and standing charge tariffs are as follows:

$$p_v = m_g + \frac{\delta + \frac{\delta}{Q}Q_D}{Q} \tag{34}$$

$$s_v = \frac{F - \delta}{K} \tag{35}$$

Consumer surplus when DER deployment replaces infra-marginal electricity consumption may be calculated as:

$$CS_k = \int_0^{p_v} D(p_v)dp_v - (m_g + \frac{\delta + \frac{\delta}{Q}Q_D}{Q})(q_{k,t} - q_{k,d}) - p_d q_d - \frac{f - \delta}{K} \tag{36}$$

A change in DER deployment leads to the following changes in consumer surplus if consumer k has a DER installation;

$$\frac{\partial CS_k}{\partial q_{k,d}} = \overbrace{\left(\frac{\partial}{\partial q_{k,d}} \int_0^{p_v} D(p_v)dp_v\right)}^{Consumption\ response\ (-)} + \overbrace{\left(m - p_d\right)}^{price\ effect\ (+/-)} + \overbrace{\frac{\delta + \frac{\delta}{Q}Q_D}{Q}}^{avoided\ surcharge(+)} - \overbrace{\frac{\delta(q_{k,t} - q_{k,d})}{Q^2}}^{surcharge\ increment\ incurred\ (-)} \tag{37}$$

An incremental increase in DER-soured electricity affects welfare through four constituent effects. First, there is a negative consumption response; an increase in the volumetric price surcharge reduces consumer welfare. Second, there is a ‘price effect’. If DER prices are less than marginal cost, this is positive. This price effect is negative if DER prices are greater than marginal cost. Third, adoptees avoid the surcharge on grid-sourced electricity for the unit of electricity substituted. This gives a positive welfare effect. Finally, the incremental increase in DER-sourced generation increases the surcharge for all grid-consumed units. This is negative but less than the avoided surcharge effect.

Assuming the consumption response is small, deployment may yield a positive welfare impact for consumer k if either (1) the price effect is positive or (2) the price effect is negative but the avoided fixed costs are sufficiently positive. This may occur if δ is sufficiently large.

It is important to note that non-adoptee surplus also changes. The change consumer surplus for household k due to a change in $q_{j,d}$ DER capacity at household j is;

$$\frac{\partial CS_k}{\partial q_{j,d}} = \overbrace{\left(\frac{\partial}{\partial q_{k,d}} \int_0^{p_v} D(p_v)dp_v\right)}^{Consumption\ response\ (-)} - \overbrace{\left(\frac{\delta(q_{k,t})}{Q^2}\right)}^{surcharge\ increment\ incurred\ (-)} \tag{38}$$

Household k incurs a welfare loss due to the negative consumption response and due to the surcharge effect, with no countering price effects or avoided surcharge increments.

A.3.4 DER adoption and non-Coasian pricing: standing charge adjustment

Under a standing charge adjustment, volumetric and standing charge tariffs are as follows:

$$p_v = m_g + \frac{\delta}{Q} \tag{39}$$

$$s_v = \frac{F - \delta + \frac{\delta}{Q} Q_D}{K} \tag{40}$$

Consumer surplus when DER deployment replaces infra-marginal electricity consumption may be calculated as:

$$CS_k = \int_0^{p_v} D(p_v) dp_v - (m_g + \frac{\delta}{Q})(q_{k,t} - q_{k,d}) - p_d q_d - \frac{F - \delta + \frac{\delta}{Q} Q_D}{K} \tag{41}$$

A change in DER deployment leads to the following changes in consumer surplus. If consumer k has a DER installation;

$$\frac{\partial CS_k}{\partial q_{j,d}} = \overbrace{\left(m - p_d\right)}^{price\ effect} + \overbrace{\frac{\delta}{Q}}^{avoided\ mark-up} - \overbrace{\frac{\delta}{QK}}^{fixed\ cost\ surcharge} \tag{42}$$

As with the volumetric price adjustment, a standing charge adjustment leads to a number of constituent effects. First, there is no consumption response as volumetric charges remain unaffected. Second, there is a price effect attributable to the difference in cost of DER and grid-sourced generation. This is positive if DER costs are less than the marginal cost of grid-sourced electricity and negative if DER costs are greater. Third, for every DER unit deployed, consumer k avoids the pre-existing (δ/Q) mark-up in excess of marginal costs. Fourth, there is an incurred standing charge increment which is less than the avoided pre-existing surcharge if $K > 1$.

Deployment yields a positive welfare impact for consumer k if either (1) the price effect is positive, or (2) the price effect is negative and δ is sufficiently large such that the avoided volumetric charge mark-up outweighs a negative price effect.

DER deployment creates the following changes in consumer surplus if consumer k does not have a DER installation;

$$\frac{\partial CS_k}{\partial q_{j,d}} = - \overbrace{\frac{\delta}{QK}}^{fixed\ cost\ surcharge} \tag{43}$$

As such, DER deployment also has spillover negative welfare impacts for non-adoptees if Coasian pricing is not in place and a standing charge adjustment is implemented. These effects are quantified in Section VII.

B Total welfare change: alternate tariff calculation

B.1 Alternative cost apportionment for tariff calculation

This section presents alternate calculations of total welfare change for each level of assumed elasticity under an alternate assumption of regional cost variation. In the central case study outlined in Section IV, all regional cost variation is assumed to be attributable to fixed cost variation. I test the sensitivity to an alternate specification whereby regional variation is equally distributed between fixed and variable costs. In Tables 12 and 13 one can see that tariffs and total welfare estimates vary by a very small degree, suggesting that the results of this paper are insensitive to this assumption.

Table 12: Coasian tariffs calculated assuming equal breakdown of regional cost variation between fixed and standing charges

	(2015) Volumetric Price (£/kWh)	(2015) Fixed price (£/week)	(2016) Volumetric price (£/kWh)	(2016) Fixed price (£/week)
North East	0.0676	5.968	0.0645	4.862
North West	0.0675	6.673	0.0622	6.549
Yorkshire	0.0646	6.201	0.0609	6.332
East Midlands	0.0636	6.465	0.0584	7.297
West Midlands	0.0650	6.552	0.0623	6.861
East	0.0630	6.677	0.0581	6.902
London	0.0653	6.756	0.0619	6.727
South East	0.0650	6.789	0.0616	6.692
South West	0.0687	6.767	0.0659	6.782
Wales	0.0702	7.151	0.0662	7.098
Scotland	0.0687	7.023	0.0653	6.874
Observations	3600	3600	1086	1086

Table 13: Welfare change due to Coasian price reform: alternative cost apportionment

Price elasticity	Average welfare change (£/annum)	Total welfare change (£/annum)
-0.1	8.604	220
	(1.195)	(77.4)
-0.2	18.20	468
	(1.235)	(80.0)
-0.3	28.24	728
	(1.277)	(82.7)
-0.4	38.77	1,000
	(1.322)	(85.6)
-0.5	49.81	1,286
	(1.368)	(88.7)
-0.6	61.39	1,586
	(1.417)	(91.9)
-0.7	73.53	1,900
	(1.468)	(95.3)
-0.8	86.27	2,230
	(1.522)	(98.9)

Note: Standard errors in parentheses calculated from 1000 bootstrap replications using LCF sampling weights. Values depicted represent average annual change in welfare on average and in total for the population.

B.2 Total welfare change: alternate Economy 7 calculation

This section presents alternate calculations of total welfare change for each level of assumed elasticity under two alternate assumptions of assumed Economy 7 night electricity usage. In the central case study outlined in Section IV, day usage represents 58 percent of total usage for the economy 7 user. I test the sensitivity to alternate specifications of this paramater in Table 14, assuming 50 percent and 70 percent for lower and upper bound tests. One can see that total welfare estimates vary by a very small degree, suggesting that the results of this paper are insensitive to this assumption.

Table 14: Testing sensitivity to alternate Economy 7 consumption assumptions

Price elasticity	50:50 day:night consumption		70:30 day:night consumption	
	Average (£)	Total (£m)	Average (£)	Total (£m)
-0.1	8.625	220	8.605	220
	(1.190)	(77.4)	(1.159)	(76.2)
-0.2	18.25	469	18.21	468
	(1.229)	(80.0)	(1.199)	(78.9)
-0.3	28.34	730	28.27	729
	(1.271)	(82.7)	(1.240)	(81.7)
-0.4	38.91	1,004	38.82	1,002
	(1.314)	(85.5)	(1.283)	(84.7)
-0.5	50.00	1,291	49.87	1,288
	(1.360)	(88.6)	(1.329)	(87.8)
-0.6	61.63	1,592	61.47	1,588
	(1.408)	(91.8)	(1.377)	(91.2)
-0.7	73.84	1,908	73.63	1,903
	(1.458)	(95.2)	(1.427)	(94.7)
-0.8	86.65	2,240	86.40	2,234
	(1.511)	(98.8)	(1.481)	(98.5)

Note: Standard errors in parentheses calculated from 1000 bootstrap replications. Values depicted represent average annual change in welfare on average and in total for the population. All calculations use LCF sampling weights.

C UK Electricity tariffs: 2015 and 2016

Table 15: Average variable unit costs and standing charges for standard electricity in 2015

Payment type	Credit		Direct debit		Prepayment		Overall	
Town/city	Average unit price (/kWh)	Average fixed cost (/year)	Average unit price (/kWh)	Average fixed cost (/year)	Average unit price (/kWh)	Average fixed cost (/year)	Average unit price (/kWh)	Average fixed cost (/year)
East Midlands	0.137	84.43	0.128	62.77	0.138	83.09	0.132	71.51
Eastern	0.136	85.12	0.128	63.90	0.138	83.10	0.131	72.13
London	0.143	76.08	0.132	65.17	0.144	76.35	0.138	71.49
Merseyside & North Wales	0.154	86.59	0.142	69.22	0.153	86.27	0.148	77.21
North East	0.147	70.70	0.134	58.34	0.145	75.10	0.139	64.03
North Scotland	0.154	92.96	0.147	63.80	0.154	92.79	0.150	76.20
North West	0.144	83.76	0.134	65.83	0.146	81.65	0.139	73.37
Northern Ireland	0.169	-	0.161	-	0.163	-	0.164	-
South East	0.143	78.59	0.132	65.94	0.144	78.88	0.136	70.52
South Scotland	0.139	87.91	0.127	73.56	0.137	89.51	0.132	80.25
South Wales	0.149	91.43	0.142	62.50	0.149	92.83	0.145	75.88
South West	0.152	77.44	0.142	64.35	0.153	78.98	0.146	69.72
Southern	0.140	88.97	0.132	63.87	0.142	87.94	0.135	72.60
West Midlands	0.147	71.65	0.133	58.83	0.145	75.48	0.139	65.08
Yorkshire	0.145	70.90	0.130	59.74	0.143	74.76	0.136	65.23
United Kingdom	0.144	78.66	0.134	62.62	0.145	76.10	0.138	69.13

Table 16: Average variable unit costs and standing charges for economy 7 electricity in 2015

Payment type	Credit			Direct debit			Prepayment			Overall		
Town/city	day (/kWh)	night (/kWh)	fixed (/year)	day (/kWh)	night (/kWh)	fixed (/year)	day (/kWh)	night (/kWh)	fixed (/year)	day (/kWh)	night (/kWh)	fixed (/year)
E. Midlands	0.17	0.07	88.92	0.16	0.06	71.30	0.18	0.07	88.10	0.17	0.07	78.20
Eastern	0.17	0.07	89.38	0.16	0.07	70.04	0.17	0.07	85.33	0.16	0.07	78.78
London	0.18	0.07	77.53	0.16	0.07	70.94	0.18	0.07	79.07	0.17	0.07	74.94
Merseyside, N. Wales	0.19	0.08	94.74	0.17	0.07	83.31	0.19	0.08	94.92	0.18	0.08	89.50
N. East	0.19	0.07	90.39	0.17	0.07	70.64	0.19	0.07	87.33	0.18	0.07	80.19
N. Scotland	0.19	0.10	98.20	0.18	0.10	61.11	0.19	0.10	99.31	0.19	0.10	81.35
N. West	0.18	0.07	90.97	0.17	0.07	72.56	0.18	0.07	91.32	0.17	0.07	81.83
N. Ireland	0.17	0.08	31.15	0.16	0.08	31.70	0.17	0.08	27.41	0.17	0.08	29.42
S. East	0.18	0.07	78.78	0.16	0.07	71.39	0.18	0.07	80.91	0.17	0.07	75.35
S. Scotland	0.17	0.09	97.31	0.15	0.07	89.83	0.16	0.08	97.84	0.16	0.08	94.72
S. Wales	0.18	0.08	95.62	0.18	0.08	65.03	0.18	0.08	96.83	0.18	0.08	79.74
South West	0.19	0.07	77.69	0.17	0.07	70.40	0.19	0.07	80.18	0.18	0.07	74.80
Southern	0.17	0.08	95.37	0.17	0.08	64.55	0.17	0.07	93.99	0.17	0.08	78.44
W. Midlands	0.19	0.07	89.97	0.16	0.07	71.74	0.19	0.07	89.95	0.17	0.07	80.42
Yorkshire	0.18	0.07	89.92	0.16	0.07	71.94	0.18	0.07	89.37	0.17	0.07	81.21
UK	0.18	0.08	88.18	0.16	0.07	70.83	0.18	0.08	86.97	0.17	0.07	79.06

Table 17: Average variable unit costs and standing charges for standard electricity in 2016

Payment type	Credit		Direct debit		Prepayment		Overall	
Town/city	Average variable unit price (/kWh)	Average fixed cost (/year)	Average variable unit price (/kWh)	Average fixed cost (/year)	Average variable unit price (/kWh)	Average fixed cost (/year)	Average variable unit price (/kWh)	Average fixed cost (/year)
East Midlands	0.137	84.92	0.125	62.90	0.138	83.23	0.130	71.23
Eastern	0.137	85.46	0.126	64.04	0.138	83.20	0.130	71.96
London	0.143	76.86	0.131	65.46	0.143	76.50	0.137	71.76
Merseyside & North Wales	0.154	86.76	0.139	69.07	0.153	86.11	0.145	76.71
North East	0.146	72.31	0.130	59.32	0.144	75.46	0.136	64.76
North Scotland	0.153	93.11	0.143	65.03	0.154	92.90	0.147	76.55
North West	0.144	84.17	0.130	65.47	0.145	81.89	0.136	72.91
Northern Ireland	0.152	-	0.140	-	0.146	-	0.148	-
South East	0.143	79.01	0.131	66.12	0.143	78.74	0.135	70.53
South Scotland	0.139	88.09	0.125	72.12	0.137	90.10	0.131	79.24
South Wales	0.149	91.69	0.139	62.98	0.149	92.73	0.143	75.36
South West	0.152	77.87	0.140	65.34	0.153	78.84	0.144	70.17
Southern	0.140	89.31	0.130	64.13	0.141	88.01	0.133	72.43
West Midlands	0.146	72.83	0.130	59.47	0.145	75.64	0.136	65.46
Yorkshire	0.144	72.27	0.127	60.46	0.142	74.88	0.134	65.74
United Kingdom	0.143	79.29	0.131	62.87	0.144	75.90	0.136	69.11

Table 18: Average variable unit costs and standing charges for economy 7 electricity in 2016

Payment type	Credit			Direct debit			Prepayment			Overall		
Town/city	day (/kWh)	night (/kWh)	fixed (/year)	day (/kWh)	night (/kWh)	fixed (/year)	day (/kWh)	night (/kWh)	fixed (/year)	day (/kWh)	night (/kWh)	fixed (/year)
East Midlands	0.17	0.07	89.28	0.15	0.06	70.13	0.18	0.07	88.33	0.16	0.07	77.33
Eastern	0.17	0.07	89.47	0.15	0.07	69.33	0.17	0.07	86.11	0.16	0.07	78.40
London	0.18	0.07	77.45	0.16	0.07	70.67	0.18	0.07	79.26	0.17	0.07	74.78
Merseyside, N. Wales	0.19	0.08	94.36	0.17	0.07	79.85	0.19	0.08	95.08	0.18	0.08	87.71
North East	0.19	0.07	92.25	0.16	0.07	71.50	0.18	0.07	88.16	0.18	0.07	81.04
North Scotland	0.19	0.10	98.47	0.18	0.10	62.75	0.19	0.10	99.32	0.18	0.10	81.85
North West	0.18	0.08	91.02	0.16	0.07	71.05	0.18	0.07	91.54	0.17	0.07	80.91
Northern Ireland	0.15	0.08	26.12	0.15	0.08	26.55	0.15	0.07	24.54	0.15	0.07	25.44
South East	0.18	0.07	78.76	0.16	0.07	70.76	0.18	0.07	80.89	0.17	0.07	74.90
South Scotland	0.17	0.09	96.47	0.15	0.07	85.09	0.16	0.08	97.82	0.16	0.08	92.68
South Wales	0.18	0.08	95.85	0.17	0.07	65.24	0.18	0.08	96.79	0.18	0.08	79.65
South West	0.19	0.07	77.77	0.17	0.07	70.21	0.19	0.07	80.21	0.18	0.07	74.63
Southern	0.17	0.08	95.49	0.16	0.08	64.97	0.17	0.07	94.01	0.17	0.08	78.21
West Midlands	0.18	0.07	91.31	0.16	0.06	71.35	0.18	0.07	90.51	0.17	0.07	80.42
Yorkshire	0.18	0.07	91.70	0.16	0.06	72.32	0.18	0.07	89.85	0.17	0.07	81.79
United Kingdom	0.18	0.08	88.46	0.16	0.07	70.08	0.18	0.07	87.27	0.17	0.07	78.62

D Distributional impacts of tariff reform: full tables

Table 19: Distribution of average welfare change

	$e = 0$	$e = -0.1$	$e = -0.2$	$e = -0.3$	$e = -0.4$	$e = -0.5$	$e = -0.6$	$e = -0.7$	$e = -0.8$
First quintile	-32.60	-24.42	-15.83	-6.826	2.624	12.55	22.97	33.91	45.41
	(2.571)	(2.660)	(2.753)	(2.851)	(2.953)	(3.061)	(3.175)	(3.295)	(3.421)
Second quintile	-19.37	-10.80	-1.827	7.583	17.45	27.80	38.67	50.07	62.04
	(2.635)	(2.723)	(2.815)	(2.912)	(3.014)	(3.120)	(3.233)	(3.351)	(3.475)
Third quintile	-6.952	2.062	11.50	21.40	31.77	42.65	54.07	66.04	78.61
	(2.495)	(2.578)	(2.666)	(2.758)	(2.855)	(2.956)	(3.063)	(3.176)	(3.294)
Fourth quintile	0.976	10.17	19.80	29.89	40.45	51.53	63.13	75.30	88.07
	(2.281)	(2.355)	(2.432)	(2.514)	(2.599)	(2.688)	(2.782)	(2.881)	(2.984)
Fifth quintile	54.98	65.88	77.28	89.21	101.7	114.8	128.5	142.9	157.9
	(2.759)	(2.848)	(2.941)	(3.038)	(3.140)	(3.246)	(3.358)	(3.475)	(3.598)

Note: Standard errors calculated from 1,000 bootstrap repetitions are reported in parantheses and are calculated using LCF sampling weights. Tariffs calculated based on 2015/16 LCF survey consumption profile, excluding households from Northern Ireland and those that spend less than £0/week or greater than £300/week on electricity. Results are representative for 25.9m GB households. Welfare change is calculated according to disposable income quintile.

Table 20: Distribution of total welfare change

	$e = 0$	$e = -0.1$	$e = -0.2$	$e = -0.3$	$e = -0.4$	$e = -0.5$	$e = -0.6$	$e = -0.7$	$e = -0.8$
First quintile	-168.4	-126.1	-81.79	-35.27	13.56	64.81	118.6	175.2	234.6
	(13.53)	(13.89)	(14.30)	(14.75)	(15.25)	(15.81)	(16.41)	(17.08)	(17.80)
Second quintile	-100.5	-56.05	-9.480	39.34	90.53	144.2	200.6	259.8	321.9
	(13.74)	(14.15)	(14.61)	(15.12)	(15.67)	(16.28)	(16.94)	(17.66)	(18.44)
Third quintile	-35.95	10.66	59.49	110.7	164.3	220.6	279.6	341.5	406.5
	(12.91)	(13.32)	(13.78)	(14.28)	(14.84)	(15.45)	(16.11)	(16.83)	(17.62)
Fourth quintile	5.059	52.75	102.7	155.0	209.8	267.2	327.3	390.5	456.7
	(11.84)	(12.23)	(12.67)	(13.16)	(13.69)	(14.28)	(14.92)	(15.62)	(16.38)
Fifth quintile	285.2	341.7	400.9	462.7	527.5	595.4	666.5	741.0	819.1
	(14.81)	(15.46)	(16.15)	(16.90)	(17.70)	(18.56)	(19.48)	(20.46)	(21.51)

Note: Standard errors are reported in parantheses are calculated using LCF sampling weights. Tariffs calculated based on 2015/16 LCF survey consumption profile, excluding households from Northern Ireland and those that spend less than £0/week or greater than £300/week on electricity. Welfare change is calculated according to disposable income quintile

E Socioeconomic distribution of welfare change: full tables

Table 21: Effect of tariff reform on homeowners

	$e = 0$	$e =$ -0.1	$e =$ -0.2	$e =$ -0.3	$e =$ -0.4	$e =$ -0.5	$e =$ -0.6	$e =$ -0.7	$e =$ -0.8
Not Owner	2.554	11.88	21.66	31.92	42.69	53.99	65.86	78.33	91.43
	(5.218)	(5.397)	(5.586)	(5.785)	(5.994)	(6.214)	(6.445)	(6.689)	(6.945)
Owner	-2.438	6.637	16.14	26.08	36.50	47.42	58.86	70.85	83.43
	(3.386)	(3.495)	(3.610)	(3.730)	(3.856)	(3.988)	(4.127)	(4.272)	(4.425)
Observations	4689	4689	4689	4689	4689	4689	4689	4689	4689

Standard errors reported in parantheses are calculated using LCF sampling weights. Calculations based on 2015/2016 Living Cost and Food (LCF) survey consumption profile, excluding households from Northern Ireland and those that spend less than £0/week or greater than £300/week.

Table 22: Effect of tariff reform on households with children

	$e = 0$	$e =$ -0.1	$e =$ -0.2	$e =$ -0.3	$e =$ -0.4	$e =$ -0.5	$e =$ -0.6	$e =$ -0.7	$e =$ -0.8
No_Children	-23.69	-15.32	-6.547	2.641	12.27	22.36	32.95	44.05	55.70
	(3.226)	(3.332)	(3.443)	(3.560)	(3.682)	(3.810)	(3.945)	(4.087)	(4.236)
Children	55.61	66.71	78.33	90.51	103.3	116.7	130.7	145.5	161.0
	(5.586)	(5.774)	(5.972)	(6.180)	(6.398)	(6.627)	(6.868)	(7.121)	(7.388)
Observations	4689	4689	4689	4689	4689	4689	4689	4689	4689

Standard errors reported in parantheses are calculated using LCF sampling weights. Calculations based on 2015/2016 Living Cost and Food (LCF) survey consumption profile, excluding households from Northern Ireland and those that spend less than £0/week or greater than £300/week.

Table 23: Effect of tariff reform on households with elderly residents

	$e = 0$	$e =$ -0.1	$e =$ -0.2	$e =$ -0.3	$e =$ -0.4	$e =$ -0.5	$e =$ -0.6	$e =$ -0.7	$e =$ -0.8
No_OAP	-1.536	7.600	17.17	27.20	37.71	48.73	60.30	72.43	85.16
	(3.046)	(3.148)	(3.254)	(3.366)	(3.484)	(3.607)	(3.737)	(3.873)	(4.017)
OAP_Present	6.126	15.51	25.33	35.61	46.37	57.66	69.48	81.88	94.89
	(8.318)	(8.583)	(8.861)	(9.152)	(9.456)	(9.776)	(10.11)	(10.46)	(10.83)
Observations	4689	4689	4689	4689	4689	4689	4689	4689	4689

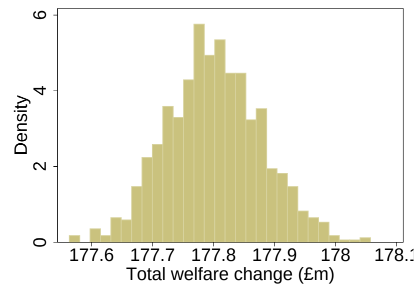
Standard errors reported in parantheses are calculated using LCF sampling weights. Calculations based on 2015/2016 Living Cost and Food (LCF) survey consumption profile, excluding households from Northern Ireland and those that spend less than £0/week or greater than £300/week.

F Sensitivity to choice of adoptees

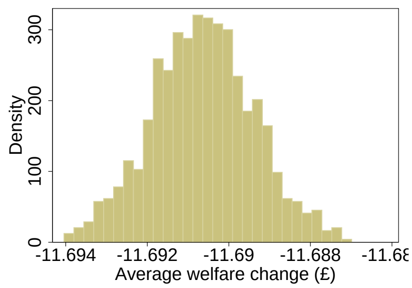
In Section VII, DER adoptees are chosen at random in the absence of data indentifying adoptees vs. non-adoptees. This section demonstrates the sensitivity to this choice. I simulate a representative DER deployment scenario, under non-coasian pricing with volumetric charge adjustment, assuming a price elasticity of demand of -0.6 and 2.5 million adoptee households. 1,000 random draws of adoptee households are chosen. Figure 8 shows that the range of potential welfare loss varies by less than 1 percent. This is because the consumption response is small due to the price adjustment and varies to an insignificant extent by household.

Figure 8: Sensitivity to simulation draw

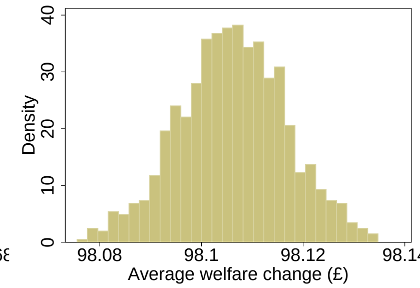
(a) Total welfare change



(b) Adoptees



(c) Non-adoptees

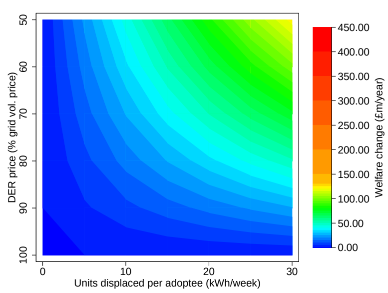


G Supplementary results: Additional scenarios of DER deployment

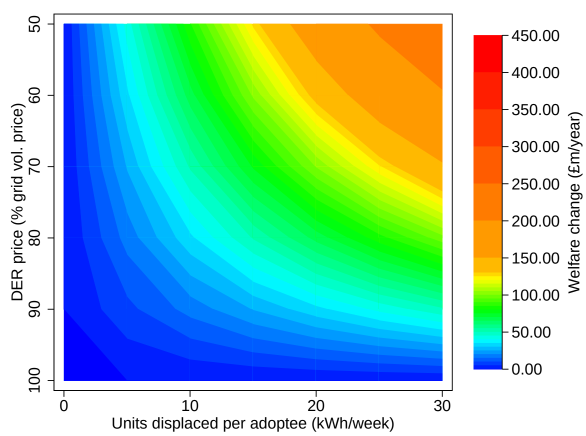
G.1 Coasian price

Figure 9: Total welfare change: Coasian price

(a) 2.5 million DER adoptees



(b) 5 million DER adoptees



(c) 10 million DER adoptees

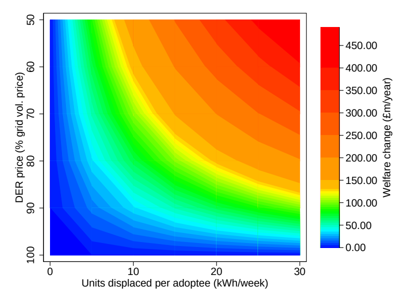
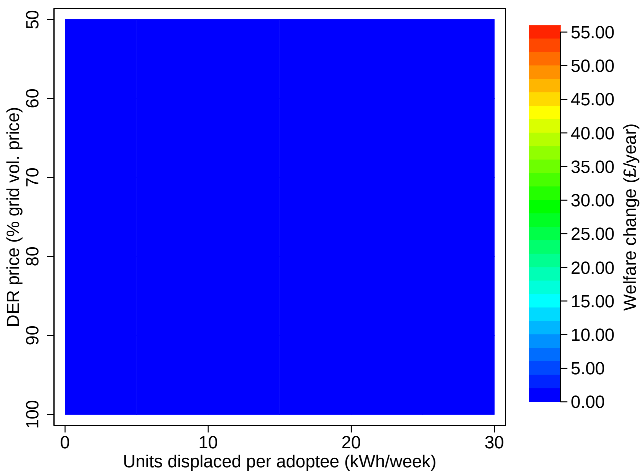
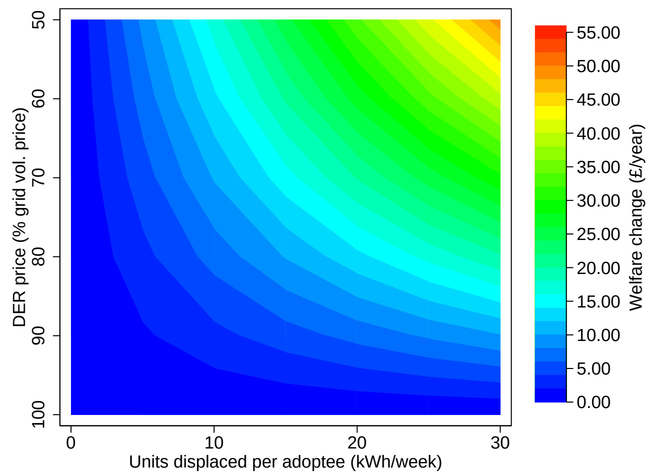


Figure 10: Average Welfare change: DER deployment and Coasian pricing

(a) DER non-adoptees



(b) DER adoptees

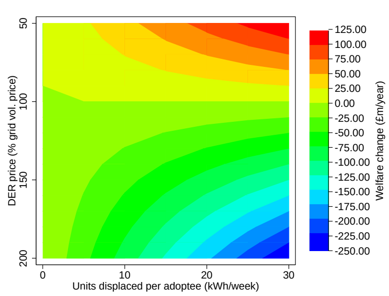


Note: Figures display average welfare change under Coasian pricing assuming 2.5m households adopt DER-sourced generation.

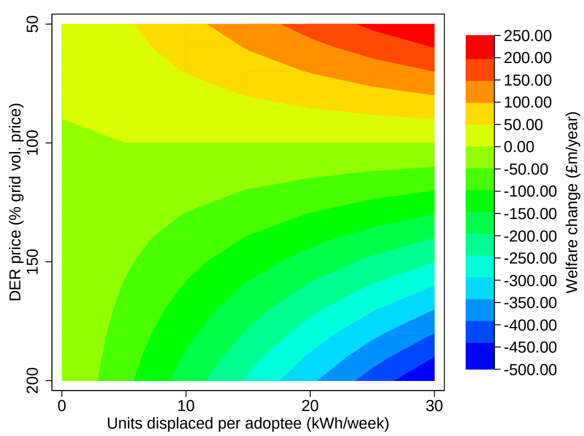
G.2 No Coasian price: total change

Figure 11: Total change with no Coasian price: standing charge adjustment

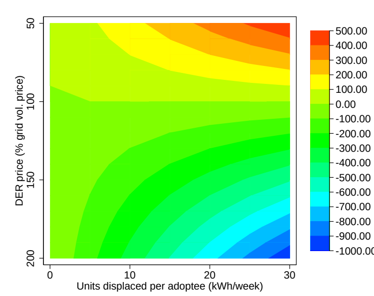
(a) 2.5 million adoptees



(b) 5 million adoptees



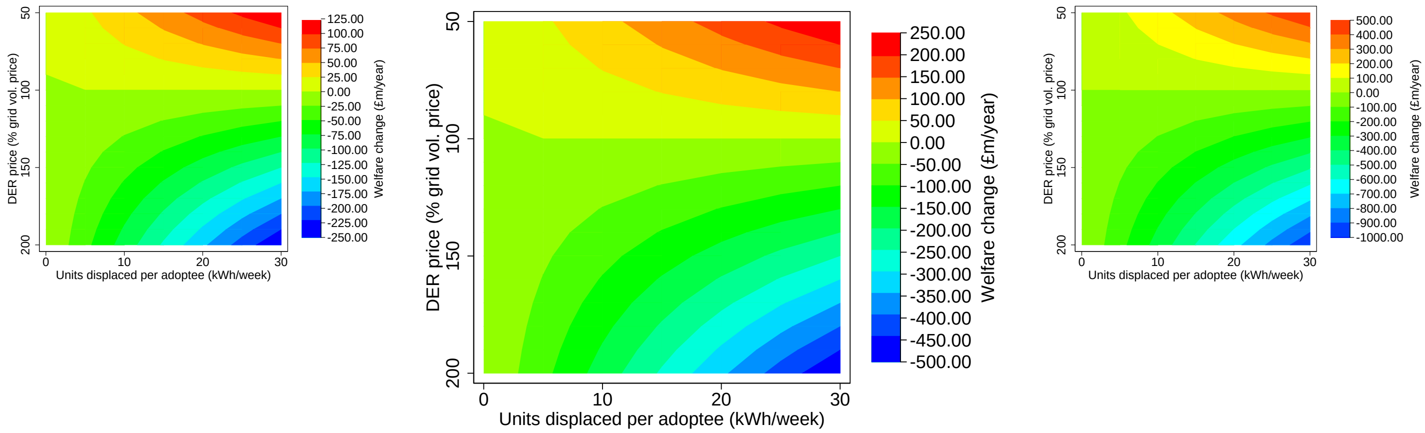
(c) 10 million adoptees



Note: Figures display average welfare change under non-Coasian pricing assuming elasticity of -0.6

Figure 12: Total change with no Coasian price: Volumetric charge adjustment

(a) 2.5 million adoptees (b) 5 million adoptees (c) 10 million adoptees

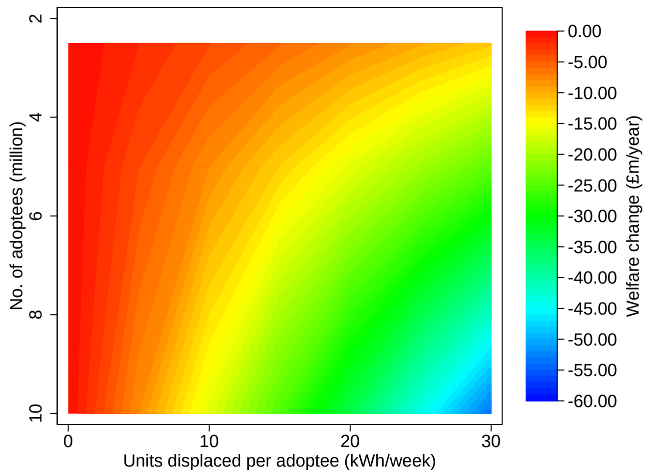


Note: Figures display average welfare change under non-Coasian pricing assuming elasticity of -0.6

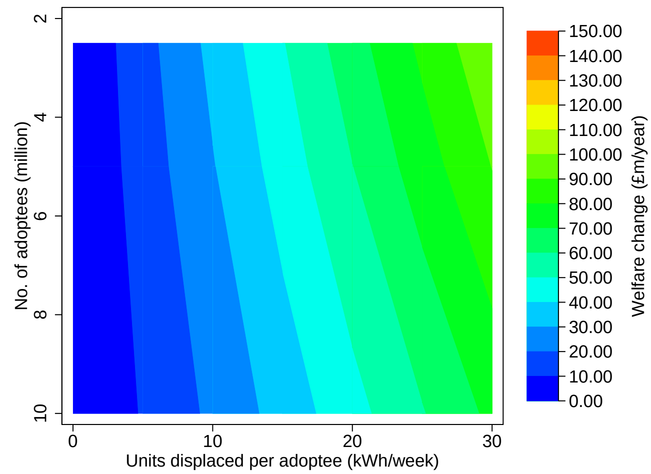
G.3 No Coasian price: average change

Figure 13: Average welfare change with DER grid parity and no Coase price

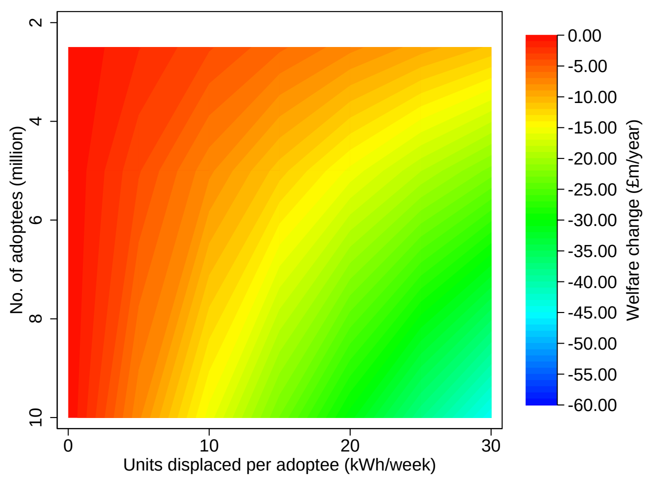
(a) Volumetric price adjustment: non-adoptees



(b) Volumetric price adjustment: adoptees



(c) Standing charge adjustment: non-adoptees



(d) Standing charge adjustment: adoptees

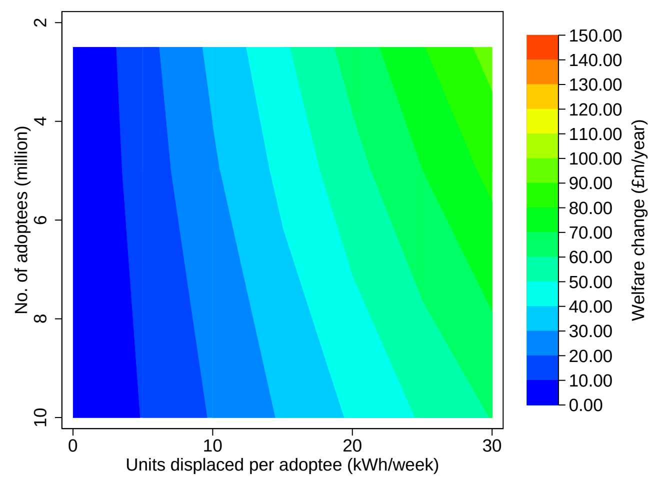
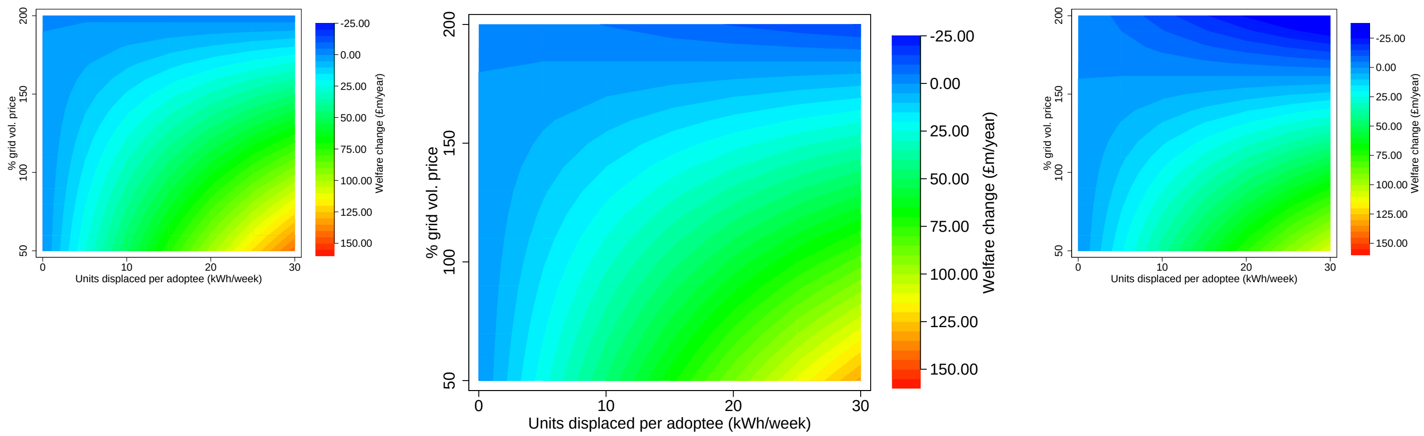


Figure 14: Average welfare change for adoptees under non-coasian tariff: standing charge adjustment

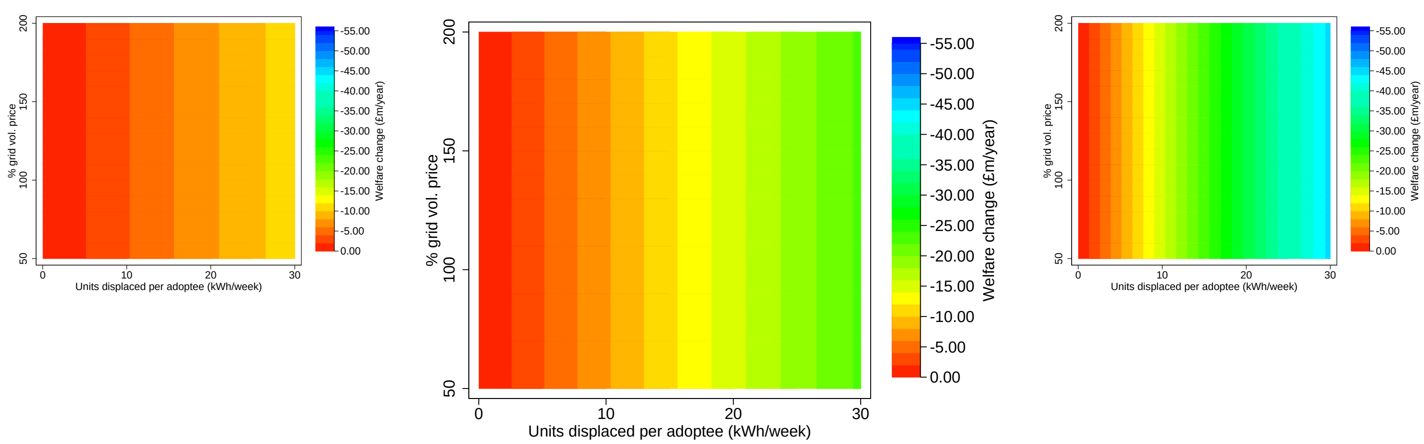
(a) 2.5 million adoptees (b) 5 million adoptees (c) 10 million adoptees



Note: Figures display average welfare change under non-Coasian pricing assuming elasticity of -0.6

Figure 15: Average welfare change for non-adoptees under non-coasian tariff: standing charge adjustment

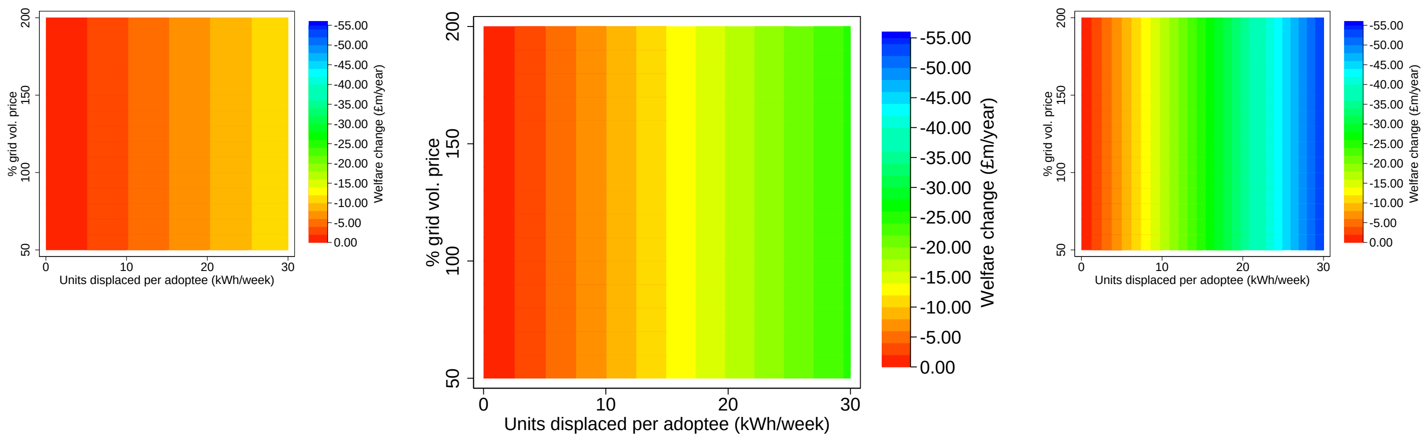
(a) 2.5 million adoptees (b) 5 million adoptees (c) 10 million adoptees



Note: Figures display average welfare change under non-Coasian pricing assuming elasticity of -0.6

Figure 16: Average welfare change for non-adoptees under non-coasian tariff: volumetric charge adjustment

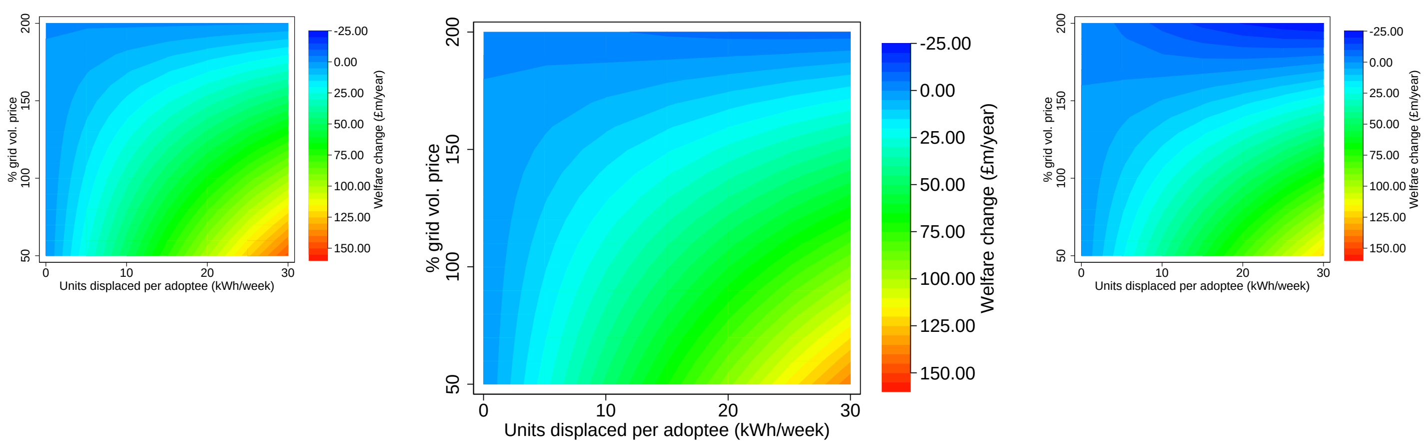
(a) 2.5 million adoptees (b) 5 million adoptees (c) 10 million adoptees



Note: Figures display average welfare change under non-Coasian pricing assuming elasticity of -0.6

Figure 17: Average welfare change for adoptees under non-coasian tariff: volumetric charge adjustment

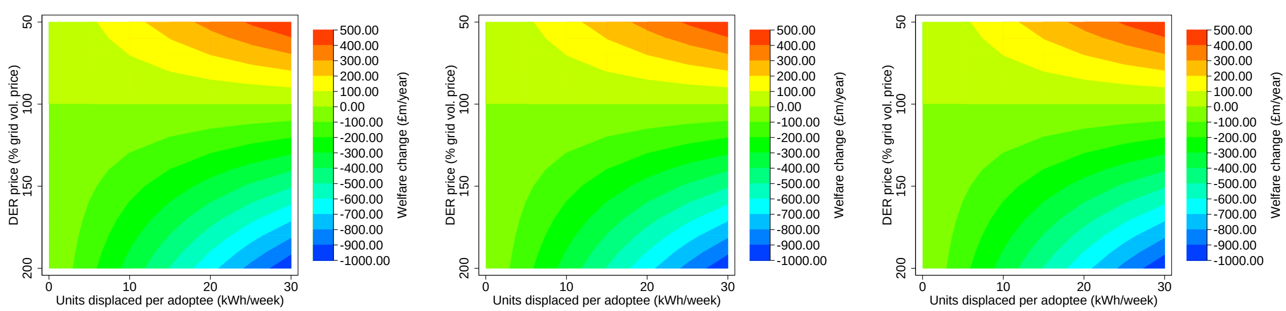
(a) 2.5 million adoptees (b) 5 million adoptees (c) 10 million adoptees



Note: Figures display average welfare change under non-Coasian pricing assuming elasticity of -0.6

Figure 18: Sensitivity of total welfare change to elasticity assuming no Coasian price and volumetric charge adjustment

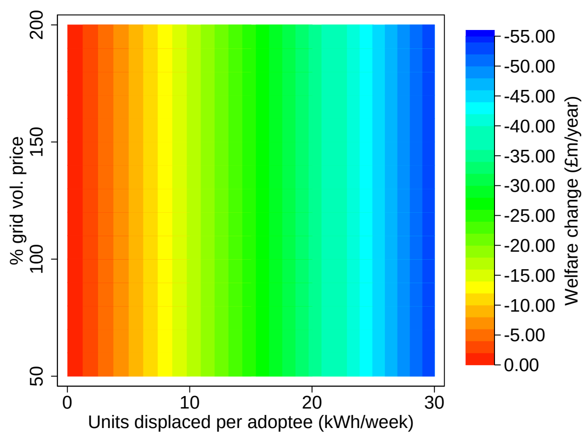
(a) Elasticity: e = 0 (b) Elasticity: e = -0.4 (c) Elasticity: e = -0.8



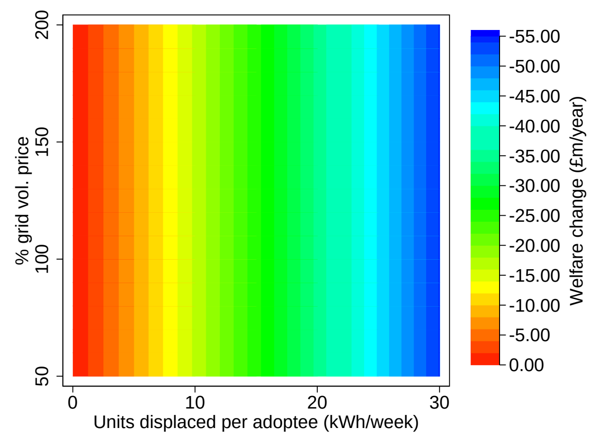
Note: Figures display average welfare change when 10 million households adopt

Figure 19: Sensitivity of average welfare change to elasticity assuming no Coasian price and volumetric charge adjustment

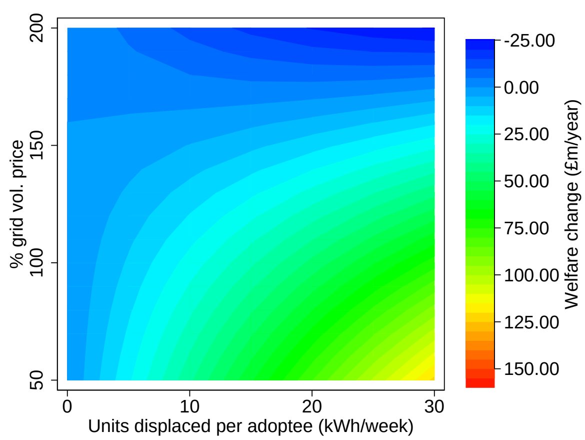
(a) Non-adoptee: Elasticity: e = -0.4



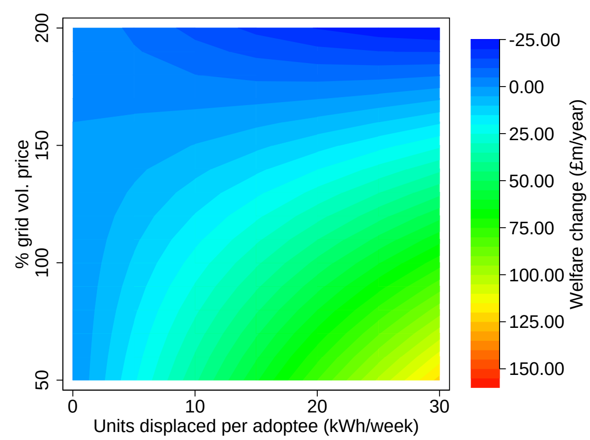
(b) Non-adoptee: Elasticity: e = -0.8



(c) Adoptee: Elasticity: e = -0.4



(d) Adoptee: Elasticity: e = -0.8



Note: Figures display average welfare change when 10 million households adopt