Power to the people

Electricity demand and household behavior

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Abstract

Paper [I] Using a unique and highly detailed data set on energy consumption at the appliance-level for 200 Swedish households, seemingly unrelated regression (SUR)-based end-use specific load curves are estimated. The estimated load curves are then used to explore possible restrictions on load shifting (e.g. the office hours schedule) as well as the cost implications of different load shift patterns. The cost implications of shifting load from "expensive" to "cheap" hours, using the Nord Pool spot prices as a proxy for a dynamic price, are computed to be very small; roughly 2-4% reduction in total daily costs from shifting load up to five hours ahead, indicating small incentives for households (and retailers) to adopt dynamic pricing of electricity.

Paper [II] Using a detailed data set on appliance-level electricity consumption at the hourly level, we provide the first estimates of hourly and end-use-specific income elasticities for electricity. Such estimates are informative about how consumption patterns in general, and peak demand in particular, will develop as households' income changes. We find that the income elasticities are highest during peak hours for kitchen and lighting, with point estimates of roughly 0.4, but insignificant for space heating.

Paper [III] In this paper, I estimate the price elasticity of electricity as a function of the choice between fixed-price and variable-price contracts. Further, assuming that households have imperfect information about electricity prices and usage, I explore how media coverage of electricity prices affects electricity demand, both by augmenting price responsiveness and as a direct effect of media coverage on electricity demand, independent of prices. I also address the endogeneity of the choice of electricity contract. The parameters in the model are estimated using unique and detailed Swedish panel data on monthly household-level electricity consumption. I find that price elasticities range between -0.025 and -0.07 at the mean level of media coverage, depending on contract choice, and that households with monthly variation in electricity prices respond more to prices when there is extensive media coverage of electricity prices. When media coverage is high, for example 840 news articles per month (which corresponds to the mean plus two standard deviations), the price elasticity is -0.12, or 1.7 times the elasticity at the mean media coverage. Similarly, media coverage is also found to have a direct effect on electricity demand.

Paper [IV] I explore how households switch between fixed-price and variable-price electricity contracts in response to variations in price and temperature, conditional on previous contract choice. Using panel data with roughly 54000 Swedish households, a dynamic probit model is estimated. The results suggest that the choice of contract exhibits substantial state dependence, with an estimated marginal effect of previous contract choice of 0.96, and that the effect of variation in prices and temperature on the choice of electricity contract is small. Further, the state dependence and price responsiveness are similar across housing types, income levels and other dimensions. A plausible explanation of these results is that transaction costs are larger than the relatively small cost savings from switching between contracts.

Keywords: electricity demand, real-time pricing, demand flexibility, appliance-level data, end-use, media, contract choice, deregulated market, household behavior, information

Acknowledgments

I think of myself as a curious person, and these last years of writing this thesis have been all I could hope for. There is so much that I have learned. However, my interest in economics actually started relatively long time ago. In fact, I have been told that already as a kid I was trying to optimize my purchasing of candy given my budget constraint. Some years later, and after studying widely different topics, I found economics to be a fruitful approach for analyzing and understanding important social questions. Thanks to Magnus Wikström, I got the opportunity to work as a research assistant and teaching assistant at the department during my master studies, which convinced me on pursuing an academic career.

My years as a PhD student have been incredibly fun, and this is in large thanks to all great colleagues. First and foremost, thanks to my supervisor Runar Brännlund for sharing your abundance of enthusiasm for science and economics. Supervision was never boring. Also thanks for bringing me onto various projects, and for introducing me to CERE. Being part of a larger research group in energy economics has turned the often lonely life of a PhD student into four-and-some years of interesting and fruitful discussions that have contributed to this thesis, and to my knowledge in general. A special thanks to Chandra Kiran Krishnamurthy for fun collaborations and your careful reading of my papers. I am really looking forward to working with you in the future. I am also grateful to Tomas Broberg for all discussions on electricity markets.

David Sundström, thanks for all discussions on teaching, research and other adventures in life. Elon, I look forward to both research collaborations and skiing in the future. Gauthier Lanot, thanks for keeping your door open and always being happy to talk. Thanks to all other brilliant persons at the Department of Economics and CERE for good times, and in particular previous and current PhD students. A special thanks to Kenneth Backlund and Niklas Hanes for creating such a positive working environment at the department. Thanks to everyone I've met at Skellefteå Kraft, and in particular Jan Strömbergsson, for exchanging of ideas and data material.

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Mattias Vesterberg, January 2017, Umeå.

This thesis consists of an introductory part and four self-contained papers related to electricity demand and household behavior:

Paper [I]
Vesterberg, M and Krishnamurthy, CKB (2016) Residential End-use Electricity Demand: Implications for Real Time Pricing in Sweden. *Energy Journal*, 37:4, 141–164 (Reprinted with permission)

Paper [II]
Vesterberg, M (2016) The hourly income elasticity of electricity. *Energy Economics* 59, 188–197 (Reprinted with permission)

Paper [III]
Vesterberg, M (2017) Heterogeneity in price responsiveness of electricity: Contract choice and the role of media coverage. *Umeå Economics Studies*, No. 940

Paper [IV]
Vesterberg, M (2017) The effect of price on electricity contract choice. *Umeå Economics Studies*, No. 941

1 Introduction

As part of realizing Swedish and European climate ambitions, it is of interest to increase demand flexibility in the residential sector of the Swedish electricity market. In particular, policy makers have recently focused much of their attention on remedying the prevailing lack of incentives for residential consumers to save electricity and cut peak demand at times of market constraints. However, households' interest in such policies has so far been limited. This thesis adds to the body of knowledge on electricity demand and household behavior, and sheds light on the extent to which price-driven policies can incentivize behavioral changes in residential electricity consumption. Using unique Swedish household level data, I explore four topics, all related to demand flexibility.

In Paper [I], we explore possible restrictions on load shifting (e.g., the office hours schedule) as well as the cost implications of different load shift patterns. In Paper [II], I estimate hourly income elasticities to analyze how consumption patterns in general, and peak demand in particular, will develop as households' income changes. Paper [III] explores heterogeneity in price responsiveness across the two most common contract types, as well as how media coverage can augment price responsiveness by providing comprehensive information about electricity prices. Paper [IV] is concerned with the choice of electricity contract and whether households switch between contracts in response to variations in price. As far as I am aware, none of these topics have previously has studied in this great detail.

In short, the key findings in this thesis are that high household income is associated with more pronounced peak demand, but that households' incentives to contribute with demand flexibility appear to be small, and that price responsiveness is limited. The results in this thesis have important policy implications, as will be discussed further below.

However, before going into detail on the four papers which make up this thesis, a brief historical background on the electricity market in Sweden is provided. In particular, in order to understand policy makers' current interest in increasing demand flexibility, it is important to understand the context: both how the deregulation of the Swedish electricity market has provided means for households to become active participants in the electricity market, and how climate and energy policies and the change in the production mix have provided incentives for policy makers to increase the responsiveness of households. In addition, understanding the past may shed new light on the current and future challenges facing the electricity market.

1.1 Background

The electrification of our society is probably one of the things which has contributed most to the development of our well-being over the past 100 years. The first experience of electricity in Sweden was when a steam engine was used to provide electric lighting at a saw mill in 1876. A lot has happened since then. During the 20th century, Sweden expanded production substantially, most notably by hydropower and nuclear power, and lately also windpower. Similarly, the demand for electricity has increased considerably. Today, Sweden has very high electricity intensity per capita, among the ten highest in the world, at roughly 14000 kWh for 2014. At the household level, the increase in electricity use is mainly explained by the growing use of electricity for space and water heating and the growing number of electrical appliances in homes and workplaces.

The long-run development of electricity consumption and GDP are displayed in Figure 1. As shown, electricity consumption and GDP grew exponentially until the end of the 1980s. Technological development, in combination with the natural conditions for the production of electricity (i.e., hydropower), is the main explanation for this development. From the mid-1960s until the late 1980s, electricity consumption grew faster than GDP, but in the last two decades GDP has had a significantly higher growth rate than electricity use. Improvements in energy efficiency seem to be the most plausible explanation for this recent development.

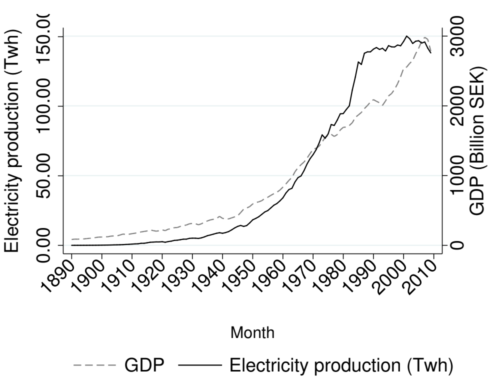

Figure 1: Electricity consumption and GDP in Sweden from 1890 to 2010. Source: Kander and Lindmark (2004).

Until 1996, the Swedish electricity market could be characterized as a regulated market: although the market was not directly regulated, government regulation was indirectly implemented via control of the state-owned company Vattenfall, with a market share of over 50 percent of total generation. On the power market, the price was implicitly determined by the state's required return from Vattenfall because Vattenfall was the price leader in the market. Further, average cost pricing was the dominant pricing strategy, not least as a result by legal requirements of "reasonable pricing" in the Electricity Act (Bergman et al. (1994) and Damsgaard et al. (2005)).

On the regulated market, households played a limited role. Lack of competition on the retail market meant that the options available to households were limited: households had to buy electricity from the incumbent retailer in that area, with no option to change retailer. Traditionally, the incumbent retailer offered only a standard tariff, where prices generally followed spot prices but were higher, smoother and somewhat lagged (Littlechild (2006)). Further, prices were traditionally both low and stable, as is illustrated in Figure 2, and most likely did not provide any substantial incentives for households to take an active interest in the market. Therefore, it seems reasonable to assume that price responsiveness and attention to electricity prices and expenditure were limited before deregulation.

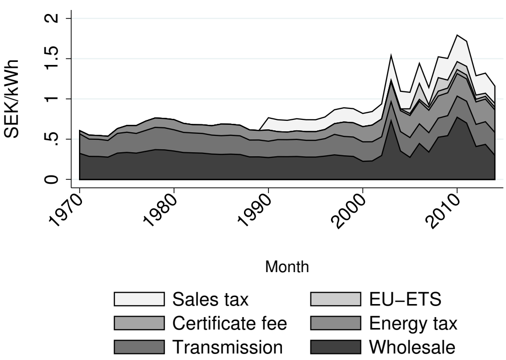

Figure 2: Consumer prices for electricity and distribution of electricity for household customers, including taxes and certificate fee, from 1970 to 2014. SEK per KWh (2014 prices). Source: Swedish Energy Agency.

1.2 Deregulation

During the 1990s, many European countries, including Sweden, deregulated their electricity markets. The deregulation was aimed mainly at increasing efficiency by creating competition in production and resale of electricity. Regulations that prevented electricity trade were abolished, while the distribution of electricity would continue to be regulated and monitored. The reason for the latter was (and is) that the power distribution system can be considered a natural monopoly.

This period also marked the beginning of the integration of the Swedish electricity market with markets in the Nordic and Baltic countries via a common spot market. Today, the price of electricity is determined by supply and demand on the day-ahead and intra-day markets on the Nord Pool power exchange. The day-ahead market, Elspot, is the main venue for trading electricity in the Nordic region, with 75 percent of total electric supply in the Nordic countries traded here. Contracts are concluded between approximately 370 sellers and buyers for delivery of power the following day, and market price is determined based upon the supply and demand of electricity on that day. Further, there exists an intraday market, Elbas, to cover potential imbalances occuring between the closing of Elspot at noon and delivery the next day. For a discussion and comparison of the retail markets in the other Nordic countries, see Littlechild (2006).

Many agree that the deregulation and integration of the Nordic markets have worked well; see, e.g., Damsgaard et al. (2005), Amundsen and Bergman (2006), Lundgren (2009) and Brännlund et al. (2012). For example, the expansion of the market has reduced market power, and pricing appears to be close to marginal pricing (Lundgren et al. (2008)). Further, retail competition has developed well in all three markets, and the proportion of customers switching to other suppliers is higher than in most other countries (Littlechild (2006)). Of particular interest in the current context is the fact that a significant proportion of residential customers have actively chosen terms of supply other than the standard contract with the incumbent retailer.

As illustrated in Figure 2, prices have been more volatile since deregulation, and this picture becomes even more evident if we look at monthly, daily or hourly prices. However, previous literature suggests that this development was not directly caused by deregulation (see, e.g., Lundgren et al. (2008) and Brännlund et al. (2012)). In particular, large variation in temperatures, together with operational problems in nuclear production, are the most likely reasons for the price volatility during the last 15 years. However, the transition from a regulated market to a market where supply and demand are the deciding factors in production has likely contributed to increased price volatility; see, for example, Lundgren (2009) and Dempster et al. (2008). The increasing share of intermittent production has likely added to this as well.

Deregulation has opened up the markets for production, wholesale and resale of electricity, thereby changing the conditions for producers, retailers and consumers in fundamental ways. Perhaps the most obvious change for households in Sweden is that they can now choose freely from a large number of electricity suppliers who offer them a multitude of different contracts. As such, deregulation has provided households with the possibility of taking on a more active role in the electricity market, compared to before deregulation. In particular, new services and contract types provide possibilities for households to respond to the increased price variability by adjusting electricity usage and/or switching between retailers and contract types.

1.3 New production mix

As of today, the bulk of electricity produced in Sweden is from hydro and nuclear sources, constituting 45 and 43 percent of total production, respectively (figures for 2014, from Svenska Kraftnät (see www.svk.se)). The remaining production is from thermal (co-generation) plants and windpower, together with some smaller sources of peak capacity. However, the production mix in Sweden is currently undergoing some major changes in response to the rather ambitious climate and energy policy targets following the EU Climate and Energy Package (the 20-20-20 target). This target stipulates, among other things, 20 percent increase in energy efficiency and 50 percent share of renewable sources in total energy consumption by 2020 (relative to 2009).

During the last ten years, the share of renewable energy in the form of wind and solar power has increased sharply, while the use of coal and oil in particular, but also nuclear power, has declined (see www.svk.se). A similar trend has been seen in other countries, for example, the Energiwende in Germany (which has been more dramatic, with a faster phasing out of nuclear power, than the case of Sweden). Further, this trend is expected to continue for the foreseeable future. This development is, and will be, reflected in the price on the Nordic market. While rising wind generation (as a result of subsidies) tends to reduce the level of spot prices, ceteris paribus, it is also likely to increase the spot-price variance, both within-day and across seasons (see, for example, Sweco (2016) for Sweden and Astaneh and Chen (2013) for the Nordic market, Woo et al. (2011) for the US and Ketterer (2014) for Germany).

Because supply of power has to equal demand for power at every moment in time, if black-outs are to be avoided, capacity has to be extended to meet demand at its peak, or demand has to be reduced to meet capacity. A consequence of a larger share of intermittent production will then be an increased demand for flexibility in the form of balancing and back-up power. In the case of Sweden, hydropower has so far allowed for an increase in intermittent production such as wind power, but this flexibility is limited. The increasing integration of Europe's electricity markets, combined with even more wind and solar power in Europe, means that Sweden will increasingly be exporting balancing power to other countries. Along with domestic changes in the production mix, this development is expected to increase the need for a more flexible demand side, where households (and firms) adjust their electricity usage in response to the current availability of electricity, both within a day and across seasons. For example, both the internal market in electricity directive (2009/72/EG) and the renewable energy directive (2009/28/EG) suggest that demand flexibility can help improve the interplay between power demand and supply in order to allow more intermittent generation in the system.

1.4 Demand flexibility

If deregulation has provided households with means of contributing with demand flexibility, the ongoing change in the production mix and integration with other countries mean that a flexible demand side must respond to the current availability of electricity. The recent surge in technological advancement has further opened up possibilities for such demand flexibility, most notably with the ongoing development of smart grids and digitalization of electricity consumption. In particular, new grid technology for metering and providing information about of electricity usage enables new services and products, and is a major reason for the possibility of contracts with hourly pricing of electricity (see, for example, the survey on smart grids in Siano (2014)).

As of today, most households have electricity contracts where either the price is fixed for a year or longer or varies by month. Neither of these types of contracts reflects the within-day variation in generation of electricity, and households therefore have no monetary incentives to adjust usage to the momentary variation in availability of electricity. This is likely to result in very high demand for certain peak hours, e.g., evening hours and cold work days during winter, as illustrated in Papers [I] and [II]. If households for any reason do not respond to the availability of electricity by adjusting their usage, sufficient generating capacity has to be built to satisfy extreme levels of demand. Note that if capacity is operating close to maximum, it only takes a small increase in demand to require an extension of capacity. If capacity is a substantial part of the cost structure (i.e., high fixed costs), the capacity reduction that could result from improving price responsiveness is then a substantial potential source of welfare gains (Borenstein (2005) and Kopsangas-Savolainen and Svento (2012)).

Perhaps one of the biggest steps toward improving demand flexibility was taken when Sweden introduced a law allowing consumers to have access to real time pricing (RTP), in the sense that consumers can choose to have hourly price contracts without having to pay for the necessary metering equipment (source: §3 Chap 11 in the the Electricity Act). Sweden is, to our knowledge, among the few countries to have adopted such an explicit and country-wide possibility for RTP. Empirical evidence for the practicability of real time pricing schemes, and in particular the possibilities and incentives for households to respond to such pricing by shifting load from "expensive" to "cheap" hours, is, however, rather scarce. Indeed, as documented in Faruqui and Sergici (2010), the evidence is relatively ambiguous and depends upon a variety of factors. Further, Allcott (2011a) notes that, even if households on RTP are fairly price elastic, the gains are rather small and amount to approximately two percent of annual household electricity expenditure. Similar findings are presented in Paper [I]. In Sweden, the demand for real time pricing contracts has so far been small.

Demand flexibility rests on the idea that consumers respond to economic incentives like prices or other forms of compensation by changing their behavior, and policies aiming to stimulate demand flexibility are commonly referred to as enabling policies that empower consumers to play a role in energy markets. However, changes in behavior will not be realized if the incentives for households to change behavior are too small, either because the gains are too small or because of transaction costs. It might also be the case that households are unaware of a policy or lack perfect information about prices and electricity usage, and therefore do not respond to the incentives.

In general, previous literature on demand typically finds price elasticities to be small and close to zero; see, for example, Nesbakken (1999), Brännlund et al. (2007), Fell et al. (2014) and Krishnamurthy and Kriström (2015). Secondly, as illustrated in Paper [III] in this thesis, roughly 40 percent of all households in Sweden have fixed-price contracts, with no incentives to adjust electricity usage to seasonal variations in price; consequently, for these households, price elasticities are close to zero. Thirdly, as illustrated in Paper [IV], few households switch between electricity contracts in the short run in response to price variation. Finally, recent literature has argued that households are inattentive to prices, and lack perfect information about both prices and electricity usage (e.g., Kažukauskas and Broberg (2015) and Sexton (2015)). If households are inelastic and inattentive to prices, this poses an obvious challenge to price-driven demand flexibility. Further, the high expectations of price-driven demand flexibility are to some extent contradicted by the literature on the so-called energy efficiency gap, arguing that consumers are rather price-insensitive and may react inefficiently to price signals due to informational, organizational and behavioral failures (for an overview, see Broberg and Kažukauskas (2014)).

Several measures have been suggested to remedy the lack of price responsiveness, and some have also been implemented by policy makers. For example, previous literature has found that information can play a key role, both by augmenting price responsiveness (as illustrated in Paper [III]) and also by increasing awareness of electricity usage (see Allcott (2011b), Delmas et al. (2013), Delmas and Lessem (2014) and Kažukauskas and Broberg (2015)), and a number of websites in Sweden provide comprehensive information about electricity prices, such as www.elskling.se and www.elpriskollen.se. Further, the expectations of smart grids are considerable, and new technology is assumed to simplify demand flexibility considerably (Siano (2014)). However, discussions on smart grids often ignore households' incentives to adopt this technology and how the neccessary behavioral changes from increasing demand flexibility are perceived among households. In particular, demand response not only requires smart meters and potentially other capital investments, but also requires that the cost of changing behavior is relatively low (Hargreaves et al. (2010), Broberg and Persson (2016)).

In the light of previous literature suggesting substantial efficiency gains from increased demand flexibility, it might appear obvious that society should strive for such behavior. However, it is important that such efficiency gains are compared to the monetary and non-monetary costs of increasing demand flexibility. From a socio-economic perspective, not only costs associated with investment in technology but also possible disutility for households from changing behavior should be accounted for. However, knowledge remains limited about how flexible electricity customers really are, as well as about the factors driving electricity consumers' behavior.

This thesis aims to fill this gap in the existing literature. This thesis contributes with a number of new insights about residential electricity demand and household behavior by providing a unique exploration of electricity usage at the end-use level, as well as analyzing topics such as the effects of media coverage on price responsiveness, and how households respond to prices by changing between electricity contracts. The papers are summerized below.

2 Summary of the Papers

Paper [I]: Residential End-use Electricity Demand: Implications for Real Time Pricing in Sweden

Using a unique data set, this paper explores the potential of Sweden's movement toward real-time pricing for residential electricity use, as well as the cost implications for retailers and consumers. Our analysis uses data from a study commissioned by the Swedish Energy Agency, which metered household electricity consumption at the appliance-level at ten-minute intervals for 200 villas, none of which were on RTP contracts. Data at this level of detail has rarely been available for most countries. The appliance-specific nature of this metered data provides a unique opportunity to better understand appliance- and end-use-specific consumption patterns. Using this data, we estimate end-use-specific load curves (conditional on household characteristics). The estimated load curves are then used to explore possible restrictions on load shifting (e.g., the office hours schedule) as well as the cost implications of different load shift patterns.

At the end-use level, our analysis sheds light on relatively intuitive facts: households use heating when it is cold, lighting when it is dark and cooking before they leave for work and when they return home. Unsurprisingly, we find that the end uses with large shares of total load are heating, lighting and cooking, in that order. Based on these results, it is not evident that households can reallocate electricity consumption across hours in the short run, as this would essentially imply that households cook dinner during the night, turn on lights when electricity is cheap and adjust heating to prices, rather than to outdoor temperature. However, even in the presence of such restrictions, households may still adjust consumption to prices if the cost savings are substantial. By matching the estimated load curves with corresponding spot prices, we are able to explore potential cost-savings from re-allocating electricity consumption from peak to off-peak hours. We find very small gains: only 2-4 percent of reduction in daily cost from shifting load up to five hours ahead. These results, we believe, may actually be interpreted as a best case scenario. On the other hand, it is also important to point out that, as the share of intermittent generation increases, the price variation, and hence potential cost savings, may well increase. However, although potential cost savings increase in price variation, restrictions to load shifting may impose significant cost increases if households are unable to reallocate load.

The results presented here have important implications for Swedish energy policy, and in particular for the Swedish government's stated goal of implementing RTP. The success of this pricing scheme depends heavily on demand response which, as our results indicate, is likely to be small, absent substantial investments in new technology and a focus on RTP by retailers. Both consumers and retailers appear to have little to gain from a potential switch to RTP, at least in the short run, based upon our simple cost shifting experiments.

Paper [II]: The hourly income elasticity of electricity

In this paper (for the first time, as far as I am aware), I estimate hourly income elasticities for end-use electricity usage. Such estimates provide an insight not only into how an increase in income affects the level of electricity usage, but also when households are expected to increase usage and how the within-day consumption pattern is expected to change with income. The results can then inform about whether the issues associated with peak demand will be magnified by an increase in income, which will be the case if households are more income elastic during peak hours. The results indicate that this is indeed the case, with estimates of income elasticities being larger for peak hours than for off-peak hours for the kitchen and lighting end uses, albeit insignificant for the heating end use. In addition, I find some heterogeneity in income elasticities across housing types and income levels, but no difference between short and long-run elasticities. Further, I use the estimated hourly elasticities to calculate daily income elasticities.

The results range from insignificant for heating and media devices to significant and positive and rather high peak elasticities for kitchen and lighting: 0.307 and 0.442, respectively. Finally, the total daily income elasticity is 0.198 (for detached houses), which is in line with previous literature.

Further, I find that short-run estimates (conditional on housing characteristics) are similar to long-run estimates (not conditional on housing characteristics). From a policy perspective, this suggests that attempts to reduce peak demand could benefit from a focus on appliances, rather than housing types. This could, for example, suggest promoting so-called smart appliances that automatically respond to prices. The finding that detached houses have a higher income elasticity might suggest that efforts should be focused on these households to make them more responsive to price variation or in other ways incentivize them to adjust consumption to the availability of electricity.

Even though the peak elasticities are relatively small, they may still be of great concern to policy makers. In particular, note that, if capacity is to cover demand at its peak, and if the supply is currently producing at maximum capacity, even a small increase in peak usage might necessitate costly expansion of supply. In other words, even small peak elasticities may result in large costs to society. All in all, the results suggest that higher income is associated with higher electricity usage, and in particular that this difference in usage is most pronounced during peak hours.

Paper [III]: Heterogeneity in price responsiveness of electricity: contract choice and the role of media coverage

In this paper, I explore how the price responsiveness of electricity varies across contract types, and, in the case of variable-price contracts, depends on media coverage of the electricity price. The hypothesis is that, because households on fixed-price contracts face little or no price variation, estimates of price elasticities for these households should be close to zero. Failing to consider this could potentially underestimate demand elasticity.

Furthermore, it seems plausible that households on variable-price contracts lack perfect information about the electricity price, which limits their behavioral response to price fluctuations. For example, it can be costly to stay informed about a price that varies by month, and billing information can be difficult to understand. Ex-post billing adds to this effect. However, these households may learn about electricity prices in media and therefore respond more to prices when media coverage of electricity prices is extensive. In comparison, it should be much easier for households on a fixed-price contract to keep track of the price, since it is constant over time.

I propose an empirical model of household demand for electricity where the price responsiveness for households on variable-price contracts depends in part on media coverage. I estimate the parameters in this model using a unique and large data set with roughly 54000 households. As far as I am aware, this is the first paper in the very large literature on electricity demand to have the data required to explore these topics. Because contract choice is endogenous to electricity usage, an instrumental variable approach is used, where the predicted probabilities from a probit choice model are used as instruments in a 2SLS model.

I find that households are responsive to prices, and that the price elasticity is substantially higher for households on variable-price contracts than for households on fixed-price contracts, as expected. Further, I find that media coverage augments price responsiveness. The estimated price elasticity for households on variable-price contracts at the mean value of media coverage is roughly -0.07, which is in line with previous literature. When media coverage is extensive, for example two standard deviations above the mean, the price elasticity is roughly 1.7 times larger. The price elasticity for households on fixed-price contracts is smaller: -0.025. Interestingly, the augmenting effect of media is found to be smaller during winter than summer.

If information increases price responsiveness, this suggests that policy makers should provide information in addition to increasing prices (e.g., through taxation) if energy conservation is a policy goal. In particular, providing information appears to be a low-cost measure to increase price responsiveness. This paper only explores the effect of media, but there might be other relevant sources of information that could affect electricity consumption and price responsiveness, such as social media and direct information through emails and text messages. For example, one potential policy measure could be to regulate the information available on electricity bills, making sure that this information (in particular price information) is easy to understand. However, credibility and households' attention to information might differ across media sources, and households might value information differently depending on the source.

Paper [VI]: The effect of price on electricity contract choice

In this paper, I explore how households choose between electricity contracts in response to short-run variation in prices, conditional on previous choice of contract, using unique panel data from Sweden with roughly 54000 households. This paper adds to the sparse previous literature by being the first study (as far as I know) to use panel data to explore determinants of the choice between fixed-price contracts and variable-price contracts. The panel structure of the data allows for dynamic modeling of the contract choice, where households respond to current and previous prices as well as to previous choice of contract. Further, the sparse previous literature on electricity contract choice has used stated preferences to understand the contract choice, whereas this paper addresses this from a revealed-preference perspective, i.e., from actual choices.

Understanding electricity contract choice is important for several reasons: price levels and the variability of prices typically differ across contracts, and, for this reason, the short-run price elasticity is also expected to differ across contracts, as illustrated in Paper [III]. Understanding the choice between electricity contracts is therefore important in order to understand the price responsiveness of electricity demand. Understanding the choice between electricity contracts is also of importance in order to understand the competitiveness of the electricity retail market. If households are price inelastic and tend to remain on their current contract, for example because of transaction costs, this may allow the retailer to increase prices above the marginal cost of electricity. While the choice of retailer has been studied before, less is known about the choice of contract. Finally, understanding the determinants of electricity contract choice can shed light on the potential demand for electricity contracts with hourly pricing.

I find that the electricity contract choice exhibits substantial state dependence, and that the previous contract choice to a very large extent determines the current choice. Prices are found to have very small marginal effects. The results are robust to different specifications. Further, households are relatively homogeneous across income groups, housing types and geographical location in terms of price responsiveness and state dependence. Given that few households switch contracts each year, these results are expected.

There are several possible explanations for the substantial state dependence and lack of price responsiveness found in this paper. First, the difference in prices between the two contract types is on average small. Second, the short-run variation in many of the variables plausibly associated with the choice of contract, such as housing characteristics and income levels, is small on average.

Third, because electricity expenditure typically is a small share of the budget, households may pay little attention to cost-saving measures. Fourth, households may perceive information regarding different contracts as hard to understand, and may believe that switching between contracts is complicated. The potential cost savings from switching between contracts are then most likely perceived to be small relative to potential monetary and non-monetary transaction costs associated with switching between contracts. With this in mind, the results in this paper appear very intuitive.

The results in this paper have some important policy implications. For example, if policy makers want households to switch more frequently, e.g., in order to decrease market power for retailers, they should put effort into providing information about potential cost savings, and should work to decrease switching costs and other barriers to switching. Removing barriers to switching may also increase price responsiveness if households switch to variable-price contracts. Some measures of this sort have already been taken, most notably with several websites providing information and guidance on prices and how to switch between contracts and/or retailers. However, the results in this paper suggest that such measures have had little effect, since the state dependence is substantial.

3 Conclusions

This thesis adds to previous literature on electricity demand and demand flexibility by exploring several topics related to challenges for the electricity market of today and the future. I have provided a detailed description of residential electricity demand at the appliance level, together with some new insights into how peak demand will evolve as household income increases. Further, I have explored how price responsiveness differs across electricity contracts, and how media can augment price responsiveness. Finally, I have explored whether households switch between electricity contracts in response to variations in price. None of these topics have been explored in such detail before. The research has accordingly contributed to the general knowledge on electricity consumption and household behavior, which constitute the starting point for policy instrument design, and has augmented knowledge on the merits of residential demand flexibility programs.

Two unique data sets are used to explore these topics. The data used in Paper [I] and Paper [II] provide detailed insights on electricity usage at the appliance-level. Such comprehensive data on electricity demand have rarely been available. The data used in Paper [III] and Paper [IV] consist of a unique household-level panel of 54000 households, including detailed information on prices and electricity contracts. These two data sets provide unique opportunities to explore new topics in electricity demand.

Several different methodological approaches are used in this thesis. Seemingly unrelated regression is used in the two first papers to account for unobserved determinants of household behavior that are common to all hours, suggesting that joint estimation across hours is likely to yield efficiency gains. In Paper [III], a fixed-effects 2SLS estimator is used to account for the possible endogeneity of electricity contract choice, and predicted probabilities from a probit model are used as instrumental variables. Finally, a dynamic random effects probit model is used in Paper [IV] to allow for dynamic modeling of electricity contract choice. The initial condition problem is accounted for as suggested by Wooldridge (2005), and a Mundlak-Chamberlain correlated random effects specification is used to account for possible correlation between the unobserved household-specific effect and other independent variables.

There are several factors suggesting that increasing demand flexibility should, in theory, be relatively straightforward. Deregulation has provided households with many options in order to contribute as active participants in the electricity market, providing, de facto, power to the people. Technological advancement, such as the digitalization of electricity consumption and the development of smart grids, has further opened up possibilities for new services and contract forms that enable and simplify demand flexibility. Finally, the changing production mix and increased variation in generation from a larger share of intermittent production create both the need for demand flexibility (from a policy perspective) and monetary incentives (i.e., price variability) for households to respond to the current avilability of electricity. However, households' interest in contributing with demand flexibility appears to be limited, not the least exemplified by the so-far low demand for real time pricing contracts.

Price-driven policies are meant to change the behavior of households. However, changes in behavior will not be realized if the incentives for households to change behavior are too small, either because the gains are too small or because of transaction costs. It might also be the case that households are unaware of the policy or the potential cost savings, and therefore do not respond to these incentives. This thesis provides some intuitive examples of why households may not be able or willing to contribute with demand flexibility to the extent that policy makers may want:

- First of all, many of the options available for a household to contribute with demand flexibility imply changing the household's behavior. As is illustrated in Paper [I], exogenous restrictions such as working hours, outdoor temperature and the availability of daylight put restrictions on electricity usage. Such restrictions might be difficult to overcome, even if prices provide incentives. Similarly, households may be used to cheap and secure electricity and may have adjusted their electricity-consuming behavior to that context.

- Secondly, the monetary incentives are in many cases limited. For example, in the context of hourly pricing of electricity, as illustrated in Paper [I], the cost savings from shifting load between "expensive" and "cheap" hours will for the average household amount to only a few percent of electricity expenditure. Similarly, as argued in Paper [IV], the monetary incentives to switch between electricity contracts are on average small.

- Thirdly, households may have imperfect information about prices (and electricity usage), as suggested by the results in Paper [III], as well as in previous literature, and there might exist transaction costs associated with increasing demand flexibility.

- Fourthly, electricity expenditure is, and has for a long time been, a small share of a household's budget. In particular, even though electricity intensity is high in Sweden, prices have historically been relatively low. On a similar note, it is important to remember that electricity in Sweden is relatively "green" (mostly hydropower and nuclear power with low emissions) and reliable (black-outs are uncommon), and that households in the past and today possibly perceive that they have little reason to bother about electricity usage. I am myself perhaps a good example of this. Although author of a doctoral thesis on residential electricity demand, I am embarrassingly unaware of my own electricity usage, and consider my total expenditures too small to bother.

As such, things are seemingly looking dark for the potential for price-driven demand flexibility. On the more positive side, we have not yet seen the full potential in smart grids and digitalization. If demand response is automatic, then transaction costs will be small and even actions that give little monetary gain at the household level may be taken. In particular, even small adjustments at the household level can have substantial effects on the aggregate level. Further, as illustrated in Paper [III], providing (more) information might be a cheap way of increasing the seemingly small response to price variation.

While this thesis answers some important questions, it also raises new questions for future research. Several interesting topics spring to mind: First, empirical estimates of the hourly response to prices are of paramount interest in order to understand the scope for dynamic pricing. Secondly, the monetary incentives for load shifting might change substantially if prices become more variable. New technology and household-level production might also have impact on the scope for RTP. Thirdly, the discussion on demand flexibility has so far focused on electricity usage, and little is known about how the transmission of electricity fits into the concept of demand response.

The detailed data used in this thesis may provide a unique opportunity for answering such topics, and the estimates in this thesis can be thought of as a baseline for, and a spur to, further investigation of different aspects of efficient pricing of electricity in Sweden. In particular, understanding electricity demand and household behavior can contribute to the design of an electricity market that is efficient from a market and system perspective, as well as being attractive and feasible for households.

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