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HEDGING HOUSEHOLDS AGAINST EXTREME ELECTRICITY PRICES

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Hedging households against extreme electricity prices*

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Abstract

Dynamic electricity prices expose households to the risk of extremely high electricity bills during scarcity events. To protect households from high scarcity prices, I explore how to combine dynamic electricity prices with forward hedging. I derive household-specific optimal forward hedge shares by applying a utility maximization model to 2,159 UK households exposed to dynamic prices. The average optimal hedge share is 59% of households' baseline consumption. Hedge shares are higher for electric heating and electric vehicle owners and lower for solar PV and battery storage owners. My key theoretical finding is that an increase in households price elasticity of demand raises optimal hedge shares if households face positive correlation between electricity prices and their weather-related desire to consume electricity. Forward hedging effectively reduces electricity bill volatility by 18% for price-inelastic households. When exposing households to scarcity events, hedging achieves sizable welfare gains equivalent to 19% reduction in average electricity prices.

JEL Codes – Q41, D11, G50

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1 Introduction

Many economists emphasize the benefits of exposing households to dynamic electricity prices. Dynamic prices are linked to day-ahead electricity prices and fluctuate on a short-term basis, e.g., every half hour. They incentivize households to reduce consumption during periods of high aggregate demand or scarce electricity supply. Thereby, dynamic prices help mitigate demand peaks and improve the integration of intermittent renewable generation into the energy system. This makes electricity markets more efficient (Houthakker (1951), Borenstein (2005), Borenstein and Holland (2005), Allcott (2011)).[1]

A drawback of dynamic pricing is that it makes consumers vulnerable to extremely high prices when electricity is scarce. When power demand exceeds supply, regulators set high scarcity prices for electricity in many power markets (Cramton, 2017).[2] For example, during the winter storm in Texas in February 2021, a scarcity price of 9$/kWh was enforced for more than 64 hours over multiple days in response to a severe electricity shortage (ERCOT, 2022). As a result, the small minority of households exposed to dynamic prices received electricity bills exceeding $100 per day (EIA, 2022). These extremely high bills sparked a public debate about whether dynamic pricing is suitable for households (McDonnel et al., 2021).

To address these concerns, economists proposed to complement dynamic price tariffs with a forward hedge (Borenstein (2007), Wolak and Hardman (2022), Winzer et al. (2023), Schlecht et al. (2023)). The objective of the forward hedge is to protect households from high electricity prices while preserving incentives to reduce demand when needed most, namely during scarcity events (Bobbio et al., 2022b). The German government recently introduced subsidized forward contracts known as gas and electricity price brakes to reduce consumers' exposure to soaring energy prices while incentivizing them to save scarce energy (Dertwinkel-Kalt & Wey, 2023).

To illustrate how a forward hedge works, consider a household with a typical daily consumption of 20 kWh. The household is offered to buy 100% of its typical consumption forward at a price of 0.2$/kWh. It pays 4$ (=20kWh*0.2$/kWh) per day for this hedge. During a Texas-style scarcity event, when the electricity price is 9$/kWh all day, the household pays the scarcity price only for the deviation of its realized consumption from the hedged quantity of 20 kWh. If the realized consumption is 20kWh, the household only

[1]Borenstein and Holland (2005) find that wide adoption of dynamic prices would lead to substantial efficiency gains in the long run, reducing consumers' total electricity bill by 3-11% in California. In the short run, Holland and Mansur (2006) obtain only small welfare gains for consumers that translate to a 0.24-2.5% reduction in total electricity bills. Holland and Mansur (2006) also reveal that dynamic prices reduce the volatility of wholesale electricity prices and load.

[2]The objective of scarcity prices is to induce all available power plants to operate at maximum level and to provide incentives for investments in additional generation capacity (Cramton, 2017).

pays 4$ for the hedge and is fully protected from the high scarcity price.

If the household reduces its consumption below the hedged quantity, e.g., to 15 kWh, it is remunerated for the negative deviation of 5 kWh at the scarcity price. This results in a daily bill of $-41\$$ ($= 4\$ + (-5\text{kWh}) * 9\$/\text{kWh}$). The hedge rewards households for doing what is socially desirable: reducing consumption when electricity is scarce. Conversely, if the household consumes more than 20 kWh, say 25kWh, the positive deviation of 5kWh leads to a high daily bill of 49$ ($=4\$ + 5\ \text{kWh} * 9\$/\text{kWh}$). This high bill creates a strong incentive to reduce consumption during scarcity. At the same time, the hedge protects the household from the far higher 225$ bill it would face without the hedge. Moreover, the household can choose to hedge more than 100% of its typical consumption to be better protected against high prices (Bobbio et al., 2022b).

In this paper, I calculate household-specific *optimal hedge shares*, i.e., the optimal share of typical consumption that a household should buy forward. I simulate these optimal shares for a dataset of 2,159 UK households that received half-hourly dynamic prices but no forward hedge.

A hedge share is defined as *optimal* if it maximizes households' expected utility. Optimal hedge shares may vary by time of day to account for intraday load patterns. I study how optimal hedge shares are influenced by households' price elasticity of demand, risk aversion, and ownership of technologies like electric heating and vehicles, and battery storage. To estimate welfare gains, I calculate the price premia households should be willing to pay for being optimally hedged.

To derive the optimal hedge shares, I solve a two-stage utility maximization model via backward induction. In the second stage, households do not face any uncertainty. They maximize their utility from electricity consumption and aggregate consumption of other goods. I assume a constant-elasticity-of-substitution utility function and exogeneously choose households' elasticity of substitution and their coefficient of relative risk aversion. Moreover, I suppose that each household spends, on average, 2% of its income on electricity since I observe household expenditure only for electricity and not for other goods. This assumption is consistent with electricity's average expenditure share in the UK (UK ONS, 2021).

In the first stage of the model, households choose optimal hedge shares subject to stochastic electricity prices and quantity shocks. Quantity shocks capture all factors except prices that impact agents' desire to consume electricity. For instance, the weather or a national holiday influence households' desire to consume. The model allows deriving the unobservable quantity shocks as a residual of households' observable unhedged electricity demand.

My main contribution is to examine the interaction between price elasticity of demand and optimal hedging when agents face two volatile factors: Prices and quantity shocks.

Previous literature analyzed how price elasticity affects optimal hedge shares when prices are the unique volatile factor (Moschini and Lapan (1992), Dionne and Santugini (2015)). They argue that optimal hedge shares decline if agents' price elasticity increases. Price-elastic agents are less vulnerable to high prices because they can reduce demand when prices are high. Hence, price-elastic agents need to hedge less when prices are the unique volatile factor.

However, electricity consumers also face volatile quantity shocks. Their desire to consume electricity depends heavily on external shocks like extreme weather. Only a few authors consider how quantity shocks influence hedge shares (Losq (1982), Cowan (2004)). They find that optimal hedge shares increase if prices and quantity shocks are positively correlated.

My key result is that this correlation also determines how an increase in price elasticity affects hedge shares. When prices and quantity shocks are positively correlated, an increase in price elasticity raises hedge shares. Assume price elasticity increases for a household with electric heating. During a winter storm, the increased price elasticity induces this household to reduce consumption more strongly in response to high scarcity prices. However, reducing consumption during a winter storm causes large disutility for an electric heating owner since she needs electricity to heat her home. As a response, the more price-elastic electric heating owner increases her hedge share to reduce her exposure to spot prices. Lower spot price exposure allows her to maintain an acceptable level of consumption even during a winter storm when both prices and her desire to consume electricity are extremely high.

In contrast, when prices and quantity shocks are negatively correlated, an increase in price elasticity decreases hedge shares. In this case, responding more strongly to high prices causes small disutility because households desire to consume is low when prices are high. Hence, increasing price-elasticity makes households less vulnerable to high prices since they respond by reducing consumption without suffering large disutility. Therefore, they need to hedge less.

From these theoretical observations, I calculate optimal hedge shares for each household in my sample. The average optimal hedge share is 59% of households' typical consumption. Optimal hedge shares differ widely both between customers and for a specific customer by time of day. Ownership of low-carbon technologies partly explains the heterogeneity in hedge shares. Electric heating or electric vehicle owners have high average hedge shares of 77% and 69%, respectively. These technologies likely increase the positive correlation between prices and quantity shocks. On the other hand, solar PV owners hedge on average only 22% of their typical consumption, indicating that their electricity consumption from the grid is negatively correlated with prices. Battery storage ownership is also associated with a slightly lower mean hedge share of 52%.

An exogeneous increase in price elasticity of demand further amplifies the dispersion in hedge shares. Some households respond to higher price elasticity by reducing their hedge shares to exploit the negative correlation between prices and quantity shocks. Other households with a positive correlation increase hedge shares. On average, optimal hedge shares decline when price elasticity rises. In contrast, increasing risk aversion has a positive effect on hedge shares. This positive effect rapidly diminishes with the level of risk aversion.

The optimal hedge is effective in reducing the volatility of monthly electricity bills. In my main specification, the optimally hedged tariff reduces households' coefficient of variation of monthly bills, on average, by 18% compared to an unhedged tariff. Hedging is particularly effective for households with large average hedge shares beyond 100% of their typical consumption. For these households, the hedge reduces their coefficient of bill volatility by 45%. Such households even experience lower bill volatility when optimally hedged than under a fixed-price tariff. The fixed tariff protects households only from price volatility, while the optimally hedged tariff protects from volatility in both prices and consumption (Borenstein, 2007).

An increase in price elasticity makes the optimal hedge less effective in reducing bill volatility. Price-elastic households consume more when prices are high on the optimally hedged tariff than on the unhedged tariff because the hedge weakens households' exposure to spot prices and lowers their price-response. Consuming more when prices are high raises bill volatility. When assuming high price-elasticity, some households even face higher bill volatility on the optimally hedged tariff than on the unhedged one.

Similarly, if households become more risk-averse, the optimally hedged tariff achieves smaller reductions in bill volatility compared to the unhedged tariff. High risk aversion induces households to choose higher hedge shares and thereby lowers households' exposure to spot prices. As explained above, low spot price exposure can increase bill volatility for price-elastic households.

Optimal forward hedging results in tiny welfare gains for households during my sample period. Augmenting a dynamic tariff with a forward hedge leads to a welfare gain compared to an unhedged dynamic tariff that translates, on average, to a 0.3% reduction in mean electricity prices. In contrast, dynamic pricing itself achieves more significant average welfare gains equivalent to a 0.8-4% reduction in mean electricity prices.

The welfare gain from hedging increases to a more substantial 19% reduction in mean electricity prices when simulating a scarcity event like the Texas winter storm. Hedging is more valuable to consumers if they face worst-case events with extremely high prices. I simulate such a scarcity event by artificially exposing households' to extremely high electricity prices over multiple days.

The small welfare gain from hedging without scarcity events can be partly explained by electricity's small share in household expenditure. UK households spend only 2% of their income on electricity (UK ONS, 2021). Electricity's expenditure share will likely increase substantially in the upcoming decades due to electrification of mobility and heating. Therefore, the relevance of hedging electricity prices might increase. However, for the given sample, the average simulated welfare gain from hedging only increases to 1.6% even when assuming that households spend a much larger income share of 10% on electricity.

My paper presents a partial equilibrium analysis. Households' hedging decisions do not affect electricity prices. In general equilibrium where all consumers are on dynamic and optimally hedged tariffs, the welfare effects of hedging are likely lower. Dynamic pricing mitigates price peaks and, thereby, reduces price volatility. When price volatility is lower, hedging creates smaller welfare benefits.

I structure my paper as follows: Section 2 relates this paper to the optimal hedge literature. Section 3 describes a utility maximization model to derive optimal hedge shares and price premia for the optimal forward hedge. In section 4, I parameterize the model to simulate optimal hedge shares for real-world domestic consumers. Section 5 presents the data set, and section 6 discusses the simulation results. Section 7 concludes.

2 Literature review

This paper contributes to the literature on optimal forward hedge shares. Danthine (1978), Holthausen (1979), and Feder et al. (1980) identify optimal hedge shares and production decisions for price-inelastic firms when selling prices are uncertain. Their main insight is the "separation result": Production decisions only depend on the forward price and not on risk attitudes. In contrast, hedge shares depend on risk attitudes and expectations about future prices. Moreover, they find that price-inelastic firms should hedge 100% of their production when forward hedge prices equal expected spot prices.

McKinnon (1967), Rolfo (1980), Losq (1982), and Lapan and Moschini (1994) derive optimal hedge shares for firms in industries like agriculture where both prices and production are uncertain. McKinnon (1967) highlights that a positive correlation between prices and production is a major motive for firms to increase hedge shares beyond 100%.

The literature also explores how optimal hedge shares change when alternative risk management tools are available. For example, if firms are price-elastic, their optimal hedge share is lower since they can flexibly adjust their production after price uncertainty resolves (Moschini and Lapan (1992), Dionne and Santugini (2015)). Similarly, storage and buffer stocks provide flexibility and reduce the need for high hedge shares (McKinnon (1967), Newbery and Stiglitz (1981), Gemmill (1985), Gilbert (1985)). In the context of this paper, battery storage will likely gain importance as a risk management tool for electricity consumers.

Moreover, multiple authors derive optimal hedge shares when firms combine forward contracts with alternative derivatives like options (Moschini and Lapan (1992), Brown and Toft (2002), Gay et al. (2002), Mnasri et al. (2017)). They argue that when the uncertainty concerning quantity is high, forward contracts are less effective than options to protect firms from profit fluctuations. The key difference is that forward contracts have a linear payoff structure, while options have a nonlinear one. When both prices and quantities are uncertain, firms' profits are nonlinear in prices. Therefore, nonlinear options provide better risk protection (Moschini and Lapan (1992), Sakong et al. (1993)). Brown and Toft (2002) customize the optimal payoff structure for a value-maximizing firm using a portfolio of forward contracts and exotic nonlinear derivatives.

Studies on hedging for small retail consumers are rare since they typically do not have access to forward markets (Newbery, 1989). Various researchers examine hedge decisions for large consumers like load-serving entities in electricity markets. Load-serving entities buy electricity on wholesale markets with volatile prices and sell it to retail consumers at fixed rates. They face high price and demand uncertainty caused by unique characteristics of electricity. Electricity demand fluctuates and is mostly price-inelastic. Large-scale storage is often unavailable or expensive. Moreover, electricity prices and demand are positively correlated as they both depend on weather conditions. Oum and Oren (2010), Zhou et al. (2017), and Azevedo et al. (2007) characterize the optimal hedge position for load-serving entities. They stress the importance of augmenting forward contracts with nonlinear options, given the large quantity uncertainty that load-serving entities face.

Antother tool that load-serving entities can use to mitigate risk are time-varying tariffs like time-of-use, critical peak pricing, peak time rebate, or dynamic tariffs (Faruqui, 2012). Time-varying tariffs reduce risk for load-serving entities as they mitigate the positive correlation between wholesale prices and demand (Zhou et al., 2017). They do so by charging end customers higher prices when wholesale prices are (expected to be) high. Numerous studies reveal that end customers lower their electricity consumption in response to high short-term prices. In a literature survey of 36 studies, Espey and Espey (2004) report an average short-term price elasticity of electricity demand of -0.35.

On the other hand, time-varying tariffs increase the risk exposure for retail consumers, especially on fully dynamic tariffs (Borenstein (2007), Faruqui (2012)). Many economists acknowledge the need to augment dynamic tariffs with risk management tools like price caps or collars[3], forward contracts, or options (Barbose et al., 2004). Caps and collars are suitable for protecting customers from high price spikes. However, caps are typically too

[3]Price collars allow the electricity price for retail consumers to vary, but it cannot be higher than a specified price cap or lower than a price floor (Goldman et al., 2004).

low to incentivize customers to lower consumption sufficiently during scarcity events (Bobbio et al., 2022b). Nonlinear derivatives like options are arguably too complex, especially for households and small business consumers. Therefore, multiple researchers propose forward contracts as an appropriate hedging tool for consumers (Borenstein (2007), Wolak and Hardman (2022), Bobbio et al. (2022b), Schlecht et al. (2023)).

Since the 1990s, several US utilities have offered commercial customers dynamic tariffs with a forward hedge, known as two-part tariffs (Braithwait and Eakin (2002), Barbose et al. (2005)). While most utilities let customers only buy exactly 100% of their typical consumption forward, some utilities allow them to choose a different hedge share (O'Sheasy (1998), Stavrogiannis (2010)). In this paper, I compare the effectiveness of a simple 100% hedge tariff used by most utilities to a tariff with an optimal forward hedge.

My paper is closest to Borenstein (2007), Stavrogiannis (2010), and Winzer et al. (2023). They do not derive optimal hedge shares but simulate how effective various arbitrary hedge shares are to reduce the volatility of electricity bills. For household samples, Stavrogiannis (2010) and Winzer et al. (2023) find that a tariff with a 100% forward hedge effectively reduces bill volatility compared to an unhedged dynamic tariff. For a sample of large industrial consumers in California, Borenstein (2007) reveals that 77% of consumers can reduce their bill volatility even further by choosing a hedge share above 100%. Such consumers face a strong positive correlation between consumption and prices. These findings suggest that a simple 100% hedge might only be optimal for few consumers.

My paper differs from Borenstein (2007) and Stavrogiannis (2010) as they assume consumers to be risk-neutral and price-inelastic. They suppose consumers do not change their consumption when transferred to a dynamic tariff with a forward hedge. In contrast, I study the interaction between price elasticity and hedging. Specifically, I simulate how households adjust their consumption in response to being optimally hedged.

I build on models by Gilbert (1985) and Cowan (2004) to simulate optimal forward hedge shares with quantity shocks. Cowan (2004) derives optimal hedge shares for price-elastic and risk-averse electricity consumers facing quantity shocks. Hedge shares increase in consumers' coefficient of relative price risk aversion and the correlation between price and quantity shocks. Hedge shares decline in consumers' income elasticity of demand. I extend Cowan's (2004) analysis by examining the effect of an exogenous increase in price elasticity on hedge shares. I also study how the ownership of technologies like electric heating and battery storage affects hedging decisions.

Apart from the literature on optimal hedge shares, I also contribute to the literature that studies how price stabilization and hedging influence consumer welfare (Waugh (1944), Turnovsky et al. (1980), Newbery and Stiglitz (1981), Gilbert (1985), Cowan (2004)). These authors emphasize that dynamic prices can increase welfare compared to stabilized prices, even for risk-averse consumers, if they are sufficiently price-elastic. Cowan (2004) reveals that optimal forward hedging always positively impacts consumer welfare under pure price volatility. I extend his analysis by showing that the positive welfare effect of hedging declines the more negatively prices and quantity shocks correlate.

3 Model

3.1 Optimal hedge shares

Below, I employ a two-stage model based on Gilbert (1985) and Cowan (2004). It allows for deriving optimal hedge shares via backward induction, starting with the second stage.

Second stage: Households choose between electricity consumption x and aggregate consumption of other goods y to maximize the indirect utility function V:

$$V(p,b,\varepsilon,f,h) = \max_{x,y}\{U(x,y,\varepsilon)|xp+y \leq b+(p-f)h^*\} \tag{1}$$

Household utility depends on quantity shock ε. The quantity shock captures all factors except prices that impact households' desire to consume electricity, such as weather, national holidays, or a national sports event on TV. Households choose the optimal consumption bundle subject to their income b,[4] dynamic electricity price $p > 0$, forward hedge price f, and the optimal hedge quantity h^* that was chosen in stage 1. Prices for y are normalized to 1. The indirect utility function V is assumed to be concave in budget b with $V_b > 0$ and $V_{bb} < 0$ being its first and second derivatives with respect to b.

There is no uncertainty in the second stage. Households observe electricity prices and quantity shocks.

First stage: Households choose the optimal hedge quantity h^* that maximizes their expected utility given stochastic electricity prices $\tilde{p}$ and quantity shocks $\tilde{\varepsilon}$.

$$h^* = \arg\max_h E[V(\tilde{p},b,\tilde{\varepsilon},f,h)] \tag{2}$$

Following McKinnon (1967) and Lapan and Moschini (1994), prices and quantity shocks can be correlated and are described via a bivariate normal distribution. Lapan and Moschini (1994) find that optimal hedge shares are robust to assumptions on utility functions and distributions of stochastic elements. For risk-averse profit-maximizing firms,

[4] The budget constraint with a forward hedge can be formulated in two equivalent ways: The first formulation is $fh+(x-h)p+y \leq b$. This formulation states that the household pays fh for the forward hedge and the dynamic price p only for the deviation of its consumption x from the hedge quantity h. Rearranging the first formulation leads to the second equivalent formulation $xp+y \leq b+(p-f)h$ as given in equation (1) (Braithwait & Eakin, 2002).

they derive similar hedge shares when comparing utility functions with constant absolute risk aversion and constant relative risk aversion, respectively, both under normal and lognormal distributions of prices and stochastic production.

Assuming an interior solution, the first-order condition of equation (2) is given by[5]

$$E[V_b(\tilde{p}-f)] = 0 \tag{3}$$

Letting $\overline{p} = E[\tilde{p}]$ and $\overline{\varepsilon} = E[\tilde{\varepsilon}]$ represent expectations of prices and quantity shocks, a first-order Taylor approximation of V_b about $(\overline{p}, \overline{\varepsilon})$ yields

$$V_b \approx \overline{V}_b + \overline{V}_{b\tilde{p}}(\tilde{p}-\overline{p}) + \overline{V}_{bb}h(\tilde{p}-\overline{p}) + \overline{V}_{b\tilde{\varepsilon}}(\tilde{\varepsilon}-\overline{\varepsilon}). \tag{4}$$

$\overline{V}_b = V_b(\overline{p}, b, \overline{\varepsilon}, f, h)$ is the first derivative of household's baseline utility level, i.e., its utility from choosing the optimal consumption bundle when the random factors $\tilde{p}$ and $\tilde{\varepsilon}$ are at their average. $\overline{V}_{b\tilde{p}}$, $\overline{V}_{bb}$, and $\overline{V}_{b\tilde{\varepsilon}}$ denote derivatives of $\overline{V}_b$ with respect to $\tilde{p}$, b, and $\tilde{\varepsilon}$. In Appendix A, I insert equation (4) into (3) and solve for the optimal hedge quantity h^*.

$$h^* = -\frac{\overline{V}_{b\tilde{p}}}{\overline{V}_{bb}} - \frac{\overline{V}_{b\tilde{\varepsilon}}}{\overline{V}_{bb}}\frac{\sigma_{\tilde{p}\tilde{\varepsilon}}}{\sigma^2_{\tilde{p}}} - \underbrace{\frac{\overline{b}}{\theta}\frac{(f-\overline{p})}{\sigma^2_{\tilde{p}}}}_{\text{Speculation}} \tag{5}$$

$\sigma_{\tilde{p}\tilde{\varepsilon}}$ is the covariance between prices $\tilde{p}$ and quantity shocks $\tilde{\varepsilon}$, and $\sigma^2_{\tilde{p}}$ represents the variance of prices. $\theta = -\frac{\overline{V}_{bb}}{\overline{V}_b}b$ is the coefficient of relative risk aversion at baseline.

Equation (5) reveals that h^* increases in $\overline{V}_{b\tilde{p}}$ because $\overline{V}_{bb} < 0$. If $\overline{V}_{b\tilde{p}} > 0$, a high price is associated with a high marginal utility of income $\overline{V}_b$. In this case, a large forward hedge quantity h^* increases utility because the forward hedge increases income when prices are high. Increased income causes large utility gains since $\overline{V}_b$ is high when prices are high (Cowan, 2004).

$\overline{V}_{b\tilde{\varepsilon}}$ captures how quantity shock $\tilde{\varepsilon}$ influences the marginal utility of income $\overline{V}_b$. If $\overline{V}_{b\tilde{\varepsilon}} > 0$ and $\sigma_{\tilde{p}\tilde{\varepsilon}} > 0$, a large $\tilde{\varepsilon}$ is associated with both high $\overline{V}_b$ and high prices in expectation. In this case, choosing a large hedge quantity h^* is beneficial because the hedge increases income when both $\overline{V}_b$ and prices are likely high. In contrast, if $\overline{V}_{b\tilde{\varepsilon}} > 0$ and $\sigma_{\tilde{p}\tilde{\varepsilon}} < 0$, the agent hedges less since $\tilde{p}$ is likely low when $\tilde{\varepsilon}$ is large. When a large $\tilde{\varepsilon}$ causes a high $\overline{V}_b$, corresponding low prices raise the household's real income. Therefore, the household reduces h^*.

The last term of equation (5) captures speculative motives for hedging. The household

[5] The second-order condition is $E[V_{bb}(\tilde{p}-f)^2] < 0$. It holds if agents are risk-averse and if there exists some volatility in spot prices (Gilbert (1985), Cowan (2004)). I assume both conditions to hold for domestic electricity consumers on dynamic tariffs.

wants to speculate more the higher its income b and the smaller its coefficient of relative risk aversion θ. Below, I assume that household customers do not hedge for speculative reasons, i.e., households believe that $f = \overline{p}$. Thus the last term in equation (5) equals 0.

Equation (5) describes the optimal hedge quantity h^* for general concave utility functions. To simulate hedge shares for real-world consumers, I assume that households' consumption decisions can be described by a homothetic constant-elasticity-of-substitution (CES) indirect utility function (Kihlstrom (2009), Lau (2016)).

$$V(p,b,\varepsilon,f,h) = \frac{1}{1-\theta}[b+(p-f)h^*]^{1-\theta}(\varepsilon p^{1-\alpha}+1)^{\frac{1-\theta}{\alpha-1}} \tag{6}$$

where $\alpha \neq 1$ is the elasticity of substitution. $\theta \neq 1$ is the coefficient of relative risk aversion at baseline. CES utility functions are commonly used to model electricity consumption, given their analytical tractability (Herriges et al. (1993), Schwarz et al. (2002), Goldman et al. (2004), Faruqui and Sergici (2011)).[6] Applying Roy's identity to equation (6) yields the Marshallian demand for electricity.

$$x^*(p,b,\varepsilon,f,h^*) = \frac{[b+(p-f)h^*]\varepsilon p^{-\alpha}}{(\varepsilon p^{1-\alpha}+1)} \tag{7}$$

The Marshallian demand illustrates how the hedge affects electricity consumption. The hedge adds $(p-f)h^*$ to income b to partially compensate for a change in p. It increases households' disposable budget when prices are high $(p > f)$ and decreases budget when they are low $(p < f)$ (Braithwait & Eakin, 2002). Since households' income elasticity of demand equals 1, the hedge induces households to increase consumption when prices are above their average $\overline{p} = f$.

In Appendix A, I substitute the derivatives of the CES indirect utility function (6) into equation (5) to obtain the optimal hedge share:

$$\frac{h^*}{\hat{x}^*} = \left(1-\frac{1}{\theta}\right)\left(1+\frac{1}{1-\alpha}\rho\frac{cv(\tilde{\varepsilon})}{cv(\tilde{p})}\right) \tag{8}$$

The optimal hedge share is the ratio of the absolute optimal hedge quantity h^* and the baseline consumption $\hat{x}^* = x^*(\overline{p},b,\overline{\varepsilon})$. $\hat{x}^*$ defines what I previously called the "typical consumption". It is not equal to the household's average consumption but describes how much a household consumes if $\tilde{p}$ and $\tilde{\varepsilon}$ are at their average level. Equation (7) highlights that $\hat{x}^*$ does not depend on the hedge quantity h^* since $p = \overline{p} = f$ at baseline. Hence, at

[6] This CES specification has a major drawback: For constant prices and quantity shocks, homothecity implies that the share of expenditure households spend on electricity remains constant when income increases. Empirically, electricity's expenditure share typically decreases with income. In the UK, electricity's expenditure share ranges from 4% for the lowest income decile to 1.3% for the highest decile in 2020 (UK ONS, 2021).

baseline, the optimally hedged household consumes as if it was unhedged.

On the right hand side of equation (8), ρ depicts the coefficient of correlation between $\tilde{p}$ and $\tilde{\varepsilon}$. $cv(\tilde{p})$ and $cv(\tilde{\varepsilon})$ are the coefficients of variation of $\tilde{p}$ and $\tilde{\varepsilon}$, respectively. The optimal hedge share increases in the coefficient of relative risk aversion θ. If prices and quantity shocks are uncorrelated, the optimal hedge share approaches 1 when households become infinitely risk-averse. The lower households' risk aversion relative to their income elasticity of demand, the more the optimal hedge share decreases.[7]

A positive correlation ρ between quantity shocks and prices leads to higher optimal hedge shares. For example, if a household uses electric heating, it likely has a high desire to consume electricity when temperatures are low. Electricity prices are typically also high when temperatures are low due to high aggregate demand. Thus, households with electric heating face a positive correlation between electricity consumption and prices. This positive correlation makes households vulnerable to high electricity prices since they consume a lot when prices are high. Therefore, households with electric heating likely have high optimal hedge shares.

An increase in the substitution elasticity α further raises optimal hedge shares when the correlation between price and quantity shocks is positive (at least for reasonably small substitution elasticities, i.e., $\alpha < 1$). For a constant h^*, increasing α makes households' price elasticity of demand γ more negative if the substitution effect of a price change exceeds the income effect.

$$\gamma = \frac{\partial x^*}{\partial p}\frac{p}{x^*} = \frac{h^* p}{[b+(p-f)h^*]} \underbrace{-(1-s)\alpha}_{\text{Substitution effect}} \underbrace{-s}_{\text{Income effect}} \tag{9}$$

$s = \frac{px^*(h^*=0)}{b} < 1$ is electricity's expenditure share for unhedged households. For electricity consumers, the substitution effect typically dominates the income effect since electricity's share in household income is small. Therefore, households' demand becomes more price-elastic when the substitution elasticity α rises. An increase in price elasticity induces households to reduce consumption when prices are high. When $\rho > 0$, households particularly dislike a reduction in consumption since high prices are associated with a high desire to consume electricity. Thus, the household raises the hedge share h^* to reduce its price elasticity. As equation (9) illustrates, hedging reduces price elasticity since it mitigates exposure to spot prices. Thereby, the hedge ensures that consumption does not decrease too much when both prices and the desire to consume are high. On the other hand, increasing α reduces hedge shares when $\rho < 0$. A higher α makes the correlation between prices and consumption even more negative since more price-elastic households

[7] In general, the first term of equation (8) is given as $1 - \frac{\eta}{\theta}$ for every concave utility function. η is the income elasticity of demand at baseline. $\eta = 1$ for the CES utility function in equation (6).

consume more when prices are low and the desire to consume electricity is high. In this case, the household reduces its hedge share since it wants to be exposed to low spot prices when its consumption is high.

To sum up, with quantity shocks, an increase in price elasticity leads to lower hedge shares only if the correlation between prices and quantity shocks is negative.

3.2 Price premia

This section derives the price premia households are willing to pay to receive a dynamic electricity tariff with an optimal forward hedge. I follow the literature on the welfare effect of price stabilization and use a fixed tariff as a benchmark (Hanoch (1977), Turnovsky et al. (1980), Newbery and Stiglitz (1981), Gilbert (1985)). Thereby, I can derive price premia for two tariffs: 1) An unhedged dynamic tariff 2) A dynamic tariff with an optimal forward hedge (optimally hedged tariff). This distinction allows disentangling the two features of optimally hedged tariffs that impact consumer welfare: dynamic pricing and forward hedging. Following Gilbert (1985) and Cowan (2004), I assume that the constant price of the fixed tariff equals the mean dynamic price $\overline{p} = E[\tilde{p}]$.

Price premia for unhedged dynamic tariffs

In the first step, I derive the price premium g_p that households are willing to pay on top of the fixed price to avoid an unhedged dynamic tariff. When unhedged ($h = 0$), household's utility function simplifies to

$$V(p, b, \varepsilon) = \frac{1}{1-\theta} b^{1-\theta} (\varepsilon p^{1-\alpha} + 1)^{\frac{1-\theta}{\alpha-1}} \tag{10}$$

Price premium g_p equals the percentage increase in fixed price $\overline{p}$ that makes the household indifferent in expectation between the fixed tariff and the unhedged dynamic tariff with stochastic price $\tilde{p}$ (Gilbert, 1985).

$$E[V((1+g_p)\overline{p}, b, \tilde{\varepsilon})] = E[V(\tilde{p}, b, \tilde{\varepsilon})] \tag{11}$$

In Appendix B, I apply Taylor approximations to both sides of equation (11) and solve for g_p.

$$g_p = \frac{1}{2} \underbrace{(\hat{\gamma} + \beta^u)}_{= \frac{\overline{V}_{pp}}{\overline{V}_p} \overline{p}} cv(\tilde{p})^2 + \rho cv(\tilde{p}) cv(\tilde{\varepsilon}) [\frac{\beta^u}{1-\alpha} + 1 - \hat{s}] \tag{12}$$

If g_p is positive, households want to pay a premium for the fixed tariff. A negative g_p indicates that households would choose the dynamic tariff even if the fixed price was smaller than the average dynamic price. The first term on the RHS of equation (12) captures the effect of pure price volatility on consumer welfare. This term increases in $\frac{\overline{V}_{pp}}{\overline{V}_p}\overline{p} = \hat{\gamma} + \beta^u$ which is the absolute value of Turnovsky et al.'s (1980) coefficient of relative price risk aversion.[8] $\hat{\gamma} = -\alpha - (1-\alpha)s$ equals electricity's price-elasticity of demand at baseline. $\beta^u = \frac{\partial \overline{V}_b}{\partial \tilde{p}} \frac{\overline{p}}{\overline{V}_b} = (\theta - 1)s$ is the price elasticity of the marginal utility of income at baseline for unhedged households. Overall, as long as $\rho = 0$, dynamic prices increase welfare for unhedged households if their price-elasticity of demand $\hat{\gamma}$ exceeds the price-elasticity of their marginal utility of income β^u in absolute values.

Term 2 of the RHS of equation (12) reveals that households do not only care about price volatility but also about the correlation ρ between prices and quantity shocks. Price premium g_p increases if $\rho > 0$. The positive effect of a positive ρ is amplified by an increase of the price-elasticities of demand $\hat{\gamma}$ and of the marginal utility of income β^u as long as $\alpha < 1$ and $\theta > 1$. Hence, households with price-elastic marginal utility of income and high substitution elasticity suffer from dynamic prices if prices and quantity shocks are positively correlated. If ρ is negative, households benefit from dynamic pricing.

Price premia for dynamic tariffs with an optimal forward hedge

In the next step, I derive the price premium g_f that denotes the percentage increase in fixed price $\overline{p}$ that makes the household indifferent in expectation between the fixed tariff and the optimally hedged tariff (Gilbert, 1985).

$$E[V((1+g_f)\overline{p}, b, \varepsilon)] = E[V(\tilde{p}, b + (p-f)h^*, \tilde{\varepsilon})] \tag{13}$$

Under the optimal hedge tariff, households buy the optimal hedge quantity h^* forward as given in equation (8). Appendix B demonstrates that the price premium g_f equals

$$g_f = g_p \underbrace{- \frac{1}{2}\beta^u cv(\tilde{p})^2 - \frac{1}{2}\frac{\beta^u}{1-\alpha}\rho cv(\tilde{p}) cv(\tilde{\varepsilon})\left(1 - \frac{h^*}{\hat{x}^*}\right)}_{g_h} \tag{14}$$

g_f consists of two terms: g_p captures the welfare effect of dynamic pricing as given in equation (12). $g_h = g_f - g_p$ describes the welfare effect of optimal forward hedging. If $g_h < 0$, the optimal hedge increases welfare compared to an unhedged dynamic tariff. g_h will never be positive since households can always choose $h^* = 0$ and stay unhedged.

The optimal forward hedge increases welfare by making the marginal utility of income V_b less elastic to price changes. When optimally hedged, the price-elasticity of V_b at baseline

[8] The income elasticity of demand at baseline equals 1 with CES preferences.

is (see Appendix B)

$$\beta^{h^*} = \frac{\partial \overline{V}_b}{\partial \tilde{p}} \frac{\overline{p}}{\overline{V}_b} = \beta^u - \theta s \frac{h^*}{\hat{x}^*} \tag{15}$$

$\beta^u = (\theta - 1)s$ is the price elasticity of the marginal utility of income for unhedged households. The higher the household's optimal hedge share $\frac{h^*}{\hat{x}^*}$, the more declines the price-elasticity of the marginal utility of income β^{h^*}. Inserting the optimal hedge share in equation (8) into equation (15) yields

$$\beta^{h^*} = -\frac{\beta^u}{1-\alpha} \rho \frac{cv(\tilde{\varepsilon})}{cv(\tilde{p})} \tag{16}$$

If $\rho = 0$, the optimal hedge makes the marginal utility of income fully inelastic to price changes ($\beta^{h^*} = 0$). Equation (14) reveals that for $\rho = 0$, stabilization of V_b raises consumer welfare whenever $\beta^u > 0$. β^u is positive if households are sufficiently risk-averse with $\theta > 1$. The welfare benefit from hedging rises in the price volatility $cv(\tilde{p})^2$ (Cowan, 2004).

If $\beta^u > 0$, $\rho > 0$ implies $\beta^{h^*} < 0$. In this case, optimal hedging causes the marginal utility of income V_b to fall when prices increase. If $\rho > 0$, the optimal hedge share is very high. Hence, the hedge shifts much income to states of the world when prices are high. This large income compensation reduces V_b since $V_{bb} < 0$. For $\rho > 0$, the income compensation strongly raises welfare because both prices and the desire to consume are high. On the other hand, equation (14) reveals that welfare benefit declines in the optimal hedge share $\frac{h^*}{\hat{x}^*}$. The higher $\frac{h^*}{\hat{x}^*}$, the more decreases the benefit from hedging since hedging reduces households' exposure to spot prices and, thereby, its price elasticity of demand. For $\frac{h^*}{\hat{x}^*} > 1$, the negative effect on demand elasticity dominates such that the welfare effect of the second term in g_h becomes negative. If $\rho < 0$, the second term of g_h will always lower welfare since households will never choose a hedge share larger than 1 when $\rho < 0$.

4 Simulation

Below, I explain how the model in Section 3 allows simulating optimal hedge shares and hedged electricity bills for real-world consumers. First, I define the hedge product that consumers can buy. In the example in the introduction, I assumed that households buy forward a particular share of their daily baseline consumption. However, such a daily hedge ignores predictable intraday patterns of both consumption and prices. Baseline electricity consumption and prices are typically low at night and high during morning and evening peaks. A hedge contract should account for these daily load and price patterns to better protect against bill volatility (Borenstein, 2007).

To do so, I define a *hedge time segment* k as a set of time intervals t.[9] Households choose a quantity to buy forward for every segment k. In the main specification, I define hedge time segments for every half hour per day for weekdays and weekends. For instance, 8-8:30 am on weekdays is a time segment. Average prices and baseline consumption are similar on weekdays 8-8:30 am, whether on Monday, Wednesday, or Friday (Bobbio et al., 2022a). Therefore, households buy the same hedge quantity for all intervals t within 8-8:30 am on weekdays. Prices and baseline consumption in this time segment likely differ from average prices and baseline consumption at midnight or 8-8:30 am on weekends. Hence, households purchase different hedge quantities for those time segments (See Appendix C for a detailed discussion of time segments).

The approach results in 48 half-hourly hedge time segments and 48 corresponding optimal hedge shares for weekdays and weekends, respectively. The advantage of such a fine-grained hedge contract is that it should protect well from bill volatility. On the other hand, a hedge contract with 96 different hedge shares is too complex to be implemented in practice. Therefore, the fine-grained hedge contract should be considered a theoretical benchmark that tests how effectively an optimally hedged tariff can reduce bill volatility. In Appendix C, I compare the results of this theoretical benchmark to less fine-grained hedge contracts that contain fewer and longer hedge time segments. Similar to Borenstein (2007), I find that choosing more granular hedge time segment has only a small effect on optimal hedge shares. However, I find that more fine-grained hedge segments lead to a substantially larger reduction in bill volatility.

The households in my sample are currently unhedged. To simulate their optimal hedge shares, I suppose that households' observable unhedged half-hourly electricity consumption x_t^* in interval t can be described by the Marshallian demand in equation (7). When households are unhedged, hedge quantity h equals 0. I invert equation (7) to obtain an expression for the unobservable quantity shocks ε_t in interval t as a residual of the unhedged Marshallian demand (Redding & Weinstein, 2019).[10]

$$\varepsilon_t = \frac{x_t^* p_t^\alpha}{b_k - x_t p_t} \tag{17}$$

I assume that households have a fixed budget b_k for hedge time segment k. I do not observe households' monthly income, let alone their budget for a half-hourly time segment.

[9] A time interval t is a specific half-hourly period. For instance, "8-8:30 am on Monday, March 1st, 2021" is a time interval. This interval falls within the hedge time segment "8-8:30 am on weekdays".

[10] The Marshallian demand is invertible since x_t and y_t are "connected substitutes" according to Berry et al. (2013). The first condition for connected substitutes is that goods are weak gross substitutes. This condition is satisfied since aggregate consumption of lother goods y_t weakly decreases in ε_t for all t and p_t. The second condition for "connected substitutes" requires that goods are connected strict substitution." This condition requires that any chain of substitution between goods leads to the outside good (i.e., y_t). Since there are only two goods in the given application, electricity consumption can only be substituted with the outside good (Berry et al. (2013), Berry and Haile (2016)).

Surveys reveal that UK households spend on average 2% of their income on electricity (UK ONS, 2021). Therefore, I assume that, in every segment k, households' budget share of electricity $s_t = \frac{x_t^* p_t}{b_k}$ is on average 2%, i.e., $\overline{s}_k = \frac{1}{T_k}\sum_{t\in k} s_t = 2\%$. T_k is the number of time intervals t that fall into segment k. Households' absolute budget for segment k can then be derived as $b_k = \frac{1}{T_k}\sum_{t\in k}\frac{x_t^* p_t}{\overline{s}_k}$.[11]

The assumption that households spend the same average share of their income on electricity in every time segment implies that households have a higher absolute budget for time segments in which they typically consume a lot. For instance, most households have a higher absolute segment budget on weekdays, 8-8:30 am, than at midnight because they typically consume more in the morning. Therefore, the segment budget follows each household's daily consumption pattern.

An important caveat for my analysis is that the assumption regarding the segment budget b_k affects the optimal hedge shares even for homothetic preferences. Changing b_k also changes the derived quantity shocks ε_t. Thereby, the choice of b_k influences the correlation between quantity shocks and prices and, ultimately, the optimal hedge shares. As a robustness check, I, therefore, run simulations for various average segment budget shares $\overline{s}_k$ in Appendix E. I find that a change in $\overline{s}_k$ only slightly affects optimal hedge shares.

To calculate ε_t in equation (17), I also choose the substitution elasticity α as a simulation parameter. Previous studies find that the short-run elasticity of substitution for electricity ranges from 0.07 to 0.21 for domestic electricity consumers (Ericson (2006), Bartusch (2011)).[12] For my main specification, I conservatively set $\alpha = 0.1$, assuming that households have a relatively low ability to substitute electricity consumption with other goods.

Having defined b_k and α, I calculate the residual quantity shock ε_t in equation (17) for every t in the data set using the observed unhedged half-hourly electricity consumption x_t^* and prices p_t. Then, I calculate the following statistics for every segment k: 1) the average quantity shock $\overline{\varepsilon}_k$ and average electricity price $\overline{p}_k$, 2) the coefficients of variation $cv(\tilde{\varepsilon}_k)$ and $cv(\tilde{p}_k)$, 3) the coefficient of correlation ρ_k between price and quantity shocks. These statistics allow calculating the baseline consumption $\hat{x}_k^*$.

Now, I am ready to calculate the optimal hedge share $\frac{h_k^*}{\hat{x}_k^*}$ in equation (8) for segment k. For the main specification, I assume that domestic electricity consumers face high levels of relative risk aversion with $\theta = 5$. Most empirical studies estimate θ in the range from 0 to 6 (Cowan (2004), Lengwiler (2004)). To avoid speculation, I set the forward hedge

[11] For a tiny number of time intervals (only 0.006% of all intervals), consumption is extremely high such that the observed expenditure exceeds the the segment budget b_k. For these rare intervals, I set the household budget equal to the observed expenditure on electricity to ensure that households' electricity expenditure does not exceed their budget.

[12] These estimates for the elasticity of substitution either refer to the substitution between electricity and other energy carriers or the substitution between electricity consumption at different times of day.

price equal to the average dynamic price in segment k, i.e., $f_k = E[p_{t\in k}]$.[13] Moreover, I follow Borenstein (2007) and require the optimal hedge shares to lie between 0% and 200% of baseline consumption to avoid unreasonably extreme hedge shares.

In the next step, I derive monthly electricity bills for optimally hedged households. I consider that the optimal hedge induces income- and price-elastic households to change their consumption compared to the unhedged tariff. Thus, I calculate the hedged households' electricity consumption $x^*_{t\in k}$ with the optimal hedge h^*_k using the Marshallian demand in equation (7). The electricity bill B_m for month m results by summing over the expenditure for electricity and the forward hedge for all intervals $t \in m$:

$$B_m = \left(\sum_{t\in m} \sum_{t\in m\cup k} [x^*_t p_t + (f_k - p_t)h^*_k] \right) * \frac{30}{Days_m} \tag{18}$$

where $Days_m$ denotes the number of days the household spends on the tariff in month m. The last term normalizes the electricity bills to a 30-day month to make sure that bill volatility is not caused by variation in the number of days the household spends on the tariff (see Section 5 and Borenstein (2007)).

5 Data

The data set contains anonymized smart meter readings of half-hourly electricity price and consumption for 9,718 households in the UK provided by electricity supplier Octopus Energy. 4,066 households are on dynamic tariffs ("dynamic households"), while 5,652 are on fixed ones ("fixed households"). The data contains smart meter readings for each household for up to one year between August 2020 and August 2021 (Bobbio et al., 2022a).

Every day between 4-8 pm, Octopus Energy informs dynamic households about the 48 half-hourly dynamic prices for the next day via a smart phone app. Dynamic prices include distribution charges and a peak-time premium. Appendix D explains how dynamic prices are calculated.

Households pay dynamic prices only up to a price cap of 0.35č/kWh. The price cap equals roughly twice the average dynamic prices. During the sample period, the cap only binds in 3% of the half-hourly periods. Therefore, the price cap has a negligible effect on my analysis as I discuss in Section 6.5.

Fixed households always receive a constant price for electricity. 8% of fixed tariff customers experience a minor adjustment of their fixed rate once during the sample period.

[13] For existing two-part tariffs with a forward hedge, some utilities set the forward price even below the average dynamic price to compensate customers for foregone cross-subsidies they would have received on a fixed tariff (Borenstein, 2007).

Apart from these one-time adjustments, these households do not face any price volatility. I do not employ households on fixed tariffs for the optimal hedge simulations. Nevertheless, I report the descriptive statistics for these households as a benchmark to analyze how dynamic prices affect consumption and electricity bills.

Figure 1: Number of customers by tariff type

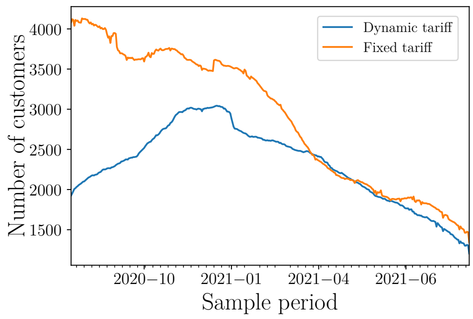


Table 1: Summary statistics

Tariff type	mean	SD[14]	min	max
	Electricity prices (pence/kWh)			
Dynamic	15.4	7.3	0.1	35
Fixed	15.2	0.1	15.2	15.3
	Monthly consumption (kWh)			
Dynamic	516	406	0	4560
Fixed	334	239	0	5040
	Monthly electricity bill (GBP)			
Dynamic	77	61	0	766
Fixed	50	36	0	798

The households in this sample have been randomly chosen from Octopus Energy's customer base. However, households have self-selected into a tariff type. Hence, households on dynamic tariffs might systematically differ from households on fixed ones. Households can also switch to a different tariff or supplier during the sample period. Figure 1 reveals a surprisingly high attrition of households on both tariffs. I drop all households for whom less than eight monthly electricity bills are observable to ensure a meaningful analysis of bill volatility. Moreover, some households spend less than an entire month on a specific tariff because they either leave or join the tariff in the middle of the month. I exclude all observations for months if the household spends less than 15 days on the tariff. This ensures that at least 720 half-hourly price-consumption observations are available per household each month. The final dataset contains a relatively large sample of 2,159 dynamic households and 2,540 fixed households.

Table 1 presents summary statistics for households on dynamic and fixed tariffs. The mean unweighted electricity price is very similar on both tariffs. The standard deviation of dynamic prices is quite large. Differences in fixed prices are driven by different fixed price levels across customers.

Table 1 also reveals that dynamic households have a 54% higher average monthly consumption than fixed households. The higher monthly consumption suggests that households who self-select into dynamic tariffs systematically differ from fixed households. Dynamic customers are first movers who might be exceptionally interested in their electricity usage. Therefore, one should be careful to extrapolate the results of this paper to the general population of domestic energy consumers. This paper is only informative about whether forward hedging is effective for first-movers. Nevertheless, energy suppliers should be particularly interested in how forward hedge tariffs work for first movers as they will likely only sell forward hedges to first-movers in the foreseeable future.

Moreover, Table 1 shows statistics on households' monthly electricity bills. I calculate these bills by multiplying consumption and prices every half an hour and adding these half-hourly expenditures every month. Following Borenstein (2007), I normalize all electricity bills to a 30-day month in order to avoid measuring bill volatility that is purely driven by variation in days per month or the number of days a household spends on the tariff in a given month (see Section 4). The higher average consumption of dynamic customers likely drives their higher average electricity bills.

Table 2: Variation and correlation statistics

		Percentiles				
tariff type	mean	0.01	0.1	0.5	0.9	0.99
	Coeff. of variation of monthly bills per customer					
Dynamic	0.32	0.10	0.16	0.26	0.57	1.06
Fixed	0.19	0.05	0.08	0.16	0.35	0.65
	Coeff. of correlation between prices and consumption					
Dynamic	-0.007	-0.363	-0.225	-0.005	0.211	0.336

Since this study is concerned with hedging bill volatility for individual customers, Table 2 reports the distributions of coefficients of variation for individual customers' monthly bills (Borenstein, 2007). The coefficient of variation of dynamic customers' electricity bills is, on average, 67% higher than for fixed customers, suggesting that dynamic prices increase bill volatility. While this might be unsurprising, it is striking that fixed customers also face substantial bill volatility. Fluctuations in electricity bills are not only caused by volatile prices but also by volatility in consumption (Borenstein, 2007).

Moreover, fixed customers in the lowest percentile of the bill volatility distribution have much lower volatility than dynamic customers in the same percentile. When moving up the distribution, the difference in bill volatility between fixed and dynamic tariffs declines. Borenstein (2007) observes a similar tendency in his study. This suggests that dynamic prices might mainly increase bill volatility for customers who would have low volatility under fixed tariffs (Borenstein, 2007).

Table 2 also reports the distribution of the correlation coefficient between dynamic electricity prices and consumption for dynamic customers. While the correlation between prices and consumption is, on average, close to zero, it varies enormously between customers. Some customers face either a significant negative or large positive correlation.

[14] Average household-specific standard deviation. Since households can choose between multiple different fixed tariff products with different fixed rate levels, the standard deviation across all fixed prices is slightly larger. In the context of this paper, the household-specific standard deviation is a more relevant indicator for the price volatility that households perceive.

Table 3: Summary statistics by low-carbon technology (LCT) ownership

LCT ownership	Number of households	Mean monthly consumption (kWh)	Mean monthly electricity bill (GBP)
All customers	2159	516	77
Electric heating only	225	352	58
Electring heating + smart thermostat	221	394	65
EV only	411	635	92
Solar only	101	365	51
Battery only	28	769	114
EV + solar	125	497	67
EV + battery	32	1088	156
Solar + battery	84	437	59
EV + solar + battery	82	592	74

Analyzing the same dataset, Bobbio et al. (2022a) estimate an average price elasticity of -0.26 for the households in this sample. For a sub-sample, they employ information on low-carbon technology (LCT) ownership to show that technologies influence households' price elasticity. Especially ownership of electric vehicles increases price elasticity.

In this paper, I analyze how LCT ownership impacts optimal hedge shares. Table 3 shows the number of customers for which information on technology ownership is available. Octopus Energy conducted a survey to gather ownership information for electric vehicles, solar PV, battery storage, and smart thermostats. For electric heating, ownership is inferred from a lack of a gas contract with Octopus Energy since households in the UK typically purchase electricity and gas from the same supplier (Bobbio et al., 2022a).[15]

Electric vehicles (EV) or battery storage owners have above-average monthly electricity consumption and monthly bills. Solar PV owners have lower consumption and bills since they likely cover a portion of their electricity consumption via self-generated solar electricity. Surprisingly, customers who likely have electric heating consume less electricity than the average household. Given small sample sizes, the analysis for some LCT groups (e.g., battery owners) should be interpreted cautiously.

[15] This might not be an exact indicator for ownership of electric heating. Some households not on a gas tariff with Octopus Energy might have oil heating rather than electric heating or buy gas from another supplier (Bobbio et al., 2022a).

6 Results

6.1 Optimal hedge shares

Figure 2 presents the distribution of optimal hedge shares that I simulate across all households and time segments. On average, the optimal hedge share is 59% of baseline consumption. There is substantial variation in optimal hedge shares. I set the optimal hedge share to zero for a surprisingly large share of 14% of the time segments. Otherwise, optimal hedge shares would be negative. The desire to hedge a negative quantity is caused by a large negative correlation between prices and quantity shocks in these time segments. Moreover, I set 3% of the hedge shares to 200% to avoid unreasonably large hedge shares.

Figure 2: Distribution of optimal hedge shares across all time segments

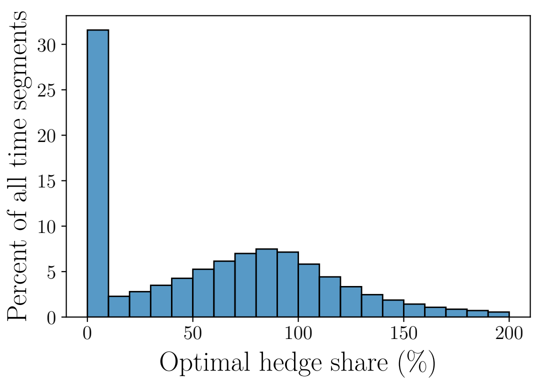
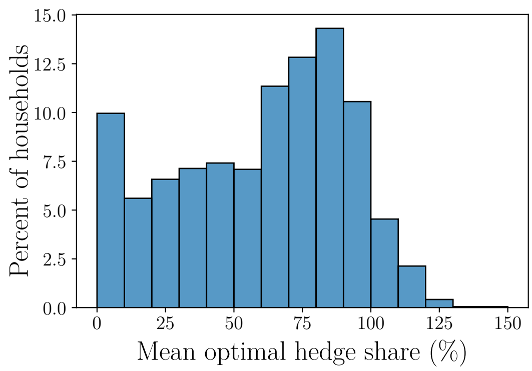


Figure 3: Distribution of mean optimal hedge shares by customer



Heterogeneity between households partly drives the considerable variation in optimal hedge shares. Figure 3 shows the distribution of the mean optimal hedge share per household. The mean hedge share for a particular household is defined as the average of the household's hedge shares across all time segments. The mean hedge shares differ widely between households. Overall, mean optimal hedge shares are far smaller than the ones Borenstein (2007) simulates for a sample of the price-inelastic industrial customers. Most households find it optimal to hedge on average less than 100% of their baseline consumption. Only 7% of households in this sample overhedge, i.e., hedge more than 100% of their baseline consumption on average. In contrast, Borenstein (2007) finds that 77% of his inelastic customers should overhedge.

Table 4 suggests that ownership of low-carbon technologies (LCTs) partly explains the heterogeneity in mean optimal hedge shares. Households with electric heating or an electric vehicle (EV) have a larger mean optimal hedge share than the average household in the sample. These appliances seem to increase the positive correlation between a household's consumption and prices. Surprisingly, solar PV owners have an average optimal hedge share of only 21%. Solar PV likely results in a strong negative correlation between prices and electricity consumption from the grid. As expected, the small sample of battery storage owners also has a slightly below-average optimal hedge share of 51%.

Given their small sample sizes, the above results should be interpreted with caution for solar PV and battery owners. I also stress that this paper does not establish a causal relationship between technology ownership, optimal hedge shares, and bill volatility. The above results merely provide first suggestive evidence that technology ownership influences optimal hedge shares.

Table 4: Optimal hedge shares and bill volatility by low-carbon technology (LCT) ownership

		Optimal hedge share		Average coefficient of bill variation		
LCT ownership	Households (#)	Average (%)	SD[16] (%)	Unhedged	Optimal hedge	Optimal vs. Unhedged (%)
All customers	2159	59	37	0.34	0.28	-18
Electric heating only	225	76	38	0.25	0.19	-23
Electric heating + smart thermostat	221	76	35	0.24	0.17	-28
EV only	411	68	43	0.26	0.18	-30
Solar only	101	21	29	0.50	0.49	-1
Battery only	28	51	41	0.42	0.42	-2
EV + solar	125	28	38	0.37	0.36	-6
EV + battery	32	68	40	0.33	0.26	-26
Solar + battery	84	17	25	0.65	0.66	1
EV + solar + battery	82	20	31	0.48	0.48	0

Table 4 also indicates that heterogeneity between households is not the only reason for the enormous variation in optimal hedge shares. Even for a specific household, optimal hedge shares differ strongly by time of day. On average, the hedge share for a specific household has a standard deviation of 37% across time segments.[16] These differences between time segments are likely caused by significant variations in household-specific daily consumption patterns. In some time segments, a household's consumption pattern might align with the aggregate load pattern and is, therefore, positively correlated with prices. The same household's consumption can correlate negatively with aggregate load and prices in other time segments. The fine-grained hedge tariff with small time segments accounts for these household-specific consumption patterns to provide adequate protection from bill volatility.

[16] Average of the standard deviation of optimal hedge shares for specific households across time segments.

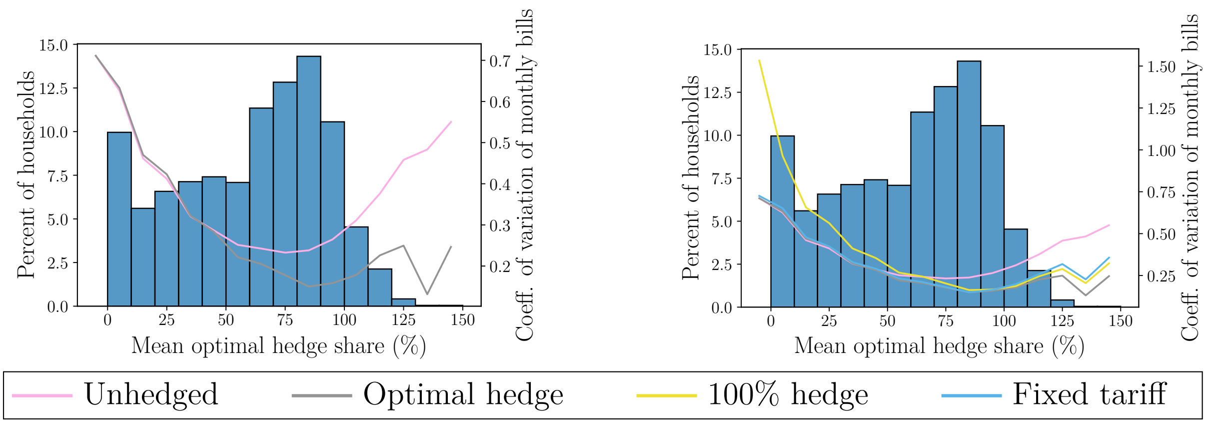
6.2 Bill volatility

In this section, I discuss how effectively the optimal hedge protects customers from volatility of monthly electricity bills. Figure 4a compares the coefficients of variations of bills for unhedged and optimally hedged tariffs across mean optimal hedge shares. The optimally hedged tariff proves effective in reducing bill volatility. On average, the optimally hedged tariff reduces the coefficient of variation of a household's monthly bill by 18% compared to an unhedged dynamic tariff. Hedging is even more effective for households who overhedge. It reduces their coefficient of bill variation by 45% on average. On the other hand, hedging hardly reduces bill volatility for households whose mean optimal hedge share is less than 50%. Naturally, hedging does not significantly affect households that only hedge a small share of their baseline consumption. These findings are similar to the ones in Borenstein (2007).

Figure 4: Distribution of mean optimal hedge shares by customer and coefficients of variation of monthly bills by tariff type

(a) Unhedged tariff vs. optimally hedged tariff

(b) Comparison of various tariff types



I also compare the effectiveness of the optimally hedged tariff to a more straightforward tariff in which households always buy 100% of their baseline consumption forward. Figure 4b reveals that when always forced to buy a 100% hedge, households with a mean optimal hedge share of less than 50% have a higher bill volatility than under the unhedged tariff. Hence, a simple 100% hedge tariff is unsuitable for households with low mean optimal hedge shares. On average, the 100% hedge tariff leads to a 15% higher coefficient of variation of monthly bills than the optimally hedged tariff.

In addition, I compare the bill volatility of the previous tariffs to the one under a fixed tariff. For customers with mean hedge shares above 100%, the optimally hedged tariff results in lower bill volatility than the fixed tariff, as Figure 4b reveals. Borenstein (2007) reports similar results in his paper. He argues that the hedged tariff protects households more effectively against price and quantity risks. The fixed tariff protects only against price risks. Protection against quantity risk is essential for households who overhedge since they face a positive correlation between prices and consumption.

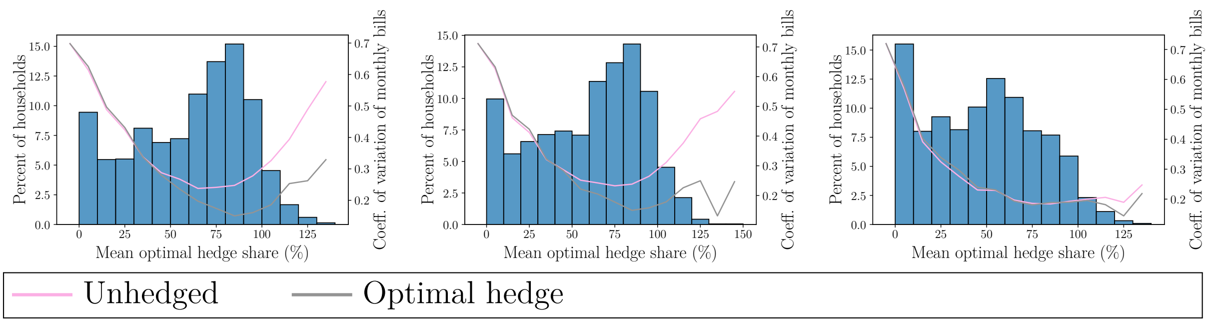
Table 4 reveals that the optimal hedge reduces bill volatility most effectively for households with electric vehicles and heating. For instance, optimal hedging reduces the bill volatility for owners with only an EV by 30%. In contrast, hedging only slightly reduces bill volatility for solar PV and battery owners with low hedge shares.

6.3 Price elasticity and risk aversion

Below, I analyze how risk aversion and demand elasticity affect hedge shares and bill volatility. Figure 5 confirms that increasing substitution elasticity α increases the variation in mean optimal hedge shares when exogenous quantity shocks remain constant.[17] Raising α leads to lower hedge shares when the correlation between prices and quantity shocks is negative and higher hedge shares when it is positive (see Section 3.1). On average, higher substitution elasticity decreases mean optimal hedge shares. Inelastic households ($\alpha = 0.001$) have an average mean optimal hedge share of 60% with a standard deviation of 36%. Elastic households ($\alpha = 0.6$) show an average mean optimal hedge share of 48% with a standard deviation of 47%. Moreover, a large α increases the share of households that overhedge or would even choose a negative hedge quantity if allowed.

Figure 5: Distribution of mean optimal hedge shares by customer and coefficients of variation of monthly bills by tariff type for different substitution elasticity α

(a) $\alpha = 0.001$ (b) $\alpha = 0.1$ (c) $\alpha = 0.6$



Hedging reduces bill volatility more effectively when households are price-inelastic. For price-inelastic households ($\alpha = 0.001$), the optimal hedge lowers the coefficient of bill volatility by 21% compared to the unhedged dynamic tariff. It does so by mitigating

[17]Since quantity shock $\tilde{\varepsilon}_t$ is a residual of the Marshallian demand function, it depends on α. To calculate $\tilde{\varepsilon}_t$ in Section 4, I use $\alpha = 0.1$ equal to the α used in the main specification above. Quantity shocks should be considered exogenous shocks to demand. Therefore, when studying the effect of a change in α on hedge shares, I hold quantity shocks constant to their level in the main specification.

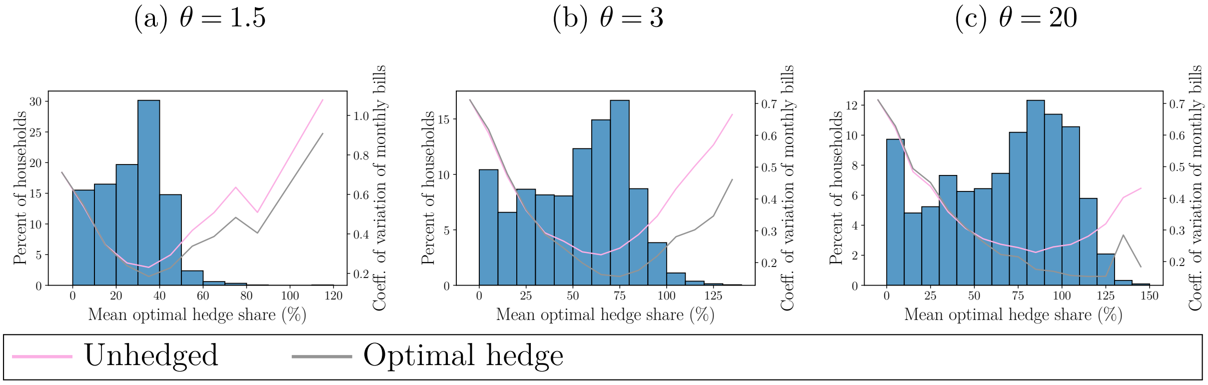
households' exposure to high prices. At the same time, the hedge hardly reduces households' price-response compared to the unhedged tariff when households are price-inelastic.

For very price-elastic households ($\alpha = 0.6$), the optimal hedge even increases bill volatility on average by 5% relative to the unhedged tariff. Price-elastic households respond less strongly to prices when optimally hedged relative to being unhedged. Therefore, households consume more when prices are high on optimally hedged tariffs than on unhedged ones. For some households, this leads to even more volatile bills on the optimally hedged tariff than on the unhedged tariff. Households who decrease their hedge when α increases experience on average a higher bill volatility on the optimally hedged tariff relative to the unhedged one. Households who increase the hedge in response to higher price-elasticity face lower average bill volatility when optimally hedged.

Moreover, optimally hedged households face an increase in bill volatility by 20% when their price elasticity increases from $\alpha = 0.001$ to $\alpha = 0.6$. This reveals that when price-elasticity rises the volatility of the optimally hedged bill does not only increase relative to the unhedged bill, but also in absolute terms. In contrast, the bill volatility of unhedged households declines by 13% when increasing α from 0.001 to 0.6.

Figure 6 shows that higher risk-aversion results in higher hedge shares. Hardly risk-averse households ($\theta = 1.5$) hedge far less than 100%. Few households still choose substantial hedge shares as protection against a positive correlation between prices and quantity shocks. When risk aversion increases, its impact on hedge shares diminishes. The distribution of mean optimal hedge shares for $\theta = 20$ only moderately differs from the distribution for $\theta = 5$ in the main specification in Figure 4b. Similar to an increase in price-elasticity, an increase in risk-aversion makes hedging less effective in lowering bill volatility relative to the unhedged tariff. Risk-aversion leads to higher hedge shares. These higher hedge shares lower households to exposure spot prices and, therefore, allow households to consume more when prices are high. For high risk aversion ($\theta = 20$), this leads on average even to a slightly higher bill volatility on the optimally hedged tariff compared to the unhedged tariff.

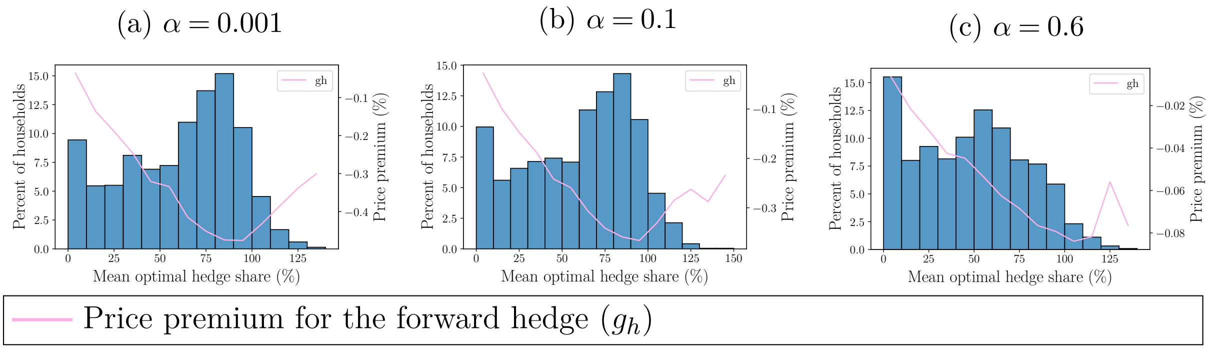
Figure 6: Distribution of mean optimal hedge shares by customer and coefficients of variation of monthly bills by tariff type for different levels of risk aversion θ



6.4 Price premia

Figure 7 shows the price premia households are willing to pay to receive the forward hedge by mean optimal hedge share. The negative price premium implies that the hedge increases households' welfare. However, the welfare effect of the forward hedge is small. Compared to an unhedged dynamic tariff, the forward hedge reduces the mean electricity price that makes households indifferent between the unhedged tariff and the optimally hedged tariff by merely 0.3% (for the main specification with $\alpha = 0.1$). The welfare benefit from hedging is most significant for households who hedge close to 100%. The hedge adds the most value for these households by stabilizing the marginal utility of income while still exposing households sufficiently to spot prices to keep demand price-elastic.

Figure 7: Distribution of mean optimal hedge shares by customer and forward hedge price premium g_h for different α



One reason for the small welfare effects of hedging might be electricity's small share in household expenditure. In the above simulations, I assumed that households spend on average only 2% of their income on electricity which is roughly the case in the UK (UK ONS, 2021). Such a small expenditure share implies that a change in electricity prices will have merely a small effect on households' marginal utility of income. When the price elasticity of the marginal utility is already tiny, the hedge can only add little value by stabilizing it.

However, electricity's share in household expenditure will likely increase in the upcoming decades. Households will start using electricity for heating, cooling, and driving cars. To assess how an increasing expenditure share of electricity affects the welfare benefits of hedging, I run the above simulation assuming that households spend on average 10% of their income on electricity. Figure 21 in Appendix F reveals that a higher expenditure share of electricity only slightly increases the welfare benefits from hedging. On average, the welfare benefit translates to a 1.6% reduction in the mean electricity price compared to a 0.3% reduction when electricity's expenditure share remains at 2%.

Figure 8: Distribution of mean optimal hedge shares by customer and forward hedge price premium g_h by tariff type for different θ

(a) $\theta = 1.5$ (b) $\theta = 3$ (c) $\theta = 20$

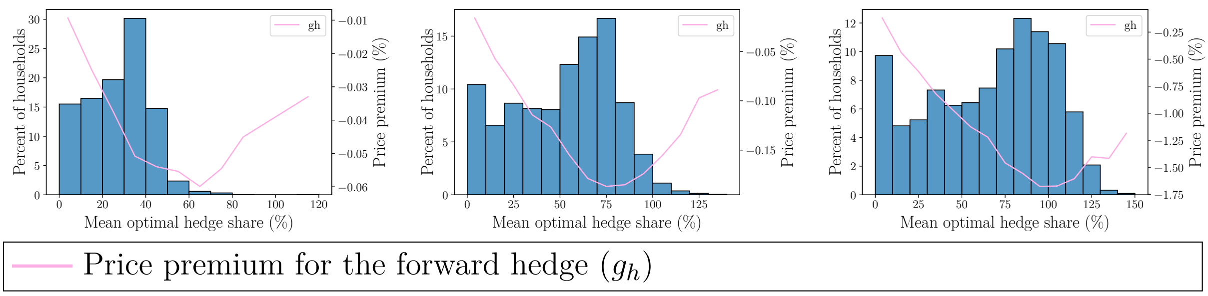


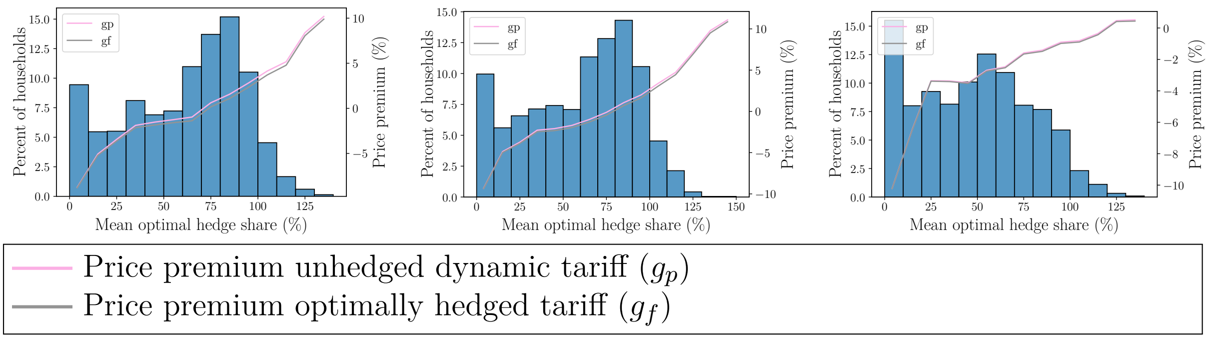
Figure 7 also highlights that increasing substitution elasticity α further diminishes the welfare benefit from hedging. The higher α, the smaller the share of households that hedge close to 100%. Households who hedge roughly 100% benefit most from hedging. When demand is elastic ($\alpha = 0.6$), the hedge only achieves an average welfare benefit of 0.05%. Meanwhile, Figure 8 depicts that an increase in risk aversion has a more substantial effect on the welfare gain from hedging. For very small levels of risk aversion ($\theta = 1.5$), the welfare gain from hedging amounts to only 0.04% expressed as a reduction in mean electricity prices. If risk aversion is large ($\theta = 20$) hedging leads to a larger but still surprisingly low 1.2% welfare gain.

Figure 9 reveals that dynamic pricing has a much stronger effect on household welfare than forward hedging. The figure shows the price premia for unhedged dynamic tariffs g_p and the optimally hedged dynamic tariffs g_f. g_f hardly differs from g_p since the welfare effect of the forward hedge $g_h = g_f - g_p$ is negligible relative to g_p. Compared to a fixed tariff, the unhedged dynamic tariff leads to an average welfare gain equivalent to a 1.4% reduction in average electricity prices for the main specification ($\alpha = 0.1$). 58% of households achieve higher welfare on the unhedged dynamic tariff than on the fixed tariff. Households that benefit most from dynamic pricing also choose low hedge shares since they have a negative correlation between electricity prices and their desire to consume electricity. Households with a positive correlation are better off on a fixed tariff.

As expected, increasing demand elasticity makes unhedged dynamic tariffs more attractive. When $\alpha = 0.6$, 85% of households prefer dynamic pricing over a fixed tariff. The average welfare gain from dynamic pricing rises to 4%.

Figure 9: Distribution of mean optimal hedge shares by customer and price premia g_p and g_f for different α

(a) $\alpha = 0.001$ (b) $\alpha = 0.1$ (c) $\alpha = 0.6$



6.5 Scarcity price event

There are two additional reasons why hedging results in low welfare gains: First, households in my sample are not fully exposed to day-ahead electricity prices but are protected via a price cap. Since the price cap already protects households from high prices, the hedge can only add small additional value. Second, households do not experience an extreme scarcity event like the Texas winter storm during the sample period. The benefit from hedging is larger when households experience worst-case events with extremely high prices.

Figure 10b depicts how the performance of the optimal forward hedge changes when removing the price cap and exposing households to fully dynamic prices. Removing the cap has a negligible effect on the distribution of mean optimal hedge shares and bill volatility. Likewise, the welfare benefits from hedging only marginally increase after removing the cap (see Figure 11b). The price cap has only tiny effects during my sample period since dynamic prices rarely exceed the cap in only 3% of time intervals. At the same time, price caps are suboptimal since they lower the incentive to respond to high scarcity prices (Appendix D provides statistics on dynamic prices after removing the price cap).

Figure 10: Distribution of mean optimal hedge shares by customer and coefficients of variation of monthly bills by tariff type for different levels of price protection

(a) Baseline results with price cap

(b) Results without price cap

(c) Results without price cap and scarcity event

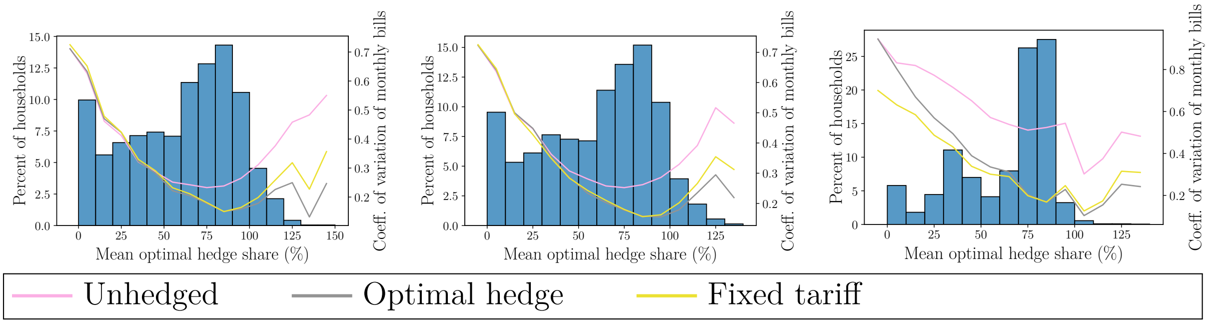
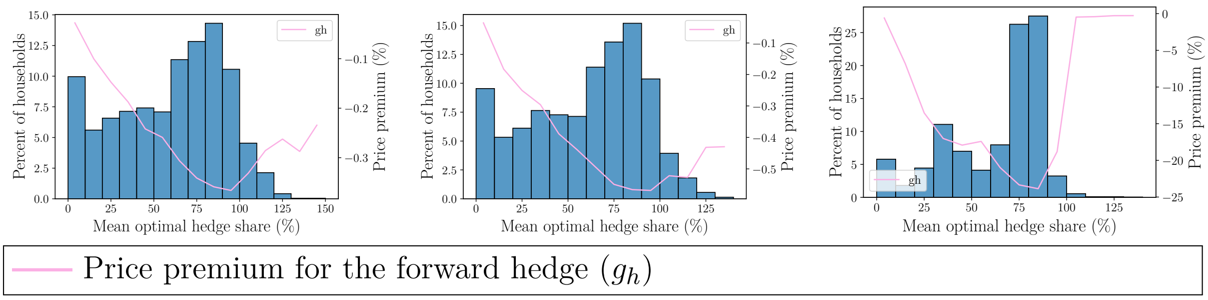


Figure 11: Distribution of average optimal hedge shares by customer and forward hedge price premium g_h by tariff type for different levels of price protection

(a) Baseline results with price cap

(b) Results without price cap

(c) Results without price cap and scarcity event



In Figure 10c, I study how a scarcity event like the Texas winter storm with extremely high prices over multiple days affects hedging and bill volatility. To do so, I run the above simulations while removing the price cap and simulating a four-day scarcity event: I manually choose a very high dynamic price of 3.5£/kWh, which is ten times the current price cap. I set the price for all 192 consecutive time intervals from 12 to 15 January 2021.

Figure 10c highlights that mean optimal hedge shares moderately increase to 63% on average when households experience a scarcity event. The scarcity event mainly induces households with initially low hedge shares to hedge more. When households face a scarcity event, the hedge tariff becomes even more effective in reducing bill volatility. The optimal hedge reduces households coefficients of bill volatility on average by 48% relative to the unhedged tariff with a scarcity event.

Overall, the scarcity event only slightly increases bill volatility on an optimally hedged tariff, as a comparison of Figures 10a and 10c reveals. The average coefficient of variation of bills is 18% higher for the optimally hedged tariff with a scarcity event compared to the optimally hedged tariff with a price cap. In contrast, bill volatility on an unhedged tariff increases by 108% for unhedged tariffs when moving from an unhedged price-capped tariff to an unhedged, fully dynamic tariff with a scarcity event. Surprisingly, the optimally hedged tariff only results in slightly higher bill volatility than the fixed tariff, even if a scarcity event occurs.

Figure 11c points out that the welfare benefits from hedging are substantially larger with a scarcity event. The average welfare benefit with a scarcity event translates to a 19% reduction in mean electricity prices compared to a 0.3% welfare benefit for the price-capped tariff. This illustrates that welfare benefits from hedging might grow in the future since households on dynamic tariffs will likely face more frequent and more extreme scarcity prices.

7 Conclusion

Dynamic electricity prices have an enormous potential to make power markets more efficient since they help align fluctuating electricity demand and supply. However, they expose households to very high electricity prices when supply is scarce. In this paper, I study how to augment dynamic electricity prices with a forward hedge. The forward hedge should protect households from high prices while incentivizing them to adjust their consumption to prices elastically.

Using a utility maximization model, I simulate optimal forward hedge shares for a sample of 2,159 UK households exposed to dynamic prices. My main contribution is that I study the relation between optimal hedge shares and households' price elasticity of demand when they face uncertainty about prices and quantity shocks.

The simulations suggest that the households in my sample should hedge on average 59% of their baseline consumption. Optimal hedge shares differ strongly among households and by time of day. These differences are due to significant variations in the correlation between prices and the desire to consume electricity. Ownership of low-carbon technologies like electric vehicles, solar PV, battery storage, and electric heating is correlated with optimal hedge shares and might contribute to their considerable variation.

The central insight of this paper is that an exogenous increase in price elasticity can increase or decrease hedge shares. Higher price elasticity increases hedge shares when prices and the desire to consume electricity are positively correlated. In this case, the household increases the hedge to ensure that it can maintain an acceptable level of electricity consumption when both prices and its desire to consume are high. In contrast, higher price elasticity reduces hedge shares when the correlation between prices and quantity shocks is negative. Households reduce their hedge shares to raise their exposure to spot prices when spot prices are negatively correlated with their desire to consume.

Optimal forward hedging effectively reduces the volatility of monthly electricity bills by an average of 18%. The reduction in bill volatility is more significant when households face a positive correlation between prices and quantity shocks. The optimal forward hedge can even achieve lower bill volatility than a fixed tariff.

However, despite reducing bill volatility, the welfare gains from optimal forward hedging are minimal. In the main specification, these welfare gains amount to just a 0.3% decrease in mean dynamic electricity prices. Welfare gains from hedging remain small for households with low price-elasticity, high risk-aversion, and even for households with a much larger share of electricity in overall expenditure.

Welfare gains from hedging are much higher and equivalent to a 19% reduction in mean electricity prices when households face a Texas-style scarcity event with extremely high prices. Hedging might become more valuable in the future when extreme weather and price events will occur more often. However, the given model might not fully capture the benefits of protecting households from extreme worst-case events. Real-world households might care more about avoiding extremely high worst-case bills than about maximizing expected consumption utility or minimizing average bill volatility. Further research should therefore analyze how to design optimal forward hedge tariffs that effectively protect against worst-case outcomes.

In addition, the practical implementation of forward hedging requires further study. Most importantly, it needs to be tested whether domestic consumers understand how forward hedging works and which incentives it creates. The experience with the German gas and electricity price breaks suggests that a widespread adoption of forward hedging would require large efforts to educate consumers. Future research also needs to examine the optimal length of the hedge time segments. Moreover, it is crucial to gain a better understanding how to determine households' baseline consumption levels, especially in the absence of historical price-consumption data. The need to determine a baseline consumption level might also reduce competition in retail power markets. Incumbent suppliers have an advantage in estimating baseline consumption based on historical data and customer characteristics. Therefore, regulators should allow households to share their historical price and consumption data with different retailers to ensure all suppliers can offer equally attractive hedged tariffs.

Despite all these challenges, forward contracts will likely play a vital role as a supplement to dynamic electricity prices in the future. Dynamic electricity pricing will become even more relevant for making electricity markets efficient in a world with primarily intermittent electricity supply. However, consumers and politicians have been hesitant to widely adopt dynamic prices up until now. One of the main reasons for this reluctance is that dynamic electricity prices can make households vulnerable to extremely high prices. Forward hedging is a powerful tool to overcome these concerns as it partly shields households from high prices while preserving the incentive to be price-responsive.

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Appendices

A Derivation of the optimal hedge share h^*

In this section, I derive the expressions for the optimal hedge share h^* as given in equations (5) and (8). The derivations follow Gilbert (1985) and Cowan (2004). The first-order condition of the optimization problem in the first stage in equation (3) can be rewritten as (Losq, 1982):

$$E[V_b(\tilde{p}-\overline{p})] = E[V_b(f-\overline{p})] \tag{A.1}$$

One can approximate V_b by a first-order Taylor approximation of V_b about $(\overline{p},\overline{\varepsilon})$.

$$V_b \approx \overline{V}_b + \overline{V}_{b\tilde{p}}(\tilde{p}-\overline{p}) + \overline{V}_{bb}h(\tilde{p}-\overline{p}) + \overline{V}_{b\tilde{\varepsilon}}(\tilde{\varepsilon}-\overline{\varepsilon}) \tag{A.2}$$

Plugging equation (A.2) into (A.1) leads to:

$$\overline{V}_{b\tilde{p}}E[(\tilde{p}-\overline{p})^2] + \overline{V}_{bb}hE[(\tilde{p}-\overline{p})^2] + \overline{V}_{b\tilde{\varepsilon}}E[(\tilde{\varepsilon}-\overline{\varepsilon})(\tilde{p}-\overline{p})] = \overline{V}_b(f-\overline{p})$$

where $E[(\tilde{\varepsilon}-\overline{\varepsilon})] = 0$ and $E[(\tilde{p}-\overline{p})] = 0$ because $E[\tilde{p}] = \overline{p}$ and $E[\tilde{\varepsilon}] = \overline{\varepsilon}$.

With $\sigma^2_{\tilde{p}} = E[(\tilde{p}-\overline{p})^2]$ and $\sigma_{\tilde{p}\tilde{\varepsilon}} = E[(\tilde{\varepsilon}-\overline{\varepsilon})(\tilde{p}-\overline{p})]$ one can solve for the absolute optimal hedge quantity h^*:

$$h^* = -\frac{\overline{V}_{b\tilde{p}}}{\overline{V}_{bb}} - \frac{\overline{V}_{b\tilde{\varepsilon}}}{\overline{V}_{bb}}\frac{\sigma_{\tilde{p}\tilde{\varepsilon}}}{\sigma^2_{\tilde{p}}} + \frac{\overline{V}_b}{\overline{V}_{bb}}\frac{(f-\overline{p})}{\sigma^2_{\tilde{p}}} \tag{A.3}$$

As discussed in Section 3.1, the last term of the above equation equals zero since I assume that households do not hedge for speculative reasons, i.e., households believe that the forward hedge price f equals the mean dynamic price $\overline{p}$.

In the next step, I aim to express the optimal hedge quantity h^* in equation (A.3) as a share of the baseline consumption level $\hat{x}^* = x^*(\overline{p},b,\overline{\varepsilon})$. At baseline, Roy's identity is given as $\hat{x}^* = -\frac{\overline{V}_{\tilde{p}}}{\overline{V}_b}$.[18] Following Turnovsky et al. (1980) and Gilbert (1985), one can differentiate Roy's identity at baseline with respect to b, which leads to

$$\begin{aligned}\overline{V}_{b\tilde{p}} &= -\overline{V}_{bb} - \overline{V}_b\frac{\partial \hat{x}^*}{\partial b}\\ \overline{V}_{b\tilde{p}} &= (\theta-\eta)\hat{x}^*\frac{\overline{V}_b}{b}\end{aligned} \tag{A.4}$$

[18]In general, Roy's identity with a forward hedge is given as $x^* - h = -\frac{V_{\tilde{p}}}{V_b}$ (Gilbert, 1985).

$\eta = \frac{\partial \hat{x}^*}{\partial b}\frac{b}{\hat{x}^*}$ is the income elasticity of electricity demand, and $\theta = -\frac{\overline{V}_{bb}}{\overline{V}_b}b$ is the coefficient of relative risk aversion at baseline consumption. Inserting equation (A.4) into (A.3) gives

$$h^* = (1-\frac{\eta}{\theta})\hat{x}^* - \frac{\overline{V}_{b\tilde{\varepsilon}}}{\overline{V}_{bb}}\frac{\sigma_{\tilde{p}\tilde{\varepsilon}}}{\sigma^2_{\tilde{p}}} \tag{A.5}$$

For the simulation of optimal hedge shares, I assume that the following CES indirect utility function can describe households' consumption decisions.

$$V(\tilde{p},b,\tilde{\varepsilon},f,h) = \frac{1}{1-\theta}[b+(\tilde{p}-f)h^*]^{1-\theta}(\tilde{\varepsilon}\tilde{p}^{1-\alpha}+1)^{\frac{1-\theta}{\alpha-1}} \tag{A.6}$$

Applying Roy's identity, the Marshallian demand functions are given as

$$\begin{aligned} x^* &= \frac{[b+(\tilde{p}-f)h^*]\tilde{\varepsilon}\tilde{p}^{-\alpha}}{(\tilde{\varepsilon}\tilde{p}^{1-\alpha}+1)} \\ y^* &= \frac{[b+(\tilde{p}-f)h^*]}{(\tilde{\varepsilon}\tilde{p}^{1-\alpha}+1)} \end{aligned} \tag{A.7}$$

The first derivative of $V = V(\tilde{p},b,\tilde{\varepsilon},f,h)$ with respect to b is

$$V_b = [b+(\tilde{p}-f)h^*]^{-\theta}(\tilde{\varepsilon}\tilde{p}^{1-\alpha}+1)^{\frac{1-\theta}{\alpha-1}} \tag{A.8}$$

Taking the derivative of V_b with respect to b and $\tilde{\varepsilon}$, respectively, gives

$$V_{bb} = -\theta[b+(\tilde{p}-f)h^*]^{-\theta-1}(\tilde{\varepsilon}\tilde{p}^{1-\alpha}+1)^{\frac{1-\theta}{\alpha-1}} \tag{A.9}$$

$$V_{b\tilde{\varepsilon}} = [b+(\tilde{p}-f)h^*]^{-\theta}\frac{1-\theta}{\alpha-1}(\tilde{\varepsilon}\tilde{p}^{1-\alpha}+1)^{\frac{1-\theta}{\alpha-1}-1}\tilde{p}^{1-\alpha} \tag{A.10}$$

Evaluating equations (A.9) and (A.10) at baseline (with $\tilde{p} = \overline{p} = f$ and $\tilde{\varepsilon} = \overline{\varepsilon}$) leads to

$$\frac{\overline{V}_{b\tilde{\varepsilon}}}{\overline{V}_{bb}} = \left(1-\frac{1}{\theta}\right)\frac{1}{\alpha-1}\hat{x}^*\frac{\overline{p}}{\overline{\varepsilon}} \tag{A.11}$$

Moreover, from equation (A.7) one can derive the income elasticity of demand at baseline $\eta = \frac{\partial \hat{x^*}}{\partial b}\frac{b}{\hat{x^*}} = 1$. The optimal hedge equation (A.5) can then be rewritten as

$$\begin{aligned} h^* &= \left(1-\frac{1}{\theta}\right)\hat{x}^* + \left(1-\frac{1}{\theta}\right)\frac{1}{1-\alpha}\hat{x}^*\frac{\overline{p}}{\overline{\varepsilon}}\frac{\sigma_{\tilde{p}\tilde{\varepsilon}}}{\sigma^2_{\tilde{p}}} \\ \frac{h^*}{\hat{x}^*} &= \left(1-\frac{1}{\theta}\right) * \left(1+\frac{1}{1-\alpha}\rho\frac{cv(\tilde{\varepsilon})}{cv(\tilde{p})}\right) \end{aligned} \tag{A.12}$$

which equals the optimal hedge share in equation (8). $\sigma_{\tilde{p}}$ and $\sigma_{\tilde{\varepsilon}}$ denote the standard deviations of $\tilde{p}$ and $\tilde{\varepsilon}$. Moreover, $cv(\tilde{p}) = \frac{\sigma_{\tilde{p}}}{\bar{p}}$ and $cv(\tilde{\varepsilon}) = \frac{\sigma_{\tilde{\varepsilon}}}{\bar{\varepsilon}}$ are the coefficients of variations of $\tilde{p}$ and $\tilde{\varepsilon}$, respectively.

B Derivation of the price premia

In this appendix, I derive the expressions for the price premia g_p and g_f as defined in equations (12) and (14), respectively.

Derivation of g_p:

g_p equals the percentage increase in fixed price $\overline{p}$ that makes the household indifferent in expectation between the fixed tariff and the unhedged dynamic tariff with stochastic price $\tilde{p}$ (Gilbert, 1985).

$$E[V((1+g_p)\overline{p},b,\tilde{\varepsilon})] = E[V(\tilde{p},b,\tilde{\varepsilon})] \tag{B.1}$$

On the unhedged dynamic tariff and the fixed tariff, the household does not hedge, i.e., $h=0$. A first-order Taylor approximation of the LHS of equation (B.1) yields

$$\begin{aligned} V((1+g_p)\overline{p},b,\tilde{\varepsilon}) &\approx \overline{V} + \overline{V}_{\tilde{p}} * E[(1+g_p)\overline{p} - \overline{p}] \\ &\approx \overline{V} + \overline{V}_{\tilde{p}} * g_p\overline{p} \end{aligned}$$

A second-order Taylor approximation of the RHS of equation (B.1) about $(\overline{p},\overline{\varepsilon})$ yields

$$\begin{aligned} V(\tilde{p},b,\tilde{\varepsilon}) \approx\; & \overline{V} + \overline{V}_{\tilde{p}}E[\tilde{p}-\overline{p}] + \overline{V}_{\tilde{\varepsilon}}E[\tilde{\varepsilon}-\overline{\varepsilon}] \\ & + \frac{1}{2}\overline{V}_{\tilde{p}\tilde{p}}E[(\tilde{p}-\overline{p})^2] + \frac{1}{2}\overline{V}_{\tilde{\varepsilon}\tilde{\varepsilon}}E[(\tilde{\varepsilon}-\overline{\varepsilon})^2] \\ & + \overline{V}_{\tilde{\varepsilon}\tilde{p}}E[(\tilde{\varepsilon}-\overline{\varepsilon})(\tilde{p}-\overline{p})] \\ \approx\; & \overline{V} + \frac{1}{2}(\overline{V}_{\tilde{p}\tilde{p}}\sigma^2_{\tilde{p}} + \overline{V}_{\tilde{\varepsilon}\tilde{\varepsilon}}\sigma^2_{\tilde{\varepsilon}}) + \overline{V}_{\tilde{\varepsilon}\tilde{p}}\sigma_{\tilde{\varepsilon}\tilde{p}} \end{aligned}$$

The term $\overline{V}_{\tilde{\varepsilon}\tilde{\varepsilon}}$ above can be neglected for comparing the relative welfare between the two price regimes. $\overline{V}_{\tilde{\varepsilon}\tilde{\varepsilon}}$ is not affected when moving from fixed to dynamic prices. Therefore, it does not affect the relative welfare difference between the fixed and dynamic prices measured by g_p (Gilbert, 1985). Inserting the Taylor approximations into equation (B.1) and solving for g_p leads to

$$g_p = \frac{1}{2}\frac{\overline{V}_{\tilde{p}\tilde{p}}}{\overline{V}_{\tilde{p}}\overline{p}}\sigma^2_{\tilde{p}} + \frac{\overline{V}_{\tilde{\varepsilon}\tilde{p}}}{\overline{V}_{\tilde{p}}\overline{p}}\sigma_{\tilde{p}\tilde{\varepsilon}} \tag{B.2}$$

Using the indirect CES utility function (10) for unhedged households ($h^* = 0$), the relevant derivatives can be derived as

$$
\begin{aligned}
V_{\tilde{p}} &= \frac{1}{\alpha-1} b^{1-\theta} (\tilde{\varepsilon}\tilde{p}^{1-\alpha}+1)^{\frac{1-\theta}{\alpha-1}-1}(1-\alpha)\tilde{\varepsilon}\tilde{p}^{-\alpha} \\
&= -V_b x^* && \text{(B.3)} \\
V_{\tilde{\varepsilon}} &= \frac{1}{\alpha-1} b^{1-\theta} (\tilde{\varepsilon}\tilde{p}^{1-\alpha}+1)^{\frac{1-\theta}{\alpha-1}-1}\tilde{p}^{(1-\alpha)} \\
V_{\tilde{\varepsilon}\tilde{p}} &= -b^{1-\theta} (\tilde{\varepsilon}\tilde{p}^{1-\alpha}+1)^{\frac{1-\theta}{\alpha-1}-1}\tilde{p}^{-\alpha}[\frac{\beta^u}{1-\alpha}+1-\hat{s}] \\
&= \frac{V_{\tilde{p}}}{\tilde{\varepsilon}}[\frac{\beta^u}{1-\alpha}+1-\hat{s}] && \text{(B.4)}
\end{aligned}
$$

Moreover, Turnovsky et al. (1980) and Cowan (2004) show that differentiating Roy's identity $V_{\tilde{p}} = -\hat{x}^* V_b$ w.r.t. $\tilde{p}$ results in

$$V_{\tilde{p}\tilde{p}} = -\frac{\partial \hat{x}^*}{\partial \tilde{p}} V_b - \hat{x}^* V_{b\tilde{p}} \qquad \text{(B.5)}$$

Inserting Roy's identity at baseline $V_b = -\frac{V_{\tilde{p}}}{\hat{x}^*}$ and equation (A.4) into the above equation (B.5) gives the absolute value of Turnovsky et al.'s (1980) coefficient of relative price risk aversion

$$\frac{\overline{V}_{\tilde{p}\tilde{p}}}{\overline{V}_{\tilde{p}}}\overline{p} = \hat{\gamma} + \hat{s}(\theta-\eta) \qquad \text{(B.6)}$$

Plugging equations (B.3), (B.4), and (B.6) into equation (B.2) and evaluating them at baseline leads to

$$
\begin{aligned}
g_p &= \frac{1}{2}\frac{\overline{V}_{\tilde{p}\tilde{p}}}{\overline{V}_{\tilde{p}}}\overline{p}\frac{\sigma^2_{\tilde{p}}}{\overline{p}^2} + \frac{\sigma_{\tilde{p}}}{\overline{p}}\frac{\sigma_{\tilde{\varepsilon}}}{\overline{\varepsilon}}\sigma_{\tilde{p}\tilde{\varepsilon}}[\frac{\beta^u}{1-\alpha}+1-\hat{s}] \\
&= \frac{1}{2}[\hat{\gamma}+\beta^u]cv(\tilde{p})^2 + \rho cv(\tilde{p})cv(\tilde{\varepsilon})[\frac{\beta^u}{1-\alpha}+1-\hat{s}]
\end{aligned}
$$

The above equals the price premium for the unhedged dynamic tariff in equation (12). $\beta^u = \frac{\partial \overline{V}_b}{\partial \tilde{p}}\frac{\overline{p}}{\overline{V}_b} = (\theta-1)s$ is the price elasticity of the marginal utility of income at baseline for unhedged households.

Derivation of g_f:

g_f denotes the percentage increase in fixed price $\overline{p}$ that makes the household indifferent in expectation between the fixed tariff and the optimally hedged dynamic tariff (Gilbert, 1985).

$$E[V((1+g_f)\overline{p}, b, \tilde{\varepsilon})] = E[V(\tilde{p}, b+(p-f)h^*, \tilde{\varepsilon})] \qquad \text{(B.7)}$$

A second-order Taylor approximation of the RHS of equation (B.7) about $(\overline{p},\overline{\varepsilon})$ yields

$$\begin{aligned} V(\tilde{p},b,\tilde{\varepsilon}) &\approx \overline{V}+\overline{V}_{\tilde{p}}E[\tilde{p}-\overline{p}]+\overline{V}_bE[\tilde{p}-\overline{p}]h^*+\overline{V}_{\tilde{\varepsilon}}E[\tilde{\varepsilon}-\overline{\varepsilon}] \\ &\quad +\frac{1}{2}\overline{V}_{\tilde{p}\tilde{p}}E[(\tilde{p}-\overline{p})^2]+\frac{1}{2}\overline{V}_{b\tilde{p}}E[(\tilde{p}-\overline{p})^2]h^*+\frac{1}{2}\overline{V}_{\tilde{\varepsilon}\tilde{\varepsilon}}E[(\tilde{\varepsilon}-\overline{\varepsilon})^2] \\ &\quad +\overline{V}_{\tilde{\varepsilon}\tilde{p}}E[(\tilde{p}-\overline{p})*(\tilde{\varepsilon}-\overline{\varepsilon})] \\ &\approx \overline{V}+\frac{1}{2}(\overline{V}_{\tilde{p}\tilde{p}}\sigma_{\tilde{p}}^2+\overline{V}_{\tilde{\varepsilon}\tilde{\varepsilon}}\sigma_{\tilde{\varepsilon}}^2)+\overline{V}_{\tilde{\varepsilon}\tilde{p}}\sigma_{\tilde{p}\tilde{\varepsilon}}+\frac{1}{2}\overline{V}_{b\tilde{p}}h^*\sigma_{\tilde{p}}^2 \end{aligned}$$

Following analogous steps as for g_p, g_f is given as

$$g_f=\frac{1}{2}\frac{\overline{V}_{\tilde{p}\tilde{p}}}{\overline{V}_{\tilde{p}}\overline{p}}\sigma_{\tilde{p}}^2+\frac{\overline{V}_{\tilde{\varepsilon}\tilde{p}}}{\overline{V}_{\tilde{p}}\overline{p}}\sigma_{\tilde{p}\tilde{\varepsilon}}+\frac{1}{2}\frac{\overline{V}_{b\tilde{p}}}{\overline{V}_{\tilde{p}}\overline{p}}h^*\sigma_{\tilde{p}}^2 \tag{B.8}$$

The first two terms of the above expression equal the ones for g_p in equation (B.2). However, when optimally hedged, Roy's identity changes to (Gilbert, 1985)

$$V_{\tilde{p}}=-V_b(x^*-h^*) \tag{B.9}$$

Differentiating expression (B.9) with respect to b yields

$$\begin{aligned} V_{b\tilde{p}}=V_{\tilde{p}b} &= -V_{bb}(x^*-h^*)-V_b\frac{\partial x^*}{\partial b} \\ &= -V_{bb}x^*-\overline{V}_{bb}\frac{\overline{V}_b}{\overline{V}_{bb}b}\frac{\partial x^*}{\partial b}\frac{b}{x^*}x^*+V_{bb}h^* \\ &= -V_{bb}(\frac{\theta-1}{\theta})x^*+V_{bb}h^* \end{aligned}$$

Evaluating the above equation at baseline with $\eta=1$ and using the optimal hedge quantity $h^*=(1-\frac{1}{\theta})\hat{x}^*\left(1+\frac{1}{1-\alpha}\rho\frac{cv(\tilde{\varepsilon})}{cv(\tilde{p})}\right)$ gives

$$\overline{V}_{b\tilde{p}}=-V_{bb}(\frac{\theta-1}{\theta})\hat{x}^*+V_{bb}(\frac{\theta-1}{\theta})\hat{x}^*+V_{bb}(\frac{\theta-1}{\theta})\hat{x}^*\left(\frac{1}{1-\alpha}\rho\frac{cv(\tilde{\varepsilon})}{cv(\tilde{p})}\right) \tag{B.10}$$

$$=-\frac{\beta^u}{1-\alpha}\frac{\overline{V}_b}{\overline{p}}\rho\frac{cv(\tilde{\varepsilon})}{cv(\tilde{p})} \tag{B.11}$$

where $\beta^u=\overline{V}_{b\tilde{p}}\frac{p}{V_b}=(\theta-1)s$ is the price-elasticity of marginal utility of income for the unhedged household (when $h^*=0$). As shown above, one can derive an expression for $V_{\tilde{p}\tilde{p}}$ from Roy's identity in equation (B.9) as

$$\begin{aligned} V_{\tilde{p}\tilde{p}} &= -x_{\tilde{p}}^*V_b-V_{b\tilde{p}}(x^*-h^*) \\ &= -\gamma\frac{x^*}{p}V_b+V_{b\tilde{p}}\frac{V_{\tilde{p}}}{V_b} \end{aligned}$$

Evaluating the above expression at baseline and using (B.11), one gets

$$\overline{V}_{\tilde{p}\tilde{p}} = \gamma \frac{\overline{V}_{\tilde{p}}}{\overline{p}} - \frac{\beta^u}{1-\alpha}\rho \frac{cv(\tilde{\varepsilon})}{cv(\tilde{p})} \frac{\overline{V}_{\tilde{p}}}{\overline{p}} \tag{B.12}$$

where I used that at baseline, Roy's identity is $\hat{x}^* = -\frac{\overline{V}_{\tilde{p}}}{\overline{V}_b}$. Hence,

$$\frac{\overline{V}_{\tilde{p}\tilde{p}}}{\overline{V}_{\tilde{p}}\overline{p}} \sigma_{\tilde{p}}^2 = \gamma cv(\tilde{p})^2 - \frac{\beta^u}{1-\alpha}\rho cv(\tilde{p}) cv(\tilde{\varepsilon}) \tag{B.13}$$

From equation (B.11) it also follows that

$$\begin{aligned} \frac{\overline{V}_{b\tilde{p}}}{\overline{V}_{\tilde{p}}\overline{p}} h^* \sigma_{\tilde{p}}^2 &= -\frac{\beta^u}{1-\alpha} \frac{\overline{V}_b}{\overline{V}_{\tilde{p}}} \rho cv(\tilde{\varepsilon}) cv(\tilde{p}) h^* \\ &= \frac{\beta^u}{1-\alpha} \rho cv(\tilde{\varepsilon}) cv(\tilde{p}) \frac{h^*}{\hat{x}^*} \end{aligned} \tag{B.14}$$

Moreover, one also needs to derive expressions for $\overline{V}_{\tilde{\varepsilon}\tilde{p}}$ when optimally hedged. Following the same steps as for g_p above, one can show that for the optimally hedged tariff, $\overline{V}_{\tilde{\varepsilon}\tilde{p}}$ is equivalent to equations (B.4) for the unhedged dynamic tariff when evaluated at baseline. Therefore, one can plug equations (B.4), (B.13), and (B.14) into equation (B.8) to obtain

$$\begin{aligned} g_f &= \frac{1}{2}\gamma cv(\tilde{p})^2 + \rho cv(\tilde{p}) cv(\tilde{\varepsilon})[\frac{\beta^u}{1-\alpha} + 1 - \hat{s}] \\ &\quad - \frac{1}{2}\frac{\beta^u}{1-\alpha}\rho cv(\tilde{p}) cv(\tilde{\varepsilon}) + \frac{1}{2} * \frac{\beta^u}{1-\alpha}\rho cv(\tilde{p}) cv(\tilde{\varepsilon}) \frac{h^*}{\hat{x}^*} \\ &= \underbrace{\frac{1}{2}[\hat{\gamma} + \beta^u] cv(\tilde{p})^2 + \rho cv(\tilde{p}) cv(\tilde{\varepsilon})[\frac{\beta^u}{1-\alpha} + 1 - \hat{s}]}_{g_p} - \frac{1}{2}\beta^u cv(\tilde{p})^2 \\ &\quad - \frac{1}{2}\frac{\beta^u}{1-\alpha}\rho cv(\tilde{p}) cv(\tilde{\varepsilon}) \left(1 - \frac{h^*}{\hat{x}^*}\right) \\ &= g_p - \frac{1}{2}\beta^u cv(\tilde{p})^2 - \frac{1}{2}\frac{\beta^u}{1-\alpha}\rho cv(\tilde{p}) cv(\tilde{\varepsilon}) \left(1 - \frac{h^*}{\hat{x}^*}\right) \end{aligned}$$

This expression equals the price premium for the optimally hedged tariff in equation (14).

C Robustness checks for different hedge time segments

In this appendix, I analyze the effect of choosing different hedge time segments on optimal hedge shares and bill volatility. As explained in Section 4, I define a hedge time segment for every half hour per day separately for weekdays and weekends in my main specification. For instance, 8-8:30 am on weekdays is a time segment. 8-8:30 am on weekends is a different time segment. In my main specification, I end up with 96 distinct time segments for all 48 half-hourly periods on weekends and weekdays, respectively.

Table 5: Description of different hedge time segments

Time segment definition	**Description**	**Number of segments per customer**
Season and half hour	customer-season-weekend-half hour	384
Main specification	customer-weekend-half hour	96
Season and time of day	customer-season-weekend-time of day	32
Time of day	customer-weekend-time of day	8
Season	customer-season-weekend	8
None	customer	1

I can define even more fine-grained time segments by differentiating the main specification by season as shown in Table 5.[19] For instance, the specification "Season and half an hour" defines 8-8:30 am on weekdays in February as a time segment and 8-8:30 am on weekdays in June as another segment. As Table 5 highlights this leads to 384 (4*96) segments per customer.

The specification "Season and time of day" leads to less fine-grained time segments. This specification differentiates by season, but groups periods in broader time of day categories.[20] For instance, 8-8:30 am on weekdays in February would fall in the winter-morning-weekday time segment. This specification results in 32 different time segments.

The specification "Time of day" only differentiates between time of days and weekday/weekends. Thus, 8-8:30 am on weekdays in February would be the same time segment as 8-8:30 am on weekdays in June.

In contrast "Season" differentiates by season and weekday/weekends but not by time of day. In this specification, 8-8:30 am on weekdays in February is the same segment as 20-20:30 am on weekdays in March but a different segment than 8-8:30 am on weekdays

[19] I define "winter" as January to March, "spring" as April to June, "summer" as July to September, and "autumn" as October to December.

[20] I define "night" from midnight to 6:00, "morning" from 6:00 to 12:00, "afternoon" from noon to 18:00, and evening from 18:00 to 24:00.

in June. The specifications "Time of day" and "Season" lead to 8 segments per customer, respectively.

Finally, the specification "None" is the less fine-grained as it counts all time intervals into the same time segment. This assumes that customers buy the same quantity forward for every time interval.

Figure 12: Distribution of optimal hedge shares across all customers by hedge time segment specification

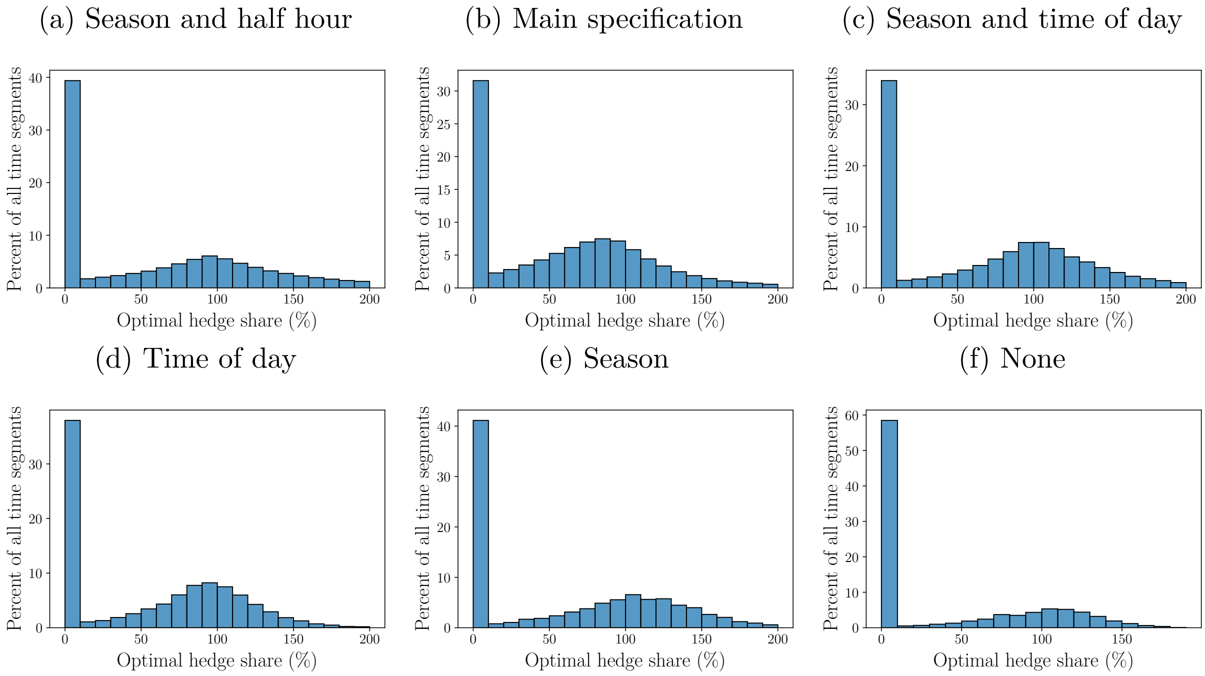
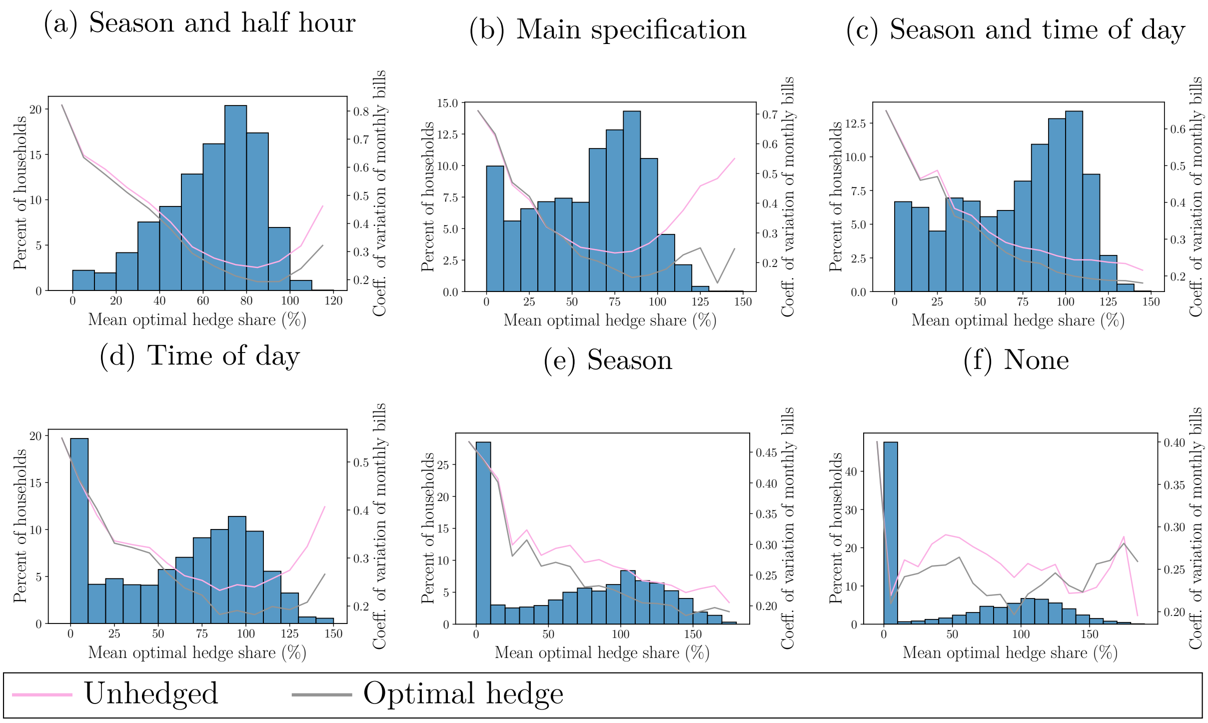


Figure 12 highlights that the distribution of optimal hedge shares across all customers is very similar for the different hedge time segment specifications. The average optimal hedge share ranges between 52% ("None") and 70% ("Season and time of day"). The less fine-grained the hedge specification, the smaller is the share of very large hedge shares (greater 150%) and the larger is the share of hedge shares that I set to zero.

Figure 13 shows the coefficients of variations of monthly electricity bills for unhedged and optimally hedged tariffs across mean optimal hedge shares per households for the different hedge time segment specifications. This figure reveals an even clearer trend in mean optimal hedge ratios. The less fine-grained the time segments, the more dispersed are the mean optimal hedge ratios between customers. Without any time segments ("None") more than 40% of households does not hedge at all while a substantial share of households chooses a mean optimal hedge share larger than 100%.

As expected, less-fine grained time segments are less effective in reducing bill volatility. Without any time-segments ("None") the optimally hedged tariff tends to reduce the coefficient of variation of monthly bills only by 3% relative to the unhedged tariff. The fine-grained main specification leads to a much larger reduction in bill volatility of 19% when moving from the unhedged to the optimally hedged tariff. Interestingly, the even more fine-grained specification “Season and half hour” achieves only a smaller reduction in bill volatility of 14%. Hence, while an increase in granularity of time segments seems to overall reduce bill volatility, too granular specification seem to raise volatility.

Figure 13: Distribution of average optimal hedge shares by customer and coefficients of variation of monthly bills by hedge time segments



D Dynamic prices with removed price cap

This appendix explains how Octopus Energy calculates dynamic prices and provides descriptive statistics for day-ahead and dynamic prices. Dynamic prices are tied to day-ahead electricity prices. Figure 14 shows the distribution of the half-hourly electricity day-ahead prices for the Great Britain (GB) price zone during the sample period obtained from EPEX SPOT (2023). Day-ahead prices are relatively low and rarely exceed 20 p/kWh. However, while overall volatility is small, there are a few significant price spike hours in which day-ahead prices are very high. Figure 15 reveals that day-ahead prices remain on average roughly stable over time during the study period.

Figure 14: Relative distribution of day-ahead electricity prices in the GB price zone (EPEX SPOT, 2023)

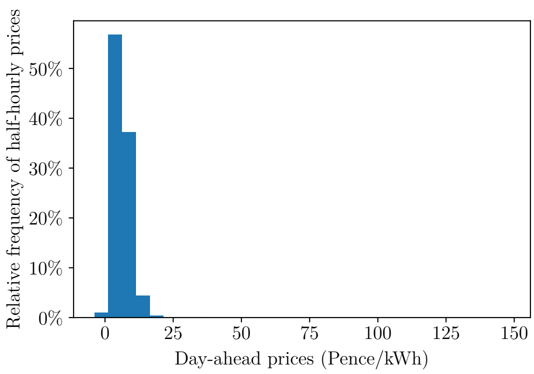
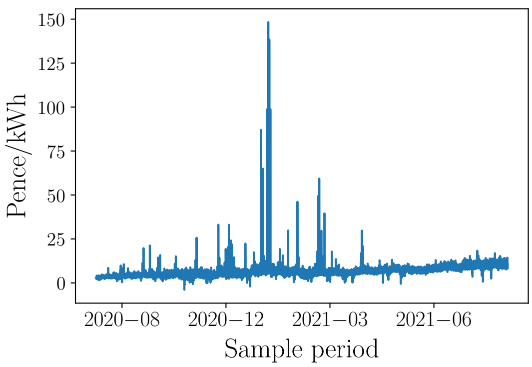


Figure 15: Half-hourly day-ahead electricity prices in the Great Britain price zone (EPEX SPOT, 2023)



Dynamic prices are based on day-ahead prices. In addition, they contain distribution charges and a peak-time premium. For every half-hourly interval, the day-ahead price is multiplied by a distribution charge multiplier that ranges from 2 to 2.4, depending on the grid supply area the household is located in. Between 4 pm and 7 pm, a peak-time premium is added that ranges from 11p to 14p, depending on the grid supply area. Afterward, VAT is added. The resulting price is the dynamic price for the respective half-hourly interval unless it exceeds the price cap of 35 p/kWh. If the calculated price exceeds the price cap, the dynamic price is set to 35 p/kWh (Octopus Energy, 2019).

For 0.3 percent of the half-hourly intervals, households received weakly negative prices due to excess supply in the day-ahead market. I exclude these rare weakly negative price events since the model in Section 3 only applies to positive prices.

Figure 16: Relative distribution of dynamic prices with price cap

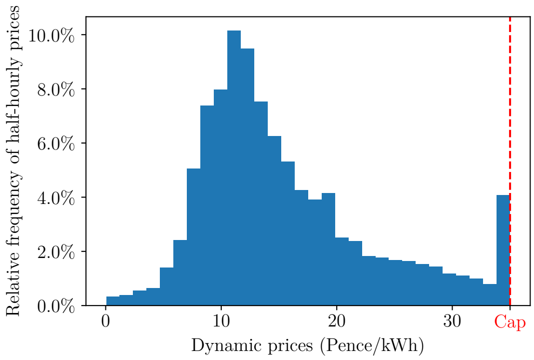


Figure 17: Relative distribution of dynamic prices without price cap

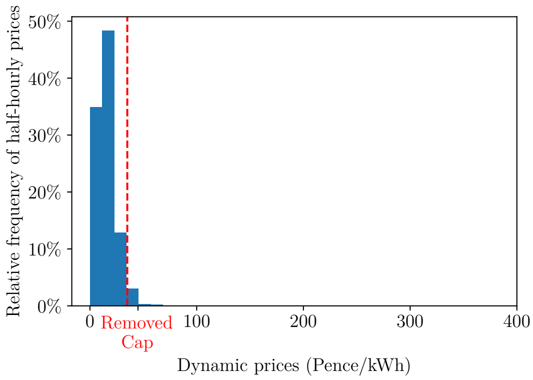
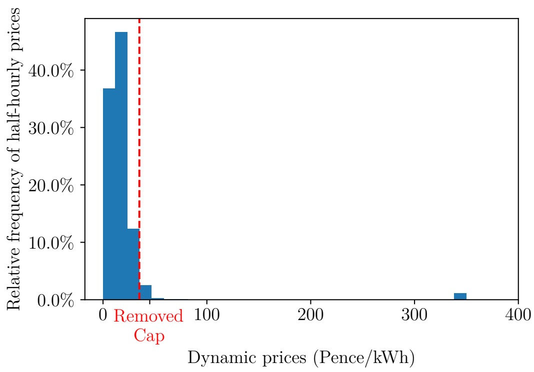


Figure 16 shows the distribution of dynamic prices that households on dynamic tariff actually paid with a price cap for the first grid supply area.[21] The graph reveals that dynamic prices are quite volatile on a relatively low level below the price cap. Figure 17 shows the distribution of dynamic prices when removing the price cap. While dynamic prices only exceed the price cap in 3% of the half-hourly time intervals, the uncapped distribution has a very long tail that consists of a few rare very high prices.

Figure 18: Relative distribution of dynamic prices without price cap and with scarcity event



Moreover, Figure 18 reveals that the distribution of dynamic prices hardly changes when households are exposed to the scarcity event. As explained in Section 6.5, I simulate a four-day scarcity event by removing the price cap and manually setting the dynamic price to 350p/kWh for all 192 consecutive time intervals from 12 to 15 January 2021. I choose the scarcity price to equal ten times the price cap. These simulated scarcity prices account for only 1% of half-hourly dynamic prices.

Table 6 compares the distribution of the dynamic prices with and without a price cap

[21] Dynamic prices for other grid supply areas slightly differ due to minor differences in grid charges and peak-time premia.

and with a scarcity event. The table highlights that the removal of the price cap and the scarcity event have only small effects on the mean of the dynamic prices, but a much larger effect on their standard deviation (SD) due to much higher maximum values.

Table 6: Distribution of different dynamic prices and fixed prices (pence/kWh)

Tariff type	mean	SD	min	1%	10%	25%	50%	75%	90%	99%	max
Dynamic capped	15.4	7.4	0.0	3.1	8.1	10.4	13.3	18.7	27.3	35.0	35.0
Dynamic removed cap	15.8	11.4	0.0	3.1	8.1	10.3	13.1	18.5	27.0	43.1	386.4
Dynamic scarcity event	20.1	40.0	0.0	3.1	8.1	10.3	13.1	18.7	27.9	350.0	350.0
Fixed	15.1	0.1	10.5								19.9

E Additional results for different shares of electricity in household expenditure

This appendix tests the robustness of the optimal hedge shares to varying the assumption with respect to the average share of electricity $\bar{s}_k$ in household expenditure in hedge time segment k. In the main specification, I assume that each household spends on average $\bar{s}_k = 2\%$ of its household budget on electricity in every hedge time segment (see discussion Section 4). In this section, I test how the optimal hedge shares and bill volatility change when changing $\bar{s}_k$ to 1%, 5%, and 10%, respectively.

Figure 19: Distribution of average optimal hedge shares by customer and coefficients of variation of monthly bills by tariff type for different average segment budget shares $\bar{s}_k$

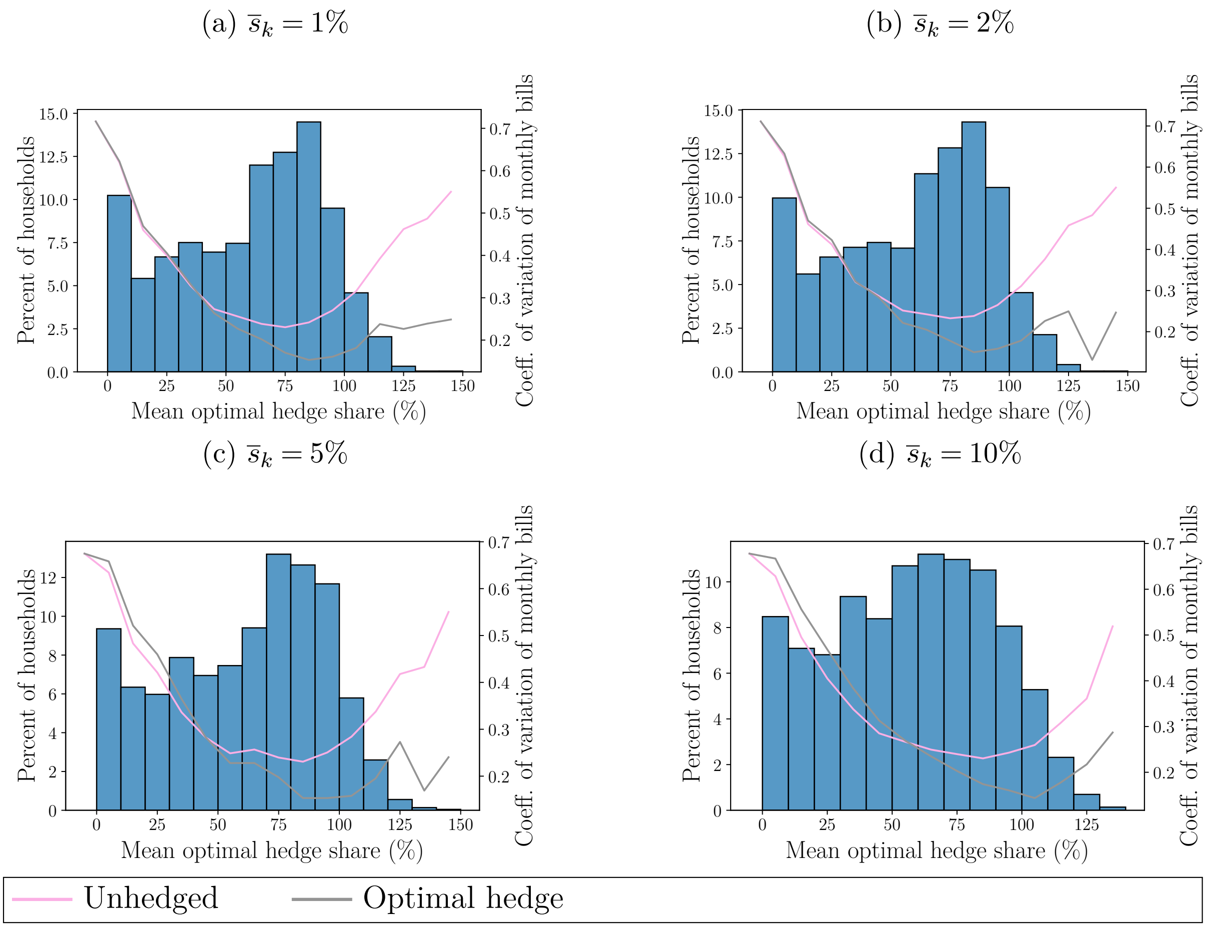
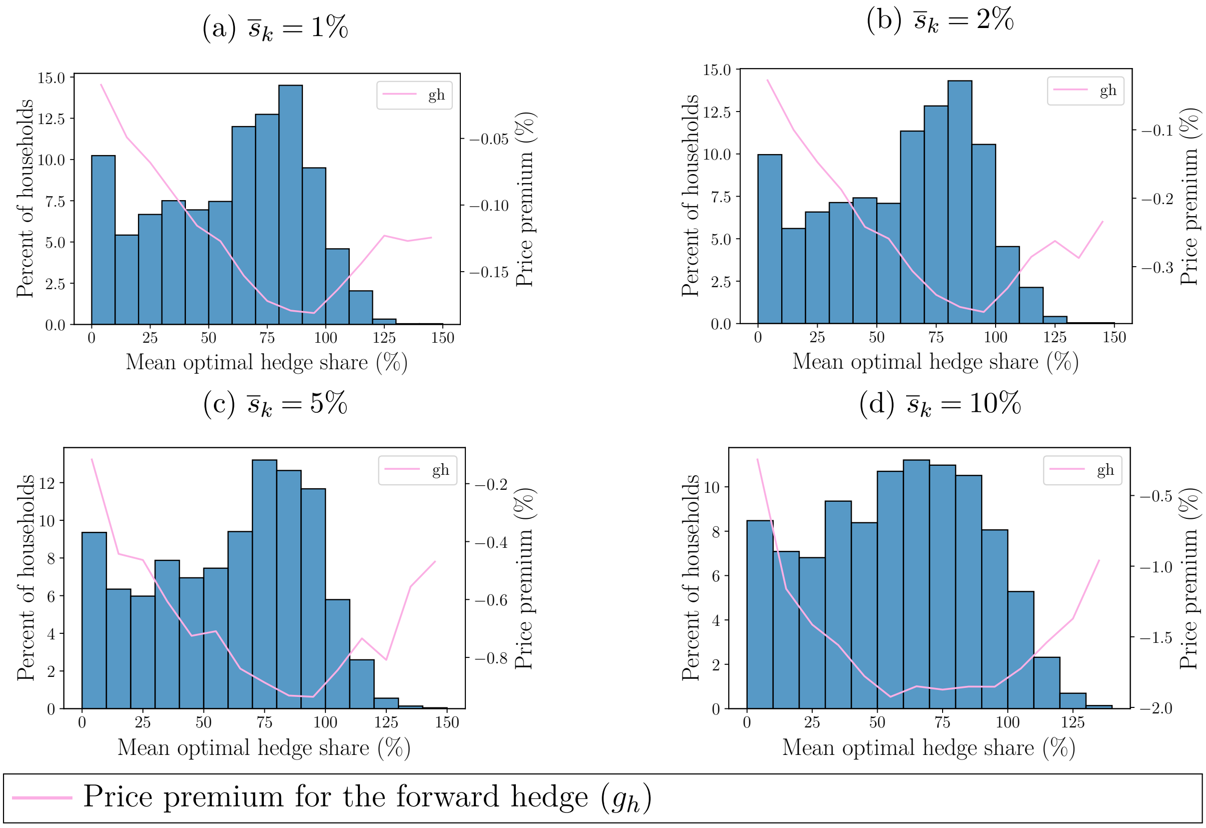


Figure 19 highlights that the mean optimal hedge shares hardly changes when the average time segment budget share $\bar{s}_k$ rises. For $\bar{s}_k = 1\%$, households' mean optimal hedge share is on average 59% compared to 57% when $\bar{s}_k = 10\%$. However, the variance in mean optimal hedge shares between households slightly rises.

The figure also shows that the bill volatility for households on the optimally hedged tariff increases relative to the unhedged tariff when $\bar{s}_k$ increases. For small segment budget shares of $\overline{s}_k = 1\%$, the optimal hedged tariff achieves on average a 19% lower coefficient of variation of monthly electricity bills than the unhedged tariff compared to 5% when $\overline{s}_k = 10\%$.

On the other hand, Figure 20 points out that an increase in budget share raises the welfare benefits from hedging. For small segment budget shares ($\overline{s}_k = 1\%$), the average welfare benefit achieved by the forward hedge only amounts to a 0.13% decrease in mean electricity prices. For large budget shares ($\overline{s}_k = 10\%$), the welfare benefits climbs to 1.6%.

Figure 20: Distribution of average optimal hedge shares by customer and hedge price premium g_h for different average segment budget shares $\overline{s}_k$



F Additional results for the price premia when increasing electricity's expenditure share

Figure 21 shows the price premium households are willing to pay for the forward hedge when electricity's expenditure share increases from $\overline{s}_k = 2\%$ to $\overline{s}_k = 10\%$.

The graph indicates that increasing the portion of expenditure on electricity to $\overline{s}_k = 10\%$ only has a marginal impact on enhancing the welfare advantages of hedging. For the main specification with $\alpha = 0.1$, the larger expenditure share of $\overline{s}_k = 10\%$ leads to a welfare improvement that corresponds to a decrease of 1.6% in the average electricity price, as opposed to a 0.3% decrease observed when the expenditure share on electricity remains at 2%.

Figure 21: Distribution of average optimal hedge shares by customer and hedge price premium g_h with an expenditure share of electricity of 10%

(a) $\alpha = 0.001$ (b) $\alpha = 0.1$ (c) $\alpha = 0.6$