# Dynamic electricity tariffs are not as risky as they seem: Peak-to-Bill Anxiety

**Working Paper**

*Lorenzo Matthias Burcheri[1], Joachim Geske[1], Gilbert Fridgen[1], Martin Weibelzahl[1]*

*[1] Interdisciplinary Center for Security, Reliability and Trust, University of Luxembourg, Luxembourg*

## Abstract

*Dynamic electricity tariffs are expected to trigger urgently required residential and industrial flexibility in a decarbonized energy system. The start has been made, i.e., by the EU enforcing energy suppliers to offer dynamic tariffs for residential consumers with the goal to incentivise demand adjustments; however, little is known about its perception and acceptance in residential electricity retail. In structured expert group discussions in Luxembourg, we identified a "Peak-to-Bill Anxiety" referring to the perception of an alleviated financial risk associated with price peaks – questioning the suitability of these tariffs for residential consumers, and the household's willingness to self-expose to these risks. But are households really exposed to significantly higher risks if contracted under a dynamic tariff? To answer this question, we designed monthly dynamic and fixed price electricity bills from smart meter data of more than 3000 households and day-ahead market prices for 2019-2023. In general, we did not find any mean risk premiums exceeding 0.04% of households' incomes – a marginal risk. In a sense, price peaks are negligible for the vast majority of households. However, households, and especially low-income consumers, can face greater risks during exceptionally volatile or high-price market events such as the 2022 European gas price peak (risk-premium-to-income ratios of 1% or higher). To mitigate misperception of price risks, a targeted, policy-driven education could help consumers to evaluate price risks adequately. Financial services, such as insurance or price caps, could protect consumers and mitigate the "Peak-to-Bill Anxiety". Our findings will contribute to the introduction of dynamic retail tariffs and thereby a cost-efficient energy transition.*

*Keywords: Dynamic electricity tariffs, real-time pricing, price risks, certainty equivalent, risk premium.*

## 1. Overview

Future carbon-free energy systems will predominantly depend on electrified heating, cooling, and mobility, powered by intermittent renewable electricity (IEA, 2024). However, since wind and solar energy are not always available when and where needed, demand must become more flexible to avoid and reduce substantial investments in generation and transmission capacities (Küpper et al., 2020). The residential sector could be a source for such flexibility. Nevertheless, under the prevailing fixed-price retail tariffs, households have no incentive to adjust their demand in response to scarcity signals from electricity generation and grid - such as by changing their consumption behaviour in the short term or investing in storage technologies in the mid-term. This has prompted global initiatives to adjust tariff structures so that corresponding market signals are effectively transmitted to households. For instance, both the European Union's Electricity Directive 2019/944 and the United States' Energy Policy Act of 2005 (EPAct 2005) promote offering, alongside fixed-price tariffs, optional dynamic tariffs based on time-variant spot market prices. Gradually, policymakers aim to supplement traditional tariffs with dynamic components that improve grid utilization, help prevent overloads, and allow for electricity bill savings (EU Directive 2023/1791).

These initiatives have promoted business models and regulations that facilitate the adoption of dynamic tariffs for end-users. Therefore, dynamic tariffs have already become widely established in the UK, with 22% of households participating in smart and dynamic tariff solutions,[1] compared to only 7% or less in Germany and Luxembourg (Hagspiel, 2024)[2]. Given this still limited diffusion and tariff-induced flexibility of household demand, it is time to evaluate the stakeholder perspectives and examine the barriers to switching to dynamic tariffs, especially in the form of real-time pricing (RTP).

In addition to its opportunities, the current literature provides an initial understanding of the challenges and obstacles of dynamic tariff adoption. A key insight from this synthesis is the new price uncertainty faced by

[1] https://octopus.energy/press/largest-electricity-supplier-market-share/?utm_source=chatgpt.com, last accessed 2nd April 2025, 13:24

[2] https://de.statista.com/statistik/daten/studie/1534971/umfrage/umfrage-zur-nutzung-dynamischer-stromtarife/, last accessed 2nd April 2025, 13:26

households accustomed to fixed-price tariffs (Dutta and Mitra, 2017). Although dynamic tariffs can offer economic benefits, these advantages are contingent upon consumers adapting their consumption to price fluctuations. If demand cannot align with wholesale prices, the associated price risk adds a new financial burden for households. The increased complexity and flexibility requirements, coupled with the fear of unpredictable risks, discourage consumers from actively choosing these tariffs and make businesses hesitant to promote them (Layer et al., 2019; Numminen et al., 2022).

To gain a more nuanced understanding of the mechanisms underlying these barriers, we first qualitatively analysed moderated group discussions concerning dynamic tariff adoption with key stakeholders, such as business practitioners, energy policymakers, and energy researchers. We repeatedly encountered the "theme" of consumer protection against the increased price risk at peak demand times (which we refer to as "*Peak-to-Bill-Anxiety*"). This encouraged us to quantify in a second step the willingness to pay ("*certainty equivalent*") of rational, risk-averse households to become indifferent between uncertain monthly RTP bills and a fixed-price tariff. For the quantitative analysis, we considered the income elasticity of demand and categorized 3,327 sufficiently representative (Appendix C)[3] residential, consumption profiles into three income classes (low, average, high; ACORN)[4]. For each household we calculated the risk premium, considering day-ahead wholesale prices between 2019-2023 in Luxembourg.

We find that for typical risk aversion levels ($2 \leq \gamma \leq 3$]) and multiple household load time series, no average risk premium exceeded 0.04% of household income. In this sense, the general fear of unpredictable price risks and added financial burden for residential consumers under RTP schemes needs to be re-evaluated. This is in line with the latest heat pump report from the European Consumer Organisation, stating that financial risks due to the unpredictability of market price fluctuations are limited (European Consumer Organisation, 2024). However, we find that few (less than 1%) households, face risk-premium-to-income ratios of up to 1% during geopolitical crises (European Gas Price Crisis from 2021-2022). While this is still moderate and price risks are still negligible for the vast majority of households, specific use cases may merit further investigation. This paper discusses the results in light of past energy crisis scenarios and highlights implications for the future electricity retail system.

## 2. Background

Dynamic electricity retail tariffs are considered a promising market-based instrument for residential flexibility provision (Parrish et al., 2020). By providing monetary incentives based on wholesale price fluctuations, these tariffs reflect supply and demand dynamics, allowing consumers to proactively adjust their electricity demand to avoid price peaks and benefit from low-price phases. Additionally, the grid benefits from such flexible consumer behavior, as grid strain during peak times is lowered, and the need for grid investments is reduced or shifted (Dutta and Mitra, 2017).

To test the feasibility of dynamic tariffs, various experiments and pilot studies have been conducted worldwide, supporting the policy motivation. Faruqui and Sergici (2010) summarized the results of 15 pilot studies from the United States in their literature review on different dynamic electricity pricing interventions. They concluded that households indeed react to price peaks and shift consumption when exposed to dynamic tariff types such as Time-of-Use (ToU) or peak rebates. Further reviews of approximately 100 pilot studies from around the world (Faruqui et al., 2013; Faruqui et al., 2017) concerning dynamic electricity pricing yield similar results, underlining the economic potential of dynamic tariffs. They reported that predictable peak conservation effects of 10% could be further enhanced by enabling technology that reduces manual efforts for consumers (such as Home Energy Management Systems - HEMS). More recent studies like Enrich et al. (2024) find reduced peak consumption by up to 9% in a Spanish pilot study with a ToU pricing intervention. While many studies focus primarily on ToU tariffs and other dynamic pricing interventions, an increasing number of studies also consider RTP interventions (Dutta and Mitra, 2017). ToU tariffs provide electricity pricing for time blocks within a day (e.g., quarter-daily price periods), whereas RTP tariffs reflect hourly changing electricity wholesale prices. Hofmann and Lindberg (2024) identified in a three-month winter trial of nearly 4,000 Norwegian households to hourly day-ahead electricity price signals robust peak electricity conservation effects of up to 2.92%. They even further suggest greater effects if households were equipped with automation assets to reduce manual efforts.

However, dynamic tariffs are often perceived as more risky than beneficial. Literature extensively elaborates on the contrast between the potential benefits of flexible consumption under dynamic tariffs and new downsides for

[3] In addition, we compared the standard British and Luxembourgish climate normals to test for signs of significant discrepancies in seasonal electricity consumption due to potential heating requirements – the most energy intensive consumption type in households (Appendix D).
[4] The segmentation follows the ACORN approach which is outlined under https://acorn.caci.co.uk/how-acorn-works/, last accessed 16th May 2025, 09:51

consumers (Dutta and Mitra, 2017), especially the unpredictability of time-variant pricing (Parrish et al., 2020). For example, Allcott (2011) analysed the first RTP trial in the US, finding promising peak-time conservation effects. However, he also noted that consumers hesitate to enroll in RTP tariffs due to their complexity and perceived price risks at peak times. Similarly, Dütschke and Patz (2013) reported in their survey-based study with 160 German participants that ToU tariffs are preferred over RTP schemes. In an additional smart home experiment, four residents were exposed to different dynamic pricing programs for 13 weeks. After the experiment, participants preferred RTP over ToU but expressed a need for safety nets and price caps due to a fear of extreme price peaks. This fear is not exclusive to consumers but is shared by energy suppliers as well. Numminen et al. (2022) analysed the market offers of 59 Finnish energy suppliers, noting that despite increasing innovation rates and dynamic tariff offerings, the promotion of fixed-price tariffs is rising again. The vulnerability of consumers to price peaks and their general disinterest in flexibility issues drive the portfolio structure of many retailers and the lack of promotion for dynamic tariffs – hindering not only the adoption directly but also the development of new business models.

This perceived unattractiveness of dynamic electricity pricing is further intensified by the inherent tariff complexity of RTP tariffs that emerges due to high price volatility. For example, Layer et al. (2017) show in their online experiment with over 600 German households that simple tariffs, requiring low mental effort, are preferred over highly dynamic ones like RTP, which require deep engagement with constantly changing price information. Even if households accept a complex RTP tariff and aim to adapt their demand, additional transaction costs of reacting and changing behaviour are often overlooked (Bejan et al., 2021). Daily life hurdles and discomfort may limit a household's ability to efficiently engage with such tariffs, leaving them feeling exposed to market dynamics and price risks.

Ultimately, the literature suggests that the fear and reluctance towards dynamic tariffs stem from the inability to manage the price complexity inherent to RTP tariffs and the challenges of reacting according to incentives. But is this fear justified, and are consumers exposed to dynamic tariffs for better or worse? We will answer this question by analysing 3000 household load curves, determining their bill risk, and comparing it to their income.

## 3. Research Design

We present a mixed-methods analysis approach, combining qualitative and quantitative methods to explore the current discourse on RTP tariffs. First, we qualitatively analyse the opinions of business practitioners, policymakers, and energy researchers regarding the adoption barriers of dynamic tariffs, confirming and extending the existing literature. Second, we challenge these qualitative findings through a quantitative analysis of the risk premiums at which households are indifferent between choosing an RTP tariff and a yearly-fixed-price tariff.

### 3.1 Qualitative Analysis of Expert Group Discussions

As a first step, the qualitative analysis of expert group discussions aims to obtain a picture of the participants' opinions that is as undistorted as possible by the observers and to condense their statements objectively into core statements. We conducted three in-person expert group discussions involving three business practitioners (BE1-3), two energy policymakers (PE1, 2), and six energy researchers (RE1-6) who are closely involved in industry partnerships in their day-to-day research activities. We present in Table 1 the expert domains of the participants.

| Stakeholder group | Identifier | Expert domain |
|---|---|---|
| Business practitioner | BE1 | Strategy and innovation in electricity retail |
| | BE2 | Innovation and product management in electricity retail |
| | BE3 | Innovation and digitalisation in electricity retail |
| Policymaker | PE1 | Energy policy |
| | PE1 | Energy policy |
| Researcher | RE1 | Smart energy systems and technology; involved in industry partnerships |
| | RE2 | Energy economics; involved in industry partnerships |
| | RE3 | Smart energy systems and technology; involved in industry partnerships |
| | RE4 | Behavioural science; involved in industry partnerships |
| | RE5 | Energy/behavioural economics; involved in industry partnerships |
| | RE6 | Energy Economics; involved in Industry Partnerships |

*Table 1. Information about expert domains*

These semi-structured discussions lasted on average 65 minutes and were guided by a conversation guideline, with a moderator focusing on key questions and a facilitator ensuring clarification and follow-ups. The questionnaire is attached to Appendix A. Although the discussions were moderated, the experts had the freedom to shape the discussions to their preferences. We analysed the recorded and transcribed discussions using an iterative qualitative coding process (Saldana, 2013). The transcripts were on average 41 pages long. The inductive coding process involved a four-step structured labelling approach to identify and organize themes across expert opinions (see Figure 1).

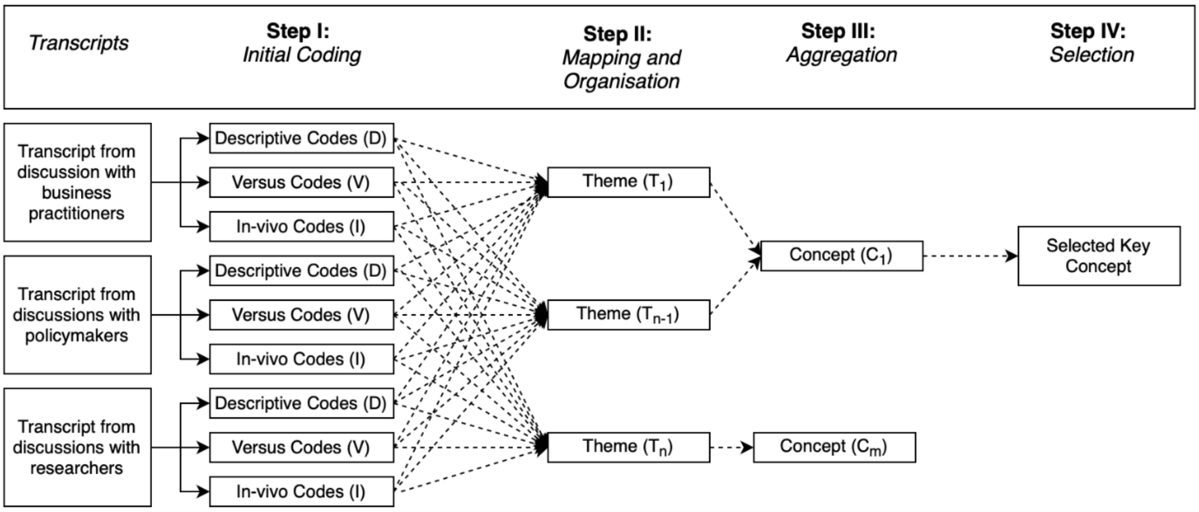


*Figure 1. Coding process; Transcripts are analysed using codes that are aggregated into summarising themes and concepts.*

In the first step, the transcript of the discussions was structured line-by-line, with one researcher assigning codes. Codes are types of labels that describe the content of a statement. For this purpose, descriptive codes were defined to explain expert statements concisely. Additionally, versus codes were used to highlight conflicts or contrasts in the content, such as "economic benefits vs. increased residential risks." In-vivo codes were also assigned, capturing representative quotes that illustrated the experts' opinions without active interpretation by the researcher. To account for potential biases, a second researcher reviewed the codes and proposed alternative codes in cases of disagreement. The researchers then discussed and aimed for consensus on the proposed codes.

In the second step, we mapped and organized the distinct codes into themes across the different expert discussions. By visualising the codes through the mapping approach, relations between codes are identified more efficiently. In the third step, we aggregated the themes into concepts that we subsequently described and verbalized. In the fourth step, we selected from the emerging concepts the key concept of this paper's research objective.

### 3.2 Quantitative Method

We use hourly household load profiles under fixed prices to determine consumption quantities and consumption times, just as these households preferably implemented them - at least they have no financial incentive to deviate. We then simulate monthly bills that would result from the same load profiles under real-time pricing. To evaluate the resulting hypothetical real-time-pricing bills, we make the extreme assumption that households perceive prices as random (independent with known expected value and variance) but know their consumption exactly. Accordingly, the bills that 'arise' under fixed prices represent certain payouts for monthly electricity consumption, while the flexible bills represent the 'equivalent' uncertain payouts for the same electricity consumption.

Assuming risk-averse rational decision-making, we then derive the risk premium of the uncertain bills that makes each consumer indifferent between both and relate it to income. In this sense, the electricity supplier – assumed to be a risk-neutral trader – takes on the uncertainty of the monthly bill from the consumer with the fixed price tariff – or, in the case of reintroducing RTP, the consumer takes on this uncertainty. We now determine the risk premium. To do so, we used an original dataset with 5,567 hourly household load profiles from 2011-2014 in London.[5] After excluding incomplete profiles and households contracted under a dynamic tariff (Time-of-Use, ToU), we proceeded with 3,327 load profiles from 2013. We excluded dynamic tariff users because their consumption patterns are likely influenced by market prices, whereas fixed-price consumers did not receive any market-driven incentive to adapt their consumption patterns. This exclusion ensures that our analysis focuses on households with consumption unaffected by prices. Additionally, this allows us to consider the consumption profiles for bill calculations in other years, weighted by other price-time series, enhancing the generalizability of

[5] https://www.kaggle.com/datasets/jeanmidev/smart-meters-in-london, last accessed 2nd April 2025, 13:23

our findings. Furthermore, the households are segmented into incomes and wealth groups,[6] We use this segmentation to consider the income elasticity of demand, differentiating between the consumption of low-, medium-, and high-income households (see Appendix B).

To understand the risk assessment of a risk-averse rational consumer opting from a fixed price to an RTP tariff, we compare the expected utility between both tariffs' resulting bills. For the analysis, we assume that consumption patterns remain unchanged when opting for an RTP tariff to account for the price risks associated with the inability to adapt to price dynamics.

In detail, we aggregated a multi-year time series of day-ahead wholesale prices from 2019–2023 from Luxembourg (acquired from the ENTSO-E Transparency Platform),[7] weighted with the measured household loads to monthly bills, and interpreted them as realizations drawn from an unknown distribution of prices (assuming equal probabilities of prices and their independence). We then determined an income-equivalent yearly "average" price - the fixed-price tariff. By comparing the expected utility from the RTP and the fixed-price tariff, we are able to determine the risk premium - that is, a hypothetical transfer that makes a risk-averse household (with constant relative risk aversion) indifferent between being billed monthly based on the uncertain wholesale prices or the certain fixed price. We selected the periods 2019-2023 for our overview, as the transition from 2020 to 2022 marked a significant shift in the European energy market (post COVID-19/European Gas Crisis).

We describe below the definition and measurement of the value of uncertainty. Let $p_{it}^{var} c_{it}$ be the hourly electricity procurement costs on the wholesale market, consisting of the wholesale price $p_{it}^{var}$ for household consumption $c_{it}$. A household ($i$) considers this price to be random and i.i.d. (independent and identically distributed) with known expectation and variance. The consumption level $c_{it}$ is known to the household. Household decisions under uncertainty can be described using a von Neumann-Morgenstern utility function $u$ with constant relative risk aversion, given by $u(x) = x^{1-\gamma}/(1-\gamma)$.

We now want to determine the value of uncertainty for the household through the risk premium $\pi_t^i$, which must be offered to a household with income $w_i$ in order to make them indifferent between a fixed-price tariff and a – considered random – dynamic tariff. The definition of the risk premium (Pratt, 1964), applied to our case, is as follows:

$$\underbrace{u\left(w_i + p_i^{fix} c_{it} - \pi_t^i\right)}_{Utility\ from\ ind\ fix\ price} = \underbrace{\mathbb{E}[u(w_i + p_{it}^{var} c_{it})]}_{Utility\ from\ variable\ Price} \tag{1}$$

So far, we have not explained the relationship between the (individualized) fixed-price tariff $p_i^{fix}$ and the wholesale price $p_{it}^{var}$. This is the price that a risk-neutral retailer would charge each household individually in a competitive (zero-profit) business model, as a maximizer of expected profit:

$$0 = \mathbb{E}Profit_t^{retailer} = \sum_i \left(p_i^{fix} - \mathbb{E}[p_{it}^{var}]\right) c_{it}. \tag{2}$$

This gives

$$p_i^{fix} = \mathbb{E}[p_{it}^{var}]. \tag{3}$$

This is an auxiliary construct that allows for individualized fixed-price tariffs. In reality, these offers are pooled across all consumers – which can have advantages in terms of risk distribution. However, since we are not interested in interpersonal redistribution by the retailer, but rather in redistribution across different states of the world, we use this personalized fixed-price tariff as a benchmark to determine the value of uncertainty. Substituting (3) into (1) yields:

$$u\left(w_i + \mathbb{E}[p_{it}^{var} c_{it}] - \pi_t^i\right) = \mathbb{E}[u(w_i + p_{it}^{var} c_{it})]. \tag{4}$$

We now solve this nonlinear equation for the risk premium. To do so, we use a second-order Taylor approximation of the right-hand side of (4) around $w_i + \mathbb{E}[p_{it}^{var} c_{it}]$, followed by simplification:

$$\mathbb{E}[u(w_i + p_{it}^{var} c_{it})] \approx \mathbb{E}\left[u + u' \cdot (p_{it}^{var} c_{it} - \mathbb{E}[p_{it}^{var} c_{it}]) + \frac{1}{2} u'' \cdot (p_{it}^{var} c_{it} - \mathbb{E}[p_{it}^{var} c_{it}])^2\right]$$

[6] The segmentation follows the ACORN approach which is outlined under https://acorn.caci.co.uk/how-acorn-works/, last accessed 16th May 2025, 09:51

[7] https://newtransparency.entsoe.eu, , last accessed 2nd April, 13:24

$$= u + u' \cdot (\mathbb{E}[p_{it}^{var} c_{it}] - \mathbb{E}\mathbb{E}[p_{it}^{var} c_{it}]) + \frac{1}{2} u'' \cdot \mathbb{E}[(p_{it}^{var} c_{it} - \mathbb{E}[p_{it}^{var} c_{it}])^2]$$

$$= u + \frac{1}{2} u'' \cdot \mathbb{E}[(p_{it}^{var} c_{it} - \mathbb{E}[p_{it}^{var} c_{it}])^2] \tag{5}$$

First Order Taylor Approximation of the left-hand side of (4) around the same $w_i + \mathbb{E}[p_{it}^{var} c_{it}]$ gives

$$u(w_i + \mathbb{E}[p_{it}^{var} \cdot c_{it}] - \pi_t^i) \approx u + u' \cdot \left(w_i + \mathbb{E}[p_{it}^{var} \cdot c_{it}] - \pi_t^i - (w_i + \mathbb{E}[p_{it}^{var} \cdot c_{it}])\right)$$

$$= u - u' \cdot \pi_t^i \tag{6}$$

Equilibrating (5) and (6) and solving for $\pi_t^i$ gives with constant relative risk aversion

$$\pi_t^i = -\frac{1}{2} \frac{u''}{u'} {c_{it}}^2 Var[p_{it}^{var}] = \frac{\gamma Var[p_{it}^{var} \cdot c_{it}]}{2(w_i + \mathbb{E}[p_{it}^{var} \cdot c_{it}])} \tag{7}$$

For better interpretation in the context of monthly bills and income with i.i.d. prices, the risk premium of the monthly bill can be determined as the sum of the hourly risk premia – that is, 24 × 30 = 720 times. We have calculated this for each household and related it to their monthly income.

# 4. Results

## 4.1 Results of Qualitative Analysis

With the qualitative coding procedure, we summarized and selected the key concept "*consumer protection*", as the associated themes occurred multiple times across all expert group discussions (see Table 2).

| Key concept | Descriptive themes |
|---|---|
| Consumer protection | Consumer stress – policy motivation vs. consumer burden |
| | Increased complexity – literacy vs. ease-of-use |
| | Information and automation – mental effort vs. enabler technology |

*Table 2. Overview of key concept and descriptive themes of expert discussions*

Policy experts shed light on the fundamental economic motivation of dynamic tariffs, explaining that "*energy supplier transfers risk to the customer and gives up part of its margin in return and can therefore make a more attractive offer to the customer in terms of expected value*" leading to "*a win-win situation, because (...) individual consumers can benefit from opportunities, especially from times of low energy prices. As well as offering benefits at the system level."* – PE1. Researchers agree on this motivation and stress that "*Europe wants to include consumers in the energy transition"* – RE3. Business experts also acknowledge the policy motivation and confirm that "*the overall (*policy*) intent is very good*" but emphasize that it "*goes (*currently*) against consumer protection*" – BE2. The business experts elaborate on the fact that consumers may be already overwhelmed as we are living in a period of "*perpetual poly-crises*" and doubt that *"the people are really so happy to have yet another thing to worry about"*- BE1. Researchers also recognize this additional burden consumers face and point to the mental utility discount dynamic tariffs experience based on the increased complexity of consuming electricity at home according to hourly price signals: "*You are inflating the complexity (...)*– RE2 and "*it's simpler if you just have a flat tariff*" – RE3. Researchers underline that without consumers being able to understand and interact with energy-related information, households will tend to opt in for tariffs that promise ease of use and ultimately fewer risks for daily life activities: "*People need to have the feeling of safety and not losing money"* – RE4.

Business experts highlighted that consumers' aversion to risk, especially concerning unpredictable monthly billing and occasional price spikes, can constitute a substantial obstacle: "*… Having this part of the energy transition in place coming from the regulation side is, I think, a very relevant one, but it's only helpful if the customers that you are addressing can make use of it. And if they can't, and such a tariff would come on top of their consumption, it would be quite expensive (...)"* – BE3. Especially research and business experts repeatedly highlighted the fear that households, if unable to react to price peaks, would be unprotected against the monetary consequences, which ultimately manifest in their electricity bill. Exceptional examples such as the Texas Winter Storm Crisis were mentioned, in which consumers with dynamic tariffs had to pay thousands of dollars as they were not able to adapt to the market price signals (RE1). Besides the price risks that reduce the attractiveness of dynamic tariffs, behavioural researchers also highlighted the additional "*mental effort*" (RE5), representing additional transaction costs, to adapt daily activities that align with electricity price fluctuations.

Thus, in the further course of discussions, the role of flexibility assets and automation emerged in all group discussions as "*a way of simplification (..) to make life easier*" – RE2. Researchers and business practitioners emphasize that more and more offerings for smart home systems and asset automation are entering the market and making dynamic tariffs more attractive as they reduce the burden of manually reacting to highly time-variant market signals. However, the deployment rate of such assets is limited due to the liquidity constraints of income households, particularly of low-income consumers (RE5, 6).

Policy experts acknowledged the current, problematic interdependency between expensive flexibility assets, such as electric vehicles or heat pumps, and dynamic tariffs but emphasized the optional character of dynamic tariffs and that households are not forced to contract dynamic retail tariffs if they do not own such assets. It is a regulation-based product that targets specifically those households that can offer flexibility and have the necessary automation assets and storage technologies: "*It (…) treats the two customer groups differently, so to speak - to be able to continue to serve the classic, non-flexible customers as before*" – PE1. However, policy experts elaborate on the remaining potential risk of non-flexible consumers choosing a dynamic tariff and that "*bad (tariff) choices are made, especially in a market (…), where customers have been very inactive up to now and have also paid very little attention to the topic.*"-PE2 and that "*it seems quite normal to me that mistakes will be made by one player or another - just as it is a priori the same case in any other market*."- PE1.

As a summarizing interpretation we found that policymakers focus on future-proofing the energy system and recognize the long-term benefits for households that are equipped with assets like electric vehicles and heat pumps, researchers and industry experts stress the immediate challenges that arise when such assets are not yet widely adopted alongside the promotion of dynamic tariffs (see Table 3).

| | **Expected Future Scenario** | **Present - 2025** |
|---|---|---|
| Description | Most customers are equipped with assets such as electric vehicles, heat pumps, and energy storage systems, often complemented by automated control technologies. As these technologies assume the task of managing daily energy complexities, the cognitive burden and risks associated with responding to price fluctuations and peaks are significantly reduced. | Currently, the majority of consumers do not own flexibility-enabling assets such as electric vehicles, heat pumps, or automation devices.<br><br>**I.** If only the relatively few households that do possess such assets opt for dynamic tariffs, there is little cause for concern. These households are typically better equipped to respond to price signals, either manually or through automation, thereby minimizing exposure to price volatility.<br><br>**II.** However, if households without flexible assets adopt dynamic tariffs, challenges may arise. Their inability to react dynamically could reduce the overall effectiveness of demand-side flexibility in the energy system, potentially leading to inefficiencies and monetary disadvantages such as electricity bill increases. |

Table 3. Expert insights - risk potential of dynamic tariffs depending on asset ownership

All experts perceived uncertainty associated with fluctuating prices and the inability to react accordingly (manually or automatically) - particularly in price peaks - as a significant barrier to the adoption of RTP tariffs. It poses new risks to the financial well-being of the residential consumers who are conditioned to consume electricity in the form of flat rates - often with yearly price guarantees. We refer to the fear of burdening (partly inflexible) consumers with continuous exposure to price uncertainty and associated price peaks that may manifest in rising bills as "*Peak-to-Bill Anxiety*".

### 4.2 Results of Quantitative Analysis

To challenge the statements that households would be unprotected against market price peaks in dynamic tariffs if they could not change consumption patterns, we determined how a risk-averse rational consumer would evaluate the uncertainty of the monthly RTP bills compared to an equivalent fixed-price tariff with its risk premium. Using the method described in the section 3.2 with a common relative risk aversion coefficient between 2 and 3 (Ljungqvist & Sargent, 2004) for three different net income segments [€1,750, €3,500, €7,000] for the years 2019-2023,[8] not a single consumption profile did exhibit an average risk premium-to-income ratio exceeding 0.04% - suggesting for the majority of households just a very minor discomfort caused by electricity bill fluctuations.

[8] https://luxtoday.lu/en/knowledge/salaries-in-luxembourg?utm_source=chatgpt.com, (average net income in Luxembourg) last accessed 2nd April 2025, 13:22

We present in Table 4 an overview of the average monthly risk premium-to-income ratios [%] of the low- and high-income households for 2019-2023 and three risk aversion levels. We report the mean values.

| Year | Relative Risk Aversion | | |
|---|---|---|---|
| | 2 | 2.5 | 3 |
| 2019 | -.0005 (-.0001) | -.0006 (-.0001) | -.0008 (-.0002) |
| 2020 | -.0005 (-.0001) | -.0005 (-.0001) | -.0007 (-.0002) |
| 2021 | -.0139 (-.0027) | -.0174 (-.0034) | -.0209 (-.0041) |
| 2022 | -.0266 (-.0042) | -.0332 (-.0053) | -.0398 (-.0063) |
| 2023 | -.0039 (-.0008) | -.0048 (-.0010) | -.0058 (-.0012) |

Table 4. Mean Risk premium-to-income ratio [%] for low-income households and high-income households (within brackets) in 2019-2023 by relative risk aversion; values peak across all household types in 2022 (post-COVID19 and European Gas Price Peak)- underlined; complementary information for average-income households to be found in the Appendix E.

The mean values are always below 0,04% (see Table 4) but increase constantly from 2019 to 2022 before they decrease again in 2023. Based on the formalism deployed in this paper, the demanded risk-premium of rational, risk-averse households linearly increases with a decrease in the monthly net income and an increase in the risk aversion level. While the mean values indicate that an RTP tariff in general does not induce significant uncertainty or create a demand for risk coverage in any income-risk-aversion scenario, there may be individual households that face increased price risks under certain consumption patterns.

Table 5 indicates for the years 2021-2022 that indeed some household profiles have greater risk-premium-to-income ratios than 0,04%, but it concerns less than 1% of the sample, and it still does not exceed a risk-premium-to-income ratio of 1%.

| Year | Rel. Risk Av. | Min. | 1st | 10th | 50th Percentile | 95th | 99th |
|---|---|---|---|---|---|---|---|
| 2021 | 2 | -.28 | -.06 | -.01 | -.002 | -.0001 | .0000 |
| | 2.5 | -.35 | -.08 | -.01 | -.002 | -.0002 | -.0001 |
| | 3 | -.42 | -.09 | -.01 | -.003 | -.0002 | -.0001 |
| 2022 | 2 | -.62 | -.10 | -.02 | -.004 | -.0003 | -.0001 |
| | 2.5 | -.78 | -.12 | -.02 | -.005 | -.0004 | -.0002 |
| | 3 | -.93 | -.15 | -.03 | -.006 | -.0005 | -.0002 |
| 2023 | 2 | -.21 | -.02 | -.00 | -.000 | .0000 | .0000 |
| | 2.5 | -.26 | -.02 | -.00 | -.000 | .0000 | .0000 |
| | 3 | -.32 | -.03 | -.00 | -.000 | .0000 | .0000 |

Table 5. Distribution of risk-premium-to-income ratio [%] in 2021, 2022, and 2023; the results for 2022 suggest that less than 1% of the sample demands risk premiums close to 1% of their income; in 2021 approximately 99% of household's risk-premium-to-income ratios do not exceed .10% while in 2022, 99% of household's risk-premium-to-income ratios do not exceed .16%. Complementary graphical visualizations of the distributions for 2019 and 2020 can be found in Appendix F.

Comparing the data for 2021 and 2022, it shows that the highest risk-premium-to-income ratio of 2022 (-.93%) is more than doubled compared to 2021 (-.42%), followed by significant decreases towards a .32% threshold in 2023. The sharp rise in electricity prices in 2022 indicates that price shocks and increasing annual price volatility are the main factors driving the rise in risk-premium-to-income ratios (see Table 6).[9]

| Year | Min. | Max. | Mean | Std. Dev. |
|---|---|---|---|---|
| 2020 | .02 | .04 | .03 | .00 |
| 2021 | .07 | .13 | .09 | .01 |
| 2022 | .19 | .32 | .23 | .03 |

Table 6. Electricity price developments in 2020-2022 in [€/kWh] in Luxembourg; Minimum (Min.), maximum (Max.), mean, and standard deviation (Std. Dev.) values are increasing year by year.

While the risk is low for the majority of households, low-income households are affected most (see Table 4), especially in crisis scenarios in which major electricity price shocks like those in 2021 and 2022 occur (see Table 5 and 6).

[9] approximately 145% for peak prices and 142% for average prices compared to 2021, and 625% and 658% respectively compared to 2020

## 5. Discussion

The expert group discussions revealed that business practitioners, researchers, and policymakers alike consider dynamic electricity pricing essential for fostering the necessary demand responses for flexibility within the electricity system. Policymakers, in particular, emphasize the importance of dynamic tariffs as products for energy-literate and flexible consumers, while acknowledging that fixed-price tariffs will continue to exist for non-flexible households. However, this does not protect consumers from choosing the wrong tariff type or being unable to shift consumption to low-price periods due to associated comfort losses and behavioural costs. Business experts and researchers stressed the central risks associated with price peaks that may manifest in monthly electricity bills, pointing to a lack of consumer protection during persistent geopolitical crises. This "*Peak-to-Bill Anxiety*" reflects stakeholders' concerns about highly time-variant tariffs within the electricity retail system.

However, we find that price peaks do not significantly impact the average residential electricity consumer financially. But starting from 2021, increasing price risks emerged even though previous years (2017-2020) were shaped by decreasing consumption levels and negative day-ahead market price trends (Halbrügge et al., 2021). This may be attributed to Europe recovering from its pandemic paralysis faster than expected, leading to increased electricity demand and subsequent price hikes for 2021 onwards (Politt, 2023). Following the historical timeline, the beginning of the war in Ukraine, together with low gas reserves in countries like Germany (Politt, 2023), led to the energy crisis unfolding in full, matching the risk-premium peaks in 2022 reported in this paper.

Traditional tariffs allocate such price risks from exceptional market events to the energy supplier, whereas dynamic tariffs redistribute these risks to consumers (PE1). In the case of Luxembourg, which relies heavily on electricity imports from Germany (Hagspiel, 2024), the increase in day-ahead market prices in 2022, and the associated risk of consumption during peak times resulted in immediate monetary disadvantages of up to 1% of consumers' incomes if equipped with RTP tariffs instead of a fixed-price tariff. Even though 1% may not sound like much, households face greater financial risks in exceptional market scenarios.

The Texas Winter Storm Crisis of 2021 serves as an extreme real-world example where enormous price peaks, combined with household's inability to shift electricity consumption due to heating needs in the cold season, resulted in substantial electricity bills in the thousands of dollars and ultimately a grid outage (Busby et al., 2021; Biggar & Hesamsadeh, 2024). The inability to react to price signals due to comfort losses or life-threatening situations underscores the need for policy reconsideration of dynamic electricity pricing for such exceptional situations (Biggar & Hesamsadeh, 2024). Although such crises remain relatively rare, this issue warrants further discussion concerning consumer protection and developments in residential consumption patterns. With the ongoing electrification of mobility, heating, and cooling in the residential sector, electricity demand is expected to increase (van Ruijven et al., 2019). According to the formalism deployed in this paper (Equation 7), an increase in the consumption level by the factor $x$ will shape the resulting risk premium by the factor $x^2$, pointing to an alleviated risk potential with the increasing electrification of households.[10]

Ultimately, the "*Peak-to-Bill Anxiety*" from the expert discussions that prompted the quantitative analysis is not unfounded but subject to a careful assessment. In the future, this may change, and "*Peak-to-Bill Anxiety*" could become more relevant as demand levels increase and new crises emerge, making consumer protection imperative. One potential approach to mitigate the risks associated with RTP tariffs in such situations may be tariff cost caps or peak insurance, particularly for households with limited options to consume electricity flexibly. Companies like Octopus Energy are already exploring these options with smart dynamic tariff options with cost caps, but they remain pioneers.[11] Policies should be developed to safeguard households from the adverse effects of dynamic pricing during exceptional market events, either through awareness campaigns to educate about price developments or by regulating dynamic tariff products that insurance measures are not optional but mandatory. Especially low-income households are at risk, as electricity consumption consumes relatively more of their income than in middle- and high-income classes. Ensuring equitable access to affordable energy, particularly during crises, should be a priority for policymakers. The study calls for a balanced approach to electricity pricing that considers both market dynamics and consumer protection.

[10] $Var(p_t Q_t \times x) = x^2 \times Var(p_t Q_t)$

[11] https://octopus.energy/blog/agile-pricing-explained/#pricing, last accessed 2nd April 2025, 13:20

## 6. Conclusion

Our findings reveal a discrepancy between the perceived and actual risks associated with dynamic electricity tariffs, which may hinder their adoption despite their significant potential to provide demand-side flexibility. Although these tariffs are designed to promote investments and demand-side response, such as conservation and load shifting, an alleviated risk perception, termed "*Peak-to-Bill Anxiety*," remains a critical barrier. Our empirical analysis indicates that, under the analysed market conditions, households in Luxembourg should not perceive dynamic tariffs as riskier than fixed-price tariffs, as even during recent critical market periods, the associated risk premium only represents up to 1% of household income.

However, this may change if price volatility in a decarbonised system increases significantly. Experiences with atypical situations, such as the European Gas Price Spike in 2022 or the Texas Winter Storm Crisis, show that unmanaged price risks can cause economic and social harm, particularly to households exposed to real-time pricing. In theory, real-time pricing could help reduce peak demand and maintain grid stability, but it also transfers extreme price spikes directly to households, thereby increasing financial vulnerability. Anxiety stemming from the uncertainty of such rare events cannot be entirely dismissed as unfounded; it must be assessed in terms of their likelihood and the political willingness to socialize the costs of these crises.

Moreover, real-time pricing may disproportionately burden low-income households, which allocate a higher-than-average share of their income to energy consumption. These households, more exposed to price risks, might be willing to mitigate these risks through asset operation (such as storage), behavioural changes, or the use of financial instruments. However, financing these strategies could be even more challenging for them. Consequently, a flexible electricity price may not be a welfare-enhancing option for these households.

However, we need a deeper understanding of the extent and specific reasons behind the "*Peak-to-Bill Anxiety*" and to identify ways to mitigate it. This could be achieved through targeted consumer education to distinguish routine price fluctuations from genuine risks. In rare cases, support may also be provided through digital tools such as automated controls to manage volatility or financial instruments to insure against risks. Future research could aim to include the actual consumer perspective through survey-based studies, elaborating on the perceived risks of price volatility and peaks. These results need to be considered under the limitation that Luxembourgish price time series were merged with non-Luxembourgish consumption profiles, pointing to potential deviations due to cultural differences regarding consumption patterns. Considering that residential electricity consumption increases in OECD countries yearly by a factor of 0-2%,[12] future risk-premium-to-income ratios may turn out higher.

In addition, this paper will benefit from an extension of the quantitative analysis, considering a future perspective by integrating price forecasts of 2040 and 2050 of Luxembourg's national energy and climate plan (NECP), as well as Luxembourgish load profiles that reflect the increasing electrification of households. These findings may also point to further investigations outside the use case of Luxembourg, as Luxembourg, with its high average salary and subsidized energy costs,[13] is not a representative country of the European electricity system. To complement the big picture, further analysis should also consider dynamic grid fees as a new price component that can contribute to greater flexibility provision or amplification of the "*Peak-to-Bill Anxiety".*

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## Declaration of Generative AI and AI-assisted Technologies in the Writing Process

To exclusively improve the readability, coherence of the content, and fix grammatical mistakes previously present in the text, the authors have utilized AI tools, including ChatGPT and Grammarly during the preparation of this work. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

[12] https://www.iea.org/reports/electricity-information-overview/electricity-consumption, last accessed 16th April 2025, 11:18

[13] https://meco.gouvernement.lu/en/domaines-activites/energie/marches-de-lenergie/subvention-electricite.html, last accessed 25th May 2025, 21:42

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## Appendix A: “Discussion Guideline”

### Introduction to discussion format:

“Hello, thank you for agreeing to answer some questions today about dynamic electricity tariffs and their implementation from an energy company perspective. I would like to remind you that everything we talk about will be anonymised and that your identity will not be disclosed to third parties. Only the summarized responses of the group discussions will appear in our research articles. Please answer our questions honestly and completely and let me know if there is anything you would like clarified. Please remember that you can refuse to answer questions and stop the discussion at any time. Let's get started...”

| Main Question | Follow-Up Question |
|---|---|
| In general, what do you think of this policy and the underlying motivation of the policy makers? | Which opportunities and risks do you see for consumers compared to a fixed price tariff? |
| Do you think consumers are sufficiently or excessively aware of risks and downsides? | |
| How do you think customers will perceive and ultimately deal with dynamic tariffs? | |
| Would you expect similar results for other countries in Europe? | Do you agree that dynamic tariffs will mainly result in consumption shifts to low-peak times rather than conservation? |
| Do you know of other real-time markets that require households to actively participate? | What can we learn from those/this market(s)?<br>Can you think of specific strategies that energy companies or policymakers could copy from these experiences? |
| How exactly do you expect dynamic tariffs to shape and change the business model of energy suppliers? | Do you expect a co-existence of dynamic and fixed price tariffs and how could this look like? |
| What technologies could support residential adoption of dynamic electricity tariffs? | What specific role do you think information systems could play? |
| Literature suggests that providing the right information at the right time and in the right format can contribute to the empowerment of consumers to exploit the advantages offered by dynamic tariffs.<br>What do you think about that? | Research also suggests not just informing households about dynamic prices but complementing this with additional feedback and information about environmental and social impacts of their consumption behaviour.<br>How important do you think this is? |
| What do you think will be the role of the automation of the home in the future? | What does it mean for the transition towards dynamic tariffs? |
| Dynamic tariffs are not the only change in residential electricity consumption – like the electrification of the heating and mobility system and prosumage.<br>What consequences do these trends hold in regard to all the endeavors of implementing dynamic tariffs in the long run? | |

### Closing to discussion format:

“Thank you for sharing your valuable insights during today’s discussion. Your perspective is incredibly important to us and will significantly contribute to our understanding and future initiatives.
Is there anything else you want to discuss or mention before we conclude? As for the next steps, we will be compiling the key takeaways from our discussion and will share details about the results soon. Additionally, we may schedule follow-up discussions to dive deeper into some of the topics we touched on today. Thank you once again for your time and contributions. We look forward to our continued collaboration.”

## Appendix B: "Household Segmentation"

The segmentation follows the ACORN approach. Households that are described with an Acorn group of A, B, C, D, and E are attributed to the high-income cluster. Households that are described with an Acorn group of F, G, H, I, J, K, L, M, N, and O are attributed to the medium-income cluster. Households that are described with an Acorn group of P, Q, R, S, T, and U are attributed to the low-income cluster. You can find more information on the ACORN approach here: https://acorn.caci.co.uk/how-acorn-works/

## Appendix C "Overview Consumption Profiles Data Set"

| 2019-2023 | Percentiles | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1st | 5th | 10th | 25th | 50th | 75th | 90th | 95th | 99th |
| **kWh/month** | 57.4 | 97.3 | 121.0 | 175.8 | 269.5 | 403.9 | 596.5 | 787.5 | 1368.8 |

*Table 6. Distribution of consumption levels of London dataset for 2013*

**Median (50th percentile):**
50% of the monthly consumption profiles indicate approximately 270 kWh/month or less.
**99th percentile:**
Less than 1% of the monthly consumption profiles have a sum higher than 1368.8 kWh.
**Mean of monthly consumption:**
333.95 kWh/month
**Mean of yearly consumption:**
4,007.29 kWh/year

**Luxembourg in 2022:**
4,085 kWh/year
Approx. 340 kWh/month
**Conclusion:**
The Luxembourgish average of 2022 matches the mean of the analysed dataset sufficiently well. Consumption patterns are difficult to compare. To account for potential major differences, we consider the climate normal in Appendix D to test for significant differences in heating needs (most energy-intensive appliances).

## Appendix D: "Comparison of Climate Normals"

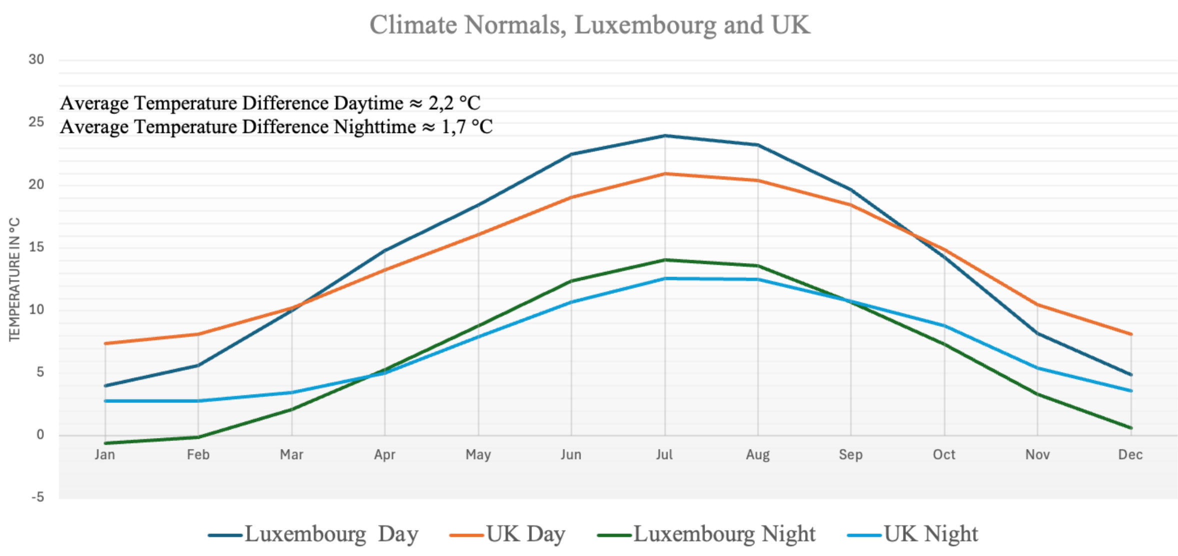



*Figure 2. Comparison of climate normals (30-year averages) of Luxembourg and the UK; based on data available on https://www.worlddata.info/europe/united-kingdom/climate-england.php and https://www.worlddata.info/europe/luxembourg/climate.php, last accessed 23 May 2025, 10:38*

**Conclusion:**
In general, the temperature trends and seasons are very similar.
The temperature profiles suggest that Luxembourg has slightly hotter summer and slightly colder winter months,

at day and night. However, the difference is quite low.
Even if we would assume that Luxembourgish households would heat more to compensate for the lower temperatures in winter months, it is not expected that it will have a significant effect on their electricity demand, as Luxembourgish households still rely strongly on fossil-fuel-based heating (Volt et al., 2024. Luxembourg: Status of the Heat Pump Market, JRC 137131, Country fiche 2024, European Commission, https://publications.jrc.ec.europa.eu/repository/handle/JRC137131; EUROSTAT, 2025. Complete Energy Balances, https://doi.org/10.2908/NRG_BAL_C).
This conclusion is in line with the consumption data from Appendix C stating that the Luxembourgish consumption average matches the one of the London dataset.

## Appendix E: "Mean Risk-Premium-to-Income Ratio per Income Class"

| Year | Rel. Risk Av. | Low Income | Medium Income | High Income |
|---|---|---|---|---|
| 2019 | 2 | -.0005 | -.0002 | -.0001 |
| | 2.5 | -.0006 | -.0003 | -.0001 |
| | 3 | -.0008 | -.0003 | -.0002 |
| 2020 | 2 | -.0005 | -.0002 | -.0001 |
| | 2.5 | -.0005 | -.0002 | -.0001 |
| | 3 | -.0007 | -.0003 | -.0002 |
| 2021 | 2 | -.0139 | -.0063 | -.0027 |
| | 2.5 | -.0174 | -.0078 | -.0034 |
| | 3 | -.0209 | -.0094 | -.0041 |
| 2022 | 2 | -.0266 | -.0104 | -.0042 |
| | 2.5 | -.0332 | -.0130 | -.0053 |
| | 3 | -.0398 | -.0156 | -.0063 |
| 2023 | 2 | -.0039 | -.0016 | -.0008 |
| | 2.5 | -.0048 | -.0019 | -.0010 |
| | 3 | -.0058 | -.0023 | -.0012 |

*Table 7. Mean risk-premium-to-income ratio for low-, medium- and high-income classes for 2019-2023*

## Appendix F: "Distribution of Monthly Risk-Premium-to-Income Ratios"

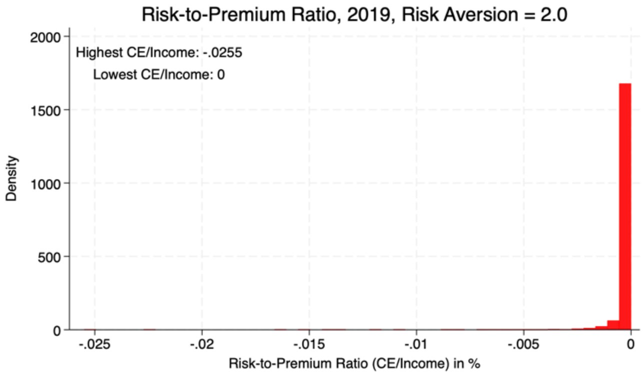
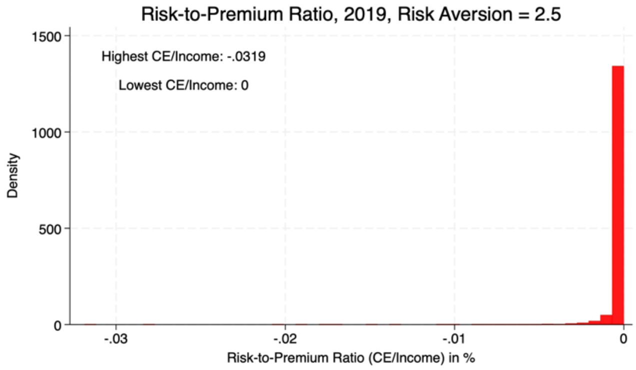
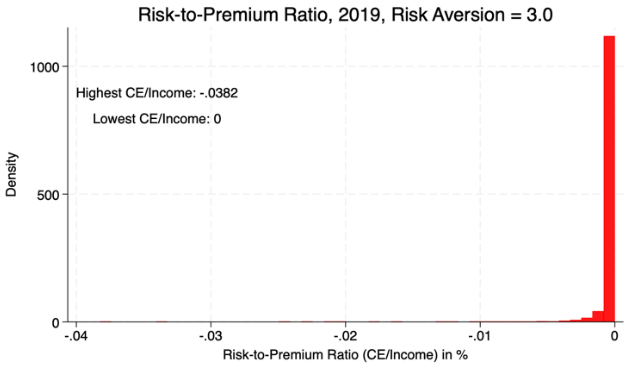
| **Relative Risk Aversion factor** | **2019** |
|---|---|
| 2 |  |
| 2.5 |  |
| 3 |  |

*Table 8. Distribution of monthly risk-premium-to-income ratios for households in 2019 by relative risk aversion factors between 2 and 3*

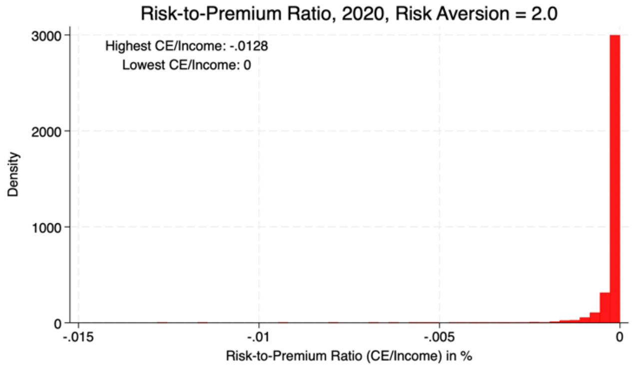
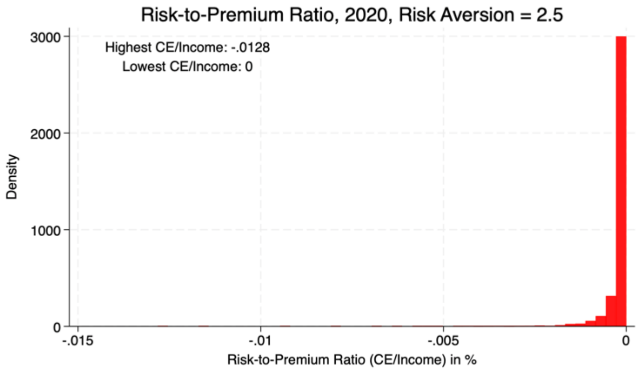
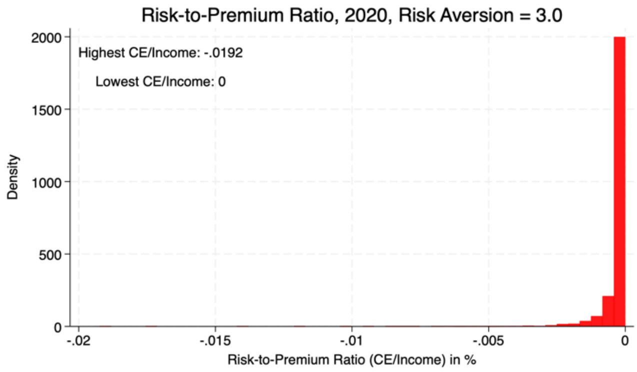
<table>
<tr><th>Relative Risk Aversion factor</th><th>2019</th></tr>
<tr><td>2</td><td>
</td></tr>
<tr><td>2.5</td><td>
</td></tr>
<tr><td>3</td><td>
</td></tr>
</table>

*Table 9. Distribution of monthly risk-premium-to-income ratios for households in 2020 by relative risk aversion factors between 2 and 3*

Conclusion: The distributions of risk-premium-to-income ratios are presented as histograms and show that the values accumulate towards 0.