Energy use in crisis - lessons for net-zero?

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Abstract

The winter 2022/23 has seen exceptional and nationally coordinated energy price changes coinciding with a general cost of living crisis. How have energy users responded?

Over the past eight years we have collected high resolution household electricity and gas readings alongside electronic activity diaries and socio-demographic survey information. These data help us to understand the vast diversity in energy use between different user groups and how they differ in their response to changes in price, incentives or information.

Over 400 households have taken part in this process. Of them, 146 form part of a panel that was specifically monitored during the price cap changes in 2022 and 2023.

This paper presents findings on the correlation of demand with tariffs, taken from half-hourly smart meter data. The findings show that the correlation is generally weak and the anticipated negative elasticity of demand with respect to price does not apply throughout the sample. Instead, and depending on the periods being compared, demand is weakly positively correlated to price. This finding appears to apply to lower income groups in particular, and it is hypothesised that for these households energy exhibits Giffen good characteristics.

The dramatic price changes and the public media attention they received provide a unique opportunity to test the assumption that energy demand is a function of price. The findings have implications for the design of energy markets and the role of price signals in the transition to net-zero. For lower income groups financial and efficiency support measures could yield better demand reduction outcomes, than higher prices as an incentive.

Keywords: Energy Demand, Price elasticity, Smart meter data, Fuel poverty, Cost of living

1 Introduction

The liberation of energy retail markets is meant to deliver two consumer benefits: Firstly, customers can make active choices over their suppliers, tariffs and energy consumption to reduce their bills. Secondly, competition between retailers drives down prices and improves service quality.

Neither of these benefits have materialised satisfactorily in practice. Too many customers fail to exercise their right to change supplier or tariff and end up on unfavourable 'standard variable tariffs'. This failing led the energy regulator OfGEM to introduce a price cap.

How effective energy prices are at signalling to energy users how to moderate their consumption therefore remains a topic of conjecture.

The synchronised and nationwide raising of this price cap in 2022 and 2023, in response to an energy wholesale price crisis combined with a cost-of-living crisis and rising interest rates, provides an unprecedented opportunity to assess the impact of price on energy demand. Detailed observation of half-hourly smart meter data with tariff and consumption information can shine a light on this relationship.

1.1 The energy price cap

The price cap was introduced by the UK energy regulator OfGEM in January 2019, following a similar scheme for pre-payment meters in April 2017. The cap was originally envisaged as a response to concerns that customers who didn't actively change suppliers tended to be moved onto more expensive 'standard variable tariffs'. It was an acknowledgement that the market was not working frictionless enough to put downward pressure on prices for all. In other commodity markets, even customers who do not 'shop around for the lowest price' benefit from others who do. A supermarket with consistently higher prices will lose its more price-conscience customers. The incentive not to lose these customers, keeps prices down for all and increases the consumer surplus for other customers, who would have paid higher prices before voting with their feet to go to a less conveniently located but cheaper supermarket. In commodity markets not everyone has to check prices all the time. Some people can benefit as free-riders.

This mechanism does not function in utility markets to the same extent. Each individual customer can have their prices raised to their personal threshold—the point at which they switch suppliers. While switching has theoretically a low hurdle cost, in practice many households pay substantial costs before changing their supplier. The price cap is intended to act as a safeguard.

The level of the price cap is tagged to the wholesale price and not intended to be the lowest available tariff. Quite the opposite. It was meant to act as a ceiling, to prevent excessive rents to suppliers at the expense of 'unengaged' market participants. This changed in October 2022, when wholesale prices had reached a level that meant many previously competitive tariffs ‘hit the price cap’. The bi-annual review of the price cap, would have seen an unprecedented increase for many tariffs that were now constrained by it. Switching suppliers no longer yielded any benefit to customers in this environment, because most tariffs are constrained by the cap and suppliers no longer compete for more customers.

To reduce the hardship for a growing number of homes in fuel poverty, the UK Government introduced the Energy Bills Support Scheme (£400 per household) and the Energy Price Guarantee - a cap on the price cap. This no longer tracked above the wholesale market price, but kept the price below the price cap and Government makes up the difference to suppliers (Bell et al., 2022). Neither of these support schemes was targeted at lower income groups or fuel poor households. The £400 discount on energy bills was automatically applied to most bill payers for the winter 2022/23, ending in March 2023. People on pre-payment meters had to follow a more complicated voucher system, which reportedly prevented many from claiming their discount. By June 2023 £130m of vouchers were still unclaimed (DESNZ, 2023).

These steps completed a temporary departure from a competitive retail market. Government sets the price and taxpayers eventually pay the shortfall in bills. Neither wholesale markets nor suppliers affect the tariffs directly during this period and many consumers have no option to change suppliers in search for a better deal.

In July 2023 the price cap fell back below the energy price guarantee (Bolton & Stewart, 2023). But the intervening period acts as a unique opportunity to observe the response of households to coordinated and enforced changes in energy prices. This paper presents data collected in real time from households during these turbulent months and shows how demand responded to changes in prices.

1.2 Elasticity of energy demand

The literature on price elasticity of energy demand gained traction in the 1970s. A 2017 meta analysis assessed 11 reviews dating between 1975 and 2012, of which only two explicitly addressed electricity, rather than gasoline and car fuels (Labandeira et al., 2017). These were Taylor (1975) and Bohi & Zimmerman (1984), which refer to the ‘energy crisis’ of the 1970s as a cause for an upsurge in the interest in energy demand. The studies they review rely on surveys and utility data. No individual household demand and tariff data is available at the time.

Most of the reviewed studies focus on fuels, which are distinct from electricity due to their ease of storage. A predictable price change can result in a demand increase to build up stores, followed by a demand reduction during a period when stores are used in preference to higher wholesale prices. Fuels therefore exhibit high short-run price elasticity.

Of the studies that consider the price elasticity of electricity use, households can often not be disaggregated from commercial or industrial use. Industrial processes are known to be price sensitive and sometimes designed with interruptibility as part of the operational optimisation, such as Aluminium smelters that interrupt production during periods of high prices, or relocate when such periods are sustained.

Households have less scope to ‘suspend operations’ or to relocate to another country. Yet, it is established practice in energy models and policy discourse that even household energy demand is a function of price.

Espey & Espey (2004) estimate the short term elasticity of electricity demand to be -0.35 and -0.85 long term. Such figures are widely used in models and simulations of demand response and electricity system models (Bradley et al., 2013; Roscoe & Ault, 2010). Numerous studies state significant short term responses to price based demand response trials (Schofield et al., 2014; Torriti & Yunusov, 2020). However, Zhu et al. (2018) conclude after extensive meta analysis of international reviews that residential electricity demand is almost inelastic in the short term.

In addition to price based incentives, Buckley (2020) and Andor & Fels (2018) review non-price signals and nudges as an alternative signal for change. Importantly, they point out that small and short-lived studies tend to report greater effect sizes than larger and longer lasting studies.

In addition to the lack of longitudinal data and small sample sizes with detailed data, there is rarely an opportunity to test price responses in a randomised, yet controlled way. It is not possible (ethically and politically) to force a group of households onto higher prices, while a control group pays less. However, the UK regulator OfGEM has in effect provided somewhat controlled conditions, by raising and lowering the ‘price cap’ and the ‘energy price guarantee’ for UK energy users several times by significant amounts between 2021 and 2023.

2 Methods

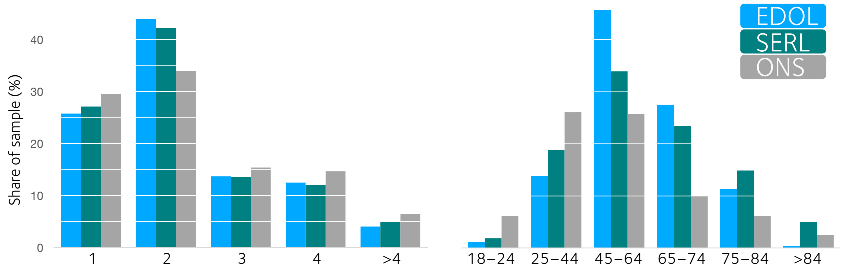
2.1 The sample

The Energy Demand Observatory and Laboratory (EDOL, 2023) seeks to establish a longitudinal and detailed energy data resource for the benefit of researchers, policymakers and the public. Alongside an observatory with n=2,000 UK households, smaller scale ‘laboratories’ seek to investigate specific technologies and policy relevant questions. Among these is the ‘cost of living lab’, for which survey information is combined with real-time energy and tariff data.

The EDOL cost of living lab sample consists of participants that were recruited with the help of a commercial partner. A proprietary online research panel of 100,000 members allowed for recruitment to be demographically, geographically and attitudinally representative of the Great Britain. To improve the representativeness of the sample for the GB population with a smart meter, quotas by gender, region and work status have been applied at the recruitment stage.

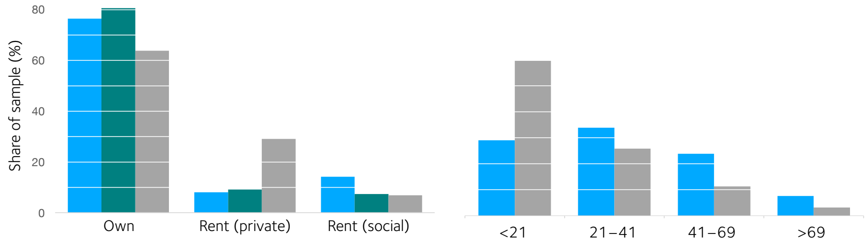
The panel is regularly subjected to online surveys, for which they get financially rewarded. For this survey the incentives is £2. The survey covers sociodemographic and energy-use relevant questions, including affordability of energy and ownership of a smart meter.

To grant access to their smart meter data, participants have to provide the 16 digit alphanumerical GUID number underneath their in-home-display, which came as part of their smart meter installation. The GUID is validated against their post-code and uniquely identifies their smart meter. If the GUID-post-code pair is valid, participants receive a follow-up email inviting them to take part in the study by agreeing to the terms and conditions to access and process their smart meter data (Hildebrand, 2022).



a) Number of household occupants

b) Age of respondent



d) Tenancy

d) Household income (£k)

Figure 1: Sample distribution comparing the EDOL lab with SERL (Webborn, 2020) and national census data (National Statistics, 2022)

For participating in the study, installing a Consumer Access Device (CAD) and sharing their data for research purposes, participants receive a total annual reward of £15 in 2022, increasing to £20 in 2023. The survey is completed by 248 respondents. Of these, 200 have a valid smart meter ID and 157 provided consent and valid data.

Attempts to ensure representativeness of the sample do not entirely guard against selection and other biases. The smart meter population in Great Britain at the time of recruitment (January-February 2022) is just below 50%, with private rented properties slightly under-represented. The panel itself is likely to be self-selecting in favour of people who are more disposed to online engagement and monetary rewards. Some key characteristics of the sample are compared to the larger SERL sample and national statistics in Figure 1.

The sample has a good representation of household sizes, an over-representation of the 45 to 75 age group, and fewer households in privately rented accommodation. The tenancy bias is consistent with the SERL sample and stems from the complication of gaining landlord consent for smart meter access. The bias towards higher incomes is consistent with the over-representation of the middle-age distribution.

2.2 The data

Survey information is collected at the recruitment stage (see above) and in annual follow-up surveys, where participants receive an email inviting them to update appliance stock, household composition and attitudinal questions.

Smart meter data is obtained via two routes. Half-hourly data is transmitted from the smart meter via mobile signal and accessed through the Data Communications Company (DCC). One minute data is transmitted from the smart meter via the Home Area Network (HAN) to the Consumer Access Device (CAD) which is connected via Ethernet to the home router and transmitted via the internet to the Glow Service. The Glow Service makes both DCC and CAD data available via secure APIs. The data flow is illustrated in Figure 2.

Smart meter data contains electricity and gas consumption and the cost of this energy at the time of use. Energy and survey data are linked via unique IDs. The data is stored in a secure database. The data is anonymised and aggregated to protect the identity of participants.

Data collection is ongoing. At the time of writing electricity consumption and tariff data is available for 157 households. Gas data is also available, but the data quality is less suitable for time resolved analysis, because periods without readings are sometimes followed by a single half hour with the accumulated consumption of the missing periods. This can distort the temporal attribution performed as part of the elasticity analysis.

2.3 Analysis

In 2021 the price cap ranged between £1,100 and £1,300. The main price cap increases occurred in April 2022, October 2022 and January 2023, when it peaked at £4,279. In April 2023 and July 2023 the cap was revised downwards to £2,074. The price cap at each review point is shown in Figure 3.

Demand in 2021 was still affected by COVID-19 interventions. These affect

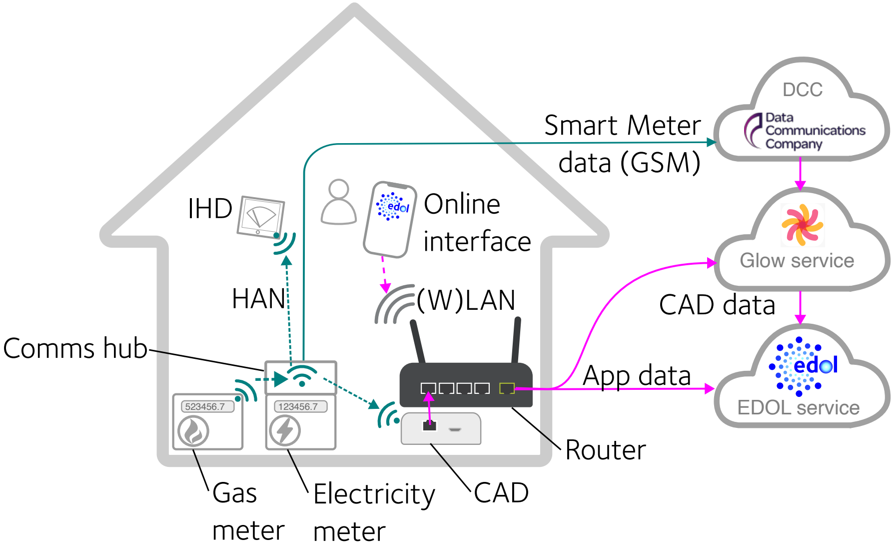


Figure 2: Data flow illustration. Smart Meter data is transmitted via GSM to the Data Communications Company, or via the internet to the GLOW service, which provides secure APIs for EDOL. User interfaces connect directly to EDOL services.

demand in ways that could distort this analysis. This period is therefore not used for price elasticity analysis. The analysis focusses on the period between January 2022 and July 2023. In particular, the periods January-July are used as like-for-like comparison. The data is not temperature corrected to account for degree-days. December 2022 was unusually cold, as is apparent from the spike in demand in Figure 3, and is not included in the comparison to reduce distortions. The relationship between temperature and electricity consumption is less direct than with gas. Some households, especially those on economy 7/10 tariffs, may use electricity for heating, such as night storage heaters. The share of households with heat pumps in the UK is still low, and they make up less than 2.5% of the sample. Even when excluding December, the winter 2023 was slightly colder than 2022, which could result is higher demand for electricity. Based on the assumption that temperature is not correlated to tariffs, this change in demand may change the offset, but not the slope of the elasticity calculations performed here.

All values presented are based on half-hourly readings of electricity consumption (measured in kWh) and the incurred cost, which is recorded as pence per period and converted to a rate (p/kWh) for that same period. When presenting data for one or more months, all half hour values are grouped and averaged by household first.

The relative changes in electricity consumption (E^*) are the difference in electricity use (kWh) and price (p/kWh) for the same time period in 2022 and 2023. These are normalised by dividing the difference by the sum:

$$E_t^* = \frac{E_{t,2023} - E_{t,2022}}{(E_{t,2023} + E_{t,2022})/2} \tag{1}$$

The same applies to for relative changes in price (P^*):

$$P_t^* = \frac{P_{t,2023} - P_{t,2022}}{(P_{t,2023} + P_{t,2022})/2} \tag{2}$$

The elasticity is the ratio of the two changes:

$$\epsilon = \frac{E^*}{P^*} \tag{3}$$

When elasticity values are negative, as would be expected for most goods, demand falls when prices rise. Positive values would mean that higher prices coincide with higher demand.

The standing charges or any other rebates and government payments, which were issued during this time, are not captured in this analysis.

3 Results

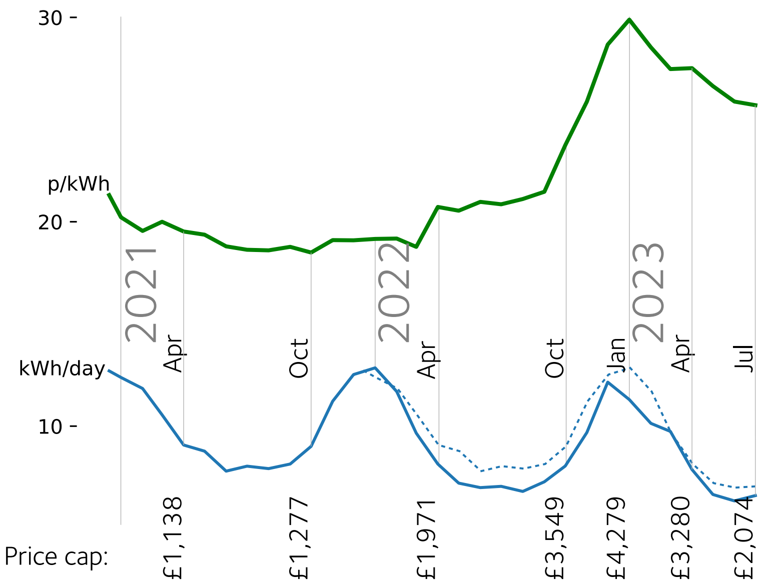


Figure 3: Demand and prices over time. Dotted line is a repeat of the previous year for reference.

Figure 3 shows the development of tariffs and electricity use, averaged across the entire sample, for the period spanning the OfGEM price cap rises. Variation in demand are dominated by seasonal effects. Electricity use after January 2022 is generally lower that in the previous year. This trend of falling electricity demand has been persistent for over two decades with an average reduction of 0.5% per annum (Barrett et al., 2023). It is therefore not self-evident that the lower demand is causally related to the higher tariffs.

Notably, December 2022 was exceptionally cold, and the high prices have not deterred demand to reach levels similar to those of the previous year.

To better understand some of the distributions within the data, Figure 4 shows how differently participants were affected by tariff changes, depending on their tariff type. Difference between Standard, Green and Other tariffs are slight, but Economy 7/10 customers exhibit high winter demand, often related to electric heating associated with these tariffs.

A more significant indicator for electricity demand are the income groups, as shown in Figure 5. The highest income group with a combined gross household

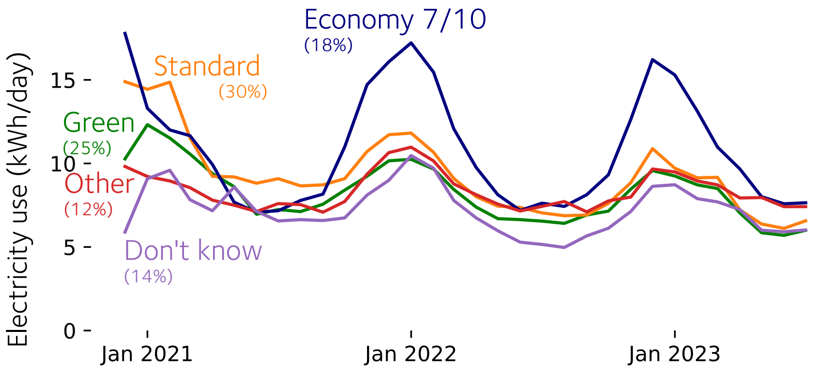


Figure 4: Seasonality of electricity demand by tariff type. Economy 7/10 customers are particularly exposed during the heating seasons.

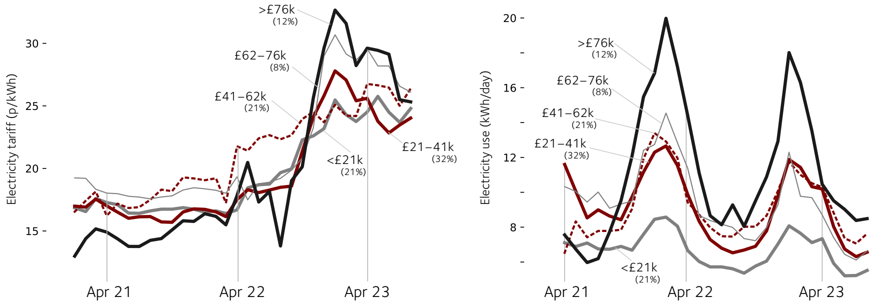


Figure 5: Electricity cost (left) and use (right) by income group during the period of price cap changes.

income of over £76k (12% of the sample), experienced the greatest change in cost per kWh. Prior to the Electricity Price guarantee, this group had the lowest electricity prices, whereas by January 2023, they experience the highest costs.

This group uses more than twice as much electricity as the lowest income group (21% of the sample) as shown on the right in Figure 5. The difference is slightly reduced after the tariff increased in 2022, but remains significant.

3.1 Elasticity of electricity demand

With the highly resolved longitudinal data for each household, it is possible to establish how each of them responds to changes in price.

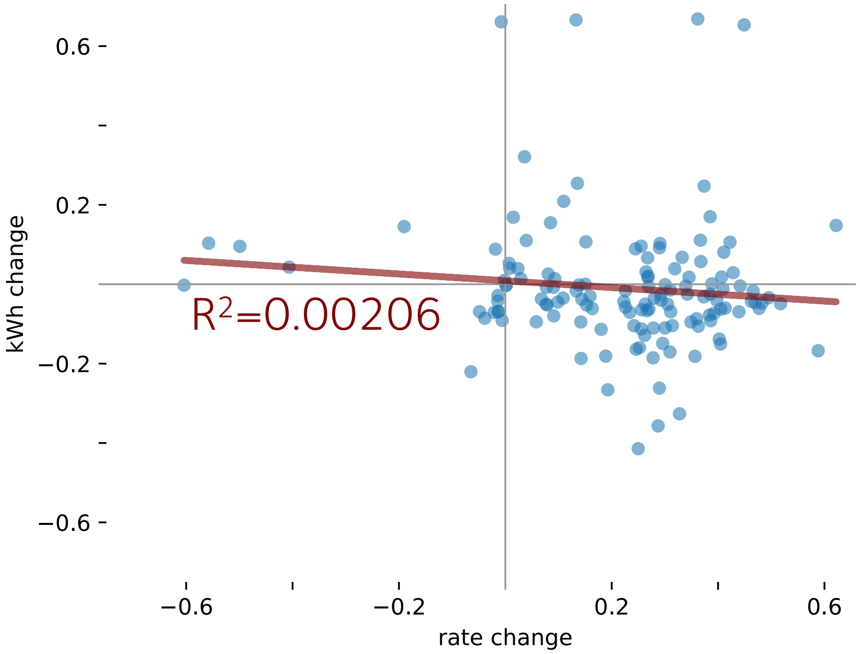


Figure 6: Comparing households in January 2022 with January 2023. Price elasticity is negative, but the correlation is weak. (n=147 households)

The scatter-plot in Figure 6 relates the relative changes in the tariff for electricity with the relative change in energy use between January 2022 and January 2023. Each data point represents one household. The majority of households are in the bottom right quadrant, meaning that their tariff increased, and average demand reduced (as seen in Figure 3). The linear regression fit has a negative slope, as would be expected for elastic prices. However, the correlation is weak with an R^2 of only 0.002.

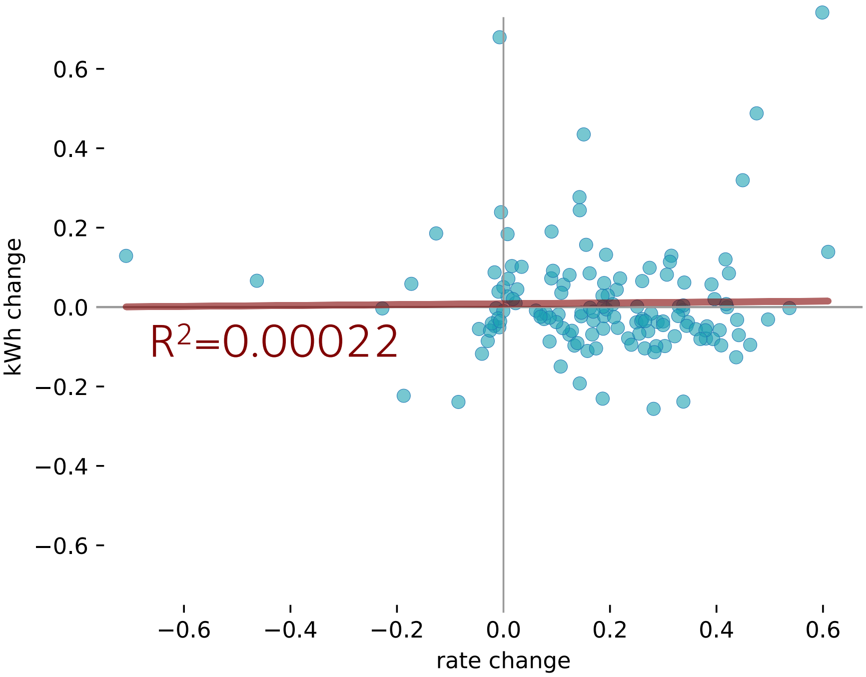


Figure 7: No negative price elasticity. Household level comparison between January–July in 2022 and 2023. Demand reductions are not correlated to tariff increases. (n=147 households)

For a more robust assessment of the relationship between cost and demand, Figure 7 expands the period of interest to span January to July (inclusive). This window also captures the second major price increase in April 2023.

Contrary to expectations, the correlation between price and demand is positive, meaning that demand has not reduced in any significant way in relation to price. The correlation neither significant, nor negative.

This finding raises serious questions over the notion of price elastic demand. Possible explanations for this unexpected finding will be put forward in the Discussion Section.

Figure 8: Comparison of each household and each day between January and July in 2022 and 2023. The positive slope remains and the relationship between price and demand is not statistically significant.

To validate the previous findings, Figure 8 shows the same analysis, but for each individual day and each household between January and July. Despite the larger number of data, the slope remains positive and the R^2 is still low at 0.017.

3.2 Income sensitivity

If demand does not respond to price across the whole population, does it affect different income groups differently? Figure 5 suggests that income groups were

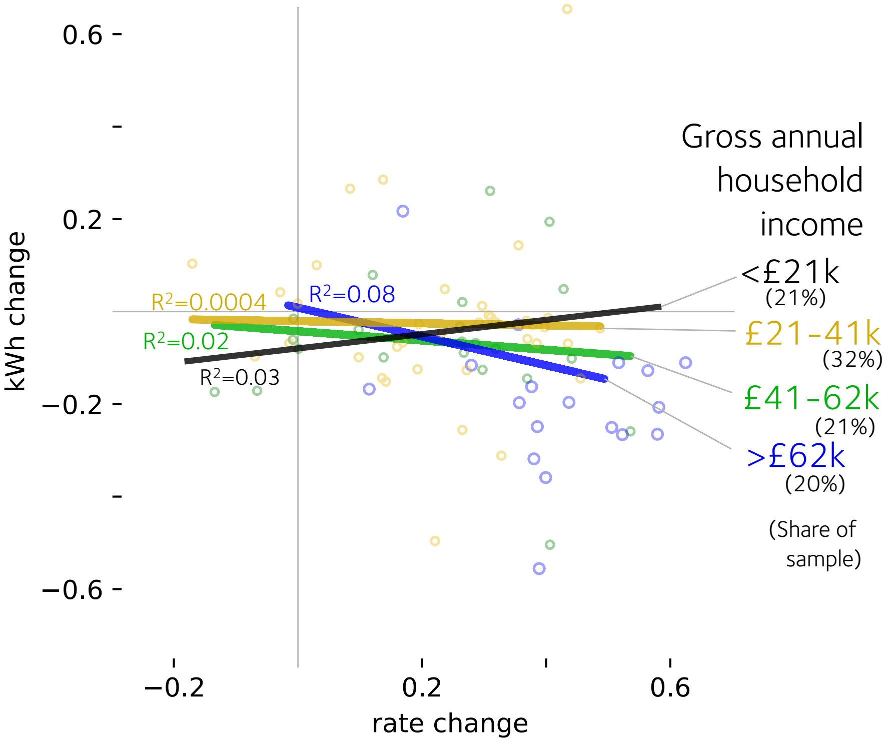


Figure 9: Elasticity varies by income, with the most affluent able to reduce the most

affected and responded differently. The figures for January 2022 and 2023 are summarised in Table 1.

Table 1: Relative electricity demand reduction and tariff increases between January 2022 and 2023 by household income band

Income [£k]	Demand [-%]	Tariff [%]
<21	5.7	21.4
21–4	1 5.0	24.9
41–6	2 8.0	13.8
62–7	6 19.6	l 25.1
>76	10.1	33.2

The top two income groups reduced demand the most, while also experiencing the greatest relative increases to their tariffs. The lowest income group reduced demand the least.

Figure 9 confirms this trend. The top two income groups have been combined, such that each group represents at least 20% of the sample. The lower the income, the less demand reduces with higher prices.

Households with incomes above £41k per year appear to be able to reduce demand in response to higher prices, those below £21k are not.

4 Discussion

The findings resulting from the past two years of unprecedented and nationally coordinated changes to electricity prices challenge a fundamental assumption in energy economics: when prices go up, demand goes down. Numerous explanations are available for potential market failures or ‘economically irrational behaviour’ of this kind. These are reviewed and discussed here.

Lack of information

It is often argued that market failures, such as this, are the result of a lack of information. It is generally true that feedback about energy use and cost is poor. Even with in-home-displays and online portals to track energy use and tariffs, few people are aware of the direct relationship between their appliance use and the cost implications.

For the period in question, public awareness of the changes in energy costs is high. The price cap rises received public and social media attention and featured in high level political debates at the time. The communication was potentially confusing by referring to a ‘cap on bills’ and ‘typical households’, whereas the cap applied to the standing charge and the rate per kWh of electricity used. Some may have misinterpreted the message as creating an upper ceiling on their bills.

It is difficult to argue that households were ‘uninformed’ about the general increases in cost of electricity.

Lack of agency

If energy were considered to be a commodity, rather than a basic service requirement, then a price rise would result in a reduction or a substitution in its consumption. The options to shift and displace energy use have been elaborated by Grunewald & Diakonova (2018a). Since both gas and electricity prices rose at the same time, ‘fuel shifting’ was not an option for many and most households do not possess appliances that would facilitate such substitutions in any case.

In the lowest income groups, electricity consumption may already have been constrained by cost, prior to the price rises. Many fundamental energy services can therefore not be reduced further, regardless of price.

Means to respond

More affluent households have a broader set of options to guard against price rises. Self-generation, such as PV, or more efficient appliances, require disposable income or access to finance that during a cost-of-living crisis and with rising interest rates is less available to households on lower incomes.

Progressive support

Some households received additional Government support measures during the cost-of-living crisis. It is therefore conceivable that lower income households were more shielded from changes to the cost of energy. However, the principle mechanisms were deliberately chosen not to be progressive. The price-cap applied to all homes in the same way. High users, who are often also from high income groups, stand to save the most money in absolute terms.

The Energy Bills Support Scheme did not distinguish by need for support either. This was argued to allow for the scheme to be implemented faster and for struggling households to receive their payments faster. In practice, many households on prepayment meters may have missed out on the support they were eligible for, due to the complication of having to claim vouchers. The data available for this study does not discriminate prepayment meters, but they tend to be more common among lower income households.

Giffen-good effect

For financially constrained households, the increase in energy prices, which form a significant part of their household budget, results in a further reduction in disposable income. In such circumstances energy may exhibit Giffen-good characteristics.

A classic example of a Giffen-good is bread. If the price of bread rises, then the poorest households may not be able to afford meat and vegetables and have to substitute their diet with more bread. The price rise results in an increase in demand.

Analogously, when energy prices rise and disposable income falls, activities, such as eating out, will be reduced. Consequently, more time and energy is expended inside the home to prepare food, resulting in higher energy demands. The exact nature of these dynamics is beyond the scope of this study, but the diary instrumentation developed by Grunewald & Diakonova (2018b) could shine more light on price dynamics in low-income and fuel-poor households.

The trends found in this study are particularly problematic, because the lowest income groups are under-represented in this and many other samples. If lower incomes were better represented the finding are likely to exhibit even stronger challenges to the notion of uniformly negative price elasticity. The results shown here have not been re-weighted to compensate for selection bias.

5 Conclusions

Energy use is weakly correlated to price. This finding contradicts a well established assumption at the heart of many energy market models, which use price elasticity as a fundamental principle for the interaction between energy users and their suppliers.

The substantial, synchronised and system-wide changes to electricity tariffs in 2022 and 2023 have shown that price is a poor predictor for responses of UK households in this sample. Overall demand has fallen during this period, as it has done for the preceding decades. However, the demand reduction is not notably correlated to the tariffs these households were exposed to over this period.

Lower income households in this sample are less able to reduce demand in response to higher prices. It is possible that this is the result of already constrained energy services and the lack of options to substitute or displace energy use. They may furthermore exhibit Giffen-good dynamics in relation to energy, where reduced disposable income results in higher energy demand due to forced substitution and higher home occupancy. Further research with larger samples and more explanatory variables, such as occupancy, in-home temperatures and activity patterns could test these dynamics. Despite the academic value in observing changes to energy prices, it is hoped that similar price rises do not repeat and that other ways can be found to test price elasticity of energy demand. The EDOL programme intends to support such research.

6 Acknowledgements

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References

Andor, M. A., & Fels, K. M. (2018). Behavioral economics and energy conservation – a systematic review of non-price interventions and their causal effects. *Ecological Economics*, *148*, 178–210. https://doi.org/10.1016/j.ecolecon.2018.01.018

Barrett, J., Betts-Davies, S., Garvey, A., & Marsden, G. (2023). *The missed opportunity – ignoring the evidence on energy demand reduction.* [Technical report]. Centre for Research into Energy Demand Solutions. https://www.creds.ac.uk/publications/the-missed-opportunity-ignoring-the-evidence-on-energy-demand-reduction

Bell, T., Brewer, M., Broome, M., Cominetti, N., Corlett, A., Fry, E., Hale, S., Handscomb, K., Leslie, J., Marshall, J., McCurdy, C., Shah, K., Smith, J., Thwaites, G., & Try, L. (2022). *Help today, squeeze tomorrow - putting the 2022 autumn statement in context* [Technical report]. Resolution Foundation. https://www.resolutionfoundation.org/publications/help-today-squeeze-tomorrow

Bohi, D. R., & Zimmerman, M. B. (1984). An update on econometric studies of energy demand behavior. *Annual Review of Energy*, *9*(1), 105–154.

Bolton, P., & Stewart, I. (2023). *Domestic energy prices* [Technical report]. House of Commons Library. https://commonslibrary.parliament.uk/research-briefings/cbp-9491/

Bradley, P., Leach, M., & Torriti, J. (2013). A review of the costs and benefits of demand response for electricity in the UK. *Energy Policy*, *52*(0), 312–327.

Buckley, P. (2020). Prices, information and nudges for residential electricity conservation: A meta-analysis. *Ecological Economics*, *172*, 106635. https://doi.org/10.1016/j.ecolecon.2020.106635

DESNZ. (2023). *Final push to get remaining £130 million in support to prepayment meter customers* [News report]. Department for Energy Security; Net Zero. https://www.gov.uk/government/news/claim-your-energy-voucher-day-launches-final-push-to-get-remaining-130-million-in-support-to-prepayment-meter-customers

EDOL. (2023). *Energy demand observatory and laboratory (EDOL)* [EPSRC Programme EP/X00967X/1]. University College London; University of Oxford. https://edol.uk

Espey, J. A., & Espey, M. (2004). Turning on the lights: A meta-analysis of residential electricity demand elasticities. *Journal of Agricultural and Applied Economics*, *36*(1), 65–81.

Grunewald, P., & Diakonova, M. (2018a). Flexibility, dynamism and diversity in energy supply and demand: A critical review. *Energy Research & Social Science*, *38*, 58–66. https://doi.org/10.1016/j.erss.2018.01.014

Grunewald, P., & Diakonova, M. (2018b). The electricity footprint of household activities – implications for demand models. *Energy and Buildings*, *174*, 635–641. https://doi.org/10.1016/j.enbuild.2018.06.034

Hildebrand. (2022). *Terms and conditions for use of glow service* [Online]. EDOL JoyMeter App. https://joymeter.uk/22_01_TC_Glow.html

Labandeira, X., Labeaga, J. M., & López-Otero, X. (2017). A meta-analysis on the price elasticity of energy demand. *Energy Policy*, *102*, 549–568. https://doi.org/10.1016/j.enpol.2017.01.002

National Statistics, O. for. (2022). *UK population - demographics* [Online - accessed June 2022]. ONS. https://www.ethnicity-facts-figures.service.gov.uk/uk-population-by-ethnicity

Roscoe, A. J., & Ault, G. (2010). Supporting high penetrations of renewable generation via implementation of real-time electricity pricing and demand response. *Renewable Power Generation, IET*, *4*(4), 369–382.

Schofield, J., Carmichael, R., Tindemans, S., Woolf, M., Bilton, M., & Strbac, G. (2014). *Residential consumer responsiveness to time-varying pricing* [Report A3 for the "Low Carbon London'' LCNF project]. Imperial College London.

Taylor, L. D. (1975). The demand for electricity: A survey. *The Bell Journal of Economics*, *6*(1), 74–110. http://www.jstor.org/stable/3003216

Torriti, J., & Yunusov, T. (2020). It's only a matter of time: Flexibility, activities and time of use tariffs in the United Kingdom. *Energy Research & Social Science*, *69*, 101697. https://doi.org/10.1016/j.erss.2020.101697

Webborn, E. (2020). *Survey data: Summary of responses* [Report]. Smart Energy Research Lab. https://serl.ac.uk/

Zhu, X., Li, L., Zhou, K., Zhang, X., & Yang, S. (2018). A meta-analysis on the price elasticity and income elasticity of residential electricity demand. *Journal of Cleaner Production*, *201*, 169–177. https://doi.org/10.1016/j.jclepro.2018.08.027