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Towards Sustainable Energy Consumption
Electricity Demand Flexibility and Household Fuel Choice

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To my Family

Abstract

Paper [I] investigates household heterogeneity in valuing electricity contract attributes that include various load controls and information sharing to induce demand flexibility. Using a stated preference choice experiment conducted with Swedish households, this paper shows that, although a large proportion of households asks for substantial compensation, some households are willing to share their electricity consumption information and require relatively lower compensation to allow load controls. In addition, this paper finds that some households that are willing to provide flexibility by accepting load controls at a relatively low compensation ask for sizeable compensation to share their electricity consumption information, and vice versa. From the perspective of the contract providers, these findings suggest that information-optional contracts can generate more customers than contracts that bundle households' consumption information with various load controls.

Paper [II] uses a flexible model to accommodate heterogeneous decision rules in analysing data obtained from a discrete choice experiment aimed at eliciting Swedish households' willingness to accept compensation for restrictions on household electricity and heating use during peak hours. The model combines behavioural processes based on random utility maximization with an elimination-by-aspects strategy, where the latter involves a two-stage decision process. In the first stage, respondents are allowed to eliminate from their choice set alternatives that contain an unacceptable level, in this case restrictions on the use of heating and electricity. In the second stage, respondents choose between the remaining alternatives in a rational utility maximizing manner. Our results show that about half of the respondents choose according to an elimination-by-aspects strategy, and considering elimination-by-aspects behaviour leads to a downward shift in elicited willingness-to-accept.

Paper [III] tests the effect of a pro-environmental framing on households' stated willingness to accept restrictions on their electricity use. We use a split-sample choice experiment and ask respondents to choose between their current electricity contract and hypothetical contracts featuring various load controls and monetary compensation. Our results indicate that the pro-environmental framing has little impact on the respondents' choices. We observe a significant framing effect on choices and marginal willingness-to-accept for only a few contract attributes. The results further suggest that there is no significant framing effect among households that are already engaged in pro-environmental activities.

Paper [IV] explores the socio-demographic and housing characteristics that affect household fuel choice and fuel use decisions in urban Ethiopia. The results indicate that, whereas households with a female head are more likely to combine traditional solid (firewood and charcoal) and modern (electricity) fuels for different uses, households with less-educated heads, many family members, and poor living conditions (fewer rooms) tend to use traditional solid biomass fuels. We find that households with an individual electricity meter are significantly less likely to use charcoal. Further, the results show the satiation effect from the increasing use of a fuel by households is relatively higher for firewood and lower for electricity.

Keywords: Choice experiment, demand flexibility, electricity contract, fuel choice, fuel stacking, household heterogeneity, load control, pro-environmental framing, willingness-to-accept

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Umeå, January 2020
Aemiro

This thesis contains a summary and the following four papers related to electricity demand flexibility and household fuel choice.

Paper [I]

Daniel, A.M. (2019). Household heterogeneity in valuing electricity demand flexibility services. *CERE working paper*, 2020:2.

Paper [II]

Daniel, A.M., Persson, L. and Sandorf, E.D. (2018). Accounting for elimination-by-aspects strategies and demand management in electricity contract choice. *Energy Economics*, 73: 80-90. (Reprinted with permission)

Paper [III]

Broberg, T., Daniel, A.M., and Persson, L. (2019). Household preferences for load restrictions: Is there an effect of pro-environmental framing? *CERE working paper*, 2019:8.

Paper [IV]

Daniel, A.M. (2019). Household fuel choice and use: A multiple discrete-continuous framework. *CERE working paper*, 2020:3.

1 Introduction

Access to energy is central to advancing human development. Recognizing this, the member countries of the UN have adopted a goal that for the first time stipulates affordable and clean energy for all, Sustainable Development Goal number seven (SDG 7) in 2015. Apart from doubling the global rate of improvement in energy efficiency, the targets in this goal are to increase the share of renewable energy in the global energy mix and to ensure universal access to affordable, reliable and modern energy services by 2030 (IEA, 2017). As part of achieving these as well as other national and international climate targets related to energy, many countries have focused on expanding electricity generation from renewable energy sources, particularly from wind and solar power, and promoting clean fuel use. Electricity generation from such sources crucially depends on wind and sun conditions, which vary over time. Therefore, increasing demand-side flexibility is important to accommodate variability in power output. If demand for electricity is better adjusted to match available supply, it will be possible to minimize the risk of power disruptions and thereby the need for investments in additional capacity. Also, it is essential to understand households' fuel use patterns to design policies that foster primary reliance on clean fuels and sustainable use of biomass fuels.

This thesis consists of four papers that address concerns related to electricity demand flexibility and household fuel choice. The first three papers in this thesis investigate Swedish households' potential to provide demand flexibility services (reduce electricity demand during peak load situations) that could facilitate the integration of renewable energy sources into the electricity production mix. The first three papers seek to answer key questions that are not sufficiently addressed in the literature: (1) Are there differences between households as to how they value demand flexibility? (2) Do households fully consider alternative contract offers that encourage participation in providing demand flexibility services? (3) Are households willing to change their electricity use behaviour for non-economic, environmental reasons? The fourth paper analyses household fuel use patterns in urban Ethiopia to shed light on the factors that affect households' behaviour in using multiple fuels, which may affect the speed of transition to clean fuel use in Ethiopia and other developing countries.

The main findings are that households in Sweden are heterogeneous in terms of their valuations of certain demand flexibility service attributes, but that many households do not consider all contract alternatives that reflect demand flexibility, and that emphasizing environmental benefits has limited impact on households' stated preferences to change electricity use patterns. The fourth paper shows, among other things, that households with a female head are more likely to combine electricity and biomass fuels (firewood and charcoal), while households with many members, few rooms, and no designated kitchen space tend to use biomass fuels, and households having a better-educated head do not generally prefer biomass fuels.

Before moving on to a detailed discussion of motivations for the papers and summarizing each paper, I present a brief overview of the developments in global renewable electricity generation and related concerns with particular reference to the Swedish electricity market.

1.1 Renewable electricity generation

It is fair to say that developed and developing countries alike are seeking solutions that promote economic growth and combat climate change by reducing greenhouse gas emissions. In this endeavour, a transition to a renewable energy system is of fundamental importance to set economies on a desired green growth path. This is because energy is an essential input in almost all economic activities and, hence, efforts to mitigate climate change should target decarbonizing the energy sector. Increasing the share of renewable sources in energy production is widely recognized as a viable strategy to reduce the climate impacts of fuel combustion for electricity and heat generation, which, combined with transportation, is responsible for two-thirds of the global CO_2 emissions (IEA, 2019a). Apart from climate reasons, investments in renewable energy technologies contribute to economic growth, enhance social welfare and create employment opportunities (IRENA, 2016).

As part of realizing ambitious national and international climate goals (e.g., the 2016 Paris Agreement to keep the increase in global average temperature below 2°C, ideally to 1.5°C), many countries have recently focused on expanding electricity generation from renewable sources. So far, 135 countries have incorporated renewable electricity targets in their national energy plans (IRENA, 2019). Consequently, global electricity generation from renewable energy sources has increased significantly over the last decade (see Figure 1), although it is not yet satisfactory to meet national and international climate ambitions. To date, hydropower is the largest source of renewable electricity globally. It accounted for 68% of all renewable electricity consumption in 2016 (IEA, IRENA, UNSD, WB and WHO, 2019). Much of the potential for hydropower, for example in Europe, has already been exploited (Hirth, 2013), and, therefore, the growth in hydropower generation is not expected to be substantial. However, driven mainly by policy support, advancement in technology and significant reductions in generation costs,[1] global electricity production from wind and solar power in general, and in most European countries in particular, is growing rapidly (IEA, IRENA, UNSD, WB and WHO, 2019). As can be seen in Figure 2,

[1]Since 2010, the average reduction in electricity generation costs of solar photovoltaics (PV) and 80% and 20%, respectively (IEA, IRENA, UNSD, WB and WHO, 2019).

Sweden is not an exception to this development. In 2017, the share of wind energy in the total electricity production in Sweden was 11%, more than double in five years and increasing more than tenfold from 2007 (IEA, 2019b).

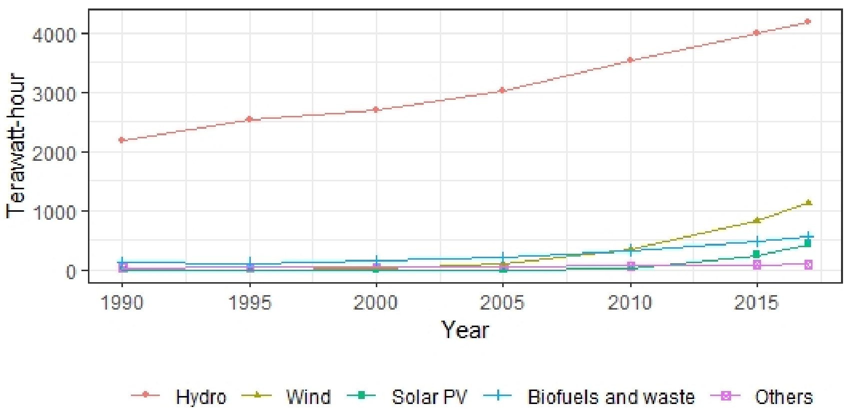

Figure 1 - Global renewable electricity generation (1990-2017). Source: IEA renewables information 2019 (https://www.iea.org/)

A fundamental concern related to high-level integration of intermittent renewable sources into the grid is how electricity systems maintain a balance between demand and supply at each moment in time. With power output from intermittent renewable sources being variable across time and space and not accurately predictable, system operators will face critical challenges to satisfy demand during peak load periods, particularly when renewable sources dominate the system. Traditionally, system operators call on dispatchable generators (conventional power-generating technologies, e.g., coal, gas) to continuously balance electricity demand and supply and maintain electricity supply security (Joskow, 2011; Kim and Shcherbakova, 2011). However, apart from cost considerations, such supply-side solutions would not be a viable balancing option in a sustainability-oriented electricity system.

Historically, Sweden has been successful in maintaining electricity supply security, mainly due to the availability of a high proportion of base load (nuclear power) and hydropower, each accounting for about 40% of the total production (Swedish Energy Markets Inspectorate, 2017). Indeed, in recent decades, a relatively stable electricity demand coupled with rapidly growing generation from wind power and biofuels has enabled the country to become a net exporter of electricity to neighbouring interconnected countries. Sweden is also among the leading countries in the race towards building a carbon-neutral energy system (IEA, 2019b).

In the future, however, it is not guaranteed that the Swedish electricity system will maintain its historical success. In this regard, Broberg et al. (2017) underline the rapid expansion of intermittent electricity

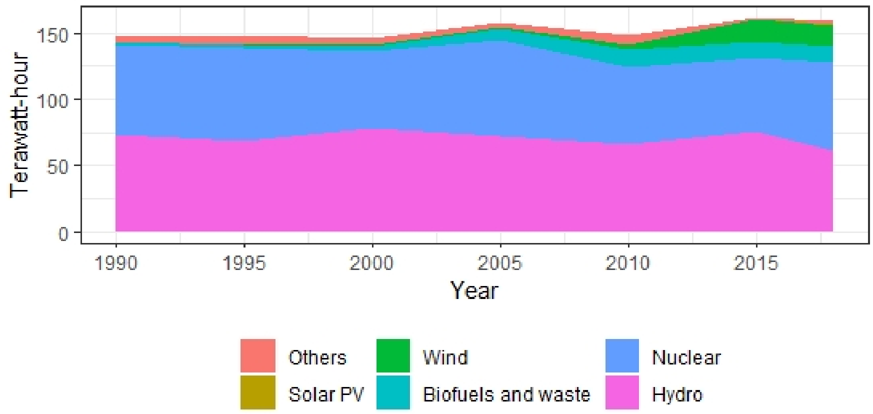

Figure 2 - Electricity generation by source in Sweden (1990-2018). Source:IEA 2019 (https://www.iea.org/)

production (mainly from wind power), the gradual phasing out of nuclear power and the increasing integration of transmission networks with other countries as the main developments that are likely to challenge the Swedish electricity system. Sweden's goal to produce its electricity with 100 percent renewable sources by 2040 (Energy Agreement, 2016) also implies that wind and solar power need to eventually replace nuclear power. Furthermore, Sweden aims to replace its strategic reserve capacity by a market-based solution to balance power (IEA, 2019b).

The discussion above indicates that additional (demand-side) flexibility may be needed for a smooth functioning of future electricity systems, with large-scale intermittent renewable sources in the production mix. This is because, while it might be technically possible, it is difficult to economically store large amount of electricity (Muratori et al., 2014). Besides, although power exchange from neighbouring countries could be an option to offset a shortage of supply in integrated electricity markets like Sweden, imports may not always be available (IEA, 2019b).

2 Demand flexibility

Demand flexibility (DF) refers to the potential to adjust demand for electricity according to electricity market constraints through demand response (DR) programs. DR comprises a broad set of actions to adjust end-users' demand (mostly to reduce demand during peak load periods or to shift electricity use to periods with lower demand) through incentives or price signals (Torriti et al., 2010). DF helps to accommodate the variability in power output and to flatten peak electricity demand in situations where generation from nuclear power plants is expected to cease; where the potential to expand hydropower is limited; and where fossil fuel-based (e.g., coal and gas) power generation needs to be reduced for environmental and economic reasons. DF is an attractive alternative to balance power, particularly in electricity systems with intermittent renewables in the production mix, since it has the potential to reduce the need for back-up generation capacity and costly investments in electricity network enhancements (Aghaei and Alizadeh, 2013; Gottwalt et al., 2016; Söder et al., 2018). Since fossil fuels are often used in conventional power plants to generate back-up capacity and satisfy peak demand, DF can also decrease emissions by reducing the need for frequent activation of such generation units (Söder et al., 2018).

In principle, the operation of most energy-intensive household appliances can be postponed; these include dishwashers, laundry machines and dryers, towel warmers and comfort floor heating. This means that there is a large potential for DF in the residential sector (Finn et al., 2013; Stenner et al., 2017). In addition, unlike the industrial sector, where the load is relatively time-invariant (Alizadeh et al., 2014), demand for electricity by households follows a cyclical pattern, with peaks in the morning and evening. Implementing DR programs in the residential sector is, therefore, essential to reduce mismatches between the demand for electricity and available supply.

Perhaps the most widely promoted DR programs in the residential sector are time-differentiated tariffs[2], which typically include time of use (TOU) pricing, real time pricing (RTP) and critical peak pricing (CPP). The simple idea behind time-differentiated tariffs is that households can adjust their electricity use according to electricity prices, which vary over time to reflect availability of power. This is facilitated by enabling technologies (smart meters) which allow two-way communication between the end-users and the electricity utility company regarding electricity consumption in real time. However, experiences in the US and Europe show that households have limited interest in adopting such types of tariffs (Hu et al., 2015). Kim and Shcherbakova (2011) highlight that lack of knowledge about the presence and potential benefits of such programs, and limited potential savings as a percentage of overall financial expenditures, are among the main reasons for low participation of households. In Sweden, for example, in a rather impractical setup of shifting loads for five hours ahead, Vesterberg and Krishnamurthy (2016) show that the savings households can realize from adopting RTP is on the order of 2-4% (0.3 -1.25 SEK) of the daily cost. This is a very small cost saving, and is perhaps a potential explanation for a very low uptake (less than 1%) of such tariffs in Sweden (Broberg and Persson, 2016).

An alternative (or supplement) to price-based programs to manage peak electricity demand is direct load control (DLC). In this case, a network company can enter into contractual agreements with households to remotely control the operation of pre-selected appliances (or limit load to a pre-specified level) during peak demand periods for a monetary compensation (Babar et al., 2014; Broberg and Persson, 2016).

[2]In such kinds of tariffs, prices differ – between peak and off-peak periods (TOU), across hours in a day (RTP), and during extreme system peaks (CPP) (Hu et al., 2015).

This is technically possible to do directly with customers or through a third-party, i.e., an aggregator or energy service company. The advantage of DLC is that it allows more accurate demand forecasts even at the local network level (Stenner et al., 2017). Also, once the contractual agreement is signed, DLC does not require households to be particularly active (Broberg and Persson, 2016; Ruokamo et al., 2019). However, it is crucial that a sufficient number of households are willing to participate for DLC to offer network benefits, generate financial gain for participating households in the form of compensation, and create business opportunities for third parties that may be involved in marketing DF. Most importantly, it could be costly to change behaviour related to daily routines in electricity use. Hence, better understanding of households' preferences for rescheduling electricity use is imperative to influence behaviour.

2.1 Household preferences for demand flexibility service attributes

Stenner et al. (2017) document that households' willingness to participate in DLC programs is limited despite the availability of enabling technologies and financial benefits. According to this study, trust in the utility implementing DLC is an important factor for households' willingness to participate, while Fell et al. (2015) highlight perceived loss of control for households as a potential explanation for low uptake of DLC contracts. Apparently, DLC involves a disutility for households as it implies that an external actor will control their electricity flow. Therefore, a thorough understanding of households' preferences for DLC contract attributes and incentives to participate in programs that involve DLC is essential to harness their DF potential.

Real markets for electricity contracts characterized by DLC are rare (if ever available), which then makes it impossible to study households' preferences for attributes of such contracts from observed behaviour. For this reason, we need to rely on stated preference or stated choice methods (Adamowicz et al., 1998; Louviere et al., 2000) that are based on hypothetical scenarios which mimic real markets (see Johnston et al., 2017, for a contemporary guide). The main idea with the use of stated choice methods is that revelation of preferences of agents should not be confined to choices made in actual markets, since it is possible to design preference experiments for attributes of goods and services that are not available in the market (Hensher et al., 2014). One such method is the choice experiment (CE), which is a multi-attribute approach widely used to analyse preferences and estimate the economic values for attributes of a good or service (Holmes et al., 2017). In a CE, agents (e.g., households) face a series of choices between hypothetical alternatives (contracts in this case) characterized by a similar set of monetary and non-monetary attributes that can have different levels across alternatives. From the choices, it is possible to elicit households' preferences for attributes and estimate the monetary value for each non-monetary attribute using statistical techniques. The use of attribute-based stated choice methods, for example CE, to reveal preferences of agents offers a flexibility that may not be obtained from market data. This is because, in a CE, the experimenter has better control over the agent's decision context, including the inclusion/exclusion of choice alternatives, attributes of alternatives, and the variations in levels of attributes (Adamowicz et al., 1998).

Over the past two decades, the CE method has been increasingly applied to study preferences and estimate economic values of attributes of nonmarket goods and services in several disciplines, including environmental economics (Holmes et al., 2017). In parallel to this, methodological advances related to the design of CEs and consequent analysis of CE data have become available. In particular, there has been an increasing interest in accommodating preference heterogeneity and accounting for alternative decision rules when analysing discrete CE data. Paper [I] in this thesis investigates household heterogeneity in valuing demand flexibility service attributes, while Paper [II] examines households' use of heterogeneous decision rules to choose their preferred contracts that reflect demand flexibility.

2.1.1 Heterogeneity in valuing demand flexibility service attributes

In recent years, several studies have examined households' preferences for DF service attributes that feature DLC in different electricity markets using the CE method (see e.g., Broberg et al., 2017; Broberg and Persson, 2016; Harold et al., 2019; Richter and Pollitt, 2018; Ruokamo et al., 2019). The findings from these studies, including the ones in Sweden (see e.g., Broberg et al., 2017; Broberg and Persson, 2016), show that households, in general, ask for sizeable compensation to accept load controls. In addition, the findings in these studies indicate that households have heterogeneous preferences for DF service contract attributes such as the level of control (in terms of actual load or electricity end-use), timing and duration of load control, and additional electricity services (e.g., handling of electricity usage information). These studies mainly use the mixed logit model[3] for estimation (McFadden and Train, 2000; Revelt and Train, 1998), which is one of the most widely applied econometric structures to accommodate unobserved preference heterogeneity. Although the mixed logit model accommodates heterogeneity in attribute parameters in the sample population, it does not directly offer any information regarding the likely location of a given household on the distribution of parameters or valuation estimates for attributes.

One way to tackle this problem is to use the mixed logit model estimates and derive individual-specific estimates that are conditional on respondents' choices (Hess, 2010; Train, 2009). Except Richter and

[3]The mixed logit model is also known as the random parameter logit model or mixed multinomial logit model.

Pollitt (2018), the studies on preferences for DF service attributes mentioned above report aggregated compensation amounts (valuations) for the DF service attributes that characterise the contracts. However, instead of concentrating on aggregated population (sample) level valuation estimates, working with individual-specific conditional estimates can provide more detailed insights about preference heterogeneity among households (Hess, 2010; Train, 2009). For example, as illustrated in Paper [I], there could be several household segments with significantly different average valuations for the contract attributes. This implies that there is heterogeneity in households' DF potential. Identifying the characteristics of different household segments can be important in designing contracts that appeal to the particular preferences of households. This can make it more efficient for contract providers to encourage households to participate in DF programs involving load controls, which could ultimately benefit the electricity system.

The main contribution of Paper [I] is that it shows how we can exploit the heterogeneity in households' valuations of demand flexibility service attributes for contract differentiation. The analysis of heterogeneity in Paper [I] uses original data from a web-based CE on electricity demand flexibility service contracts that Broberg and Persson (2016) conducted with 918 Swedish residential electricity customers in 2014. In the CE, respondents were faced with a choice between two hypothetical contracts and a contract that mimics existing situations related to the management of their load during peak demand and extreme situations, as well as electricity consumption information. The attributes that characterised the hypothetical contracts were: control of heating and domestic electricity during the morning (7:00-10:00 a.m.) and evening (5:00-8:00 p.m.) peak demand hours on weekdays and during extreme situations (including weekends), anonymous distribution of electricity consumption information, and a one-off annual monetary compensation. In Paper [I], I estimate a mixed logit (MXL) model in willingness-to-pay space (Train and Weeks, 2005) on the CE data and perform a posterior analysis. When utility is specified in willingness-to-pay space, the parameters for nonmonetary attributes can be directly interpreted as marginal valuation estimates. Train and Weeks (2005) show that this results in more reasonable valuation distributions and avoids the need to derive valuation distributions from the estimated distributions of attributes' parameters, which is the case when utility is specified in preference space.

I find that the average annual compensation that Swedish households ask ranges from 43 SEK to allow control of heating in the morning to 1263 SEK to accept control of electricity for domestic use in the evening peak hours. These estimates are very close to the finding in Broberg and Persson (2016) that is based on the same data estimated in preference space with a constant (non-random) compensation parameter. The higher compensation for accepting control of electricity for domestic use is not unexpected, since most people stay at home and use electricity in the evening. I also find that households are significantly heterogeneous in their valuations for control of heating in the morning and domestic electricity use in the evening and distribution of electricity consumption information. The significant heterogeneity in valuation of contract attributes indicates that there might be variation in electricity demand flexibility potential of households, which contract providers can exploit to design and market such contracts. To better illustrate this, I derive individual-specific valuations for all attributes conditional on respondents' choices. I perform a cluster analysis using the individual-specific conditional mean valuations and identify four distinct household consumer segments.

The first segment consists of households that require relatively lower compensation to accept load controls, and households that are willing to share their electricity consumption information anonymously. These households may provide considerable flexibility in terms of peak load reductions, particularly in the evening. Their electricity usage information can also help design energy services that include consumption feedback, peer comparisons and energy-saving advice. For households in this segment, a contract that bundles various load controls with information distribution can be appealing. Although the compensation to accept load controls is substantial, households in the second segment are willing to share their electricity consumption information. This implies that contract providers can partly offset the higher compensation required for accepting load controls by also offering households a contract that asks for electricity usage information. In contrast to this, I find that households in segment three are willing to accept load controls at a lower cost but require considerable compensation to share their electricity consumption data. This suggests that usage data privacy can be a concern for some households, and contract providers may need to consider this in designing contracts. Finally, households in the fourth segment, which constitutes 57% of the sample, ask for sizeable compensation to accept load controls and share electricity usage information.

The findings in Paper [I] suggest that households are heterogeneous in terms of valuing some demand flexibility service attributes. Therefore, contract providers should account for variations in the valuations of contract attributes in designing and marketing such contracts. By designing contracts that suit the particular preferences of households, contract providers can more efficiently acquire customers who sustain their business and potentially offer system-level benefits.

2.1.2 Accommodating heterogeneous decision rules in contract choices

Over the last two decades, much of the research effort in choice modelling has been devoted to studying heterogeneity in preferences, assuming that the underlying behavioural process or decision rule is the same across respondents. In most of the applications, the core behavioural process is represented by the standard random utility maximization approach (McFadden, 1974), i.e., based on the notion of compensatory behaviour, which implies that gains in one attribute can be traded against losses in another. However, a growing number of studies document that the heterogeneity across respondents is not limited to preferences but extends to differences in respondents' choice processes (Hess et al., 2012). In particular, recent studies show that some respondents in a given sample adopt different decision rules, including attribute non-attendance (see e.g., Campbell et al., 2011; Erdem et al., 2015; Hensher et al., 2005; Sandorf et al., 2016; Scarpa et al., 2009), lexicographic choice rules (see e.g., Hess et al., 2012), random regret minimization (see e.g., Chorus, 2010; Chorus et al., 2008; Hess et al., 2012) and an elimination-by-aspects strategy (Tversky, 1972a,b). In stated choice methods, Johnston et al. (2017) highlight that such anomalous response behaviours should be investigated during survey pretesting and addressed in the experimental design or later in data analysis if issues persist.

One approach to accommodate heterogeneous decision rules as part of data analysis is through latent class models, where each class represents a decision rule (Hess et al., 2012). This approach has been applied to accommodate decision rules based on random utility maximization (RUM) and the elimination-by-aspects (EBA) strategy, which involves eliminating from the choice set any alternative that includes an undesirable aspect or does not include a desirable one (see e.g., Campbell et al., 2014; Erdem et al., 2014; Hess et al., 2012). In the context of electricity contract choices where the contracts are characterized by DLC to reflect DF, some households could consider certain restrictions (e.g., restrictions on electricity for heating and domestic use in the evening) totally unacceptable, at least given the compensation levels offered. As a result, they may not consider alternatives with such restrictions when making their choice. If this is indeed the case and not accounted for, it leads to wrong inferences regarding preferences and estimates of value, as shown in Paper [II].

In Paper [II], we examine the effect of considering alternative decision rules on households' preferences and willingness-to-accept (WTA) compensation for various load controls during peak demand hours. The paper is based on the same discrete choice experiment survey data as in Paper [I]. In this paper, we use a flexible latent class model that combines two decision rules, namely RUM and EBA type strategy. The EBA component is based on a two-stage decision process. In the first stage, respondents eliminate from their choice set alternatives (hypothetical electricity service contracts) that contain an unacceptable level, in our case restrictions on the use of heating and electricity. In the second stage, respondents choose between the remaining alternatives in a compensatory manner. This contrasts with the conventional method of analysing discrete choice data based on a RUM model framework, which assumes that people consider all attribute information and all alternatives in each choice set when making choices.

In Paper [II], we hypothesize that both heating and electricity may be considered "essential" goods, and people may therefore not be willing to accept any restriction related to these services, at least not within the compensation levels offered. If people do not make trade-offs with respect to these attributes but exclude alternatives containing them from their choice sets, failing to consider this may lead to wrong inferences with respect to preferences, and hence the applicability of the results for prediction and policy recommendation can be limited. We examine our hypothesis with and without considering preference heterogeneity over respondents.

Our results show that about half of the respondents choose according to an EBA type strategy and that, on average, they are unwilling to accept any control on heating in the evening or on electricity use at any time of the day. This result is robust across models that do and do not consider preference heterogeneity. The result is also intuitive and reflects a typical weekday in the average Swedish household. People use electricity in the morning to make breakfast, while it is not essential to consider the indoor temperature later in the day when they are at work and school. Consequently, when coming home in the evening they need electricity to cook, run dishwashers, do laundry, etc., and they might want to turn up the heat.

The results from our model that accommodate preference heterogeneity reveal two groups of people: those who are more likely to make trade-offs and those who tend to stay with the status quo, which does not entail any kind of load controls. Importantly, we observe that respondents who are willing to make trade-offs tend to choose alternatives in which heating in the morning is restricted. This result suggests that restriction on heating in the morning does not inconvenience respondents and, therefore, the required compensations should reflect this.

Furthermore, we find that the willingness-to-accept estimates are sensitive to whether we consider EBA behaviour. Considering such behaviour leads to a downward shift in willingness-to-accept. Intuitively, by considering a respondent's actual consideration set, we restrict the calculation of willingness-to-accept only to consider alternatives that were indeed considered. The findings in this paper can be useful to design compensation schemes for flexibility (peak load reduction) services that household consumers may provide to the power system.

2.1.3 Pro-environmental framing of demand flexibility services

In the literature, financial motives are presented as the main triggers for households' participation in programs designed to reduce peak electricity demand. Nevertheless, as discussed above, potential electricity cost savings from reducing peak load or shifting peak load to off-peak periods are not large enough to motivate households to undertake such efforts. Studies on households' motivation to save energy (Bolderdijk et al., 2013; Dogan et al., 2014; Schwartz et al., 2015; Steinhorst et al., 2015) show that emphasizing environmental benefits (disclosing environmental information) induces actions that reduce energy use. For example, using a split sample CE study, Buryk et al. (2015) found that disclosing the environmental and system benefits of dynamic tariffs reduces the electricity bill discounts households require to switch contracts from fixed to dynamic tariffs by 10%. Although this result seems promising, it was a pilot study. Therefore, it is of interest to use a larger sample size to test whether households would be more interested in providing demand flexibility (more willing to accept load controls) in response to environmental appeals. In Paper [III], we studied the effect of disclosing information that briefly explains the role of demand flexibility through load control in facilitating renewables integration for power sector decarbonization. If disclosing environmental benefits makes households more willing to accept load control, it will be a cheaper way to harness the demand flexibility potential in the residential sector.

The objective of Paper [III] is to test the effect of a pro-environmental framing on household preferences for load control in Sweden. To do this, a split-sample choice experiment approach is used. Respondents were assigned randomly to either a treatment or a control group. The number of respondents in each group was 1007. In the choice experiment, respondents were asked to choose between a contract without any type of load control, which represents their current contract, and hypothetical contracts, which restrict load to a certain level in the winter (December to February) during peak demand hours in the evening (4:30-7:30 p.m.). Four non-monetary attributes characterise the contracts: load control, duration and timing of load control, number of days of load control, and flexibility to choose appliances for load control. Also, to give respondents an incentive to accept load controls, the contracts include an annual monetary compensation as one of the attributes. All respondents were told that the purpose of the contracts is to reduce electricity use at times when the electricity grid is threatened, in exchange for compensation. In addition, respondents in the treatment group were explicitly informed that load control contracts would reduce CO_2 emissions and make Swedish electricity production CO_2-free in the future. To highlight the CO_2 aspect, this information was placed as a reminder before each choice set in the treatment group.

We hypothesize that a pro-environmental framing of load curtailment activities may encourage respondents to opt in and accept contracts with stricter load control for a given compensation level (or request lower compensation for accepting a specific contract). We test our hypothesis in several ways. First, we test whether the framing results in different distributions of choices over alternatives (contracts) in the same choice set. Second, we estimate a probit model to check whether the treatment affects respondents' tendency to choose the status quo contract. Third, we estimate a mixed logit model that accounts for potential scale differences and test whether the preference parameter and willingness-to-accept estimates for the corresponding attribute levels are statistically different between the two groups. Fourth, we test whether the framing causes any differences in preference parameters and willingness-to-accept estimates when we control for respondents' pro-environmental behaviours. Finally, we examine the effect of the framing on respondents' propensity to use an alternative processing strategy, where respondents consider only the hypothetical alternatives (relative to considering all alternatives).

The results in Paper [III] show that there is no clear-cut difference between the two groups in terms of the frequency with which alternatives were chosen in each choice set that is identical across groups. We find that the treatment group is marginally less likely to choose the status quo contract, which might indicate that the pro-environmental information caused a more positive attitude towards being restricted. The mixed logit model results show that significant differences associated with the treatment relate to only a few attributes. Specifically, the treatment group is significantly less negative towards the number of days with load restrictions and prefers restrictions to be on appliances that are pre-specified. However, the significant differences apply only to respondents who stated relatively lower engagement in certain kinds of pro-environmental activities. Furthermore, although framing positively influences respondents' propensity to consider only contracts with a load control (relative to all possible contract alternatives), the effect is not statistically significant.

The findings in Paper [III] suggest that there is limited potential to influence household electricity use behaviour through a pro-environmental framing of load curtailment, at least for our particular framing. However, it is important to point out that the pro-environmental framing effect in our study could have been confounded with the information on supply security (which in itself can be perceived as a pro-social framing) through load management, which we provided for both groups. A future study that disentangles such pro-social framing effects may shed more light on the effect of pro-environmental framing on stated behaviours.

3 Multiple fuel use behaviour

Whereas electricity is the primary household fuel in advanced economies, many households in developing countries combine modern energy (e.g., electricity and liquefied petroleum gas), transitional fuels (e.g., charcoal and kerosene – "dirty" commercial fuels), and traditional solid biomass (e.g., firewood, animal dung and crop wastes) to meet their energy demands, particularly for cooking (Heltberg, 2005; IEA, 2017; Masera et al., 2000; Yonemitsu et al., 2014). The continued prevalence of biomass fuels exposes many households to indoor air pollution, which caused 3.8 million premature deaths in 2016 (WHO, 2018) globally. Multiple fuel use behaviour is common in urban areas of developing countries, even in households with higher income and better access to modern fuels (Mekonnen and Köhlin, 2008). This is mainly due to unreliable supply, high prices of modern fuels, and tastes and cultural preferences of households (Heltberg, 2005; Masera et al., 2000). If households continue to rely on solid biomass and dirty commercial fuels despite access to cleaner modern fuels, electrification and modern fuel subsidy programs will not be effective in reducing the environmental and health damages from combustion of solid fuels. Therefore, any intervention that promotes modern fuel use and adoption and sustained use of improved biomass stoves requires a better understanding of factors that affect the households' fuel use patterns (Heltberg, 2005).

Previous household fuel choice studies in developing countries have focused on analysing the main cooking fuel type (see e.g., Heltberg, 2005; Rahut et al., 2014; Rao and Reddy, 2007) or main fuel category in terms of cleanliness (see e.g., Alem et al., 2016; Karimu, 2015). These studies neglect other fuels on which households might spend a non-trivial share of their budget. Most importantly, the approaches used in previous fuel choice studies are not suited to model the fuel quantity (expenditure) decision households make associated with the choice of each fuel type. Since households using multiple fuels also face choices related to quantity for each fuel type choice, it is more appropriate to simultaneously model such discrete and continuous decisions. Furthermore, the substitution between different types of fuels by households might be limited (imperfect) since some foods taste better when cooked with specific fuels (Masera et al., 2000). Also, households might experience satiation effects from increasing consumption due to the polluting nature of some fuels, for example, firewood and charcoal. This is to say that there may be high marginal disutility from polluting fuels at a high level of use of such fuels, and hence, the models used to analyse fuel choice should capture this.

In Paper [IV], these issues are addressed using the multiple discrete-continuous extreme value (MDCEV) model (Bhat, 2005, 2008). The model is borrowed from the transport demand and time-use literature to explore the factors that affect household fuel choice and use in urban Ethiopia. The MDCEV model has the following merits. First, unlike models previously applied to analyse household fuel choice (i.e., classical discrete choice models), the MDCEV model accommodates multiple fuel use household behaviour as it does not assume that the choice of a fuel alternative excludes the choice of other fuel types. Second, it enables us to model the fuel quantity (fuel expenditure) choice along with the discrete choice of each fuel type in a single step. The ability to model both choices jointly with a discrete and continuous dimension is a clear advantage over models for demand system estimation based on Deaton and Muellbauer (1980). A single-step estimation of multiple discrete-continuous choices is also more efficient than a two-step estimation procedure (see e.g., Dubin and McFadden, 1984) to handle discrete-continuous choices. Third, the MDCEV model uses a nonlinear utility functional form that avoids, in our case, the need to assume unlimited inter-fuel substitution by households. Lastly, the MDCEV model framework makes it possible to capture potential satiation effects from the increasing use of (expenditure on) a specific fuel. As far as I am aware, this approach has not been used to study household fuel choice and use in a developing country context.

The application of the MDCEV framework in Paper [IV] is based on two rounds of household survey data from urban Ethiopia. As discussed above, the objective is to analyse the factors that affect household fuel choice and use for domestic purposes, mainly cooking. The fuels considered are the four most commonly used fuels in urban Ethiopia, namely firewood, charcoal, kerosene and electricity.

The results in Paper [IV] reveal that households with many family members are more likely to use traditional solid biomass fuels (firewood and charcoal), whereas households with a female head are more likely to combine modern (electricity) and traditional fuels. The result related to gender is an important addition to the literature on fuel choice, establishing that female household heads have strong preferences to adopt modern fuels. We find that households with a female head are more likely to combine modern and traditional fuels to satisfy their energy needs. Households with a large family size, on the other hand, may need a relatively higher amount of energy, which could make modern fuels unaffordable since these households are also usually poor. In line with the literature, the results in this paper show that the use of firewood, charcoal and kerosene is negatively related to the education level of the head of the household, while the opposite holds true for electricity. This could be due to more awareness concerning health and the environment among more educated household heads. The results related to household income (as proxied by monthly expenditure) indicate that lower-income households (with less than the median monthly expenditure) are more likely than higher-income households to spend on all four types of fuels, which suggests that poor households could be vulnerable to increasing fuel prices. Housing characteristics such as the number of rooms and availability of designated kitchen space are found to relate positively with the use of electricity but negatively with other fuel types. We also find that households accessing grid electricity through a private meter (which is required to benefit from lifeline rates in progressive electricity tariff structures) are less likely to use charcoal. The latter result is perhaps related to better access to electricity.

Further, the results show that the satiation effect from the increasing use of a fuel is relatively higher for firewood and lower for electricity. This implies that the satiation from firewood use is reached more quickly than it is for electricity use, which seems intuitive since electricity is a clean fuel that can flexibly serve different energy end uses. The findings in this paper are useful to inform energy policy. For example, the results are important to target subsidies for liquefied petroleum gas purchases and private electricity meter installations, and interventions that promote adoption of improved biomass cookstoves.

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