How the Behavior of Consumers and Firms Influences the Effectiveness of Policy Instruments Tackling Climate Change. Three Essays in Economics.

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“So what?”

Miles Davis

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Contents

Introduction

Every undergraduate student of economics is aware of the fundamental theorems of welfare economics. Furthermore, it is well known that unaccounted externalities violate the assumptions of the first fundamental theorem and lead the efficient allocation of resources to fail, unless the externalities are internalized in some way. Textbooks, such as Varian (1992), present simple and intuitive mechanisms for such internalization. For example, levying a Pigovian tax could internalize the externality cost, just as the introduction of the missing market for the externality could.

Even though the concepts of such corrective measures are straightforward, actual policy implementations often fail to capture the essence of the proposed textbook solutions. This failure is most prominently visible in the externality that is almost always used as an example in textbooks: greenhouse gas emissions and their impact on global climate change.

In particular, the consumption of fossil energy resources contributes to greenhouse gas emissions and hence to climate change. Energy-related emissions contribute 65% of total greenhouse gas emissions as of 2000 (Stern et al., 2006). This puts energy consumption at the center of attention in the discussion on climate change, a discussion that is of humanitarian and also economic importance. The economic cost of climate change is difficult to assess. However, estimates from Stern et al. (2006) suggest that the impact and risks from unmitigated climate change are equivalent to a 5 - 20% average reduction in global per-capita consumption. These numbers cannot account for all the implications from climate change, but they illustrate the magnitude of the externality from consuming fossil fuels and the related emission of greenhouse gases.

Given the expected huge costs from unmitigated climate change, internalization of the related externality should be of the utmost importance. Its relevance was emphasized by over 2000 economists, including Nobel Laureates such as Kenneth Arrow, John Harsanyi, Robert Solow and Joseph Stiglitz, by signing the “Economists’ Statement on Climate

Change" in 1997 (Arrow et al., 1997). In their statement, they encouraged the implementation of market mechanisms (e.g., an international emission trading agreement) to mitigate climate change.

Unfortunately, an international agreement on such mechanisms has thus far failed to materialize. Closest was the Kyoto Protocol, which came into force in 2005. It set emission reduction targets for industrialized countries and incorporated quasi-economic mechanisms termed *flexibility mechanisms* (i.e., emissions trading, Joint Implementation and Clean Development Mechanism) that aimed to make emission reduction as cost-effective as possible. Although countries such as Russia, the United Kingdom, Germany, France, and Italy are on course to achieve their goals (mostly for reasons other than proactive emission reduction), many countries do not. For example, Australia, Spain and Sweden will likely fail their targets. So will Canada, which withdrew from the Kyoto Protocol in 2011, and the United States, which never ratified it (Harris and Roach, 2007). Together with the fact that developing countries such as India and China, nowadays emitting the more greenhouse gases than all other countries, had no reduction target under the Kyoto Protocol, the four countries emitting the most greenhouse gases did not take on any liabilities towards emission reduction under that international treaty. This potentially shattered the mitigation movement as a whole. As climate change acts globally, there are few incentives for individual countries to incur preventive measures against climate change.

It was not until December 2015 that the successor to the Kyoto Protocol, the Paris Agreement, was successfully negotiated between the members of the UN Framework Convention on Climate Change. For the first time, the 195 member states agreed upon taking actions to limit the increase of the global average temperature to below 2°C. In order to reach that target, countries will make intended nationally determined contributions. This means that each country sets their contributions individually (and may cooperate internationally), but there is no enforcement if these targets are not met. Hence, contributions are hardly made outside national borders and market mechanisms such as a global carbon market are completely neglected. A shortcoming that was quickly criticized by for example, Jean Tirole (Schubert, 2015).

Even though an international agreement could be achieved, contributions are organized at national levels. A rise in national measures is to be expected and thus a continuation of current policies. That is because several measures at a national and supranational level have already been introduced in recent years. Germany stands out among the countries that have already implemented national measures: numerous political targets related to mitigating climate change have been defined in the past decade. In order to reach these targets, even more instruments of differing types (e.g., standards or subsidy programmes) were introduced.

The multiplicity of policy instruments to mitigate climate change raises the question of whether the instruments actually address the externalities appropriately and efficiently. For instance, the most frequently discussed climate change mitigation policy scheme in Germany is the renewable energy act. In order to increase the share of renewable energy sources in electricity generation, renewable energy sources receive subsidies of more than 20 billion euros each year (BDEW, 2015). The number of these schemes and the corresponding expenditure require a well-grounded academic evaluation of their efficiency and effectiveness. In this thesis, my aim is to give at least some insights into the economic questions on the effectiveness and efficiency of policy instruments to mitigate climate change. Aside from efficiency considerations with respect to the regional scope of instruments, this work is concerned with the interaction of consumer and firm behavior and policy instruments to reduce energy demand or consumption of nonrenewable resources. Over three chapters I discuss three topics: the consumer response to energy efficiency improvements, incentives for firms to offer energy efficiency, and incentives for firms to deplete reserves of nonrenewable resources. Thus, on the one hand the thesis contributes an economic evaluation of climate change policy, and on the other hand highlights the importance of consumer and firm behavior to such policies.

Overshadowed by the expenses of the support for renewable energy sources, other support schemes are rarely critically debated. This holds particularly true for those that improve the efficiency of energy consumption. As of 2015, renovating buildings to improve energy efficiency is supported with 686 million euros and research into energy efficiency has received 127 million euros of funding in Germany (BMWi, 2015). In principle, such governmental intervention is welcomed by many studies. For example, Granade et al. (2009) assert huge energy saving potential from energy efficiency. However, there seem to be investment inefficiencies that hinder leveraging these potentials (Allcott and Greenstone, 2012). Therefore, governmental intervention, e.g., by means of funding support, could overcome these inefficiencies. From an economic standpoint, it is worth taking a closer look at such instruments addressing energy efficiency. First, the issue is relevant far beyond the scope of Germany, as in 2013 250 million US dollars were provided to the Energy Efficiency and Conservation Loan Program in the US Climate Action Plan (White House, 2013) and in 2015 70 million GB pounds sterling were made available for energy efficiency improvements in the residential sector in the United Kingdom (DECC, 2015), to name two examples. Second, it is not clear whether energy efficiency actually addresses the emission externality appropriately. As most studies are solely based on engineering calculations, economic and behavioral responses to energy efficiency remain unconsidered. Nonetheless, research suggests that savings from energy efficiency fall short of expectations, due to direct and indirect *rebound effects* from economic and behavioral responses (e.g., Gillingham et al., 2013, Greening et al., 2000). And third, the source of the investment inefficiency is not well understood so far. This raises the question whether the political instruments are suitable to address the investment inefficiencies in energy efficiency.

The second chapter, based on a paper jointly written with Helena Meier, addresses the question of whether economic and behavioral responses counteract reductions in energy demand from implementing energy efficiency measures.

Chapter 2: How Technological Potentials are Undermined by Economic and Behavioral Responses - Selection Bias and Endogenous Energy Efficiency Measures (with Helena Meier). *EWI Working Paper 15/04.*

Regardless of whether energy efficiency does actually reduce energy demand or not, it contributes to consumer welfare. If consumers purchase more energy after the implementation of energy efficiency measures, they simply spend the additional related income on energy and hence attain a higher utility level. Given the observation that actual investments in energy efficiency fall short of expectations, this leads to the suggestion that consumers might not be aware of the potential of energy efficiency (e.g., Allcott and Greenstone, 2012). So, is governmental intervention necessary to inform consumers? Or would competition between energy retail firms drive them to voluntarily inform consumers and offer energy efficiency? From an industrial organization perspective this is not entirely clear. On the one hand, it is reasonable to assume that firms that supply energy would prefer energy efficiency to remain concealed, as energy efficiency would reduce demand for energy deliveries. However, on the other hand, if the energy retail market is characterized by a competitive market structure, it could be that competitive forces drive firms to introduce energy efficiency in equilibrium.

Building on this, the third chapter discusses the incentives for firms to offer energy efficiency under duopolistic competition and consumer inattention.

Chapter 3: Offering Energy Efficiency Under Imperfect Competition and Consumer Inattention.

Even though national instruments, such as energy efficiency support schemes, barely intersect with the proposed market mechanisms, they might nevertheless have an economic raison d'être. For most market mechanisms, transaction costs are disproportionally large for small-scale consumers of energy, e.g., within the residential, trade and commerce sectors. Therefore, implementing national instruments such as funding support for energy efficiency could be a second-best solution.

As for supranational measures to mitigate climate change, in 2005 the European Union (EU) introduced an emission trading scheme just like those proposed by economic textbooks. Under the EU Emission Trading System (EU-ETS) large-scale emitting units from several industries and European countries can trade emission allowances under a cap-and-trade scheme. The EU-ETS is divided into several phases and is currently in its third phase, which runs until 2020. The third phase has been marked by substantial critique of the system. With low prices for allowances set in 2012 and continuing to this day, some argue that the trading scheme brings about too little incentive for emission reductions. In the shadows of such mainstream critisism, Sinn (2008) has been expressing reproval on such policies, which become stricter over time, ever since 2007. His *Green Paradox* is deeply rooted in economic theory and argues that if policies hold up the prospect of ever stricter environmental regulation, owners of natural resources that contribute to climate change have incentives to extract the resource more rapidly. In order to counteract future deterioration, extraction at a faster pace also accelerates climate change. The academic foundation of Sinn's arguments is Harold Hotellings work on nonrenewable resources (Hotelling, 1931). The real-world validity of the *Green Paradox* depends on the real-world validity of Hotellings theory of nonrenewable resource industries. Unfortunately, empirical tests of the theory of nonrenewable resources are inconclusive and often based on strong assumptions.

For that reason, the fourth chapter, based on a paper, jointly written with Raimund Malischek to which the authors contributed equally, tests the theory of nonrenewable resources, for the first time incorporating imperfect competition and exploration activities.

Chapter 4: A Test of the Theory of Nonrenewable Resources - Controlling for Market Power and Exploration. *EWI Working Paper 15/01.*

A short overview of the chapters is given below. The overview includes summaries and critical discussions of the methodologies used and the results obtained.

Subsequently, mathematical symbols are used differently in the different chapters. The notation is summarized in a table in the supplementary material for each chapter.

Summary: How Technological Potentials are Undermined by Economic and Behavioral Responses

Governments worldwide spend increasing amounts of money on policy schemes to reduce energy consumption and related carbon emissions. For instance, in the UK, in 2015 GBP 70 million is available for improvements in energy efficiency in the residential sector. In Germany, in 2015, renovation work on buildings to improve energy efficiency is being supported with EUR 686 million and in the US the Obama administration provided USD 250 million in an energy efficiency loan program. Whether or not energy consumption and carbon emissions were reduced by such policies is the focal point of effectiveness evaluation. However, this evaluation is mostly based on engineering calculations and ignores economic and behavioral responses to energy efficiency, and therefore it overestimates the effectiveness of these policies.

However, adequate evaluation of engineering, economic, and behavioral drivers as well as their interactions need to be addressed. Furthermore, endogeneity issues are luring researchers into biased estimates. In this respect, our research makes three contributions. First, we are the first to evaluate the effectiveness of energy efficiency measures in a multi-product framework that is consistent with microeconomic theory. Application of a combination of Hicksian and Marshallian demands in an implicit Marshallian demand system allows us to address direct and indirect responses to energy efficiency measures. Second, we address endogeneity using an approximation approach known from productivity analysis. This allows us to identify the impact of unobserved heterogeneity has on energy consumption. And third, by comparing the effects of several energy efficiency measures, we can separate economic from behavioral responses and show that the latter greatly influences the effectiveness. We used German household survey data for the period 2006-2008 for our research.

Our results suggest that economic and in particular behavioral responses to energy efficiency measures counteract energy savings from energy efficiency measures. In this respect we find that the Energy Efficiency Gap as well as the Rebound Effect have a fundamental impact on efficiency and effectiveness of policies that enforce the implementation of energy efficiency measures. We find that only two out of five energy efficiency measures give estimation results in line with expectations from engineering calculations. Thus, two conclusions follow: first, rebound effects are likely to counteract demand reductions from energy efficiency measures. These effects might completely counteract efficiency gains and even result in backfiring. Second, results suggest a large heterogeneity within the rebound effect for the different efficiency measures. Furthermore, we identify a cross-product rebound effect for outer wall insulation, such that for each

additional EUR 1 spent on natural gas due to the direct rebound effect, another EUR 0.38 are spent on electricity.

Better understanding household responses to energy efficiency policies and energy efficiency implementation contributes to target-oriented policy designs and the increased effectiveness and efficiency of policies for energy efficiency. Thus, our research promotes the effectiveness of policy schemes and the achievement of the overarching goal to reduce carbon emissions and mitigate climate change.

Our identification strategy is mainly based on the assumption that consumers are better off implementing energy efficiency measures and that the main reason why some refrain from doing so is their lack of knowledge about energy efficiency. We argue that unobserved heterogeneity linked to a households *energy awareness* is the sole driving factor behind consumers' knowledge of the results and benefits of energy efficiency.

This is why we approximate *energy awareness* by using the households' choice of automobile. The line of argument is as follows: all else fixed, energy aware households are more likely to be informed about energy efficiency options. Two problems arise. First, energy awareness is unobserved. Second, if energy aware households are marginal adopters of energy efficiency, their awareness for energy will also result in more attention to energy costs. Hence, it is reasonable to assume that energy aware households will have lower energy expenditures, all else fixed. This obviously hampers the identification of the effectiveness of energy efficiency, as it is not clear whether lower demand for energy by adopters of energy efficiency is based on the energy efficiency measure or the households energy awareness. With energy awareness being unobserved and heterogeneous between households, one could either use an instrumental variable approach, or approximate it. We approximate energy awareness semi-parametrically by households' choice of automobile (similar to Olley and Pakes, 1996). Using specific carbon dioxide emissions as an equivalent to vehicle mileage, we assume that households that have a more efficient car are more energy aware.

Even though we obtain reasonable and robust results, one should be skeptical about whether energy awareness is the only omitted variable. For instance, we explore as much dwelling related data as is available in the dataset. However, it is impossible to cover all heterogeneity among dwellings that might impact on energy demand (e.g., the number and insulation level of windows).

Another issue associated with our modeling is the assumptions made regarding separability. We assume household preferences to be separable in budgeting groups. That means the total utility maximization problem under a budget constraint can be disaggregated into several subutility maximization problems. For instance, households divide income with respect to several subutility functions (e.g., housing or food) such that total utility is maximized. In a subsequent step, households maximize subutility by making purchasing decisions within groups. By way of example, within the energy group households could decide whether to buy natural gas or electricity. This separability assumption is made based on reasonable arguments as well as a lack of data on total household spending. This limits our analysis to the subutility stage and hinders our presenting of definite answers to the research question.

Fundamentally, our results are based on strong assumptions. However, as it is one of the first analyses to address unobserved heterogeneity in the evaluation of energy efficiency, our line of thought as well as empirical strategy could provide a spark for more research in this field.

Summary: Offering Energy Efficiency Under Imperfect Competition and Consumer Inattention

The provision of energy efficiency often remains in the shadows of other measures to mitigate climate change, e.g., renewable energy support schemes. However, there is a large body of literature that asserts the large-scale economic and environmental benefits of energy efficiency (e.g., Granade et al., 2009). All the more surprising is the observation that actual energy efficiency improvements fall short of expectations, in spite of governments worldwide introducing support schemes for energy efficiency to incentivize such investments. As already noted above, research suggests that consumers are simply unaware the potential of energy efficiency and the products on the market (Allcott and Greenstone, 2012). But why does the market fail to inform all consumers about energy efficiency?

At first, it is reasonable to assume that firms in the energy retail market prefer energy efficiency to be concealed, simply because this would reduce the demand for energy. However, from an industrial organization perspective, it not clear why firms would not coordinate on an equilibrium in which both firms offer and advertise energy efficiency. Taking into account that energy retail firms usually compete in a market with an oligopolistic market structure, a firm has incentives to offer and disclose energy efficiency if the other firms refrain from doing so, to win over consumers from competitors. Similar to the prisoner's dilemma game, this suggests that in equilibrium every firm introduces energy efficiency.

In this chapter, I analyze under which conditions energy retail firms introduce and advertise energy efficiency. In order to do so, I model the energy retail market as a duopoly with spatial competition as in Hotelling (1929). Competition on the market for energy efficiency is assumed to be non-spatial and between the energy retail duopoly and a competitive fringe. Energy retail firms compete for two consumer groups between which they cannot differentiate (i.e., price discrimination is impossible). First, there are naive consumers that are unaware of energy efficiency and purchase energy only. Second, there are sophisticated consumers that have informed themselves about energy efficiency and purchase energy efficiency and have reduced demand for energy. Firms decide whether to offer and disclose energy efficiency to the naive consumers (and inform a share of naive consumers) alongside energy or to offer energy only and what prices to set for energy.

Apart from the result that consumer inattention and imperfect competition are essential drivers for firms decisions to offer energy efficiency, I find that two symmetric equilibria exist. For the first, firms coordinate on not offering energy efficiency and concealing it from consumers and for the second firms coordinate on offering and disclosing energy efficiency. Which equilibrium firms coordinate on depends mainly on the distribution of consumer types. Firms will only offer and disclose energy efficiency to naive consumers if doing so leaves only a very small share of consumers uninformed. If that is the case, firms can charge higher prices for energy (as competition on the energy retail market is relaxed) and compensate for profit losses from reduced demand on the energy retail market. Furthermore, it is shown that informing consumers about energy efficiency always increases total welfare. Even under a consumer surplus standard, mandatory disclosure laws are always weakly welfare-increasing.

The above-mentioned results are based on arguable assumptions. This holds particularly with respect to modeling the energy retail market as spatial competition. Spatial competition models are used to model horizontal product differentiation. However, energy delivery, e.g., electricity or natural gas, are technically homogeneous goods. Similar to assumptions made by Laffont et al. (1998) in the telecommunications industry, I assume firms to offer different product characteristics that attract different consumers. I further argue that branding plays an important role in the energy retail market. Branding persuades consumers that products are less homogeneous than they actually are. Furthermore, assuming a competitive fringe in the energy efficiency market is reasonable when compared to the real-world example. Nevertheless, it simplifies the market mechanisms for energy efficiency immensely and should be relaxed to gain further insight from the model.

Essentially, the results of this chapter should be analyzed in context. Outcomes are based on a simple analytical model with strong assumptions and a very particular focus (i.e., energy efficiency). Nonetheless, the chapter shows that it is worthwhile to pay additional attention to the interaction between consumer inattention and imperfect competition in other markets too.

Summary: A Test of the Theory of Nonrenewable Resources

There is hardly a field in economics that is as greatly influenced by one single publication as the field of resource economics. Harold Hotelling published his work on the economics of exhaustible resources in 1931 (Hotelling, 1931). It received the attention it deserved in the 1970's due to the oil embargo and corresponding energy crisis as well as the publication of Meadows et al. (1972). Even today, the assumption of inter-temporal optimization of a non-renewable resource industry, as introduced by Hotelling, is the foundation for policy recommendations, such as the *Green Paradox*. Even though the theory has maintained academic attention for over 80 years, empirical applications and, more importantly, tests of the theory are rarely found. However, to apply policy recommendations the significance of the theory for the practice is crucial. Thus, the question is whether the scarcity of a nonrenewable resource - as proposed by Harold Hotelling - influences the actual decision-making process of a mining industry.

So far, tests of Hotelling's model for nonrenewable resources omitted issues of market power and exploratory effort in order to increase the resource base. Our paper contributes to the existing stream of literature in several ways. Our analysis combines the literature on empirically testing the Hotelling model (e.g. Halvorsen and Smith, 1991) with the literature focusing on extensions of the Hotelling model, namely the extensions introduced by Ellis and Halvorsen (2002) regarding market power and Pindyck (1978) regarding exploration activity. Hence, by taking a step towards more realistic assumptions and bringing our model to a newly constructed industry data set, i.e., the uranium mining industry between 2002 and 2012, we look for evidence for the theory in actual data.

In our model the firm operates a two-stage production process: in the first stage, a nonrenewable resource is extracted, before it is processed into a final output in the second stage. We thus assume vertical integration, which applies for most companies in resource industries. Using duality theory, we derive the firms intertemporal optimization problem. The corresponding Hamiltonian incorporates shadow prices for the resource and exploration. Exertion of market-power (one-shot Nash-Cournot oligopoly) is accounted for by means of a supply function, in which the relationship between the firm's own price and quantity and the other firms' supply responses is given by an inverse residual demand curve (Baker and Bresnahan, 1988).

Our strategy for testing the theory is as follows: estimating the model excluding the dynamic optimality condition for resource extraction provides consistent estimates. If the firm optimally extracted its resource, adding the dynamic optimality condition for resource extraction should result in the same consistent but more efficient estimates. Hence, under the null hypothesis, estimates of the model with and without the dynamic optimality condition should give the same results. Under the alternative hypothesis, both models give statistically different results. Testing is conducted using a Hausman specification test.

The related system of equations is estimated using Three-Stage-Least-Squares (3SLS). We test the Hotelling model using different interest rates in the dynamic optimality condition. Following Halvorsen and Smith (1991), we test constant discount rates (i.e., $r = 0.01$ to 0.25) and variable interest rates, which are proportional to actual real (2012) Canadian interest rates r_{CAN} (i.e., $r = r_{CAN} \cdot 0.25$ to $r_{CAN} \cdot 4$). Test results indicate a rejection of the null hypothesis for both the constant discount rate and the variable interest rate calculations. That means the firm's behavior does not satisfy the dynamic optimality condition.

Parameter estimates show that there exists a substantial mark-up over marginal costs that does not account for the shadow price of the resource in situ for the earlier observations and lower and even negative mark-ups over marginal costs for later observations. For the earlier observations, only a very small share of market prices can possibly represent resource user costs. This changes as the shadow price of the resource in situ increases steeply over time. The negative mark-up illustrates that the firm fails to assess the shadow price appropriately. Our results suggest that the hypothesis of Halvorsen (2008) partly holds, i.e., that the shadow price of the resource in situ may be too small to be considered in a firm's decision-making process and that the *mistake* firms are making by not optimizing inter-temporally may be small. Nonetheless, we find that even as the shadow price increases steeply, firms fail to incorporate this development appropriately in their price-setting.

Similar to the tests previously performed in other analyses, our results call the predictive power of the theory for nonrenewable resources into question. However, the results should always be critically scrutinized based on assumptions made with respect to the methodology and data. The theoretical model derived in this chapter is based on the assumption that firms that own a nonrenewable resource stock intertemporaly optimize the extraction of the resource. This means they incorporate opportunity costs of future extraction into their decision-making. It is obvious that uncertainty about future developments plays a crucial role in the validity of this modeling approach. Our model assumes perfect foresight not only with respect to market residual demand, but also with respect to exploration. Regardless of the (comparably) predictable uranium demand due to long nuclear reactor construction times, uncertainty prevails in the market, e.g., as a result of unknown international inventories. As shown, e.g. in Pindyck (1980), uncertainty does alter the optimal extraction path of the resource in situ. This is even more compelling as the years following the financial crisis as well as the Fukushima incident are within the time period considered.

Furthermore, data availability and quality is another issue often critically discussed with respect to empirical tests (e.g., Halvorsen, 2008). Apart from the fact that an empirical researcher of Hotellings theory can never know for sure if the published data is correct and suitable for her modeling approach, data availability often restricts the analysis with respect to aggregation. For example, Chermak and Patrick (2001) test the theory of nonrenewable resources under perfect competition and without exploration, but on the basis of individual wells. Contrary to most other empirical tests, they find proof of the validity of Hotellings theory. Data availability constrains our analysis to firm level and requires the implicit assumption that all relevant information is consistent with this level of aggregation. The unavailability of data on resource additions is another aspect deserving of critique. We approach this issue by estimating the exploration function using an extended data set based on national data and tackle missing data using a multiple imputation approach (Little and Rubin, 2002). Even though this approach gives robust results, it might come with efficiency and consistency problems.

Finally, our modeling of market power is assumed to be a one-shot interaction between firms. However, as numerous firms in the market are decades old, it could be a reasonable assumption that firms interact repeatedly.

However, this certainly does not mean we should neglect the theory proposed by Harold Hotelling when making predictions on the development of nonrenewable resource markets: the general logic of Hotellings model remains convincing. Besides, the critical discussion of the validity of assumptions shows that potential flaws in these assumptions could be the reason our test gives negative results.

How Technological Potentials are Undermined by Economic and Behavioral Responses - Selection Bias and Endogenous Energy Efficiency Measures

2.1 Introduction

Different countries worldwide aim at minimizing the consumption of fossil fuels and hence, carbon emissions. Carbon taxes or cap-and-trade mechanisms are implemented to address negative environmental externalities of fossil fuel consumption. While these are mostly directed at large-scale consumers like the manufacturing industries, transaction costs tend to be disproportionately large within the residential, trade and commerce sectors. For these, second-best policies are implemented.

Most of these policies aim at changing the stock of energy durable, energy consuming and converting goods as well as improving the thermodynamic characteristics of dwellings. Examples for these policies could be energy efficiency standards, such as the internationally known Energy Star label[1], or policies that reduce financial barriers for investment in energy efficiency, such as subsidies or loans. In recent years, governments have invested increasing amounts of money in such schemes. In 2013, the Obama Administration provided USD 250 million to the Energy Efficiency and Conservation Loan Program in the US Climate Action Plan (White House, 2013). In Germany, in 2015 renovations of buildings to improve energy efficiency are supported with EUR 686 million (BMWi, 2015). In the UK, in 2015 GBP 70 million are available for energy efficiency improvements in the residential sector (DECC, 2015).

A meaningful evaluation of these policies requires addressing effectiveness towards achievement of the programme objectives and cost-efficiency of the policy design. Cost-efficiency

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[1] `https://www.energystar.gov/`

focusses on free-ridership as well as non-additionality and was recently discussed in Boomhower and Davis (2014). Whether or not energy consumption and carbon emissions were reduced by a policy is the focal point of effectiveness evaluation. Most evidence on this effectiveness is solely based on engineering calculations and often ignores economic effects. A well-known example is the study on energy efficiency by the McKinsey Company (Granade et al., 2009) which is entirely based on engineering calculations. The UK Government Energy Review Report 2006 (DTI, 2006) does not even mention economic responses to energy efficiency investments (Madlener and Alcott, 2009), either.

That is surprising, as fundamental economic responses have been discussed ever since Jevon (1865). But even in economic studies on energy efficiency investments, the reference level for the effectiveness is generally given by engineering calculations for potential technological efficiency improvements. The actual efficiency improvements, thus demand reductions, are related to these potential technological efficiency improvements. The difference in percentages is quoted as the *rebound effect* (e.g., Gillingham et al., 2013, Greening et al., 2000). The evaluation of effectiveness is therefore strongly linked to understanding the rebound effect. Within economics, demand theory provides arguments for the rebound effect. With reduced demand for energy services due to large-scale implementation of energy efficiency measures, the price for energy drops. Since point price elasticities of demand differ, demand adjustments can be of ambiguous directions and also increase the consumed quantity. At the household level, this direct effect is accompanied by an indirect effect. The increase in available income from reduced energy consumption can be spent on other goods as well as on additional energy services, increasing the energy consumption, again.

However, next to price and income effects, insights from behavioral economics need to be considered. It needs to be investigated if behavior counteracts energy savings and further rises the rebound effect. While income effects will have a substantial influence, short-term temptations towards energy consumption should do likewise. Firstly, while individuals will have developed habits in energy consumption prior to implementing an energy efficiency measure (Jessoe and Rapson, 2014), research shows that adaptation to new habits is limited (Neal et al., 2011). Persistence in habits and therefore energy consumption behavior is likely. An example could be that individuals overheat their homes after an energy efficiency implementation.

Secondly, if we consider mental-accounting and self-licensing, these might also trigger additional demand, in the short term. Under self-licensing, investing in energy efficiency can be regarded as something (ecologically) *good*, due to its positive connotation to climate change. Hence, temptation to consume more energy in the present (which might be seen as something equivalently *bad*) might be permitted by having made the *good* investment/purchase in the past (Mazar and Zhong, 2010). Further, mental-accounting might classify expected savings from energy efficiency measures as additional short-term disposable income or energy consumption, leading to an even higher energy demand (Thaler, 1990).

As a summary, the previous discussion illustrates two issues of great importance. Ignoring economic as well as behavioral responses in the evaluation of energy efficiency policies will overestimate the effectiveness of energy efficiency measures and the accompanied policies. However, an adequate evaluation of the effectiveness is not trivial, since engineering, economic, and behavioral drivers as well as their interactions need to be addressed.

So far, a large body of literature analysed the rebound effect. Valuable literature reviews are given in Greening et al. (2000), Sorrell et al. (2009) and most recently Gillingham et al. (2013) and Gillingham et al. (2015). Due to the up-to-dateness of the latter articles, we refrain from reviewing the literature once again and refer to Gillingham et al. (2015) for a sound presentation of the status of the academic debate.

Most of recent studies use either experimental (e.g., Davis et al., 2014) or econometric methods (e.g., Frondel and Vance, 2013b). A well known issue with the latter is that demand models used for identification are simplified for methodological practicability rather than microeconomic accuracy (Deaton and Muellbauer, 1980). Sometimes cross-product and income effects are completely ignored. That is suprising, as demand systems that were derived from the expenditure minimization problem of consumers were introduced by Deaton and Muellbauer (1980) and further developed up until Lewbel and Pendakur (2009). These allow among others for aggregation of preferences, separability, budget-constraints as well as unobserved heterogeneity. While energy demand has been explored in such demand models (e.g., Baker and Blundell, 1991, Labandeira et al., 2006), the evaluation of energy efficiency measures and thus, the rebound effect, has not been undertaken based on such modeling.

The findings based on engineering calculation[2] (such as Granade et al., 2009)) show that it is cost-efficient to invest in energy efficiency technologies. But actual adoption rates suggest that something drives a wedge between optimal and actual investments. Research on this so-called *energy efficiency gap* argues that this can be explained by heterogeneity among consumers, asymmetric information, and inattention (e.g., Allcott and Greenstone, 2012, Boomhower and Davis, 2014). The marginal individual who implements an energy efficiency measure is either better informed or more attentive

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[2] Engineering calculations represent expected reductions in energy demand from implementation of an energy efficiency measure, considering only thermodynamic improvements and taking demand for the final energy service as fixed.

to energy costs than extramarginal individuals. This gives rise to a selection problem in the evaluation of energy efficiency measures. If well-informed consumers that are more attentive to energy costs are marginal adopters of energy efficiency measures, they are also more likely to have differing energy consumption patterns (Jessoe and Rapson, 2014). Therefore, unobserved heterogeneity that drives investment and utilization decisions needs to be taken into account (e.g., Kahn, 2007, Kotchen and Moore, 2007, 2008). Within an adequate evaluation of energy efficiency effectiveness, this endogeneity issue needs to be resolved.

In this paper, we investigate the effectiveness of energy efficiency measures by identifying the reduction effect of these on energy demand. Therein, we incorporate economic and behavioral responses to address the rebound effect.

Our analysis makes three main contributions. First, we apply the implicit Marshallian demand system developed by Lewbel and Pendakur (2009) that combines Marshallian and Hicksian demands. To our knowledge, we are the first to evaluate the effectiveness of energy efficiency measures in such a multi-product demand system consistent with microeconomic theory. That is, we explore consumption of different fuel types within the overall household budget. By applying a multi-product approach, we evaluate direct as well as indirect effects on energy consumption simultaneously. Direct effects give consumption responses to the fuel demand that is directly addressed by an energy efficiency measure, while indirect effects also take into account interdependencies with consumption of other goods within the household budget. There has been extensive work on the direct effect (as reviewed by Gillingham et al., 2015), by means of evaluating the price elasticity of demand. However, our approach allows to address both effects at the same time and identify the semi-elasticity of demand with respect to the implementation of an energy efficiency measure.

Second, we rely on an approach from productivity analysis to resolve the selection issue within our demand model. We define unobserved heterogeneity that reflects unobserved energy cost attentiveness and the information level regarding energy efficiency measures as *energy awareness*. Our analysis approximates energy awareness using the approach by Olley and Pakes (1996). The validity of our approximation approach is tested by investigating the impact of unobserved energy awareness on the decision to implement an energy efficiency measure. Further, we explore how the energy efficiency measures drive energy consumption. Hence, within our application of the Olley-Pakes-Approach, we map unobserved heterogeneity and obtain insights on how unobserved heterogeneity drives energy consumption and how much energy is saved from energy efficiency measures.

Our third contribution lies in the identification of behavioral responses to energy efficiency measures. By evaluating and comparing the energy saving effect of different energy efficiency measures, we explore whether or not behavioral responses do play a role in the rebound effect. This has not been addressed in the literature so far and our results show that behavioral effects impact significantly on the effectiveness of energy efficiency measures.

We use micro data of German households for 2006-2008. By analyzing billing information, we estimate the actual effectiveness of energy efficiency measures, incorporating the rebound effect. Exploring a German dataset is suitable for our approach for several reasons given in Germany. Energy usage is an important topic within the political economy and public attention on energy issues is large. Also, several large-scale promotion schemes for energy efficiency measures are in place.

We find that unobserved heterogeneity is a significant driver of the decision to invest and of energy usage. These results regarding efficiency of policy schemes are overshadowed by the fact that economic and behavioral responses to energy efficiency measures counteract expectations based on technological potentials. Understanding these can contribute to target-oriented policy designs and increased effectiveness and efficiency of policies.

The next section presents the theoretical model followed by the econometric approaches. Data is described in Section 2.3. Results follow in Section 2.4, Section 2.5 concludes.

2.2 Methodology

In this section, we first discuss our theoretical approach. We point out the resulting endogeneity issue and continue with the econometric application. We explain the methodology of incorporating energy awareness in our models.

2.2.1 Theoretical Framework

Our modeling reveals the underlying decision process with respect to the choice of energy efficiency measures and consumption of non-durable energy goods. The theoretical framework in Figure 2.1 presents the drivers of energy efficiency measures and of energy demand. Key policies aim at inducing a reduction in energy demand by supporting the implementation of energy efficiency measures. The implementation then impacts itself on energy demand, but is endogenous. Next to observable characteristics such as socio-economic and building characteristics, unobserved drivers, here energy awareness, determine whether or not a household implements an energy efficiency measure.

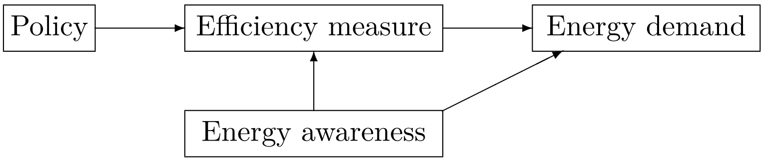

Figure 2.1: Energy awareness is unobserved but impacts on various causal paths

Energy aware individuals can be described by a larger attention to energy costs. They further possess more information on energy efficiency measures. Accordingly, individuals with a high level of energy awareness should be marginal adopters of energy efficiency measures and could demonstrate a different behavior regarding energy good consumption. Not addressing energy awareness and neglecting this type of unobserved heterogeneity leads to selection and omitted variable biases and therewith, endogeneity.

We address this endogeneity problem using the approximation approach by Olley and Pakes (1996) and approximate unobserved energy awareness by observed automobile choices. Assuming that selection is random conditional on unobserved energy awareness, the approximation approach resolves the endogeneity issue. With a given demand for automobile transportation[3], the decision to purchase a more efficient automobile, with lower fuel consumption and corresponding higher mileage[4], depends on the demand for automobile transportation and the awareness of future energy costs. Here, we use specific CO_2-emissions as an inverse equivalence for mileage[5]. Further, we approximate demand for automobile transportation by population density. We assume that in more densely populated areas private transportation demand is lower, given that alternative means of transportation increase in population density. Equation (2.1) reflects the above mentioned decision making process.

$$\text{Specific } CO_2\text{-emissions} = f(\text{energy awareness}, \text{population density}) \tag{2.1}$$

More energy aware individuals should always prefer an automobile with lower specific CO_2-emissions. However, transportation demand intensifies this effect. Meaning, with low population density and thus high demand for automobile transportation, the variable energy costs have a larger share in total automobile costs than with a low demand for

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[3] Automobile transportation demand is assumed to be exogenous within our modeling framework. Thus, means of changing automobile demand, such as moving, as well as substitution options are unconsidered.

[4] In particular in the United States of America, mileage describes the automobile fuel economy by means of the ratio of distance traveled per unit of fuel. Often given in miles per gallon.

[5] Specific CO_2-emissions reflect grams of CO_2 emitted by driving one kilometer. Hence, larger specific CO_2-emissions correspond to lower mileage. Data on automobile fuel consumption is not available within the data set.

automobile transportation. Therefore, consumers with large specific emissions and a high demand for automobile transportation can be considered as comparably energy unaware.

Under the assumption of strict monotonicity in the effect of energy awareness and population density on automobile specific CO_2-emissions, we can invert function f as follows:

$$\text{Energy awareness} = f^{-1}(\text{specific CO}_2\text{-emissions}, \text{population density}) \tag{2.2}$$

As the exact functional form of this relationship is unknown, we control for energy awareness allowing for semi-parametrical forms. We use a fourth-order Taylor polynomial with all interaction terms (as in Olley and Pakes, 1996). Hence, we construct a measure of the joint effect of unobserved energy awareness and observed population density. Decomposing the unobservables within the decision processes into the approximated energy awareness and the truly random error term resolves the selection and omitted variable biases[6].

We begin with modeling the decision to implement an energy efficiency measure using an ordered probit approach, taking into account observed characteristics and unobserved energy awareness. This way we get a better understanding of the underlying decision making process and show that energy awareness does have an effect within this decision. As a next step, we estimate a consumer demand system for non-durable energy goods to explore the demand-reducing effect of energy efficiency measures. We resolve the endogeneity issue by accounting for energy awareness.

2.2.2 Model I - Ordered Probit Approach

Within the ordered probit approach, the dependent variable m is the implementation of one or more energy efficiency measures. Thus, we focus on the question of whether or not efficiency measures have been implemented rather than exploring them separately. m is a discrete, ranked and ordinal variable that incorporates the number of all energy efficiency measures implemented by each household since 2002. m captures the following measures: roof or top story ceiling insulation, basement ceiling insulation, outer walls insulation, replacement of windows as well as replacement of the heating system. The effectiveness of these measures is differing in practice. These differing effects however are excluded from our analysis and average energy efficiency effects alone are captured in m. Resulting coefficient estimates are interpreted correspondingly.

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[6] An illustration can be found in Appendix A.

We derive a model that regresses m on observed and unobserved household characteristics. We denote exogenous observed and preference related characteristics, such as demographics and dwelling conditions, by vector $\vec{z}$. In addition to $\vec{z}$, we control for $\vec{a}$, the semi-parametric approximation of unobserved energy awareness and observed population density. As discussed, we apply an approach similar to the Olley-Pakes methodology for unobserved energy awareness[7]. The error term ρ is assumed to be joint normally distributed (Train, 1986). We specify the following ordered probit estimation equation and estimate it via standard maximum likelihood[8].

$$m = \sum_{c=1}^{C} \alpha_c z_c + \sum_{d=1}^{D} \beta_d a_d + \rho \tag{2.3}$$

Equation (2.3) allows us to calculate the continuous predicted energy efficiency variable $\tilde{m}$ and cut points that enable us to derive probabilities for implementing specific numbers of energy efficiency measures. If a significant effect of $\vec{a}$ on the decision to implement an energy efficiency measure shows, the above mentioned endogeneity issue arises and needs to be resolved by controlling for unobserved heterogeneity.

So as to explore the effect of energy efficiency measures on household energy demand, we discuss the demand system analysis in the following section.

2.2.3 Model II - Demand System

Our demand system is based on standard assumptions regarding consumer preferences, including reflexiveness, completeness, and transitivity. Consumers maximize their utility following the properties of homogeneity of degree one in prices, being increasing in utility, non-decreasing, continuous, and concave in prices, and derivable (Edgerton, 1996). Given the nature of the problem as well as the available data, we apply a product space approach with multiple products and heterogeneous agents. The efficient estimation of a multi-product system requires simplifications. Methods of simplifications such as aggregation and assumptions regarding separability are commonly used in literature (e.g., Hausman et al., 1994). Assuming (weak) separability corresponds with partitioning goods into groups and restricting preferences within groups to be independent of quantities purchased within other groups (Deaton, 1980). Therewith, overall utility

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[7] As a fourth-order polynomial with all interaction terms $D = 17$ in Equation (2.3).

[8] An overview about variable notations is given in Appendix A in Table A.1.

maximization under a budget constraint can be split into maximization of several subutility functions ν. In our particular application this coincides with households distributing overall household income on different aggregated groups of goods (i.e., budgeting groups), such as housing, food and energy, in a first budgeting stage.

$$u = f(\nu_{housing}, \nu_{food}, \nu_{energy}, ...) \tag{2.4}$$

The resulting distribution of overall household income gives the subgroup expenditures which restrict the maximization process for the subutility functions. For our analysis, we focus on the energy budgeting group and the related conditional demand function. That implies, the consumption of different energy goods is optimized taking individual prices and energy good subgroup expenditures (from the first budgeting stage) into account. In this multi-stage approach, separability of preferences is implicitly assumed. Hence, we assume that consumption of energy and other goods are separable but separability for consumption of different fuels is not assumed.

However, as Moschini et al. (1994) point out: “the convenience of an assumption [regarding separability] is no substitute for its truth”. Therefore, several tests for separability were proposed in the past (e.g., Moschini et al., 1994, Varian, 1983). Unfortunately, data availability hinders us to test our separability assumptions. Therefore, we reason the assumption by intuition. Firstly, grouping non-durable energy goods into one budgeting group is plausible for several reasons: Energy goods can be transformed into different forms of energy and are used for different kinds of services, such as heating or cooking, and a general substitutability exists. Households also tend to be contracted to one single provider that supplies most of the non-durable energy goods used. This applies in particular to electricity and heating fuels. Joint billing thus creates a perceptional linkage between these energy goods that is also invigorated by public attention being given to energy as a whole rather than to individual fuels (e.g., regarding the German *Energiewende*). Further, non-durable energy goods can be regarded as contributing to housing comfort (e.g., in terms of heating, warm water, lighting, entertainment). Lastly, the assumption is consistent with comparable energy demand estimations, see among others Baker and Blundell (1991) or Labandeira et al. (2006).

Yet, we have to consider the energy efficiency investment as a durable energy good within our budgeting approach. The discrete decision to implement an energy efficiency measure indirectly contributes to the energy subgroup utility ν_{energy}. The contribution is indirect by means of increasing the specific utility from consuming nondurable energy goods for heating. Therefore, we cannot assume intertemporal separability between the implementation of the energy efficiency measure and non-durable energy good consumption. Even though Deaton (1980) shows that durable goods can be easily expressed in a way similar to nondurable goods, the necessary assumptions of indivisibilities and perfect reselling of the durable good do not hold in our application. However, the highly individualized nature of energy efficiency measures, in particular in insulation applications, puts an absolute selling constraint on the durable energy efficiency measure. Hence, despite contributing to the subutility function, after the decision to invest[9], households stick with their choice. Expenditures associated with the investment[10] are predetermined and reduce subgroup expenditures without altering the subutility cost minimization problem dual to the subutility maximization problem. Thus, restricting our analysis on the residual subgroup expenditures is an appropriate approximation.

The implementation of the identification strategy requires the assumption that changes in durable energy goods that consume electricity are not correlated with the implementation of an energy efficiency measure. Such a correlation would be a likely scenario if energy efficiency measures are just a part of several investments when moving into a new house (e.g., larger kitchen space allows for larger/more kitchen appliances such as refrigerators). However, data suggests that energy efficiency measures are generally implemented after a change in occupation took place[11].

We use the Exact Affice Stone Index (EASI) implicit Marshallian demand system introduced by Lewbel and Pendakur (2009)[12]. In contrast to other product space approaches with multiple products and heterogeneous agents[13], the EASI demand system allows for almost unrestricted Engel curves, thus an unbounded relationship between product expenditure and household income, as well as unobserved preference heterogeneity.

The main trick of Lewbel and Pendakur (2009) is the combination of Marshallian and Hicksian demands. By expressing utility u by implicit utility y and replacing it in Hicksian budget share equations, they define implicit Marshallian demand equations described entirely by observable and approximable variables[14].

Households are considered as single consumers (based on the assumption of additivity of individual household member preference functions). As previously discussed, we assume a multi-stage budgeting approach. In a first budgeting stage, total income is distributed to subgroup expenditures, of which the energy group is in the focus of this

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[9] Because of expected utility returns.

[10] E.g., by means of credit payments.

[11] For an illustration refer to Figure A.1 in Appendix A.

[12] See Pendakur (2009) for a less technical introduction to the EASI demand systems and implicit Marshallian demands.

[13] Such as e.g., Deaton and Muellbauer (1980) and Banks et al. (1997).

[14] The approach used here as well as the estimation procedure are based on Pendakur (2009). A detailed description of the approach is given in Appendix A.

study. Households receive utility u from consuming a bundle of some subset of J different goods within the energy group. They spend total nominal group expenditures x on that bundle, taking the vector of prices $\vec{p}$ into account. The value of the chosen bundle can be described by $\vec{w}$, a vector of budget shares of length J. Observed and preference related characteristics, such as demographics and housing conditions are given by vector $\vec{z}$. We separate energy efficiency measures $\vec{m}$ from $\vec{z}$[15]. Contrary to the ordered probit estimation, we now disaggregate $\vec{m}$ and explore individual dummy variables for each type of efficiency measures. This enables us to capture behavioral aspects linked to differing measures implemented.

We further control for two types of unobserved preference heterogeneity: energy awareness and random utility. In line with the notation of the ordered probit estimation, energy awareness is incorporated in $\vec{a}$. Random utility is denoted by $\vec{\varepsilon}$.

Our matter of interest is the effectiveness of energy efficiency measures, i.e., the change in demand for an energy good by implementing an energy efficiency measure ($\partial Q^j/\partial m$). With $w^j = p^j Q^j/x$ and exogenous prices, Equation (2.5) follows.

$$\frac{\partial Q^j}{\partial m} = \frac{\partial w^j}{\partial m}\frac{x}{p^j} + \frac{\partial x}{\partial m}\frac{w^j}{p} \tag{2.5}$$

For good j a change in purchased quantity Q^j is described by changes in the group budget share w^j and changes in group expenditures x. Engineering calculations on the effect of an energy efficiency measure would give alterations in both w^j and x. With all considered energy efficiency measures aiming at reducing the demand for heating fuels, a reduced consumption of heating fuels due to an energy efficiency measure would decrease their budget share and related group expenditures.

The effectiveness of an energy efficiency measure, as follows from Equation (2.5), can be measured by changes in both the budget share of heating fuels and group expenditures. However, due to data limitations, the first budgeting stage (determining group expenditures) cannot be accounted for. Nevertheless, we can identify whether there is a positive[16] impact of implementing energy efficiency measures by considering energy group budget shares only and comparing these with engineering estimates.

For identification, we utilize the fact that the physical (i.e., thermodynamic) effect of energy efficiency measures affects heating fuels only. Consider three scenarios by which we illustrate that a demand-reducing effect should always relate to $\partial w^j/\partial m < 0$. Firstly,

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[15] See Table A.2 in Appendix A for the distribution of energy efficiency measures within the data.

[16] From a policy point of view, by means of reduced nondurable energy good consumption.

assume the energy efficiency measure would lower group expenditures but keeps the budget shares unaltered (i.e., $\partial Q^j/\partial m < 0$). Hence, behavioral reductions in demand for other energy goods would compensate thermodynamic as well as behavioral induced reductions in heating fuel demand. Secondly, assume the energy efficiency measure would unalter group expenditures and budget shares (i.e., $\partial Q^j/\partial m = 0$). This would correspond to behavioral effects in heating fuels that counteract thermodynamic effects entirely. Hence, no demand reducing effect of energy efficiency measures is observable. Similar results follow if considering $\partial Q^j/\partial m > 0$. Hence, in combination with estimates from engineering calculations (Stolte et al., 2012) we can identify and quantify economic and behavioral responses to implementation of energy efficiency measures.

Consider the endogeneity issue resulting from energy aware households being marginal adopters of energy efficiency measures. We argue that energy aware households tend to have a higher share of heating fuels compared to other energy goods (i.e., mostly electricity). Observable characteristics such as dwelling, heating and other things equal, energy aware households should still have a more efficient stock of energy consuming durable goods. In addition, research shows that the lower bound for heating demand is restricted by individual comfort levels (e.g., Nicol and Humphreys, 2002), while such a lower bound for other energy services is currently unknown. Therefore, consumption restrictions induced by energy cost attentiveness should primarily occur in non-heating fuels and hence, increase the budget share for heating fuels. Consequential, endogeneity needs to be addressed when evaluating the second stage budgeting process.

The following estimation equation for the budget shares results from the EASI implicit Marshallian demand system[17]:

$$w^j = \sum_{e=1}^{E} \gamma_e^j \tilde{y}^e + \sum_{f=1}^{F} \delta_f^j z_f + \sum_{g=1}^{G} \tau_g^j m_g + \sum_{h=1}^{H} \psi_h^j a_h + \sum_{k=1}^{J} b^{jk}(\vec{z}, m, \vec{a}) \ln p^k + \varepsilon^j \qquad (2.6)$$

In addition to the variables already specified, the linear approximation of the implicit utility $\tilde{y}$ and its powers are implemented in Equation (2.6). These variables give rise to another endogeneity problem: implicit utility y (and its powers) is simultaneously defined by exogenous variables $\ln x$, $\vec{z}$ and $\ln \vec{p}$ as well as the endogenous budget share $\vec{w}$. However, this is solved by the exogeneity of $\ln x$, $\vec{z}$ and $\ln \vec{p}$. By simply regressing the exogenous variables on y and its powers, this endogeneity problem can be resolved. We estimate Equation (2.6) using a Two-Stage-Least-Squares (2SLS) approach.

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[17] Derivation of this equation based on Pendakur (2009) as well as an overview of variable notations (Table A.1) are given in Appendix A.

2.3 Data

Our study is based on the German Residential Energy Consumption Survey (GRECS[18]) 2006-2008. The survey is conducted triennialy based on a tendering by the German Federal Ministry of Economic Affairs and Energy[19]. So as to obtain information on the use of energy in private households, a representative sample of the German population is interviewed on their consumption of various fuels and corresponding characteristics. The dataset consists of cross-sectional information on socio-economic characteristics (income, residence, number of children etc.), housing conditions (year of construction, type of building, rent/ownership etc.), heating system (fuel used, type of heating, auxiliary systems etc.), hot-water supply and food preparation (fuel etc.), billing information for the individual fuels/energy services, potential renewable energy systems (year of construction, type etc.), data on the implementation of energy efficiency measures as well as automobile ownership and climate indicators (heating degree days) for the years 2006 to 2008. The survey aims at observing energy efficiency measures implemented since 2002. We thus assume persistence in the households' observed and unobserved characteristics that influence the investment decision since 2002.

Within the dataset information for some variables (billing information[20] for energy goods, heating degree days, number of energy efficiency measures and household size) is given on a yearly level for 2006 to 2008. For all other variables information is only given for one point in time. This particularly concerns the socio-economic characteristics[21]. However, under the assumption of permanence in the cross-sectional information of the survey, we expand the dataset for the years 2006-2008. Given the yearly variation of some of the variables, we handle it as a cross-sectional dataset but allow for more than one observation per household.

We further analyse the choice of automobiles to proxy unobserved energy awareness. We match the stated automobile manufacturer key number and type key number in the survey with specific CO_2-emissions of the ADAC automobile database (Allgemeiner Deutscher Automobilclub, 2014). Based on this information, we calculate household average CO_2-emissions per kilometer as the mean of the specific CO_2 emissions of all automobiles in each household. Population density is matched from German Federal Statistical Office and the Land Statistical Offices (2014) at the local authority level.

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[18] GRECS was used in energy demand related articles among others in Grösche and Vance (2009), Frondel and Vance (2013a) and Grösche and Schröder (2011).

[19] The report, including the questionnaire used to generate GRECS, is given in Frondel et al. (2011).

[20] Billing information includes individual price data for each household. We thus account for individual supply side characteristics within the data.

[21] The survey was conducted between February 22nd and April 15th in 2010.

Fuel combination	Frequency	Percent
Electricity and natural gas	393	32.37 %
Electricity, natural gas and wood	182	14.99 %
Electricity and heating oil	156	12.85 %
Electricity, heating oil and wood	122	10.05 %
Electricity and wood	56	4.61 %
Electricity, heating oil, wood and solar thermal energy	34	2.8 %
Electricity, natural gas and solar thermal energy	34	2.8 %
Electricity, natural gas, wood and solar thermal energy	33	2.72 %
Only electricity	29	2.39 %
Electricity, heating oil and solar thermal energy	24	1.98 %
Electricity, natural gas, wood and lignite	19	1.57 %
Electricity and liquefied petroleum gas	15	1.24 %
Electricity and district heating	12	0.99 %
Electricity, heating oil, wood and lignite	12	0.99 %
Observations	1121	

TABLE 2.1: Distribution of energy goods utilization among households

We subset the original dataset in various ways. We restrict our analysis to homeowners of detached and semi-detached houses. These households directly benefit from potential energy efficiency measures and we can circumvent the tenant-landlord problematic. In order to minimize the measurement bias, households with heat cost allocators are excluded. Our sample only includes households with stated automobile ownership. Further, the lack of filing of energy bills leads to a missing data problem. We assume that missing variables are missing at random and thus, list wise deletion of the corresponding observations does not bias our results (Little and Rubin, 2002).

Table 2.1 gives an overview of the different combinations of energy goods used by households in the dataset[22]. It shows different energy good combinations. Even though all relevant data for the different combinations for estimating each combination individually are in principle available, two data problems make such an endeavor impossible. First, a low number of observations for some combinations would lead to inefficient estimates and second, for combinations including wood, prices at the household level are unavailable. Despite the fact that price indices for wood exist, the application of such energy indices (e.g., on federal state level) for households is inappropriate. With a vast number of different sources and thus, large differentiation in costs and prices, heterogeneity of wood prices on a regional level cannot be captured within the data. For these reasons, we will restrict our demand analysis on households that only utilize electricity and natural gas.

Summary statistics for the samples used are given in Table A.3, Table A.4, and Table A.5 in Appendix A.

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[22] For reasons of clarity, fuel combinations with less than ten observations are omitted. The information is given for the data used in the ordered probit estimation.

2.4 Results

Prior to identification of the demand-reducing effect of energy efficiency measures, we discuss whether unobserved heterogeneity, as approximated by energy awareness, impacts on the decision to implement an energy efficiency measure. Recall that if we find a statistically significant impact of the approximation of unobserved heterogeneity results on the investment decision, neglection of unobserved heterogeneity results in biased estimates within the demand model estimation. According to the model described in Section 2.2.2, the ordered probit estimation results are presented in Table 2.2. Exogenous and observable characteristics $\vec{z}$ show the expected tendencies. For example, the probability of implementing energy efficiency measures is significantly higher for older buildings and lower for the lowest income group in our data.

Dependent Variable: Number of energy efficiency measures		
Exogeneous and observable characteristics (**$\vec{z}$**)		
Dwelling completion:		
before 1918	1.933***	(0.261)
1919 - 1948	1.710***	(0.260)
1949 - 1957	1.912***	(0.269)
1958 - 1968	2.042***	(0.254)
1969 - 1977	1.786***	(0.253)
1977 - 1983	1.426***	(0.243)
1984 - 1994	0.890***	(0.246)
1995 - 2001	0.222	(0.245)
2002 - 2008	(ref.)	
Dwelling characteristics:		
Living space (sq m)	-0.000710	(0.000740)
Year of heating system completion	0.0233***	(0.00367)
Semi-detached house	(ref.)	
Detached house	0.0327	(0.0850)
Monthly income:		
below 500 EUR/month	-5.385***	(0.286)
500 - 1000 EUR/month	0.181	(0.317)
1000 - 1500 EUR/month	-0.0768	(0.190)
1500 - 2000 EUR/month	-0.0866	(0.154)
2000 - 2500 EUR/month	-0.137	(0.125)
2500 - 3000 EUR/month	-0.189+	(0.127)
3000 - 3500 EUR/month	-0.107	(0.125)
3500 - 4000 EUR/month	-0.0931	(0.119)
above 4000 EUR/month	(ref.)	
Age:		
18-29 years (ref.)		

Continued on next page

Table 2.2: Ordered probit estimation results

Continued from previous page

30-49 years	-0.119	(0.308)
above 50 years	-0.190	(0.305)
Energy awareness ($\vec{a}$)		
Automobile specific CO^2 emissions (SCE)	-0.0296+	(0.0202)
SCE^2	0.000129+	(0.0000848)
SCE^3	-0.000000212+	(0.000000142)
SCE^4	9.96E-11	(7.89E-11)
Population density (PD)	-0.0106**	(0.00437)
PD^2	0.00000923***	(0.00000320)
PD^3	-1.81E-09***	(6.08E-10)
PD^4	5.18E-14**	(2.24E-14)
SCE × PD	0.000115**	(0.0000468)
SCE^2 × PD^2	3.40E-10***	(1.18E-10)
SCE^3 × PD^3	6.51E-17***	(2.39E-17)
SCE^2 × PD	-0.000000412***	(0.000000151)
SCE × PD^2	-9.52E-08***	(3.48E-08)
SCE^3 × PD	4.57E-10***	(1.50E-10)
SCE × PD^3	1.61E-11**	(6.32E-12)
SCE^2 × PD^3	-5.79E-14***	(2.19E-14)
SCE^3 × PD^2	-3.80E-13***	(1.26E-13)
Cut-off point 1	45.14***	(7.583)
Cut-off point 2	46.02***	(7.587)
Cut-off point 3	46.60***	(7.589)
Cut-off point 4	47.25***	(7.597)
Cut-off point 5	47.89***	(7.590)
Observations	1026	

Standard errors in parentheses

$^{+}$ $p < 0.15$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Standard errors are clustered by household

Table 2.2: Ordered probit estimation results

Coming to the coefficients for the proxy of unobserved energy awareness as well as population density $\vec{a}$ our findings show that the polynomials of specific CO$_2$-emissions and population density as well as their interactions are statistically significant in their impact on the implementation of energy efficiency measures. To illustrate the relationship between the proposed functional form for energy awareness and the implementation of energy efficiency measures, we map the estimated coefficients for $\vec{a}$ graphically in Figure 2.2.

The figure shows that households that are by assumption less energy aware, and thus own a higher emitting automobile, tend to have a lower probability to implement an energy efficiency measure. Further, this result suggests that the first derivative with

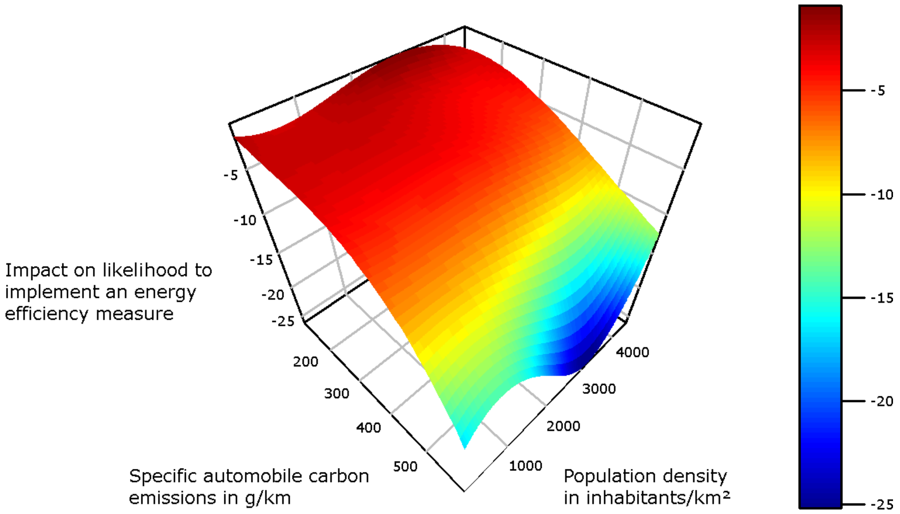

FIGURE 2.2: Joint impact of energy awareness and population density on the likelihood to implement an energy efficiency measure

respect to specific automobile carbon emissions is negative along the entire range[23]. We further observe a slight population density effect. A larger number of efficiency measures is more likely to be implemented in less densely populated areas. This could be explained by lower social norm effects due to an increased anonymity in densely populated areas. Here, monumental protection and stricter building regulations are also more likely, restricting the potential for implementation of energy efficiency measures.

The estimation results support our hypothesis that unobserved energy awareness impacts on the decision to implement an energy efficiency measure. The validity of our approximation approach is thus confirmed and disregard leads to biased estimates.

Turning to the demand-reducing effect of energy efficiency measures, the results of the demand system estimation are given in Table 2.3. Estimated coefficients represent semi-elasticities within the energy budget group, as illustrated in Equation (2.6). With these, demand reduction is identified from Equation (2.5). As the budget shares in the budgeting group for energy goods sum up to unity, one budget share equation is dropped within the estimation process. With only electricity and natural gas under consideration, we estimate the system once with the electricity budget share and once with the natural gas budget share only. Coefficients do not express direct effects on energy demand, but distributional effects among energy goods within the energy budget group. For the exogenous and observable characteristics $\vec{z}$, we find among others the budget share for natural gas is increasing in dwelling age and the budget share for electricity is rising in the number of household members.

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[23] Figure A.2 and Figure A.3 in Appendix A visualize the first derivatives with respect to specific automobile carbon emissions and population density.

Semi-elasticities of budget shares	Electricity		Natural Gas	
Normalized price of energy good (ln)	0.0735***	(0.0224)	0.0735***	(0.0224)
Implicit utility/log real expenditures:				
Linear	0.501	(0.411)	-0.497	(0.415)
Squared	-0.0306+	(0.0205)	0.0304+	(0.0207)
Exogeneous and observable characteristics $(\vec{z})$				
Dwelling completion:				
before 1918	-0.0333	(0.0332)	0.0330	(0.0333)
1919 - 1948	-0.0494+	(0.0331)	0.0498+	(0.0331)
1949 - 1957	-0.0406	(0.0358)	0.0424	(0.0359)
1958 - 1968	-0.00571	(0.0338)	0.00644	(0.0337)
1969 - 1977	0.00667	(0.0308)	-0.00632	(0.0308)
1977 - 1983	-0.0428+	(0.0292)	0.0435+	(0.0293)
1984 - 1994	0.0118	(0.0273)	-0.0110	(0.0273)
1995 - 2001	0.0164	(0.0266)	-0.0162	(0.0267)
2002 - 2008	(ref.)			
Dwelling characteristics:				
Year of heating system completion	-0.000732	(0.000534)	0.000745	(0.000533)
Living space	0.000184	(0.000190)	-0.000187	(0.000190)
Detached house	-0.000524	(0.0107)	0.000625	(0.0107)
Semi-detached house	(ref.)			
Climate characteristics:				
Heating degree days	-0.00000674	(0.0000146)	0.00000647	(0.0000146)
Year	-0.000582	(0.00122)	0.00108	(0.00123)
Monthly income:				
below 500 EUR/month	0	(.)	0	(.)
500 - 1000 EUR/month	0	(.)	0	(.)
1000 - 1500 EUR/month	-0.00853	(0.0342)	0.00935	(0.0341)
1500 - 2000 EUR/month	0.0324	(0.0285)	-0.0322	(0.0284)
2000 - 2500 EUR/month	-0.0182	(0.0178)	0.0184	(0.0178)
2500 - 3000 EUR/month	-0.00252	(0.0165)	0.00278	(0.0164)
3000 - 3500 EUR/month	-0.00377	(0.0180)	0.00367	(0.0180)
3500 - 4000 EUR/month	-0.0152	(0.0203)	0.0151	(0.0202)
above 4000 EUR/month	(ref.)			
Head of household characteristics:				
Age: 18-29 years	(ref.)			
Age: 30-49 years	0.0159	(0.0364)	-0.0159	(0.0365)
Age: above 50 years	0.0148	(0.0353)	-0.0152	(0.0353)
Education: High-School and above	0.00963	(0.0112)	-0.00906	(0.0112)
Number of household members	0.0297***	(0.00552)	-0.0298***	(0.00554)
Energy efficiency measures $(\vec{m})$				
Type of energy efficiency measure implemented:				
Roof or top story ceiling	-0.0378*	(0.0195)	0.0378*	(0.0195)
Basement ceiling insulation	0.0379+	(0.0259)	-0.0392+	(0.0257)
Outer walls insulation	0.0594**	(0.0241)	-0.0598**	(0.0241)

Continued on next page

TABLE 2.3: Demand system estimation results

Continued from previous page

Semi-elasticities of budget shares	Electricity		Natural Gas	
Window replacement	0.0118	(0.0220)	-0.0120	(0.0220)
Heating system replacement	0.00897	(0.0158)	-0.00974	(0.0158)
Energy awareness ($\vec{a}$)				
Autom. spec. CO^2 emissions (SCE)	0.0115**	(0.00474)	-0.0119**	(0.00478)
SCE^2	-0.0000513**	(0.0000246)	0.0000521**	(0.0000246)
SCE^3	9.88E-08*	(5.59E-08)	-9.72E-08*	(5.57E-08)
SCE^4	-7.21E-11+	(4.82E-11)	6.80E-11	(4.80E-11)
Population density (PD)	0.00310***	(0.000780)	-0.00337***	(0.000845)
PD^2	-2.74E-6***	(6.13E-7)	2.93E-6***	(6.58E-7)
PD^3	5.07E-10***	(1.18E-10)	-5.41E-10***	(1.26E-10)
PD^4	4.08E-15	(3.29E-15)	-4.15E-15	(3.30E-15)
SCE × PD	-0.0000340***	(9.20E-6)	0.0000373***	(0.0000100)
SCE^2 × PD^2	-1.01E-10***	(2.41E-11)	1.09E-10***	(2.64E-11)
SCE^3 × PD^3	-1.90E-17***	(4.50E-18)	2.06E-17***	(4.94E-18)
SCE^2 × PD	1.05E-7***	(3.36E-08)	-1-17E-7***	(3.67E-08)
SCE × PD^2	3.12E-08***	(6.92E-09)	-3.36E-08***	(7.51E-09)
SCE^3 × PD	-9.55E-11**	(3.82E-11)	1.09E-10***	(4.15E-11)
SCE × PD^3	-6.03E-12***	(1.26E-12)	6.44E-12***	(1.36E-12)
SCE^2 × PD^3	9.65E-14***	(2.59E-14)	-1.06E-13***	(2.84E-14)
SCE^3 × PD^2	1.96E-14***	(4.31E-15)	-2.11E-14***	(4.69E-15)
Observations	387		387	

Standard errors in parentheses

$^{+}$ $p < 0.15$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Standard errors are clustered by household

Table 2.3: Demand system estimation results

The estimation results for the joint impact of energy awareness and population density $\vec{a}$ as presented in Figure 2.3[24] illustrate two results. First, energy aware individuals have a higher (lower) share of natural gas (electricity) consumption compared to less energy aware households. This confirms our hypothesis that energy aware households are not only marginal adopters of energy efficiency measures, but in addition show different consumption patterns. This is a reasonable result, as it is to be expected that these households also utilize more efficient durable goods that consume electricity, hence, bolstering budget shares for natural gas. The related endogeneity problem should result in an undervaluation of the effectiveness of energy efficiency measures. Additionally, a population density effect becomes apparent: With an increase in population density, the budget share for natural gas decreases which can be explained by the urban heat island effect.

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[24] First derivatives are given in Figure A.4 and Figure A.5 in Appendix A.

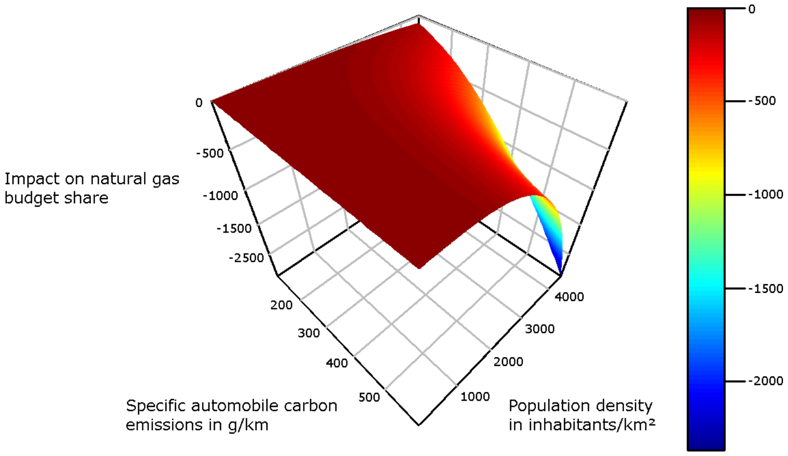

FIGURE 2.3: Joint impact of energy awareness and population density on budget share of natural gas

The most important results, that is the impact of energy efficiency measures on natural gas budget shares, are given by the coefficients for $\vec{m}$. Prior to discussing these, let us summarize what engineering calculations would suggest. All measures considered aim at reducing the consumption of heating fuels only. Therefore, expenditures on natural gas should decrease after implementation. Assuming that direct and indirect rebound effects within energy consumption are absent, the additional income from savings in heating fuel expenditures will be spent on other goods, for instance food. Within our specification of the demand system, this translates to a reduction in energy budget group expenditures ($\partial x/\partial m < 0$) and thus, increasing budget share for electricity ($\partial w^{\text{electricity}}/\partial m > 0$) and decreasing budget share for natural gas ($\partial w^{\text{natural gas}}/\partial m > 0$). Lack of appropriate data hinders us to evaluate the first budgeting stage, necessary to quantify $\partial x/\partial m$. Hence, in our discussion we focus on the semi-elasticities of budget shares with respect to the implementation of energy efficiency measures. In this respect, we would expect statistically significant reductions in budget shares for natural gas. Nevertheless, one has to keep in mind that statistically insignificant results do not show that there is no demand reducing effect whatsoever. A small effect might still exist.

We find statistically significant results with expected signs for the implementation of basement ceiling and outer wall insulation. Implementation of either of these reduces the budget share of the heating fuel, i.e., natural gas. Further, no statistically significant impact of either window or heating system replacement shows. As for roof or top story ceiling insulation, we also find statistically significant changes in budget shares. These however are counterintuitive: implementation corresponds with an increasing budget share for natural gas. Assuming constant spending on electricity, these results indicate an increase in natural gas spending, which can probably be explained by strong *backfiring* *effects*[25].

As a first summary, we find that only two out of five energy efficiency measures give estimation results which signs are in line with expectations from engineering calculations. Thus, two conclusions follow: first, rebound effects are likely to counteract demand reductions from energy efficiency measures. These effects might completely counteract efficiency gains and even result in backfiring. Second, results suggest a large heterogeneity within the rebound effect for the different efficiency measures.

In order to evaluate and make these conclusions more plausible, we compare our budget share semi-elasticities with engineering calculations within exemplary model calculations. For reference, we consider a detached house, built between 1969 and 1977, with living space of 144 m^2. Further, the overall heating demand prior to implementation of the insulation is assumed to be at 237 kWh/m^2a and electricity demand is assumed to be 3500 kWh/a. Electricity (0.2526 EUR/kWh) and natural gas (0.0675 EUR/kWh) prices for 2011 are taken from BNetzA and BKartA (2012)[26]. Engineering calculations for energy savings from different energy efficiency measures are taken from Stolte et al. (2012). Using this information, we can calculate expected changes in budget shares and compare these to our results.

Table 2.4 illustrates the expenditures for electricity and natural gas as well as related budget shares from engineering calculations in Stolte et al. (2012). Further, it compares these to our estimation results. We find that economic and behavioral responses increase the budget share for natural gas from roof or top story ceiling insulation by 6.0 pp, from window replacement by 2.2 pp and from heating system replacement by 5.4 pp. These results relate to a direct rebound effect that is on the one hand of the expected sign and on the other hand heterogeneous with respect to energy efficiency measure. These results suggest that the rebound effect significantly counteracts technological efficiency gains. Assuming that households maximize their utility, these results could still imply a higher level of utility. For roof and top story insulation, results suggest that even backfiring (i.e., $\partial Q^{\text{natural gas}}/\partial m > 0$) is likely.

The results for outer walls insulation closely resemble engineering expectations. Hence, there are either hardly any such effects, or cross-product effects (i.e., indirect effects reducing consumption of electricity) counteract reductions in natural gas budget shares. As the absence of rebound effects is rather unlikely, this result allows us to calculate the cross-product, i.e., indirect, rebound effect.

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[25] If rebound effects counteract efficiency gains from energy efficiency measures in its entirety and even overshoots these, this effect is called backfiring.

[26] We restrict our analysis to one example setting due to lack of available data.

	Annual expenditures in EUR (Stolte et al., 2012)		Budget shares in % (Stolte et al., 2012)		Changes in budget shares of natural gas in pp		
	Electricity	Natural gas	Electricity	Natural gas	Engineering expectation	Our estimation results	Δ
Without efficiency measure	884	2304	27.7%	72.3%	-	-	-
Roof or top story ceiling insulation	884	2069	29.9%	70.1%	-2.2pp	3.8pp	+6.0pp
Basement ceiling insulation	884	2134	29.3%	70.7%	-1.6pp	-3.9pp	-2.3pp
Outer walls insulation	884	1758	33.5%	66.5%	-5.7pp	-6.0pp	-0.3pp
Window replacement	884	2065	30.0%	70.0%	-2.2pp	0.0pp	+2.2pp
Heating system replacement	884	1782	33.2%	66.8%	-5.4pp	0.0pp	+5.4pp

Table 2.4: Comparison of expectations from engineering calculations and estimation results

Given that additional consumption of natural gas from the direct rebound effect requires additional consumption of electricity to keep budget shares similar to engineering calculations, we can calculate additional spending on electricity in relation to additional spending on natural gas. This results in further 0.38 EUR spent on electricity for each 1 EUR spent on natural gas due to the direct rebound effect.

Contrary, we find additional budget share reductions originating from economic and behavioral effects by 2.3 pp from implementation of basement ceiling insulation. This result suggests behavioral responses that either further reduce natural gas demand or increase electricity demand. Hence, an *inverse* rebound effect shows. However, as for low numbers of observations for this energy efficiency type[27] focus on this result should be restricted.

Yet, these results are not an unimpeachable evidence as we can only control for the second budgeting stage. This implies that regarding Equation (2.5), we can identify $\partial w^j/\partial m$ only and have no information on $\partial x/\partial m$. By showing necessary changes in electricity consumption that would allow for the joint realization of the estimation results and the demand reduction from engineering calculations, we illustrate the plausibility

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[27] See Table A.2 in Appendix A.

of our results. Further, assume no behavioral effects in heating fuels (i.e., no rebound effect[28]). By this approach, we want to illustrate how improbable these scenarios are and hence, qualify our results by contradiction.

	Annual expenditures in EUR (Stolte et al., 2012)		Budget shares in %		Additional spending on electricity	
	Electr.	Nat. gas	Nat. gas (Stolte et al., 2012)	Nat. gas (our est.)	in EUR	in %
Without efficiency measure	884	2304	72.3%	-	-	-
Roof or top story ceiling insulation	884	2069	70.1%	76.0%	-231.9	-26.2%
Basement ceiling insulation	884	2134	70.7%	68.4%	104.2	+11.8%
Outer walls insulation	884	1758	66.5%	66.3%	8.8	+1.0%
Window replacement	884	2065	70.0%	72.3%	-94.2	-10.7%
Heating system replacement	884	1782	66.8%	72.3%	-200.0	-22.6%

Table 2.5: Necessary changes in electricity spending for the joint realization of savings from engineering calculations and our estimation results

The necessary changes in electricity demand that would explain a joint realization of the engineering calculations and our estimation results are presented in Table 2.5. The results suggest that large reductions in electricity consumption from -10.7% to -26.2% would be required for window, heating system replacement and roof or top ceiling insulation. As no plausible driver for such reductions exists, we can conclude that significant economic and behavioral rebound effects exist for these measures. As for outer walls insulation, only 1% additional spending on electricity were required.

Taken all together, comparing our results to engineering calculations confirms our prior conclusions. Rebound effects are likely to counteract demand reductions in particular for roof or top story insulation and window and heating system replacements. For outer wall insulation, we find that our results are either in line with engineering calculations or suggest existence of indirect rebound effects of considerable magnitude. Therefore, heterogeneity in the rebound effect manifests.

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[28] Behavioral responses in heating fuels by means of a positive rebound effect would require opposed behavioral responses in electricity and heating fuels.

This heterogeneity allows for the following classification. On the one hand, we have measures leading to moderate or high direct rebound effects and on the other hand, outer wall insulation showing either no direct effect or a combination of direct and indirect effects. As previously discussed, rebound effects as in the first group were to be expected. The differing effect for outer wall insulation needs to be explained in the context of other factors. Expected savings of this measure are high, but this is also the case for other measures, such as heating system replacement. Looking at the investment costs and disutility resulting from construction for outer wall insulation, these are comparatively high. That is, this measure is linked to high costs that need to be amortized over a longer period of time. In addition, the high visibility of this measure leads to a repeated priming of these costs and suggesting altogether *sunk cost fallacy*. For outer wall insulation, we thus propose the strongest impact on habit formation within the group of energy efficiency measures that we explore.

2.5 Discussion and Conclusion

While governments worldwide spend increasing amounts of money on policy schemes to reduce energy consumption and related carbon emissions, economic and behavioral responses undermine their effectiveness. In this paper, we investigate the actual demand-reducing effect of energy efficiency measures and therein compare actual demand responses to technological potentials. This is crucial as evaluation of measures to increase energy efficiency relies mostly on engineering based calculations.

Based on German household survey data for the period 2006-2008, we find that unobserved energy awareness does impact on the decision to implement an energy efficiency measure. Controlling for energy awareness approximated by the automobile choice and population density shows that more energy aware households are more likely to invest. This has implications not only for the effectiveness and efficiency of policy schemes, but further gives rise to a selection problem in evaluation.

Target-oriented policy measures should thus either increase the number of energy aware households by for example information campaigns or addressing particularly households that are energy aware. This would increase the adaption and hence, reduce the energy efficiency gap. Further, targeting policy schemes to marginal adopters increases the efficiency of respective policies.

Additionally, our demand system estimation illustrates two important findings. First, economic and behavioral responses counteract demand reductions from energy efficiency measures. Second, our results confirm heterogeneity in these responses for different energy efficiency measures. Even if energy awareness is taken account of, technological potentials are not fully realized due to economic and behavioral responses to the measures. Our results suggest that rebounding effects might actually increase energy demand and hence, fail policy target levels. The effectiveness of policies thus falls short of its expectations, but must not be negative per se. Individual utility will still be maximized and it might be that households reach a higher level of utility due to the implementation.

Our results further show response heterogeneity of the different energy efficiency measures. This suggests that behavioral aspects are linked to the measures themselves. These seem to be relevant in particular for high cost and visible investments, such as outer wall insulation. Habit formation, priming, and the sunk cost fallacy seem to be likely drivers of the effectiveness of energy efficiency measures. However, further research is required to fully understand these behavioral effects and their policy implications.

To conclude, understanding the economic and behavioral responses of such measures will contribute to a better policy design and public discussion. Thus, it will promote the effectiveness of policy schemes and the achievement of the overarching goal to reduce carbon emissions and mitigate climate change.

Offering Energy Efficiency Under Imperfect Competition and Consumer Inattention

3.1 Introduction

In some markets there are products that allow consumers to partly substitute away from other products they receive positive utility from. However, the availability and substitutional characteristics of these products are often unknown to consumers, thus leading to underconsumption of the partial substitute compared with the welfare optimum. This is particular true for the provision of energy efficiency. In general, the purpose of energy efficiency is to reduce the consumption of energy used to create a certain product or deliver a certain service. Apart from obvious economic gains by reducing input costs, energy efficiency is also beneficial with respect to abating climate change.

Although a large body of articles and studies (e.g., Granade et al., 2009) asserts a huge potential for investments in energy efficiency, actual implementation rates fall short of expectations. This difference between actual and optimal implementation of energy efficiency is often termed the *energy efficiency gap*. On the one hand, research on this issue, for example by Allcott and Greenstone (2012), suggests that consumers are simply unaware of energy efficiency as a substitute for energy consumption, resulting in potential inefficiencies in market outcomes. To address these, numerous energy efficiency support schemes aim to incentivize such investments. For instance, within the US Climate Action Plan USD 250 million is assigned to the Energy Efficiency and Conservation Loan Program (White House, 2013) and in Germany, renovation work on buildings to improve energy efficiency is supported with approximately EUR 700 million each year (BMWi, 2015). On the other hand, energy for domestic heating is usually supplied by a utility competing in a market with an oligopolistic market structure. This leaves the question of whether firms could strategically coordinate on an equilibrium in which none introduces energy efficiency?

This chapter is motivated by the observation of such gaps between optimal and actual consumption of energy efficiency. If the underconsumption of partial substitutes originates from consumer inattention[29], it is of interest whether *informational regulation* by means of mandatory disclosure should be used to inform consumers about the existence and characteristics of energy efficiency. Given the popularity of such interventions ever since the 1980s (Sunstein, 1999), it is to be expected that such markets would potentially face mandatory disclosure laws. But are these interventions really necessary? From an industrial organization perspective, it is not clear whether firms would refrain from offering and disclosing energy efficiency that interacts with their energy retail business in equilibrium. The arguments for and against the voluntary introduction of energy efficiency by the firms are as follows: Energy efficiency reduces demand for energy offered by the firms. Intuitively, firms offering energy would not want to bite the hand that feeds them. However, assuming energy efficiency is efficient for consumers, firms could offer and disclose energy efficiency. Even though this would reduce demand for energy, it would allow the firm to win over consumers from the competing firms that do not offer energy efficiency, thus resulting in a strategic interaction similar to the prisoner's dilemma. This suggests that in equilibrium firms could voluntarily introduce energy efficiency.

From the interactions of the above-mentioned arguments with respect to imperfect competition and consumer inattention it is unclear whether firms would voluntarily introduce energy efficiency and if not, whether there is a case for mandatory disclosure laws.

In this chapter, I investigate why and under what conditions firms that supply energy choose to introduce energy efficiency. Correspondingly, I show that consumer inattention and imperfect competition play substantial roles in firm strategies and how they determine voluntary introduction. These results are mainly driven by the distribution of informed and uninformed consumers as well as the inability of firms to price discriminate between consumer types.

Furthermore, it is shown that mandatory disclosure could in general reduce consumer surplus and that optimal mandatory disclosure under a consumer surplus standard would not inform all consumers. However, in equilibrium, mandatory disclosure leads to a weak increase in the consumer and total surplus.

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[29] As Loewenstein et al. (2014) have recently discussed, there are quite a few types of consumer inattention that influence firms' disclosure efficiency and price setting. Therefore, consumer naivety, limited attention to given information, and inattention to missing information are important aspects of consumer bounded rationality when discussing firm strategies in the framework introduced above. The different types of inattention originate in differing internal search costs for the subordinate good. Internal search costs are cognitive costs associated with the investigative search for the subordinate good and sorting and evaluating search results (Smith et al., 1999, Stigler, 1961).

The remainder of the chapter is structured as follows: Section 3.2 introduces the model setup, and the subsections in Section 3.3 describes the analysis and results. Welfare implications and the efficacy of mandatory disclosure are discussed in Section 3.5. In Section 3.6, the results are reconsidered for if consumers fail to recognize the competition on the market for energy efficiency. Section 3.7 discusses the results and Section 3.8 concludes. Additional figures and tables, proofs and example visualizations are given in the Appendix.

3.2 Model Setup

Consider a duopoly with spatial competition in the energy retail market and non-spatial duopoly competition with a competitive fringe without capacity restriction in the market for energy efficiency. As for energy retail, consumers are uniformly distributed along a linear city with normalized length of 1 (as in Hotelling, 1929). Firms A and B are positioned at $x_A = 0$ and $x_B = 1$ along the linear city, respectively. Each consumer receives a surplus of v from consuming energy and has a taste parameter for energy represented by her location on the linear city x. I assume v to be sufficiently large, such that the entire market is covered in all instances. For each location $0 \leq x \leq 1$, consumers at that location have a disutility of tx if buying from firm A and $t(1-x)$ if buying from firm B. The demand elasticity in the market for energy retail is assumed to be perfectly inelastic. Hence, demand for energy can be normalized to one.

Turning to energy efficiency, this can in general take numerous different forms. For instance, energy efficiency could be provided by installing efficient windows, a new heating system or insulating the outer walls, among others. For this chapter, I will use home energy counseling as a running example for the provision of energy efficiency (subsequently, the product will be termed efficiency service). Home energy counseling is suitable for two reasons. First, it is often stated that information provision on inefficient energy consumption behavior (e.g., by illustrating energy consumption patterns for old and new domestic appliances) has large saving potential at low costs. Second, there is a large potential supply for home energy counseling, as professionals from a wide range of backgrounds can become accredited home energy counselors after some advanced training. This therefore justifies the assumption of a competitive fringe in efficiency service supply.

Consumers receive no direct utility from consumption of the efficiency service, but reduce their consumption of energy. After consumption of the efficiency service, consumers purchase only $\rho \in (0, 1)$ of the energy, keeping the utility from consumption v fixed. That means the efficiency service reduces demand for energy by shifting the utility function outwards, such that the same utility level is reached with less quantity consumed. I assume positive marginal costs of production for energy to be greater than zero ($c > 0$). This reflects the fact that firms have to cover the costs for extraction, transportation, importing and refining the energy supplied to the consumers. However, I normalize the marginal costs for the efficiency service to zero. Hence, marginal costs for energy c reflect the cost savings from the efficiency service.

However, whether or not the efficiency service is consumed depends on the types of consumers with regards to inattention. One fraction of the population $\alpha \in (0, 1)$ is naive. They are well informed about the characteristics and prices of energy (e.g., from repeated interactions on the market). Nonetheless, naive consumers are unaware of the efficiency service. That is, they completely ignore its existence and therewith its potential to increase welfare for the consumer. The complementary fraction of the population $1 - \alpha$ is sophisticated. Sophisticated consumers are fully aware of the existence, characteristics and prices of both products. The existence of a competitive fringe for the efficiency service allows a sophisticated consumer to partly substitute away from consumption of energy, by purchasing the service at marginal costs from the competitive fringe or the firms (if they decide to offer the efficiency service). Similar to Klemperer (1987) and Karle and Peitz (2014), I assume the consumer types α and $1-\alpha$ to be evenly distributed along the linear city.

A visualization of the linear city and distribution of consumer types is given in Figure 3.1.

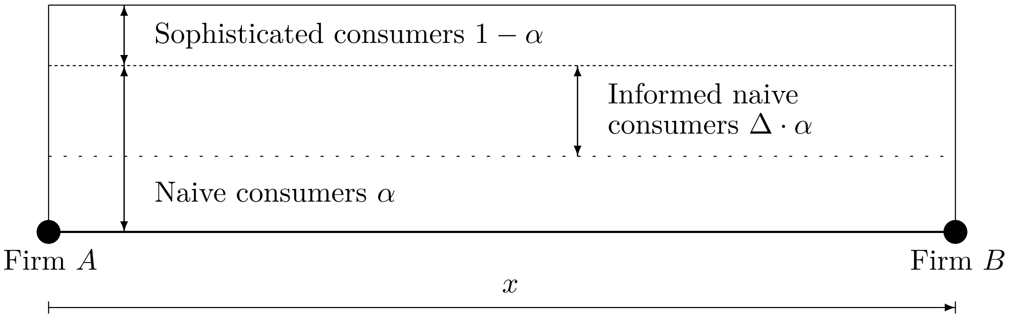

FIGURE 3.1: Illustration of the mass of consumers and consumer types α, $1 - \alpha$ and Δ.

Prior to discussing firms' actions and the timing of the game, it is worth analyzing the modelling approach. First, an oligopolistic market structure describes the energy retail market best, as in most countries regional monopolies were the norm prior to the liberalization of energy markets. After liberalization, firm entry was scarce and hence previously monopolized incumbent firms compete mainly with one another. Second, even though energy supply is technically a homogeneous good, it is unlikely that the assumptions for a strict capacity-unrestricted Bertrand equilibrium hold. Similar to Laffont et al. (1998), I assume the firms to offer different product characteristics that attract different consumers. In my example, firms could admix certain percentages of bio methane to their supply of natural gas in order to appeal to environmentally cautious consumers. Another source of differentiation could be branding and marketing by the firms. By branding the products, firms persuade consumers that these products are less homogeneous than they actually are. In particular, the latter can be illustrated by sponsorship energy companies provide for sport events and teams. In addition, branding aims at horizontal rather than vertical differentiation, as in grid-bound markets the quality (i.e., the security of supply) is determined by the infrastructure and is unaffected by the firm supplying energy. Third, the demand elasticity of energy demand is highly inelastic, leading to the assumption of short-term inelastic demand in the energy retail market. In summary, the above-mentioned characteristics of the problem are well captured by the spatial competition approach applied in this chapter.

The strategy profiles of the firms as well as the consumer responses are subsequently discussed in an overview of the timing of the game.

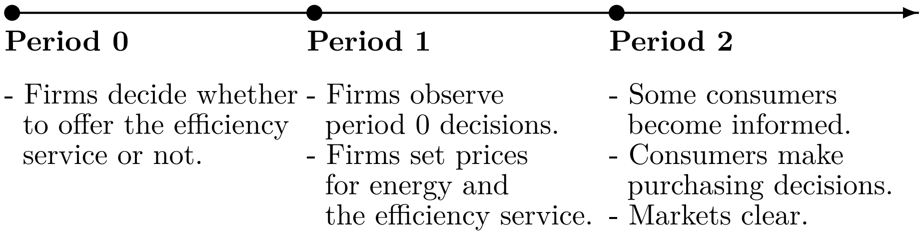

FIGURE 3.2: Illustration of the time line of the game.

Period 0: Firms A and B decide whether to introduce the efficiency service or not. If firms choose to offer the efficiency service, they have to initiate an information campaign to disclose the existence of the efficiency service and the firms offer to the consumers. Hence, I assume the decision to offer and to inform about the efficiency service to be linked. Offering and disclosing do not incur costs. Furthermore, it is assumed that firms must not bundle energy and efficiency services and that the competitive fringe is unable to disclose the existence of the efficiency service to the consumers[30]. Hence, Firms A and B can choose one of the following strategies in period 0:

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[30] In line with the running example of home energy counseling as the efficiency service, it is reasonable to assume that home energy counselors, often self-employed, initiate a supra-regional information campaign.

Not offering the efficiency service (*NO*) The firm refrains from offering the efficiency service and does not provide information on the existence of the energy service.

Offering the efficiency service (*O*) The firm offers the efficiency service and advertises the existence of the efficiency service as well as their offer to all consumers. For example, firms could set up billboard ads or distribute leaflets to all consumers.

Period 1: Firms A and B observe the decisions made in period 0 and set prices for energy $(p_{A,e}, p_{B,e})$ and the efficiency service $(p_{A,s}, p_{B,s})$, if they chose to offer it. Firms set uniform prices for all consumer types.

Period 2: Consumers choose which products to buy from which firm. Sophisticated consumers $1-\alpha$ observe the existence, characteristics and prices of the energy and efficiency service and purchase the efficiency service at marginal costs from either the firms or the competitive fringe, thereby consuming only $\rho \in (0,1)$ of energy. The actions of the naive consumers α depend on the period 0 decisions of the firms. If neither firm chooses to offer and disclose the efficiency service, naive consumers observe the characteristics and prices on the energy retail market only and purchase energy either from firm A or B. If, however, at least one firm offers and discloses the efficiency service, a share $\Delta \in (0,1)$ of all naive consumers becomes informed naive consumers and behaves like sophisticated consumers. This is because the information provision reduces their search costs for the efficiency service, such that they become aware of it. The mass of consumers becoming informed from disclosure and offering being strictly smaller than the entire mass of naive consumers represents the insight that consumers have *limited attention and awareness to given information* and therefore differing internal search costs. As Loewenstein et al. (2014) summarize, disclosure effects are counteracted by limited capacity to digest the information. As a result, a share of naive consumers are left uninformed.

An illustration of the consumer mass with the different consumer types is also given in Figure 3.1[31]. After the different consumer types make their purchasing decisions, the market clears and firms make profits π_i, with $i \in \{A, B\}$.

3.3 Analysis and Equilibrium Results

In order to identify the subgame-perfect Nash equilibria (SPNE), every potential interaction of firm period 0 decisions has to be evaluated. In period 0 both firms decide to

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[31] A table summarizing the notation is given in the Appendix in Table B.1.

either offer and disclose the efficiency service (O) or refrain from doing so (NO). This requires a total of three subgames to be considered: both firms refrain from offering and disclosing the efficiency service *(NO, NO)*, both firms offer and disclose the efficiency service *(O, O)*, and one firm discloses and offers the efficiency service, while the other firm does not *(NO, O)* or *(O, NO)*.

3.3.0.1 Both Firms Refrain from Offering and Disclosing the Efficiency Service *(NO, NO)* - (Subgame 1)

If both firms refrain from offering and disclosing the efficiency service, the mass of naive consumers α purchases energy only and has unit-demand for it. Sophisticated consumers $1-\alpha$ purchase the efficiency service from the competitive fringe at zero marginal costs and consume only ρ of energy. That means, they reduce their demand for energy by $1-\rho$. As neither firm offers and discloses the efficiency service to the naive consumers, not a single naive consumer becomes informed and hence Δ equals 0.

Therefore, there are two consumer groups with different utility functions.

A naive consumer at location x in the linear city has utility $U_{\alpha,A,x}$ buying energy from firm A and utility $U_{\alpha,B,x}$ buying from firm B.

$$U_{\alpha,A,x} = v - p_{A,e,1} - tx \tag{3.1}$$

$$U_{\alpha,B,x} = v - p_{B,e,1} - t(1-x) \tag{3.2}$$

A sophisticated consumer at location x has utility $U_{1-\alpha,A,x}$ buying energy from firm A and utility $U_{1-\alpha,B,x}$ buying from firm B.

$$U_{1-\alpha,A,x} = v - p_{A,e,1}\,\rho - tx \tag{3.3}$$

$$U_{1-\alpha,B,x} = v - p_{B,e,1}\,\rho - t(1-x) \tag{3.4}$$

Comparing Equations (3.1) and (3.2) with Equations (3.3) and (3.4) shows that the efficiency service alters the utility function of sophisticated consumers by means of the energy costs. Compared to naive consumers, sophisticated consumers purchase less energy, yet receive the same level of utility from energy consumption.

The firms demands for energy follow from the consumers $\hat{x}_\alpha$ and $\hat{x}_{1-\alpha}$ that are indifferent between purchasing from firm A or firm B.

$$q_{A,e,1}(p_{A,e,1}, p_{B,e,1}) = \alpha\,\hat{x}_\alpha + (1-\alpha)\,\rho\,\hat{x}_{1-\alpha} \tag{3.5}$$

$$q_{B,e,1}(p_{A,e,1}, p_{B,e,1}) = \alpha\,(1-\hat{x}_\alpha) + (1-\alpha)\,\rho\,(1-\hat{x}_{1-\alpha}) \tag{3.6}$$

Resulting in the following profits of the firms, with $i \in \{A, B\}$:

$$\pi_{i,1} = q_{i,e,1}\,(p_{i,e,1} - c) \tag{3.7}$$

Solving this subgame for equilibrium prices and profits results in the following Lemma.

Lemma 1. *If neither firm offers and discloses the efficiency service, equilibrium firm profits are given by, with* $i \in \{A, B\}$*:*

$$\pi^*_{i,1} = \frac{t}{2}\frac{(\alpha + \rho - \rho\alpha)^2}{\alpha + (1-\alpha)\rho^2}. \tag{3.8}$$

Proof. Given in the Appendix.

The formula for the equilibrium profits of this subgame $\pi^*_{i,1}$ has the expected characteristic that with an increasing degree of product differentiation, as modeled via t, profits increase likewise. That also means that if firms were to offer identical products, i.e., $t = 0$, they would receive zero profits. Also, equilibrium profits are independent of marginal costs, as firms reimburse these costs via the prices they charge for energy. Another characteristic of the equilibrium profits is best shown using graphical illustrations.

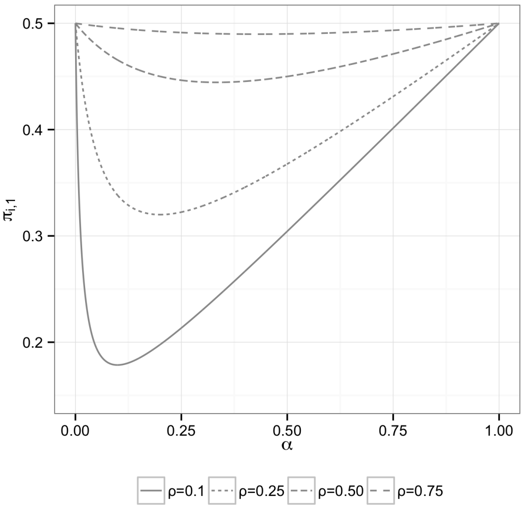

FIGURE 3.3: Exemple visualization of $\pi^*_{i,1}$, with $i \in \{A, B\}$, at $t = 1$.

Figure 3.3 shows the (symmetric) equilibrium profits of both firms for $t = 1$ and four different values for ρ. It can clearly be seen that profits are at a maximum, and independent of ρ, if either all consumers are naive or sophisticated. The result is intuitive for all consumers being naive (i.e., $\alpha \to 1$). In equilibrium prices are set at $c + t$ and profits equate to $t/2$. This result is well known from Hotellings spatial competition models. As for all consumers being sophisticated (i.e., $\alpha \to 0$), these results are also intuitive. If firms face a reduction of demand by ρ, they compensate this demand-reducing effect by increasing the price by a factor of $1/\rho$. This also results in profits of the firms of $t/2$. Prohibiting price discrimination between both consumer types requires the firms to set prices that are in between these extremes, for all $0 < \alpha < 1$. Hence, resulting in Lemma 2.

Lemma 2. *If neither firm offers and discloses the efficiency service, the firms' profits are U-shaped in the share of naive consumers α. Equilibrium profits are at a minimum if*

$$\bar{\alpha} = \frac{\rho}{1 + \rho}. \tag{3.9}$$

Proof. Given in the Appendix.

If firms offer and disclose the efficiency service, they shift a share Δ from the naive consumers α towards the sophisticated consumers. Thus, the result of Lemma 2 allows a first step to be taken towards the identification of the consumer type distribution that is most beneficial for the firms. As Lemma 2 states, profits of both firms $\pi^*_{i,1}$, with $i \in \{A, B\}$, are U-shaped in α. Adhering to Figure 3.3, it is clear that firms will only want to offer and disclose if disclosing results in a mass of uninformed naive consumers $\alpha(1 - \Delta)$ that is smaller than $\bar{\alpha}$ and results in a higher profit level than it was at α. This result will be further elaborated upon in the subsequent evaluations.

3.3.0.2 Both Firms Offer and Disclose the Efficiency Service *(O, O)* - (Subgame 2)

If both firms offer and disclose the efficiency service, the mass of naive consumers α is reduced by informed naive consumers $\Delta\,\alpha$. Hence, the uninformed naive consumers $\alpha(1 - \Delta)$ purchase energy only and have unit-demand for it. The sophisticated share of consumers $1 - \alpha$ purchases the efficiency good from either the competitive fringe or firms A or B. Thus, they consume only ρ of energy. The informed naive consumers $\Delta\,\alpha$ behave like sophisticated consumers.

Even though the firms face three consumer groups in this subgame, the informed naive consumers behave just like sophisticated consumers. Hence, the existence of informed naive consumers simply changes the distribution of consumers for the firms. This has a direct impact on the quantities demanded on the energy retail market:

$$q_{A,e,2}(p_{A,e,2}, p_{B,e,2}) = \alpha(1-\Delta)\,\hat{x}_{\alpha(1-\Delta)} + (1-\alpha(1-\Delta))\,\rho\,\hat{x}_{1-\alpha(1-\Delta)} \tag{3.10}$$

$$\begin{aligned} q_{B,e,2}(p_{A,e,2}, p_{B,e,2}) =& \alpha(1-\Delta)\,(1-\hat{x}_{\alpha(1-\Delta)}) \\ &+ (1-\alpha(1-\Delta))\,\rho\,(1-\hat{x}_{1-\alpha(1-\Delta)}) \end{aligned} \tag{3.11}$$

Although the firms offer the efficiency service, price pressure from the competitive fringe, as well as the inability to bundle sales of energy and the efficiency service, drive the price for the efficiency service down to marginal cost. This means that $p_{i,s,2}$ $(i \in \{A, B\})$ equals zero. Equilibrium profits are as expressed in Lemma 3.

Lemma 3. *If both firms offer and disclose the efficiency service, firms' equilibrium profits are given by* $(i \in \{A, B\})$*:*

$$\pi^*_{i,2} = \frac{t}{2}\frac{(\alpha(\Delta-1)(\rho-1)+\rho)^2}{\alpha(\Delta-1)\,(\rho^2-1)+\rho^2}. \tag{3.12}$$

Proof. Given in the Appendix.

At first sight, it is difficult to evaluate the differences between $\pi^*_{i,1}$ and $\pi^*_{i,2}$. The effect of informing a share of the naive consumers is best highlighted using a graphical illustration.

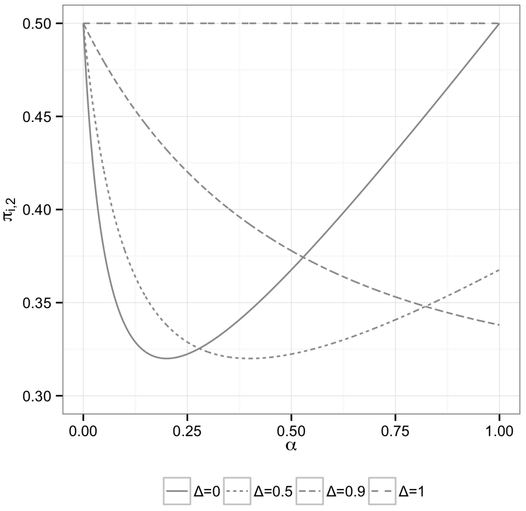

FIGURE 3.4: Example visualization of $\pi^*_{i,2}$, with $i \in \{A, B\}$, at $t = 1$ and $\rho = 0.25$.

Figure 3.4 shows $\pi^*_{i,2}$ as a function of the share of naive consumers α and four values for Δ, keeping ρ and t fixed. As $\pi^*_{i,2}$ with $\Delta = 0$ is equivalent to $\pi^*_{i,1}$, the figure shows that for small values of α firms are better off offering and disclosing the efficiency service, as this results in higher pay-offs (for any value of Δ). Conversely, for higher values of α (and $\Delta \ll 1$) firms are worse off offering and disclosing the efficiency service. These findings are in line with the presumption expressed in Subgame 1.

3.3.0.3 One Firm Offers and Discloses the Efficiency Service, while the Other Firm Does Not *(NO, O)* or *(O, NO)* - (Subgame 3)

Without loss of generality I assume Firm A to offer and disclose the efficiency service, while Firm B does not offer nor disclose it. If Firm A offers and discloses it, the mass of naive consumers α is reduced by a share Δ. Hence, leading to informed naive consumers $\Delta\,\alpha$ as if both firms offered and disclosed the efficiency service. As the firms observe the period 0 decisions of both firms prior to their pricing decision, the resulting equilibrium prices and profits are equivalent to the profits in subgame 2.

Lemma 4. *If one firm offers and discloses the efficiency service and the other firm does not, the firms' equilibrium profits are given by (with $i \in \{A, B\}$):*

$$\pi^*_{i,3} = \pi^*_{i,2}. \tag{3.13}$$

Proof. The proof is straightforward and thus omitted.

3.4 Subgame Perfect Nash Equilibrium Strategies

The subgame results allow us to identify the subgame perfect Nash equilibria (SPNE). With the previously defined model and the related profits of the firms the normal form of the strategic game and the firm total payoffs are given by the illustration in Figure 3.5.

	NO	*O*
NO	$\pi^*_{i,1},\ \pi^*_{i,1}$	$\pi^*_{i,2},\ \pi^*_{i,2}$
O	$\pi^*_{i,2},\ \pi^*_{i,2}$	$\pi^*_{i,2},\ \pi^*_{i,2}$

FIGURE 3.5: Normal form of the strategic game with the firms' payoffs (with $i \in \{A, B\}$).

Prior to the identification of the steady state, i.e. the SPNE of the game, it is necessary to understand the preference relation of the firms. I assume firms to act rationally and to prefer higher to lower profits. With the findings of Lemma 4 that $\pi^*_{i,3} = \pi^*_{i,2}$ ($i \in \{A, B\}$) and the fact that if at least one firm chooses to offer and disclose the efficiency service, both firms earn $\pi^*_{i,2}$, it is necessary to understand whether $\pi^*_{i,1}$ dominates $\pi^*_{i,2}$ or vice versa.

Lemma 2 already led to the conclusion that the optimality of disclosure depends on the location of a critical value for α, i.e., $\bar{\alpha}$, that gives the minimal value for profits with respect to the share of naive consumers (that remain uninformed even though the firms disclosed the information). Evaluating the firms profits in Subgame 1 (see Lemma 1) and in Subgame 2 (see Lemma 3) gives the preference relation described in the subsequent proposition.

Proposition 1. *If at least one firm offers and discloses the efficiency service (i.e., (O, O), (NO, O) or (O, NO), i.e., firms earn* $\pi^*_{i,2}$*) it dominates the profit compared to if both firms refrain from offering and disclosing the efficiency service (i.e., (NO, NO) and firms earn* $\pi^*_{i,1}$*), if*

$$\alpha(\Delta - 2) > -1 \tag{3.14}$$

as well as

$$\rho \geq \Gamma(\alpha, \Delta) = \sqrt{\frac{\alpha^2(1-\Delta)}{(1-\alpha)(1-\alpha+\Delta\alpha)}} \tag{3.15}$$

holds. This implies that for any fixed Δ *the marginal returns of offering and disclosing the efficiency service decrease for increasing values of* α*. Thus making the optimality of introducing the efficiency service less likely the higher the share of naive consumers.*[32]

Proof. Given in the Appendix.

Proposition 1 states algebraically the conditions for the payoff dominance of $\pi^*_{i,2}$ over $\pi^*_{i,1}$. Both conditions spell out the presumptions made in the discussion of Subgames 1 and 2. Equation (3.14) gives the necessary condition between the fraction of consumers that is naive α and the share of naive consumers that becomes informed Δ. As $\Delta \in (0, 1)$, $(\Delta - 2)$ takes values between -1 and -2. Hence, it becomes apparent that even if only a very small fraction of the naive consumers becomes informed from introducing the efficiency service, firms receive higher payoffs if both firms offer and disclose it, if the fraction of naive consumers α is smaller than 0.5. However, if a large share

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[32] Exemplary visualizations of $\alpha(\Delta-2)$ and $\Gamma(\alpha, \Delta)$ are given in Figures B.1 and B.2 in the Appendix.

of naive consumers becomes informed, the firms receive higher payoffs if at least one firm introduced the efficiency service, for almost any value of α. Equation (3.15) gives the second necessary condition. In general, it states that the demand for energy after consuming the efficiency service should not be below a threshold value $\Gamma(\alpha, \Delta)$. As $\partial\Gamma(\alpha, \Delta)/\partial\alpha > 0$ and $\partial\Gamma(\alpha, \Delta)/\partial\Delta < 0$, higher threshold values for ρ follow for higher shares of naive consumers, while lower values follow for higher shares of naive consumers that become informed.

The logic behind this result is as follows. Both firms face two consumer groups in period 1: uninformed naive $\alpha(1-\Delta)$ and sophisticated consumers as well as informed naive consumers $1-\alpha(1-\Delta)$. If only the prior are supplied with energy, the reaction functions of the firms are independent of ρ. However, if only the latter would have been supplied, the reaction functions are shifted outwards with decreasing values for ρ, i.e., larger energy demand reduction effects from the efficiency service. The demand reduction effect changes the relation of taste mismatch costs and the price paid for energy. This is therefore equivalent to an elevated degree of product differentiation and more captivity of consumers to the nearest firm (e.g., Tirole, 1988). As the market is covered, both groups purchase, and price discrimination is not feasible, the mass of uninformed naive consumers restricts the firms' possibility of compensating the demand reduction caused by the sophisticated and informed naive consumers with elevated prices. Hence, as the demand reduction effect induced by ρ cannot be entirely compensated, the firms are worse off for all of $\alpha \in (0,1)$, compared to when α is at its limits (i.e., $\alpha \to 0$ or $\alpha \to 1$). With stronger demand reduction effects, i.e., smaller values of ρ, the firms require higher prices to compensate for the reduction in energy demand. However, as the mass of uninformed naive consumers $\alpha(1-\Delta)$ places limits on such an endeavor, a smaller share (i.e., $\alpha < \bar{\alpha}$) of uninformed naive consumers is required to get marginal increases in profits from decreasing the mass of naive consumers by means of introducing the efficiency service, i.e., $\partial\pi_{i,2}/\partial\Delta \geq 0$ with $i \in \{A, B\}$.

The preference relation evaluated above allows for identification of the SPNE strategies in period 0.

Proposition 2. *If* $\alpha(\Delta-2) > -1$ *and* $\rho \geq \Gamma(\alpha, \Delta)$ *hold, there are three period 0 SPNE strategies in pure strategies: (NO, O), (O, NO) and (O, O). All of which are payoff equivalent. However, only (O, O) is a Trembling Hand Perfect Equilibrium (THPE). If either one of these conditions is violated there is one period 0 SPNE strategy in pure strategies (which is also a THPE): (NO, NO).*

Proof. The proof is straighforward and based on the findings of Proposition 1 and omitted for the most part. Trembling Hand Perfection, as in Selten (1975), of *(NO, NO)* and *(O, O)* follows from the fact that neither *(O, NO)* nor *(NO, O)* are robust to small mistakes that lead the other firm to play an off-equilibrium strategy. Consider for example *(NO, O)*, if $\alpha(\Delta - 2) > -1$ and $\rho \geq \Gamma(\alpha, \Delta)$. It follows from Proposition 1 that this is a period 0 SPNE pure strategy. However, if firm B assigns a small probability to playing NO instead, firm A would have been better off playing O alternatively. □

Subsequently, I will focus on the THPE *(NO, NO)* and *(O, O)*, as even though *(NO, O)*, *(O, NO)* and *(O, O)* are payoff equivalent SPNE pure strategies, in an actual business setting, both firms would prefer to play *0* to mitigate risks. This would change, if costs ϵ for introducing the efficiency service were to arise. Assuming $\epsilon \gtrapprox 0$ such that period 1 decisions are independent of ϵ, firms would only coordinate on asymmetric equilibria, i.e., *(NO, O)*, *(O, NO)*, if $\alpha(\Delta - 2) > -1$ and $\rho \geq \Gamma(\alpha, \Delta)$. This is because both firms would want the other firm to bear the costs of informing consumers and free ride on the information provision. This leaves the firms with a situation similar to the Battle-Of-The-Sexes (Osborne and Rubinstein, 1994) and a related equilibrium selection problem. As this complicates the problem rather than giving new insights, I do not consider introduction costs in my analysis.

In summary, Propositions 1 and 2 showed that there are conditions under which the firms coordinate on an equilibrium in which they introduce and therefore voluntarily disclose efficiency services. At first, this is counterintuitive, as introducing the efficiency service will inevitably reduce the demand on the energy retail market, where firms A and B generate their profits. However, due to imperfect competition on this market, firms A and B can compensate for demand reductions by increasing prices. The potential to do so is restricted by the distribution of consumers that purchase the efficiency service and those that do not. Introducing the efficiency service does not occur in equilibrium if either $\alpha(\Delta - 2) \leq -1$ or $\rho < \Gamma(\alpha, \Delta)$. This means that if a major share of consumers is naive (i.e., $\alpha \gg 0$) and of these only a minor share of naive consumers becomes informed (i.e., $\Delta \ll 1$), firms will refrain from introducing the efficiency service. Likewise, if the demand reduction effect from consuming the efficiency service is large, firms are unable to recover losses by increasing prices and refrain from introduction. Therefore:

- The returns from introducing the efficiency service are decreasing with increasing shares of naive consumers α. This makes introduction less profitable if there are just a few sophisticated consumers.
- High shares of naive consumers that become informed Δ cause increasing returns from introduction. This means that if a very high share of naive consumers processes the information provided by the firms and becomes informed naive consumers, the firms will introduce the efficiency service in equilibrium.

Hence, the failure of introducing and subsequently voluntarily disclosing efficiency services in markets with imperfect competition may therefore originate from high shares of naive consumers, low shares of additional adopters or severe demand reduction effects caused by the efficiency service. How this translates into welfare effects is discussed below.

3.5 Welfare Effects and Mandatory Disclosure

Proposition 2 showed that there are SPNE strategies in which both firms offer and disclose the efficiency service as well as those with both firms refrain from doing so. To evaluate these equilibria, it is necessary to examine their welfare implications. I will present the welfare implications, discuss them from a competition policy point of view and analyze the merits of mandatory disclosure policies below.

Using a model of spatial product differentiation with symmetric firms, inefficiencies arise from taste mismatch as well as the marginal energy costs c. Lemma 5 immediately follows.

Lemma 5. *Total surplus is at its highest value if all consumers purchase the efficiency service and with an increasing share of sophisticated and informed naive consumers.*

Proof. Proof is straight forward and omitted.

Consequently, from a total surplus point of view, it is always preferable for the firms to introduce the efficiency service. This is because introduction reduces the quantity of energy consumed and hence the surplus lost from marginal costs c. If the competition jurisdiction were based solely on a total welfare standard, public policies would always want to inform consumers about the efficiency service. Nonetheless, it is worth taking a look at competition policy that is based on a consumer welfare standard. I identify which outcome is preferable from consumers' perspective and describe mandatory disclosure policies that maximize consumer surplus.

Focussing on consumer surplus and the implied question of whether courts, authorities and competition policy in general abide by a consumer rather than a total welfare standard is highly controversial. Motta (2004) discusses this issue in detail. Given all the arguments for and against a strict consumer surplus standard (Motta, 2004), I apply this standard mainly based on arguments regarding an unbalanced set of powers on the side of the firms, e.g., informational advantages or lobbying (Lyons, 2002).

Lemma 5 illustrated that under a total welfare standard, mandatory disclosure policies would always increase total surplus. However, under a consumer surplus standard, this is not the case, as the following Lemma 6 points out.

Lemma 6. *In general, under a consumer surplus standard, mandatory disclosure laws can lead to a decrease in welfare.*

Proof. The alteration of consumer surplus is given by the difference of changes in total surplus, i.e., Λ_{TS}, and the changes of the firms' total profit, i.e., $2\,(\pi^*_{i,2} - \pi^*_{i,1})$. Changes in total surplus are given by

$$\Lambda_{TS} = \alpha\Delta\, c\,(1-\rho). \tag{3.16}$$

In other words, total surplus changes solely based on the fact that as a result of forcing firms to introduce the service, a consumer mass of $\alpha\,\Delta$ reduces consumption of energy by $(1-\rho)$ and hence payments to cover marginal costs. Hence,

$$\begin{aligned}\Lambda_{CS} &= \alpha\Delta\, c\,(1-\rho) - 2\,(\pi^*_{i,2} - \pi^*_{i,1}) && (3.17)\\ &= \alpha\Delta(1-\rho)\left(c - \frac{(1-\rho)t\,\left((1-\alpha)\rho^2(\alpha(1-\Delta)-1)+\alpha^2(1-\Delta)\right)}{\left((1-\alpha)\rho^2+\alpha\right)\left(\alpha(1-\Delta)\left(1-\rho^2\right)+\rho^2\right)}\right). && (3.18)\end{aligned}$$

Evaluating if Λ_{CS} is below zero using `Mathematica` computational software[33], it follows that $\Lambda_{CS} < 0$ if the following conditions hold:

$$\frac{(1-\rho)t\,\left((1-\alpha)\rho^2(\alpha(1-\Delta)-1)+\alpha^2(1-\Delta)\right)}{\left((1-\alpha)\rho^2+\alpha\right)\left(\alpha(1-\Delta)\left(1-\rho^2\right)+\rho^2\right)} > c, \tag{3.19}$$

$$\alpha(\Delta-2) > -1, \tag{3.20}$$

$$\rho > \Gamma(\alpha,\Delta). \tag{3.21}$$

□

Given the result of Lemma 6, it immediately follows that competition authorities under a consumer surplus standard would refrain from informing consumers under certain conditions. Given the results so far, this is intuitive, as informing consumers such that only a small share of uninformed naive consumers remains allows the firms to charge higher prices for energy. However, the conditions under which informing consumers would have adverse consumer surplus effects give rise to the following proposition.

Proposition 3. *In equilibrium, mandatory disclosure is never welfare-reducing.*

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[33] The code is available by the author on request.

Proof. Lemma 6 highlighted that if certain conditions hold mandatory disclosure can reduce consumer surplus. However, it is clear that two of these conditions are equivalent to the conditions under which firms voluntarily coordinate on an equilibrium in which both firms offer and disclose the efficiency service. This means that if the conditions for mandatory disclosure to be consumer surplus-decreasing hold, firms nevertheless voluntarily introduce the efficiency service. Hence, welfare is not lost from mandatory disclosure but instead from firms' period 0 decisions. If the conditions do not hold, mandatory disclosure is at least weakly consumer surplus-increasing. Total surplus will always increase from mandatory disclosure, as was shown in Lemma 5. □

With the findings of Proposition 3 it became apparent that *informational regulation* by means of mandatory disclosure laws is weakly consumer surplus-increasing. This means that if firms refrain from introducing the efficiency service, mandatory disclosure increases the competition between firms and leads to elevated levels of consumer surplus. Furthermore, it is worth mentioning that the mere existence of the efficiency service weakly increases consumer surplus regardless of the firms' period 0 decisions or mandatory disclosure policies. The inability to price discriminate and the related existence of naive as well sophisticated consumers make the firms worse off compared to a situation without the efficiency service. Even though consumer surplus increases in total, sophisticated and informed naive consumers are better off in terms of surplus than uninformed naive consumers.

The findings of Lemma 2 suggest that the optimal action for the authorities could be to mandate disclosure such that some uninformed naive consumers $\alpha(1-\Delta)$ remain. As it is known that if uninformed naive consumers $\alpha(1-\Delta)$ are at $\bar{\alpha}$ the firms' profits are minimized, a share of uninformed naive consumers that maximizes consumer surplus exists.

Corollary 1. *Under a consumer surplus standard, mandatory disclosure would optimally refrain from debiasing all consumers. Optimally, it would leave a share of*

$$\breve{\alpha} = \frac{(\rho-1)^2\rho^2(c\rho+c+t) - \sqrt{(\rho-1)^4\rho^2 t(c\rho+c+t)}}{(\rho-1)^3(\rho+1)(c\rho+c+t)} \tag{3.22}$$

uninformed. Furthermore, the consumer surplus-maximizing share of uninformed naives is strictly smaller then the profit-minimizing share, i.e., $\breve{\alpha} < \bar{\alpha}$.

Proof. Given in the Appendix.

With the results of Corollary 1, the optimal action of the competition authorities would be to inform consumers such that a share of $\breve{\alpha}$ of uninformed naives remain. This illustrates that in markets with product interactions that have substitution effects, it might be optimal from a consumer welfare perspective to refrain from debiasing all consumers in order to cap the price-setting behavior of the firms. Given the functional form of the firms' profits with respect to the share of the uninformed naive consumers $\alpha(1-\Delta)$, it is clear that firms would want to further inform consumers from that point onwards, as profits are strictly decreasing in the share of uninformed naive consumers below $\bar{\alpha}$.

3.6 Extension: Positive Profits from the Efficiency Service

So far it has been assumed that fierce competition on the efficiency service market drives prices of all firms down to marginal costs, which are normalized to zero. Nonetheless, I assumed consumer inattention with respect to the existence of the efficiency service. One could argue that in addition to this dimension of inattention, consumers fail to recognize the entire supply side on the market for efficiency services, once they have learned about the efficiency service.

Assume that if the firms introduce the efficiency service a fraction of the naive consumers $\varphi \in (0,1)$ will fail to assess the existence of a competitive fringe offering the efficiency service at marginal costs. With respect to search costs, informed naive consumers that fail to recognize the existence of the competitive fringe have reduced their internal search costs for the existence of the product. However, the internal search costs for competing offers for the efficiency service remain such that other offers remain unknown. Hence, the fraction φ of informed naive consumers $\alpha\,\Delta$ buys the efficiency service from firm A or B depending on their preferences and the offering and pricing decisions of the firms. The complementary fraction $1-\varphi$ behaves like sophisticated consumers.

It follows immediately that this second dimension of consumer inattention allows the firms to partly price discriminate between a share φ of informed naive consumers and the rest of the consumers. Hence, in the introducing equilibrium *(O, O)*, firms will capture additional surplus from some of the informed naives by charging a positive price for the efficiency service (which is only purchased by $\varphi\,\Delta\,\alpha$ from firms A and B) and a strictly lower price for energy compared to Subgame 2.

Additionally, this second dimension of inattention will partly destabilize the neither offering nor disclosing equilibrium *(NO, NO)*. If one firm were to refrain from introducing the efficiency service, the other firm would want to offer and disclose the efficiency service, thereby receiving monopoly power over the share φ of the informed naives. This means that it can set higher prices for the efficiency and lower prices for energy. In general, this will make the introducing firm better and the other firm worse off, making the situation similar to a prisoner's dilemma game. However, the monopoly power over φ consumers is restricted. The introducing firm has to trade off attracting consumers farther away in the linear city by lowering its prices off against reducing profits from consumers in the vicinity of the firm's location. Given that the other firm offers energy at a certain price at the other end of the city, to attract the consumers farthest away from the introducing firm, the firm would have to charge such a low price for both goods that these prices and the mismatch costs would still be below the offer for energy from the other firm. It is therefore obvious that the introducing firm will sacrifice demand for higher profits and let a share of informed naive consumers make decisions similar to uninformed naive consumers. Therefore, firms make a part of informed naive consumers behave like uninformed naive consumers. Under certain values for α, Δ, φ and ρ this restricted monopoly power destabilizes the *(NO, NO)* equilibrium. However it does not apply to all values[34]. The general conditions for a failure of the voluntarily introducing equilibrium still hold: i.e., a high share of naive consumers α and a low share of naive consumers that become informed Δ result in an equilibrium in which neither firm offers or discloses the efficiency service. Furthermore, a low share of informed naives that are inattentive to the competition on the efficiency service bolsters the *(NO, NO)* equilibrium. Hence, the different dimensions of consumer inattention have different effects on the incentives of firms to introduce the efficiency service.

Overall, consumer inattention with respect to the supply side of the market for the efficiency service will reduce the degree of competition. Making informational regulation, by means of making the degree of competition on the efficiency service market transparent, essential to increase consumer surplus.

3.7 Discussion

I will now summarize the results so far and outline some general conditions for the voluntary introduction of energy efficiency. First, the returns of voluntary introduction are decreasing with increasing shares of naive consumers α. This, making voluntarily offering and disclosing the efficiency service less profitable if there are just a few sophisticated consumers. Second, high shares of naive consumers that become informed Δ have increasing returns to introduction. This means that if a very high share of naive consumers processes the information provided by the firms, firms want to introduce the efficiency service. And third, the existence of consumers inattentive to the competition

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[34] The calculations are straightforward, but come with rather unsightly, lengthy and complex expressions. Presentation of the algebraic results has been omitted for improved readability. Related `Mathematica` expressions are available from the author on request.

on the efficiency service market allows the firms to price discriminate by charging prices above marginal costs for the efficiency service.

Informing consumers about the efficiency service is always total welfare-increasing. However, the existence of an equilibrium in which both firms choose to refrain from introducing also leaves a case for mandatory disclosure laws under a consumer welfare standard. Notably, under this standard, authorities would want to refrain from debiasing all consumers in order to maximize consumer surplus and limit the firms' price-setting. Hence, the existence of consumer inattention promotes competition between the firms. However, it was shown that the share of consumers that remains inattentive (i.e., the uninformed naive consumers) is worse off than its informed counterparts. This brings about distributional effects that might influence interventions by the competition or political authority. Also, it raises the question of what other forms of intervention could be applicable to the described economic problem. This further suggests that partial information provision might actually be optimal under a consumer welfare standard.

Furthermore, the results have shown that the opportunity to (at least partly) compensate for energy demand reductions by increasing the price of energy might encourage firms to introduce the efficiency service. Do results change with an oligopoly rather than a duopoly in the market for energy? Quickly reconsidering the equilibrium profits proves this presumption wrong: increasing the number of firms is equivalent to reducing the mismatch costs t. Firm profits after the technology of the efficiency service becomes available are lower than when it was unavailable. This is because the different consumer types only emerge once this technology becomes available. Therefore, it is unreasonable that new firms enter the energy retail market after the efficiency service becomes available[35]. Hence, entry should not occur. Nonetheless, with more firms in the market, which is equivalent to decreasing values for t, price mark-ups are proportionately decreasing. However, this does not alter the firms' introduction decisions.

So what does this mean for the example given in the introduction? Consider the case of weatherization. Estimates for the range of ρ suggest values somewhere between 0.95 up to 1.05 (see Chapter 2)[36]. Unfortunately, reliable estimates for parameters α and Δ are difficult to find[37]. Borrowing from research on the efficacy of warning labels provides a broad idea of parameter values for Δ. In this respect, McCarthy et al. (1984) summarize

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[35] I assume that the general conditions for market entry remain unaltered (e.g., fixed costs of entry etc.).

[36] The counterintuitive result from even more consumption originates in the so-called *rebound effect*. See e.g. Gillingham et al. (2013) or Meier and Tode (2015).

[37] This is because, the respective values depend on a large number of different influencing factors. For instance, on the way the information on the introduction of the efficiency service is provided, i.e., how was the information provided, how readable was the information, was the information targeted, to name just a few examples.

that a mere $2-11\%$ adopt to information provision[38]. Making the plausible assumption that there are more naive than sophisticated consumers, e.g., $\tilde{\alpha} = 0.7$ and $\tilde{\Delta} = 0.1$, gives for Equation (3.14): $-1.33 \not> -1$. Hence, the condition in Equation (3.14) is violated. Further, $\tilde{\rho} = 0.95 \ldots 1.05 \not\geq \tilde{\Gamma}(\tilde{\alpha}, \tilde{\Delta}) \approx 1.99$. So, also the second condition, i.e., Equation (3.15) is also violated. Firms would coordinate on refraining from introducing the efficiency service.

Within my model, I assume that all consumers are generally interested in purchasing energy efficiency. This means that I assume that all consumers benefit directly from energy efficiency. Statistics on tenure status, e.g., in Europe, illustrate that this is not the case. Eurostat (2015) shows that in 2014 approx. 30% of the EU-28 population were tenants. It is a well-known landlord-tenant problem that landlords have hardly any incentives to invest in energy efficiency as the energy costs are born by the tenants. Hence, the share of tenants within a population is equivalent to uninformed naive consumers within my model. This leads to the conclusion that within a population with a relatively large share of tenants, firms will refrain from introducing energy efficiency.

Assuming perfectly inelastic demand for energy makes the calculations and the underlying mechanism more tractable. But this makes it impossible to discuss quantity effects in more detail. However, there are numerous real world problems that could be better understood by relaxing the model in this direction. For example, why did car rental companies start offering car sharing services (often under another brand) or why do some public transportation companies operate a bicycle-rental system and others do not. There are undoubtedly driving factors that are not considered in my model (e.g., increasing population density and related congestion in urban areas). However, it is also very likely that consumer attention and inattention are relevant drivers of firms' decisions.

3.8 Conclusion

In this chapter I showed that consumer inattention and imperfect competition are the crucial drivers for firms' decisions to introduce energy efficiency to consumers or to conceal it. I find two symmetric equilibria: one in which both firms introduce energy efficiency and one in which both firms conceal energy efficiency. Whether or not firms coordinate on an equilibrium in which both firms introduce energy efficiency depends mainly on the distribution of consumers that are attentive to energy efficiency and

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[38] While the purpose and presentation of warning labels contrast strongly with advertisement and information provision from firms, one could argue that the relevance of the information on warning labels for the consumer is very much higher. This therefore suggests that the values of $2-11\%$ represent upper bounds for the share of naive consumers that become informed from the information, i.e., Δ.

consumers that are not. Firms will only want to offer energy efficiency that partly substitutes for their energy offer, i.e., bite the hand that feeds them, if introducing and informing consumers about energy efficiency leaves only a comparably small share of consumers uninformed. In that case, competition on the energy retail market is relaxed and firms can charge higher prices. The consumer type distribution is essential as the mass of uninformed naive consumers restricts the firms' price-setting.

Furthermore, it was shown that it is always total welfare-increasing to inform consumers about energy efficiency. Also, mandatory disclosure laws are always weakly welfare-increasing, i.e., even under a consumer surplus standard.

This chapter examines a rather specific market, with rather specific assumptions (e.g., duopoly etc.). Nonetheless, the results suggest that it is worth paying additional attention to the interaction of consumer inattention and imperfect competition in other markets too. I found that consumer naivety causes different consumer groups to emerge, thereby limiting firms' price-setting. Interestingly, consumer inattention under imperfect competition both increase and reduce competition.

A Test of the Theory of Nonrenewable Resources - Controlling for Market Power and Exploration

4.1 Introduction

There is hardly a field in economics that has been influenced by one single publication as much as the field of resource economics. Harold Hotelling published his work on the economics of exhaustible resources in 1931 (Hotelling, 1931). The paper gained attention in the 1970s due to the oil embargo and the subsequent energy crisis as well as the debate initiated by Meadows et al. (1972). Even today, the assumption of inter-temporal optimization within the nonrenewable resource industry, as introduced by Hotelling, is the foundation for many policy recommendations as seen in Hans-Werner Sinn's green paradox (Sinn, 2008).

Even though Hotelling's theory maintained academic attention for over 80 years, empirical applications and tests of the theory are rarely found mainly due to the vast number of influencing factors within the model paired with the unavailability of appropriate data sets. However, in order to derive policy recommendations, such as the ones implied by the green paradox, understanding the significance of the theory is crucial. Thus, the question as to whether the scarcity of a nonrenewable resource influences the actual decision-making process of a mining industry is the focus of this analysis.

This process depends on the value of the resource in situ (which can be represented by the shadow price, the scarcity rent or the user cost) and whether it is large enough to be incorporated into the firm's choice of variables. The relative size of the shadow price of the resource in situ compared to the full cost of production crucially depends on different characteristics of the extraction and processing of the resource as well as the market in which the firm is operating.

So far, the majority of empirical tests addressed methodological or data issues and hardly found evidence of the practical relevance of Hotelling's theory. Yet, two factors are mostly ignored that directly influence the shadow price and a firm's decisions. First, the resource shadow price depends not only on the extraction decisions but also on decisions made in order to increase the resource stock by exploratory activities. Exploration influences the shadow price as under the assumption that lower cost deposits will be produced first, increasing resource stock decreases extraction costs (Pindyck, 1978). For that reason, exploration is a critical feature of mining industries (Krautkraemer, 1998). Second, the market structure has impacts on a firm's decision regarding extraction. For instance, for a monopolistic producer of a nonrenewable resource, it might be optimal to restrict production in order to increase prices (Lasserre, 1991). Further, the existence of rents from market power might support a conjecture by Halvorsen (2008), namely that the shadow price of the resource in situ is too small to be considered in a firm's decisions. The existence of rents from market power might therefore overshadow shadow prices and hence, explain, why tests tend to reject the theory.

Given the relevance of market power and exploration in nonrenewable resource industries, we extend the literature on tests of Hotelling's theory by conducting a test based on the methodology introduced by Halvorsen and Smith (1991), incorporating for the first time the concepts of market power, as introduced by Ellis and Halvorsen (2002), and exploration, as in Pindyck (1978) into a single model. Using data from a newly constructed data set for the uranium mining industry, we study the consistency of the behavior of the shadow price with the Hotelling model and perform an implicit price behavior test for a major firm in the industry. We estimate two models: one accounting only for the static optimality implied by the Hotelling model and another accounting additionally for dynamic optimality. Applying a Hausman specification test, the null hypotheses of the firm extracting the resource inter-temporally optimal is rejected in all of the settings analyzed. Despite this rejection, parameter estimates of the model still allow us to derive information on costs, resource scarcity and market power mark-ups. These estimates suggest that the shadow price of the resource in situ is comparably small at the beginning of the observations and may be overshadowed by market power, which may explain why the firm fails to optimize inter-temporally. However, even as steep increases in shadow prices occur in the later observations, the firm still fails to incorporate its size into its decision making.

The remainder of this chapter is structured as follows: Section 4.2 presents existing literature on the topic. Section 4.3 describes the theoretical model, while Section 4.4 introduces the applied econometric framework. Section 4.5 introduces the data used and market considered. Test results and parameter estimates are discussed in Section 4.6. Section 4.7 concludes.

4.2 Literature Review

Hotelling (1931) was the first to introduce and solve the inter-temporal optimization problem in nonrenewable resource economics. As a consequence, the concept of the shadow price of the resource in situ was also established. Academic and public interest was low until the end of the second half of the last century when the publication of Meadows et al. (1972) and Solow's lecture on Hotelling's model (Solow, 1974) boosted interest in the theory of nonrenewable resource extraction. Subsequent additions to the literature are extensively surveyed by Krautkraemer (1998). Today, Hotelling's work is considered to be the foundation of resource economics and plays a significant role in the discussion on climate change and, e.g., in the discussion on the green-paradox (Sinn, 2008).

As academic interest rose, first tests of the theory were conducted. Different analyzes have since been done, which Chermak and Patrick (2002) classified into two main groups: price path and price behavior tests. Price path tests examine whether the price of a nonrenewable resource changes according to Hotelling's r-percent rule (i.e., whether the price increases at the rate of interest). None of the price path analyzes done by Barnett and Morse (2013), Smith (1979) and Slade (1982) could find evidence for the theory in actual data. However, these tests come with strong assumptions resulting from simplifications in Hotelling's model: First, technology is assumed to be constant over time and second, the relation of extraction costs to the resource base and marginal costs is not considered.

Price behavior tests incorporate the price path into the decision-making process of the extracting firm. Explicit price behavior tests assume a process that consists of extraction and direct selling of the nonrenewable resource. This implies that the extracted resource is not processed and therefore marginal costs are simply given by the extraction costs. The results of these analyzes are ambiguous: While Farrow (1985) and Young (1992) reject the theory, Stollery (1983) and Slade and Thille (1997) obtain positive results whereas Miller and Upton (1985) present mixed results. As Chermak and Patrick (2002) point out, even though the test approach is similar across analyzes, data handling and underlying assumptions vary strongly.

For most nonrenewable resources, processing of the resource is a necessary step (e.g., extraction of the mineral of interest from the ore) before the good can be sold. As the majority of mining firms can, in general, be considered vertically integrated (i.e., offering both mining and processing of the resource), explicit price behavior tests are not applicable to most nonrenewable industries. Implicit price behavior tests, on the other hand, take vertical integration into account. The results of previous analyzes considering implicit price behavior are again mixed. While Halvorsen and Smith (1991) reject the theory, Chermak and Patrick (2001)[39] obtain positive results. Caputo (2011) develops a nearly complete set of the testable implications of the Hotelling model; however, he finds that data inadequacies prevent testing all the implications of the theory. Compared to Caputo's analysis, the test in this paper could be considered to be only a partial test, as we closely follow the approach of Halvorsen and Smith (1991).

Table 4.1 gives an overview of the tests conducted thus far and their main characteristics.[40] It becomes obvious that the tests do not only vary in their testing approach but also in the data time resolution and level. Furthermore, almost all articles assume perfect competition in the input and output markets. Exploration activities as a means of increasing the resource base are generally not considered.

Assumptions of perfect competition or monopoly market structure for nonrenewable resource markets have been the norm ever since Hotelling (1931). The idea that this may not be an appropriate assumption for the mining industry was first empirically shown by Ellis and Halvorsen (2002). They extend the general Hotelling framework with respect to a one-shot Nash-Cournot oligopoly and find that prices substantially exceed marginal costs in an application to the international nickel industry. However, these mark-ups can be attributed to a large extend to market power rather than the resource scarcity rent.

The impact of exploration activities and an extension of the resource base on the Hotelling framework was first investigated by Pindyck (1978). By allowing the firm to simultaneously decide on exploration activities (with certain outcomes) and resource extraction, they find that exploration activities and the resource price and production path are related: With an increase in reserves comes an increase in production. However, as the discovery of further reserves and, hence, the exploration activity declines, production also decreases. Subsequent research on exploration in the context of nonrenewable resources was surveyed by Cairns (1990) as well as Krautkraemer (1998). A noteworthy empirical application was made by Pesaran (1990). By investigating exploration and production decisions for oil at the United Kingdom continental shelf, they find a reasonable degree of support for the theoretical consideration of exploration in the Hotelling framework.

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[39] Using data from Chermak and Patrick (2001) and the test approach of Halvorsen and Smith (1991), Chermak and Patrick (2002) do not reject the theory.

[40] Table 4.1 is a slightly extended version of Table 1 in Chermak and Patrick (2002).

Article	Test type	Time	Level	Product	Market	Exploration	Result
Barnett and Morse (2013)	Price path	Annual	Cross-industry	Various	Price taking	Not considered	Reject
Smith (1979)	Price path	Annual	Cross-industry	Various	Price taking	Not considered	Reject
Slade (1982)	Price path	Annual	Cross-industry	Various	Price taking	Not considered	Reject
Farrow (1985)	Explicit price behavior	Monthly	Single mine	Metals	Price taking	Not considered	Reject
Miller and Upton (1985)	Explicit price behavior	Monthly	Firm	Oil/gas	Price taking	Not considered	Mixed
Stollery (1983)	Explicit price behavior	Annual	Firm	Nickel	Price leader	Not considered	Do not reject
Young (1992)	Explicit price behavior	Annual	Individual mine	Copper	Price taking	Not considered	Reject
Slade and Thille (1997)	Explicit price behavior	Annual	Individual mine	Copper	Price taking	Not considered	Do not reject
Halvorsen and Smith (1991)	Impl. price behavior model, expl. price behavior test	Annual	Cross-industry	Metals	Price taking	Not considered	Reject
Chermak and Patrick (2001)	Implicit price behavior	Monthly	Individual well	Natural gas	Price taking	Not considered	Do not reject
Caputo (2011)	Implicit price behavior	Annual	Individual mine	Copper	Price taking	Not considered	-

TABLE 4.1: Overview of different tests of the theory of nonrenewable resources.

Our paper contributes to the existing stream of literature in several ways: First, we extend the literature on empirical tests of Hotelling's theory by means of incorporating two important features of nonrenewable resource industries, namely, combining the theoretical extensions found in Ellis and Halvorsen (2002), with regard to market power, and Pindyck (1978), with regard to exploration activity. Second, we conduct an implicit price behavior test in the spirit of Halvorsen and Smith (1991) using a newly constructed data set for the uranium mining industry. In order to address data limitations, we apply a multiple imputations approach. Third, despite obtaining negative test results, our analysis allows us to provide suggestions for why firms may not optimize inter-temporally. More specifically, we find that among others market power mark-ups may cast a shadow on the scarcity rent and therefore incentivize short-term rather than long-term planning.

4.3 Theoretical Model

We consider the optimization problem of a resource extracting and processing firm[41]. The firm faces an inverse residual demand function which is assumed to be given by

$$P(t) = P\left(Q(t), T(t), Y(t), V(t)\right), \tag{4.1}$$

where P denotes the price of the firm's final product, Q the quantity of the firm's product, Y a set of exogenous demand shifters entering the demand system and V the firm-specific factor prices of the other firms including, e.g., location-dependent costs for labor and capital. The observable arguments of the residual demand curve are threefold: own quantity, structural demand variables and the other firm's cost variables. Modeling of inverse residual demand curve hence closely follows Baker and Bresnahan (1988).

The firm is assumed to maximize its profits U, which are defined as revenues minus full total costs FTC:

$$U(t) = P(t) \cdot Q(t) - FTC(t). \tag{4.2}$$

The necessary first order condition gives

$$FMC(t) = \frac{\partial FTC(t)}{\partial Q(t)} = P(t) + \frac{\partial P(t)}{\partial Q(t)} \cdot Q(t), \tag{4.3}$$

where FMC denotes the firm's full marginal costs, obtained by taking the derivative of the firm's full total cost with respect to its own quantity.

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[41] An overview about variable notations is given in the Appendix in Table C.1.

In order to derive the firm's full marginal costs, we have to analyze the firm's decision-making process in more detail. The firm operates a two-stage production process: In the first stage of production, a nonrenewable resource is extracted and fed into the second stage of production, where it is processed into a final output. We thus assume a vertically integrated firm, which holds true for most companies in resource industries. The production function of the firm is given by

$$Q(t) = Q(E(t), X(t), S(t), T(t)), \tag{4.4}$$

where E is the extraction rate of the nonrenewable resource, X is the amount of reproducible inputs (i.e., capital and labor), S the amount of proven resources and T the state of technology.

Dual to this cost function is the restricted cost function of reproducible inputs, CR, which is defined by

$$CR(t) = CR(Q(t), E(t), W(t), S(t), T(t)) \tag{4.5}$$

with W denoting the market price of the reproducible inputs (see, e.g., Halvorsen and Smith, 1984). The firm's decision-making process is then given by the following (generalized) Hotelling model

$$\max_{E(\tau),Q(\tau),B(\tau)} \int_t^{\overline{T}} e^{-r(\tau-t)} \left[R(Q(\tau)) - CR(Q(\tau), E(\tau), W(\tau), S(\tau), T(\tau)) - B(\tau)\right] d\tau \tag{4.6}$$

$$\text{subject to:} \qquad \dot{\chi}(\tau) - E(\tau) = \dot{S}(\tau) \tag{4.7}$$

$$f(B(\tau), \chi(\tau)) = \dot{\chi}(\tau) \tag{4.8}$$

$$S(\tau), Q(\tau), B(\tau), \chi(\tau), E(\tau) \geq 0. \tag{4.9}$$

As shown in Equations (4.7) and (4.8), our model incorporates the exploration activities of the firm: Given a certain effort B and already discovered resources χ, new resources $\dot{\chi}$ are found by means of the exploration function $f(B, \chi)$. Consequently, the available stock is equal to discoveries minus extracted quantities. Pindyck (1978) introduced the concept of exploration into the Hotelling framework, arguing that producers "are not endowed with reserves but must develop them through the process of exploration" (Pindyck, 1978). Therefore, the producer's choice set is increased by the decision to invest in exploration activities. The approach in this chapter is to assume a set of characteristics for the exploration function f. Those include (i) increasing discoveries with increasing exploratory expenditures, (ii) diminishing marginal productivity and (*iii*) the discovery decline condition (see, e.g., Pesaran, 1990). Letting λ_1 and λ_2 denote the costate variables (or shadow prices) of Equations (4.7) and (4.8), we derive the Hamiltonian of the optimization problem as

$$\begin{aligned} H(t) =& R(Q(t)) - CR(Q(t), E(t), W(t), S(t), T(t)) - B(t) \\ &- \lambda_1(t) \cdot (\dot{\chi}(t) - E(t)) - \lambda_2(t) \cdot f(B(t), \chi(t)). \end{aligned} \tag{4.10}$$

In the following, time arguments are omitted for improved readability. The static optimality conditions, i.e., the first-order conditions of Equation (4.10) with respect to the control variables E, B and Q, are given by

$$0 = -\frac{\partial CR}{\partial E} + \lambda_1 \tag{4.11}$$

$$0 = -1 - (\lambda_1 + \lambda_2) \cdot \frac{\partial f}{\partial B} \tag{4.12}$$

$$0 = \frac{\partial R}{\partial Q} - \frac{\partial CR}{\partial Q}. \tag{4.13}$$

Following the maximum principle, Equations (4.11) to (4.13) state that the Hamiltonian has to be maximized by the control variables in every point in time t (Chiang, 2000). Rearranging Equations (4.11) and (4.12), the static optimality conditions result in the following equations for the shadow prices λ_1 and λ_2:

$$\lambda_1 = \frac{\partial CR}{\partial E} \tag{4.14}$$

$$\lambda_2 = -\left(\frac{\partial f}{\partial B}\right)^{-1} - \frac{\partial CR}{\partial E}. \tag{4.15}$$

The interpretation of Equations (4.13), (4.14) and (4.15) is rather straightforward. Equation (4.13) states that the firm chooses output quantity Q such that the marginal revenue equates the marginal changes in restricted costs CR. Equation (4.14) states that extraction is optimally chosen if marginal changes in restricted costs (due to changes in extraction E) correspond to the shadow price of the resource in situ λ_1. Finally, Equation (4.15) gives the relationship between the shadow price of exploration λ_2 and changes in the exploration function f with respect to exploration expenditures B as well as the shadow price of the resource in situ, which is equivalent to the marginal changes in restricted costs with respect to extraction E. This illustrates that, even though the restricted cost does not directly depend on the exploration activities, a connection exists via the amount of proven resources S and the values λ_1 and λ_2.

The dynamic optimality conditions of the generalized Hotelling model follow from the relation of the choice for the control variables and the state variables. The dynamic optimality conditions give the optimal path for the shadow prices (see, e.g., Chiang, 2000, Wälde, 2012)

$$\begin{aligned}
\dot{\lambda_1} &= \frac{\partial CR}{\partial S} + r \cdot \lambda_1 && (4.16)\\
\dot{\lambda_2} &= (\lambda_1 + \lambda_2) \cdot \frac{\partial f}{\partial \chi} + r \cdot \lambda_2. && (4.17)
\end{aligned}$$

Inter-temporal changes in the shadow price of the resource in situ λ_1 equate changes in restricted costs CR with respect to the amount of proven resources S and the changes in interest rates r. Similar, inter-temporal changes in λ_2 result from variations in the interest rates but also from changes in the exploration function f with respect to cumulative resource additions χ[42], weighted by both shadow prices.

4.4 Econometric Model

The restricted cost function covers different variable types: E is an intermediate good, X_L and X_K are production inputs of capital and labor, respectively, Q is the output of the final good, and S is an environment variable. We approximate the true restricted cost function using an transcendental logarithmic (translog) functional form (see, e.g., Ellis and Halvorsen, 2002, Ray, 1982). The small time-span covered by our data (compared to innovation cycles in mining industries) allows us to exclude the state of the technology T from the cost function. Therefore, the interaction terms of the translog-representation of the restricted cost function are limited to the intermediate as well as the production input and output variables. We median-adjust our independent variables, allowing for first-order coefficient estimates to be interpreted as cost elasticities at the sample median (Last and Wetzel, 2010).

The restricted cost function is given by

$$\begin{aligned}
\ln CR &= \alpha_0 + \alpha_Q \ln Q + \sum_j \alpha_j \ln W_j + \alpha_E \ln E + \alpha_S \ln S\\
&\quad + \frac{1}{2}\sum_j \sum_k \gamma_{jk} \ln W_j \ln W_k + \frac{1}{2}\gamma_{QQ}(\ln Q)^2 + \frac{1}{2}\gamma_{EE}(\ln E)^2\\
&\quad + \sum_j \gamma_{jQ} \ln W_j \ln Q + \sum_j \gamma_{jE} \ln W_j \ln E + \gamma_{QE} \ln Q \ln E \qquad (4.18)
\end{aligned}$$

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[42] By the discovery decline condition: $\partial f / \partial \chi < 0$.

with $j \in \{K, L\}$ and L and K being subscripts for labor and capital. Symmetry and homogeneity of degree one in inputs are given by the following restrictions:

$$\begin{aligned}
\gamma_{KL} &= \gamma_{LK} \\
\sum_j \alpha_j &= 1 \\
\sum_j \gamma_{jQ} &= \sum_j \gamma_{jE} = \sum_j \gamma_{jk} = \sum_j \gamma_{kj} = 0.
\end{aligned} \tag{4.19}$$

We impose homogeneity in prices by dividing by one price and thus account for just one price in the estimation. Symmetry conditions are imposed directly into the model.

In order to increase estimation efficiency, we incorporate cost share equations into our system of equations. The cost share equations for production inputs follow directly from the logarithmic differentiation of the implicit cost function with respect to input prices (Ray, 1982):

$$M_K = \alpha_K + \sum_j \gamma_{Kj} \ln W_j + \gamma_{KQ} \ln Q + \gamma_{KE} \ln E \tag{4.20}$$

$$M_L = \alpha_L + \sum_j \gamma_{Lj} \ln W_j + \gamma_{LQ} \ln Q + \gamma_{LE} \ln E \tag{4.21}$$

with $M_K = W_K X_K / CR$ and $M_L = W_L X_L / CR$ equal to the shares of reproducible inputs in restricted cost.

Following Equation (4.3), the supply relation requires an expression for full marginal costs (FMC), which are given by the partial derivative of full total costs (FTC) with respect to output quantity Q.

In our model, FTC are represented by the sum of restricted costs, exploration expenditures, the shadow price of the resource in situ multiplied by the changes in resource stock and the shadow price of exploration multiplied by the discoveries from exploration:

$$FTC = CR + B + \lambda_1(f - E) + \lambda_2 f. \tag{4.22}$$

From this, we derive the FMC as

$$FMC = \frac{\partial FTC}{\partial Q} = \frac{\partial CR}{\partial Q} + \frac{\partial CR}{\partial E}\frac{\partial E}{\partial Q} - \lambda_1 \frac{\partial E}{\partial Q} = \frac{\partial CR}{\partial Q} \tag{4.23}$$

given the firm sets E at its optimal level. Therefore, the full marginal costs contain no direct expression of the unknown shadow prices λ_1 and λ_2 and therefore can be estimated without further transformations (see also Ellis and Halvorsen, 2002)[43]. An expression for the right-hand side is obtained inserting the specification for the restricted cost function, i.e., Equation (4.18):

$$\begin{aligned} FMC = \frac{\partial CR}{\partial Q} &= \frac{\partial \ln CR}{\partial \ln Q}\frac{CR}{Q} \\ &= (\alpha_Q + \gamma_{QQ}\ln Q + \sum_j \gamma_{jQ}\ln W_j + \gamma_{QE}\ln E)\frac{CR}{Q}. \end{aligned} \tag{4.24}$$

The relationship between the firm's own price and quantity and the other firms' supply responses is given by the inverse residual demand curve, which we specify following the methodology introduced in Baker and Bresnahan (1988). In other words, the inverse residual demand curve of the firm of interest covers the firm's price P and quantity Q as well as the other firms' factor prices V and global demand shifters Y. As shown in Baker and Bresnahan (1988), estimation results are not sensitive to the particular specification (i.e., log-log or linear-linear) of the inverse residual demand curve. For our application, it is convenient to apply a linear-log specification as it simplifies further calculations. Thus, the residual demand curve is specified as follows (Baker and Bresnahan, 1988):

$$P = \beta \ln Q + \sum_k \varrho_k \ln V_k + \sum_l \tau_l \ln Y_l. \tag{4.25}$$

In order to allow for time-varying mark-ups, we apply a semi-parametric approach following Ellis and Halvorsen (2002) and Diewert (1978) and represent β as a polynomial function in time. In the subsequent estimation procedure, we estimate different functional specifications for the polynomial representation of β. Overall, we find robust estimation results among different specifications for $\beta(t)$. Results suggest that specifying the mark-up term as a biquadratic polynomial yields satisfactory results. Further insights on this procedure are displayed in Appendix C. It follows the inverse residual demand curve as

$$P = (\beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3 + \beta_4 T^4)\ln Q + \sum_k \varrho_k \ln V_k + \sum_l \tau_l \ln Y_l. \tag{4.26}$$

Having specified the FMC (Equation (4.24)) as well as the inverse residual demand curve (Equation (4.26)), we can transform and use these estimation equations to obtain the estimation equation for the supply relation, i.e., Equation (4.3). First, we take the first derivative of price with respect to firm quantity

$$\frac{\partial P}{\partial Q} = \frac{\partial P}{\partial \ln Q}\frac{\partial \ln Q}{\partial Q} = (\beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3 + \beta_4 T^4)\frac{1}{Q}. \tag{4.27}$$

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[43] Note however, that the price of the resource in situ is included in the full marginal costs.

The supply relation for estimation follows as

$$\begin{aligned} P =&(\alpha_Q + \gamma_{QQ} \ln Q + \sum_j \gamma_{jQ} \ln W_j + \gamma_{QE} \ln E) \frac{CR}{Q} \\ &- (\beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3 + \beta_4 T^4). \end{aligned} \tag{4.28}$$

We apply the implicit price behavior test by Halvorsen and Smith (1991). In doing so, we utilize the fact that estimation of the marginal cost function, cost share equation, inverse residual demand curve and supply relation (i.e., Equations (4.18), (4.21), (4.26) and (4.28), respectively) is consistent. The resulting estimates of this model represent the static optimization problem of the firm. However it should be noted that as static optimality in each point in time is a prerequisite for dynamic optimality, this result can also represent the dynamically optimal solution. Under the null hypothesis that the firm optimally extracted its resource, within the framework of the Hotelling model, the addition of the first dynamic optimality condition given by Equation (4.16) in the system of equations should result in consistent but more efficient estimates. Under the alternative hypothesis, the extended model with the dynamic optimality condition is inconsistent. We test the null hypothesis applying a Hausman specification test.

In order to estimate the model including the dynamic optimality conditions, we first need to derive the discrete time form of the dynamic optimality condition (4.16), which is given by

$$\lambda_1(t) = \frac{\partial CR}{\partial S}(t) + (1+r)\lambda_1(t-1). \tag{4.29}$$

With

$$\begin{aligned} \lambda_1 =& \frac{\partial CR}{\partial E} = \frac{\partial \ln CR}{\partial \ln E} \frac{CR}{E} \\ =& \underbrace{(\alpha_E + \gamma_{EE} \ln E + \sum_j \gamma_{jE} \ln W_j + \gamma_{QE} \ln Q)}_{a^{\lambda_1}} \underbrace{\frac{CR}{E}}_{b^{\lambda_1}} = a^{\lambda_1} b^{\lambda_1} \end{aligned} \tag{4.30}$$

and

$$\frac{\partial CR}{\partial S} = \frac{\partial \ln CR}{\partial \ln S} \frac{CR}{S} = \underbrace{\alpha_S}_{c^{\lambda_1}} \underbrace{\frac{CR}{S}}_{d^{\lambda_1}} = c^{\lambda_1} d^{\lambda_1}, \tag{4.31}$$

we obtain

$$a^{\lambda_1}(t) b^{\lambda_1}(t) = c^{\lambda_1}(t) d^{\lambda_1}(t) + (1+r) a^{\lambda_1}(t-1) b^{\lambda_1}(t-1). \tag{4.32}$$

Summarizing, we estimate two models and apply a Hausman specification test. The two lists below summarize the equations used in each model.

Model 1 (without dynamic optimality condition):

1. The restricted cost function, Equation (4.18);
2. The cost share equation, Equation (4.21);
3. The inverse residual demand curve, Equation (4.26);
4. The supply relation, Equation (4.28).

Model 2 (with dynamic optimality condition):

1. The restricted cost function, Equation (4.18);
2. The cost share equation, Equation (4.21);
3. The inverse residual demand curve, Equation (4.26);
4. The supply relation, Equation (4.28);
5. The dynamic optimality condition, Equation (4.32).

Within our model, the market price of final output P, the quantity of final output Q, as well as the extracted resource quantities E, are endogenous and need to be treated in order to prevent biased estimates. Having to deal with endogeneity and simultaneous equations, we utilize an iterative Three-Stage-Least-Squares approach (3SLS). Despite being linear in parameters, our system of equations will be nonlinear in endogenous variables due to transformations of the endogenous variables (e.g., interactions with other variables and squaring). Even though nonlinear transformations of endogenous variables are not necessarily a problem[44], we follow Wooldridge (2002) (Chapter 9.5) and use a set of squared and higher-order transformations of exogenous variables. In addition to exogenous variables already used in our system of equations, we introduce the following instrumental variables: $\ln Q^3$, $\ln Q^4$, $\ln S^3$, $\ln S^4$, $\ln P^3$, $\ln P^4$, T and T^2.

4.5 Data

We construct a data set for the Canadian uranium mining firm Cameco Corporation[45]. We use quarterly firm-level data for the years 2002-2012. In our estimation, we therefore work under the implicit assumption that all relevant information is consistent with this level of aggregation.

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[44] With endogeneity corresponding to correlation of one variable with the error term, nonlinear transformations may eliminate the correlation.

[45] The decision to choose Cameco was made for no particular reason other than it showed a better data availability compared to competing firms.

Nowadays, uranium is a mineral that is used almost entirely to fuel nuclear power plants. The market for uranium mining shows considerable concentration on the supply side, with KazAtomProm, Cameco and Areva covering almost 50% of global uranium production (as of 2013) (World Nuclear Association, 2014). These firms are vertically integrated, i.e., they extract the ore, and later mill and process it via leaching to obtain a uranium concentrate powder (yellowcake or U_3O_8) that is subsequently processed in enrichment and fuel fabrication facilities, which are usually operated by other companies. Yet, the subsequent processing steps do not alter the buyer and seller interaction, as consumers (i.e., operators of nuclear power plants) directly purchase the yellowcake from mining firms and afterwards contract subsequent fuel processing (e.g., Neff, 1984). In the past, contracting was entirely based on long term agreements. However, nowadays the spot market and spot price indices gained relevance also in terms of spot market-related contractual agreements (TradeTech, 2011).

Even though uranium itself is abundant in the earth's crust, most of the deposits are of such low concentration that production is not profitable. Deposits with relevant uranium concentration are found predominantly in Australia, Kazakhstan, Canada and Russia and hence, making these regions targets for exploratory activity by mining firms. With exploration expenditures of approx. USD 100 million in 2012 (Cameco, 2012a) it becomes clear that exploration is an important feature of the considered firm and industry.

This short industry description illustrates that the uranium mining industry is suitable for the proposed test of Hotelling's theory for various reasons. First, firms are vertically-integrated, i.e., they are producing and processing the nonrenewable resource. Second, there is a considerable amount of market concentration. Third, exploration activity is a relevant decision variable of uranium mining firms. Fourth, because of the time-span necessary for nuclear power plants to pass authorization and construction, future demand is comparably certain compared with other mining industries. Hence, short-term price path deviations (Krautkraemer, 1998) are not to be expected. Fifth, consumption of uranium has no externalities on the climate such as other nonrenewable resources. Therefore, environmental externalities are not expected to alter the optimal path of resource depletion. And sixth, the chemical alteration of uranium in the process of consumption in nuclear power plants makes recycling of uranium almost impossible under normal circumstances. This is contrary to most other resources used in previous tests, e.g., nickel and copper. As reintroduction of recycled resources into the system, alters the extraction path, uranium is in this regard a more suitable resource to consider.

The main data sources are introduced in the following, while a detailed description of data sources and calculation steps is given in the Data Appendix. Extraction rate

E, rate of final output Q, exploration expenses B, market price of final output P, amount of proven reserves S and the amount of reproducible inputs for labor X_L and capital X_K (using the perpetual inventory method) are taken from Cameco (2012a) and Cameco (2012b). Prices for reproducible input labor W_L are based on Canadian average wages in the mining industry (Statistics Canada, 2013a), and prices for capital W_K are calculated from producer price indices, depreciation rates and real rate of interest $\tilde{r}$ (Bank of Canada, 2014b, Statistics Canada, 2013b).

The other firms' factor prices V used for the estimation of the inverse residual demand curve contain labor and capital costs as well as proven reserves. With the main competitors of Cameco active in Kazakhstan and Australia, we approximate the other firms' factor prices using values for these countries (e.g., ABS, 2014b, Agency of Kazakhstan of Statistics, 2014c, Australia, 2013). The global demand shifters Y cover the global thermal capacity of nuclear power plants (International Atomic Energy Agency, 2013), changes in global uranium inventories (Nuclear Energy Agency, 2011) and market quantities from military warhead recycling through, e.g., the "Megatons to Megawatts Program" (Centrus, 2014).

Specification of the exploration function f is done by testing different functional forms using available firm-level data as well as extended data sets on Canadian exploration expenditures and discoveries (Nuclear Energy Agency, 2006). As no functional form proved consistent with (*i*) increasing discoveries with increasing exploratory expenditures, (*ii*) diminishing marginal productivity and (*iii*) the discovery decline condition, we have to assume that the multiplicative error term in the discovery function is large. Given the relatively low number of observations available, it makes it impossible to accurately estimate the exploration function.

Therefore, we use a functional form that deviates from the theoretic relationship specified in Equation (4.8). In the following, we use a simplified variant, given by $\dot{\chi} = f(B)$:

$$\dot{\chi}(t) = B(t)^{\underset{(11.1)}{0.4829}}\,\omega(t). \tag{4.33}$$

The error term associated with exploration activities is given by ω. The value in brackets below the exponent of the exploratory expenditures B represents the resulting t-value for this model.

This specification satisfies the conditions (*i*) and (*ii*) but can not account for the discovery-decline phenomenon (*iii*). The insignificance of the discovery-decline condition could correspond to numerous global discoveries made in recent years (similar results are obtained by Pesaran, 1990).

While quarterly data for exploration expenditures B are published by the firm (see also Data Appendix), the amount of proven reserves S and hence resource additions $\dot{\chi}$ are only available on an annual basis. Therefore, we follow Little and Rubin (2002) and use the exploration function f to impute the resource additions $\dot{\chi}$. By using a multiple imputation approach, we create fifty different time series for the amount of resource additions $\dot{\chi}$ and hence, proven reserves S. Thus, we have 50 different data subsamples that are identical except for S and $\dot{\chi}$. We estimate each subsample individually. Using quarterly data from 2002 to 2012 yields 44 unique observations per variable and subsample.[46]

4.6 Empirical Results

Prior to comparing the estimates for Model 1 and Model 2, we first need to define the interest rate r in the dynamic optimality condition Equation (4.32) of Model 2. We test the Hotelling model using different interest rates. Following Halvorsen and Smith (1991), we test constant discount rates ($r = 0.01$ to 0.25) as well as variable interest rates that are proportional to actual real (2012) Canadian interest rates $\tilde{r}$ ($r = \tilde{r} \cdot 0.25$ to $\tilde{r} \cdot 4$). This results in a total of 41 different interest rate settings to be tested. Having 50 data subsamples and 41 different interest rates gives a total of 50 estimation results for Model 1 (i.e., one result per individually estimated subsample) and 2050 estimation results for Model 2 (i.e., one result for every combination of the 50 subsamples with the 41 different interest rates). In order to make the estimation results as tractable as possible as well as to illustrate the distribution of results appropriately, we present the mean values of estimates together with their standard deviation.

Our test results indicate a rejection of the null hypothesis for both the constant discount rate (see Table 4.2) and the variable interest rate calculations (see Table 4.3) at least at the 5%-level (except for two cases, which are significant at the 10%-level). Within our modeling approach, these results suggest that the firm's behavior does not satisfy the dynamic optimality condition.[47]

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[46] Obtaining a larger sample size is often impossible in the mining industry. Hence, 40 to 50 observations can be considered standard in this respect (e.g., Ellis and Halvorsen, 2002).

[47] In 326 models of the 2050 combinations of subsamples and interest rates, we find near-singular matrices. This collinearity is not originating from a particular set of subsamples or interest rates, but rather different combinations of them. Therefore, this statistical issue should be solely based on the inappropriateness of certain interest rates for the rest of the data.

Interest rate	χ^2 *test statistic*		*p-value*	
	Mean	Std. Dev.	Mean	Std. Dev.
0.01	900.037	1038.959	0.047^{**}	0.191
0.02	1181.12	1966.562	0.013^{**}	0.056
0.03	1051.912	1385.697	0.028^{**}	0.112
0.04	979.57	1254.118	0.045^{**}	0.191
0.05	1035.038	1269.951	0.052^{*}	0.218
0.06	1064.868	1526.222	0.026^{**}	0.154
0.07	1262.86	1876.377	0.033^{**}	0.143
0.08	1025.725	1240.366	0.029^{**}	0.157
0.09	1151.013	1608.189	0.046^{**}	0.18
0.1	1112.523	1648.475	0.024^{**}	0.154
0.11	1041.461	1240.148	0.02^{**}	0.129
0.12	1045.752	1220.42	0.025^{**}	0.141
0.13	1037.033	1255.913	0.043^{**}	0.196
0.14	1097.268	1434.342	0^{***}	0.001
0.15	2846.733	11971.337	0.018^{**}	0.111
0.16	1193.924	1847.219	0.046^{**}	0.21
0.17	1178.983	1453.245	0.002^{***}	0.011
0.18	1110.566	1521.609	0.008^{***}	0.054
0.19	1005.5	1233.742	0.024^{**}	0.151
0.2	925.503	1168.636	0^{***}	0.003
0.21	1049.172	1282.834	0.019^{**}	0.12
0.22	945.77	1134.375	0.024^{**}	0.152
0.23	939.674	1130.028	0.004^{***}	0.024
0.24	954.936	1159.637	0.023^{**}	0.151
0.25	1530.604	3029.573	0^{***}	0

$^{***}\ p < 0.01,^{**}\ p < 0.05,^{*}\ p < 0.1,^{+}\ p < 0.15$

The critical value (CV) for p=0.01 is at 37.566

Table 4.2: Hausman test results for constant interest rates.

Interest rate	χ^2 *test statistic*		*p-value*	
	Mean	Std. Dev.	Mean	Std. Dev.
$r \cdot 0.25$	1682.839	5031.267	0.029^{**}	0.151
$r \cdot 0.5$	1141.45	186.521	0.015^{**}	0.076
$r \cdot 0.75$	973.025	194.366	0.08^{*}	0.251
$r \cdot 1$	1139.035	172.047	0.05^{*}	0.213
$r \cdot 1.25$	1073.7	203.451	0.026^{**}	0.154
$r \cdot 1.5$	1179.135	179.52	0.034^{**}	0.152
$r \cdot 1.75$	1044.678	217.54	0.053^{*}	0.22
$r \cdot 2$	1509.901	209.176	0.025^{**}	0.148
$r \cdot 2.25$	1049.269	261.291	0.022^{**}	0.143
$r \cdot 2.5$	1024.811	279.253	0.025^{**}	0.147
$r \cdot 2.75$	1056.235	163.517	0.041^{**}	0.166
$r \cdot 3$	1210.659	159.604	0^{***}	0
$r \cdot 3.25$	1307.49	180.983	0.046^{**}	0.207
$r \cdot 3.5$	2358.77	211.189	0.004^{***}	0.023
$r \cdot 3.75$	1110.498	233.241	0.018^{**}	0.116
$r \cdot 4$	1147.636	231.08	0.004^{***}	0.028

*** $p < 0.01$,** $p < 0.05$,* $p < 0.1$,$^{+}$ $p < 0.15$

The critical value (CV) for p=0.01 is at 37.566

TABLE 4.3: Hausman test results for proportional variations of the actual Canadian interest rate r.

Even though the null hypothesis is rejected, estimation results of Model 1 provide information on cost factors, market power and the shadow price of the resource in situ. Table 4.4 gives the related mean values and standard deviations for coefficients, standard errors and p-values.[48]

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[48] Tables C.6, C.7, C.8 in Appendix C provide quantiles and further descriptions of the distribution of coefficient estimates, p-values and standard errors of the Model 1 estimation results.

Parameter	*Estimate*		*p-value*		*Std. Error*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
α_0	20.715	0.034	3.14E-32***	1.51E-31	0.105	7.41E-3
α_Q	1.57E-8	1.92E-9	3.25E-5***	2.28E-5	2.82E-9	2.02E-10
$\alpha_K = 1 - \alpha_L$	0.102	1.26E-5	1.36E-45***	4.13E-46	1.11E-4	1.88E-6
α_E	2.116	0.092	9.23E-9***	1.49E-8	0.211	0.015
α_S	-0.204	0.134	0.174	0.219	0.116	0.039
$\gamma_{KK} = -\gamma_{LK}$ $= \gamma_{LL} = -\gamma_{LK}$	-4.72E-4	1.90E-4	0.237	0.161	3.49E-4	4.20E-5
γ_{QQ}	1.34E-8	2.46E-9	0.104^{+}	0.050	7.58E-9	5.80E-10
γ_{EE}	1.665	0.313	0.031**	0.059	0.606	0.090
$\gamma_{KQ} = -\gamma_{LQ}$	-9.39E-9	1.56E-9	0.021**	0.023	3.47E-9	3.12E-10
$\gamma_{KE} = -\gamma_{LE}$	2.35E-3	6.44E-5	2.89E-8***	2.27E-8	2.59E-4	6.83E-6
γ_{QE}	-1.93E-8	2.14E-9	5.68E-4***	4.14E-4	4.53E-9	4.36E-10
β_0	-18.297	1.909	7.66E-4***	2.18E-3	3.910	0.270
β_1	0.038	0.090	0.741	0.188	0.209	0.020
β_2	0.112	0.017	1.11E-3***	8.78E-4	0.028	2.61E-3
β_3	-8.98E-4	2.32E-4	0.318	0.133	8.45E-4	6.83E-5
β_4	-1.84E-4	3.81E-5	0.011**	8.55E-3	6.13E-5	5.87E-6
τ_{MFM}	14.216	8.742	0.617	0.176	26.319	1.589
τ_{CAP}	93.717	17.295	0.324	0.096	91.125	4.263
ϱ_{LAU}	14.580	1.400	0.028**	0.014	6.012	0.123
ϱ_{LKZ}	10.609	1.984	0.076*	0.074	5.183	0.282
ϱ_{KAU}	25.376	3.004	0.049**	0.031	11.694	0.778
ϱ_{KKZ}	8.555	0.811	0.041**	0.025	3.809	0.205
τ_{INV}	10.713	0.101	3.66E-16***	8.69E-17	0.419	4.96E-3
ϱ_{SAU}	19.788	2.295	0.016**	8.31E-3	7.268	0.276
ϱ_{SKZ}	-4.434	2.130	0.513	0.210	6.446	0.373
Observations	50×44					
Adjusted R^2	Eq. (4.18): mean 0.55 std. dev. 0.05, Eq. (4.21): mean 0.68 std. dev. 0.02, Eq. (4.26): mean 0.02 std. dev. 0.22, Eq. (4.28): mean 0.55 std. dev. 0.05					

*** $p < 0.01$,** $p < 0.05$,* $p < 0.1$,$^{+}$ $p < 0.15$

Table 4.4: Estimation results for Model 1.

Given the logarithmic form in Equation (4.19) as well as the convergence point set at the sample median, first-order coefficients for this equation represent the logarithmic first-order partial derivatives of the cost function and, thus, the cost elasticities at the sample median. Alternatively, the level-log specification of Equation (4.26) gives the absolute change in prices P under a percentage change in the independent variables (i.e., own quantity Q, the other firms factor prices V and global demand shifters Y).

A majority of coefficients are statistically significant at the 1%- and 5%-level. Furthermore, the first-order coefficients for the cost function (4.19) follow intuition: costs increase with higher costs for labor, capital, increased extraction and higher final output. Larger reserves tend to result in lower extraction costs. This estimate is not statistically significant at the 10%-level for all, but some subsamples. The mean p-value is at 0.238 with a standard deviation of 0.256. This illustrates that a considerable amount of subsamples give statically significant results also for the amount of reserves. With respect to the inverse residual demand function in Equation (4.26), the coefficients for own quantity is of the expected sign whereas the other coefficients have no clear interpretation as they reflect direct and indirect effects due to adjustments made by competing firms (Baker and Bresnahan, 1988). The estimated coefficients are of plausible magnitude.[49]

Apart from our main finding, that the firm seems to fail to optimize inter-temporally, the estimation results for the cost function allow us to also highlight firm/industry cost characteristics. First, processing of the good into the final output is much less cost intensive as is the extraction of the resource: Increasing extraction E by 1% corresponds to an average approximate increase in costs by 2.414%, whereas increasing output Q by 1% hardly changes costs. Second, increasing the reserves, i.e., the resource base, by 1% through exploration results in an average approximate reduction in production costs of 0.188%.

The estimation results allow us to to directly calculate the market power mark-up in Equation (4.23) from the difference in the market price of final output P and $\partial CR/\partial Q$, which equals the FMC if the firm optimally chooses its control variables. Note that the FMC also include the price of the resource in situ.

Figure 4.1 illustrates the Lerner index calculated from our model.[50] The mean value of the Lerner index is given by the solid line, while the dark gray ribbon illustrates the standard deviation from the mean values. The light gray ribbon captures all subsample results. The graph clearly shows a substantial mark-up over marginal costs of approximately 0.5 for the first half of the last decade and a clearly decreasing trend towards zero in the first half of 2012. Given that the mark-up corresponds to such a large share of

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[49] Due to the logarithmic form of the restricted cost function, all α- and γ-coefficients represent percentage changes in the dependent variable with respect to changes in the corresponding independent variables. Therefore, plausible magnitudes are single-digit. Under the level-log specification of the inverse residual demand curve, all β-, τ- and ϱ-coefficients give level changes in the dependent variable, i.e., P, with respect to percentage changes in the independent variables. As the price levels vary between 31.75 and 57.38 (see Table C.15 in the Appendix), plausible coefficient magnitudes are in the lower half of the two-digit spectrum.

[50] The Lerner index is given by $(P - \partial CR/\partial Q)/P$.

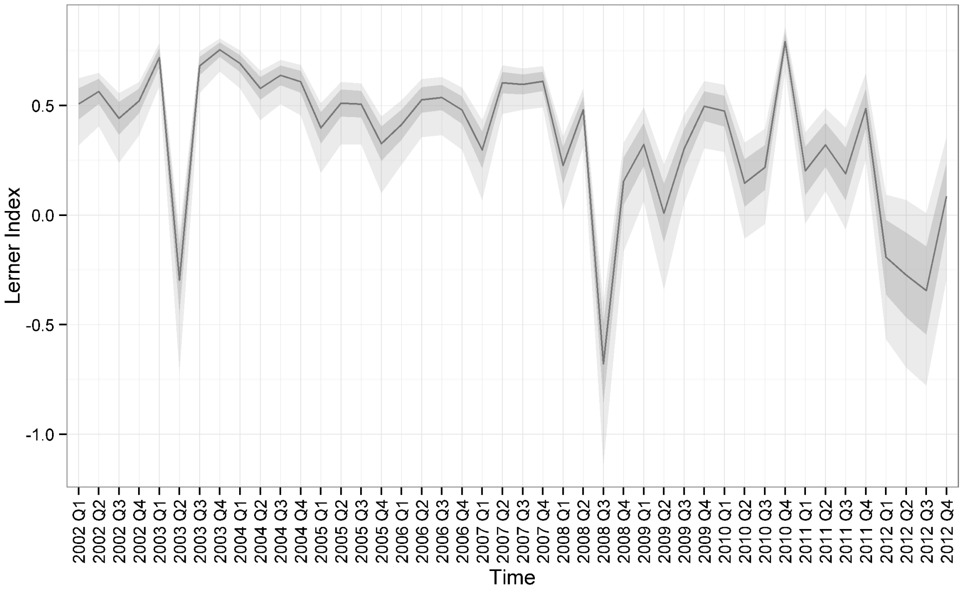

FIGURE 4.1: Lerner index

the final output price for most of the observations, it becomes apparent that firms may optimize their output with respect to this mark-up rather than the optimal depletion of the resource.

However, Figure 4.1 shows that the mean value of the Lerner index drops below zero in five observations. This represents prices below FMC. The latter four points suggests that shocks from the global financial crisis in 2008 and the shut down of several nuclear power plants in the aftermath of the Fukushima nuclear disaster might be the source of these results. We test these suggestions (see Appendix C) and find that there seems to be no shock effect impacting global price setting at these observations. As for 2003 Q2, no immediate explanation for the negative value can be given.

Further conclusions can be drawn from the development of the shadow price (i.e., the scarcity rent) of the resource in situ. For this, we derive an index of scarcity, as done in Halvorsen and Smith (1984), by computing an indexed version of the shadow price λ_1 given in Equation (4.30). The value for the first quarter of 2002 is set at 100. Figure 4.2 shows a drastic increase in shadow price of the resource in situ and, thus, an increasing scarcity of the resource. The solid line represents the mean value, the dark gray ribbon gives the standard deviation and the light gray ribbon illustrates the minimum and maximum values, similar to Figure 4.1. The nonexistence of ribbons at 2008 Q3 suggests that there is a data issue of some sort as the source of the negative spike in the Lerner index. The steep increase in the shadow price at the latter observations might be the source of the negative Lerner index for 2012 Q2 and Q3. While the relative market power mark-up is large at the beginning of the observations, the firm might have based

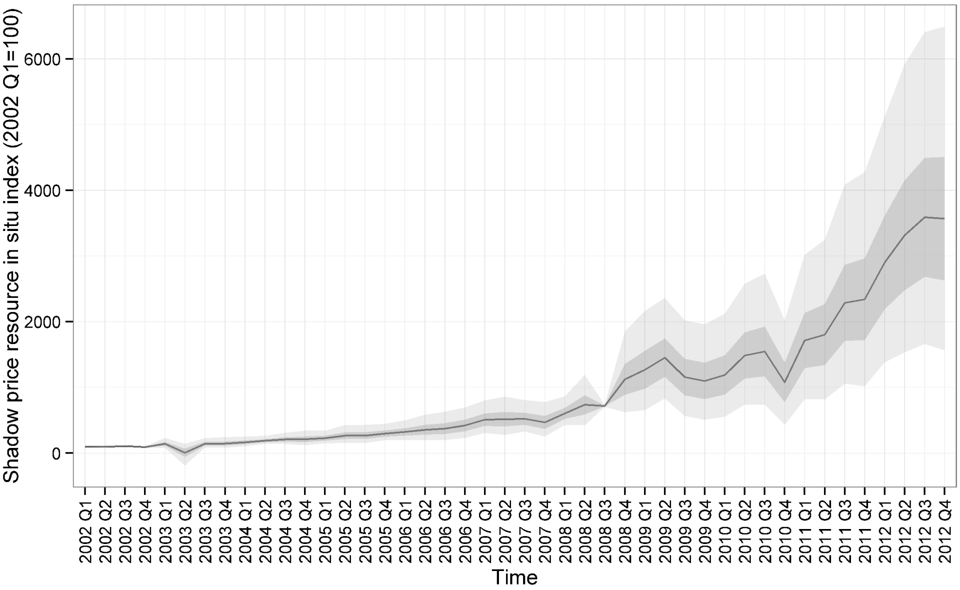

FIGURE 4.2: Indexed shadow price of the resource in situ (2002 Q1=100).

extraction decisions mainly on mark-ups originating from market power. However, for the latter observations, the shadow price of the resource in situ increases steeply and the firm fails to incorporate this development in their price setting. As the shadow price of the resource in situ is a part of the FMC, this might explain the negative Lerner index.

4.7 Discussion and Conclusions

In this paper, we conduct an implicit price behavior test based on the methodology introduced by Halvorsen and Smith (1991). We extend the literature on tests of Hotelling's theory by incorporating for the first time the concepts of market power, as introduced by Ellis and Halvorsen (2002), and exploration, as in (Pindyck, 1978) into a single model. Applying the test to a newly constructed data set for the uranium mining industry, we reject the null hypothesis of the firm optimizing inter-temporally. This complements prior research, which mostly failed to find evidence for the empirical validity of Hotelling's model.

Parameter estimates show that there exists a substantial mark-up over marginal costs that does not account for the shadow price of the resource in situ for the earlier observations and lower and even negative mark-ups over marginal costs for later observations. For the earlier observations, only a very small share of market prices can possibly represent resource user costs. This changes as the shadow price of the resource in situ increases steeply over time. The negative mark-up illustrates that the firm fails to assess the shadow price appropriately. Our results suggest that the hypothesis of Halvorsen

(2008) partly holds, i.e., that the shadow price of the resource in situ may be too small to be considered in a firm's decision-making process and that the *mistake* firms are making by not optimizing inter-temporally optimal may be small. Nonetheless, we find that even as the shadow price increases steeply, firms fail to incorporate this development appropriately in their price setting.

Furthermore, and as already stated by Halvorsen and Smith (1991), inadequacy of the theoretical model could be another likely reason for the theory to be rejected. Possible reasons for this inadequacy can be found in the assumptions made in the model. As we assume a uniform price for the good, we omit issues of transaction costs and imperfect information (also regarding foresight).

Similar to the tests previously performed in other analyzes, our results put the predictive power of the theory for nonrenewable resources into question. However, regardless of the (comparably) predictable uranium demand due to long nuclear reactor construction times, uncertainty prevails in the market, e.g., as a result of unknown international inventories. Therefore, relaxing the assumption regarding perfect foresight could be a promising next step in testing the theory of nonrenewable resources.

Supplementary Material for Chapter 2

Notation

Abbreviation	Explanation	Coefficient	Length
$\vec{a}$	Semi-parametric approximation for energy awareness and population density	$\vec{\beta}^{(1)}$, $\vec{\psi}^{(2)}$	$D^{(1)}$, $H^{(2)}$
$\boldsymbol{b}$	Slutsky coefficients	-	$J \times J$
C	Cost function	-	-
$m^{(1)}$,$\vec{m}^{(2)}$	Number of implemented energy efficiency measures	$\tau^{(2)}$	$1^{(1)}$, $G^{(2)}$
n	Hicksian budget share function	-	J
$\vec{p}$	Prices of energy goods	$b^{(2)}$	J
u	Utility	-	-
$\vec{v}$	Hicksian budget share	-	J
$\vec{w}$	Budget share	-	J
x	Total (group) expenditures	-	-
y	Implicit utility	$\gamma^{(2)}$	$E^{(2)}$
$\vec{z}$	Exogenous, observed characteristics	$\alpha^{(1)}$, $\delta^{(2)}$	$C^{(1)}$, $F^{(2)}$
ρ	Ordered probit error term	-	-
ε	EASI random utility	-	J
ν	Budgeting group subutility	-	-

(1) Econometric Model I: Ordered Probit, (2) Econometric Model II: EASI

Table A.1: Notation

Data

Type of energy efficiency measure	Frequency	Percent
Roof or top story ceiling insulation	72	19%
Basement ceiling insulation	8	2%
Outer walls insulation	36	9%
Window replacement	66	17%
Heating system replacement	88	23%
Observations	387	100%

Table A.2: Distribution of energy efficiency types among households

	Mean	Standard deviation	Min	Max
Dependent Var.: Number of en. eff. meas.	.8421053	1.118545	0	5
Exogeneous and observable characteristics ($\vec{z}$)				
Dwelling completion:				
before 1918	.0896686	.2858457	0	1
1919 - 1948	.0935673	.2913677	0	1
1949 - 1957	.0662768	.2488866	0	1
1958 - 1968	.0984405	.2980547	0	1
1969 - 1977	.128655	.334981	0	1
1977 - 1983	.1364522	.3434356	0	1
1984 - 1994	.1315789	.3381973	0	1
1995 - 2001	.1666667	.3728597	0	1
2002 - 2008	.0877193	.2830242	0	1
Dwelling characteristics:				
Living space (sq m)	137.0575	43.38398	40	772
Year of heating system completion	1993.896	11.02201	1924	2009
Detached house	.6929825	.4614817	0	1
Semi-detached house	.3070175	.4614817	0	1
Monthly income:				
below 500 EUR/month	.0009747	.0312195	0	1
500 - 1000 EUR/month	.0155945	.123961	0	1
1000 - 1500 EUR/month	.0526316	.2234058	0	1
1500 - 2000 EUR/month	.1130604	.3168211	0	1
2000 - 2500 EUR/month	.1578947	.3648201	0	1
2500 - 3000 EUR/month	.1510721	.3582938	0	1
3000 - 3500 EUR/month	.1374269	.3444654	0	1
3500 - 4000 EUR/month	.1159844	.3203624	0	1
4000 - 4500 EUR/month	.1023392	.3032417	0	1
above 4500 EUR/month	.1530214	.3601837	0	1
Age:				
18-29 years	.0175439	.1313503	0	1
30-49 years	.3489279	.4768636	0	1
above 50 years	.6335283	.4820754	0	1
Energy awareness ($\vec{a}$)				
Autom. spec. CO^2 emissions (SCE)	229.4425	98.22171	90	828
SCE^2	62281.96	61222.64	8100	685584
SCE^3	2.01E+07	3.49E+07	729000	5.68E+08
SCE^4	7.62E+09	2.18E+10	6.56E+07	4.70E+11
Population density (PD)	612.0979	894.262	14	4592
PD^2	1173589	3377958	196	2.11E+07
PD^3	3.56E+09	1.38E+10	2744	9.68E+10
PD^4	1.28E+13	5.90E+13	38416	4.45E+14
SCE × PD	141736.3	239259.4	2156	2459488
SCE^2 × PD^2	7.73E+10	3.35E+11	4648336	6.05E+12
SCE^3 × PD^3	8.16E+16	6.25E+17	1.00E+10	1.49E+19

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Table A.3: Ordered probit estimation - summary statistics.

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	Mean	Standard deviation	Min	Max
$SCE^2 \times PD$	3.86E+07	8.99E+07	332024	1.49E+09
$SCE \times PD^2$	2.77E+08	9.02E+08	30184	1.00E+10
$SCE^3 \times PD$	1.23E+10	4.11E+10	5.08E+07	8.97E+11
$SCE \times PD^3$	8.54E+11	3.69E+12	422576	4.20E+13
$SCE^2 \times PD^3$	2.43E+14	1.37E+15	6.51E+07	2.46E+16
$SCE^3 \times PD^2$	2.54E+13	1.54E+14	7.16E+08	3.65E+15
Observations	1026			

Table A.3: Ordered probit estimation - summary statistics.

	Mean	Standard deviation	Min	Max
Budget share of energy good	.3784045	.1075553	.0590275	.7483409
Implicit utility/log real expenditures:				
Linear	10.00476	.3889487	8.65094	11.07085
Squared	100.2462	7.750888	74.83876	122.5638
Normalized price of energy good (ln)	1.082285	.2263139	-1.077474	2.337301
Exogeneous and observable characteristics ***($\vec{z}$)***				
Dwelling completion:				
before 1918	.0801034	.2718045	0	1
1919 - 1948	.0956072	.2944325	0	1
1949 - 1957	.0697674	.2550845	0	1
1958 - 1968	.0878553	.2834508	0	1
1969 - 1977	.118863	.3240462	0	1
1977 - 1983	.0878553	.2834508	0	1
1984 - 1994	.1524548	.3599265	0	1
1995 - 2001	.255814	.4368826	0	1
2002 - 2008	.0516796	.2216659	0	1
Dwelling characteristics:				
Year of heating system completion	1995.196	9.550123	1963	2009
Living space	128.5736	33.54599	60	250
Detached house	.4806202	.500271	0	1
Semi-detached house	.5193798	.500271	0	1
Climate characteristics:				
Heating degree days	3324.92	343.0874	2537.892	4560.433
Year	2006.863	.7406439	2006	2008
Monthly income:				
below 500 EUR/month	0	0	0	0
500 - 1000 EUR/month	0	0	0	0
1000 - 1500 EUR/month	.0465116	.210863	0	1
1500 - 2000 EUR/month	.0620155	.2414959	0	1
2000 - 2500 EUR/month	.1808786	.3854158	0	1
2500 - 3000 EUR/month	.1963824	.3977753	0	1
3000 - 3500 EUR/month	.1447028	.3522564	0	1
3500 - 4000 EUR/month	.0904393	.2871813	0	1
4000 - 4500 EUR/month	.121447	.3270689	0	1
above 4500 EUR/month	.1576227	.3648586	0	1
Age: 18-29 years	.0077519	.0878167	0	1
Head of household characteristics:				
Age: 30-49 years	.3100775	.4631238	0	1
Age: above 50 years	.6821705	.4662355	0	1
Education: High-School and above	.5193798	.500271	0	1
Number of household members	2.821705	1.051396	1	8
Energy efficiency measures ***($\vec{m}$)***				
Type of en. eff. measure implemented:				
Roof or top story ceiling	.1317829	.3386925	0	1

Continued on next page

TABLE A.4: Demand system estimation electricity - summary statistics.

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	Mean	Standard deviation	Min	Max
Basement ceiling insulation	.0155039	.1237055	0	1
Outer walls insulation	.0594315	.2367366	0	1
Window replacement	.0775194	.2677599	0	1
Heating system replacement	.1111111	.3146765	0	1
Energy awareness **($\vec{a}$)**				
Autom. spec. CO^2 emissions (SCE)	217.6331	96.0457	109	604
SCE^2	56565.1	57856.37	11881	364816
SCE^3	1.77E+07	3.02E+07	1295029	2.20E+08
SCE^4	6.54E+09	1.58E+10	1.41E+08	1.33E+11
Population density (PD)	746.5672	986.9007	14	4592
PD^2	1528819	3535677	196	2.11E+07
PD^3	4.44E+09	1.36E+10	2744	9.68E+10
PD^4	1.48E+13	5.50E+13	38416	4.45E+14
SCE × PD	177846.5	306968.3	2156	2459488
$SCE^2 \times PD^2$	1.26E+11	5.22E+11	4648336	6.05E+12
$SCE^3 \times PD^3$	1.64E+17	1.13E+18	1.00E+10	1.49E+19
$SCE^2 \times PD$	5.18E+07	1.39E+08	332024	1.49E+09
$SCE \times PD^2$	3.93E+08	1.12E+09	30184	1.00E+10
$SCE^3 \times PD$	1.84E+10	7.41E+10	5.11E+07	8.97E+11
$SCE \times PD^3$	1.19E+12	4.25E+12	422576	4.08E+13
$SCE^2 \times PD^3$	4.89E+13	2.85E+14	7.16E+08	3.65E+15
$SCE^3 \times PD^2$	4.00E+14	2.03E+15	6.51E+07	2.46E+16
Observations	387			

Table A.4: Demand system estimation electricity - summary statistics.

	Mean	Standard deviation	Min	Max
Budget share of energy good	.6215955	.1075553	.2516591	.9409724
Implicit utility/log real expenditures:				
Linear	10.0048	.3889485	8.651021	11.07089
Squared	100.2469	7.750915	74.84016	122.5646
Normalized price of energy good (ln)	-1.082285	.2263139	-2.337301	1.077474
Exogeneous and observable characteristics **($\vec{z}$)**				
Dwelling completion:				
before 1918	.0801034	.2718045	0	1
1919 - 1948	.0956072	.2944325	0	1
1949 - 1957	.0697674	.2550845	0	1
1958 - 1968	.0878553	.2834508	0	1
1969 - 1977	.118863	.3240462	0	1
1977 - 1983	.0878553	.2834508	0	1
1984 - 1994	.1524548	.3599265	0	1
1995 - 2001	.255814	.4368826	0	1

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Table A.5: Demand system estimation natural gas - summary statistics.

Continued from previous page

	Mean	Standard deviation	Min	Max
2002 - 2008	.0516796	.2216659	0	1
Dwelling characteristics:				
Year of heating system completion	1995.196	9.550123	1963	2009
Living space	128.5736	33.54599	60	250
Detached house	.4806202	.500271	0	1
Semi-detached house	.5193798	.500271	0	1
Climate characteristics:				
Heating degree days	3324.92	343.0874	2537.892	4560.433
Year	2006.863	.7406439	2006	2008
Monthly income:				
below 500 EUR/month	0	0	0	0
500 - 1000 EUR/month	0	0	0	0
1000 - 1500 EUR/month	.0465116	.210863	0	1
1500 - 2000 EUR/month	.0620155	.2414959	0	1
2000 - 2500 EUR/month	.1808786	.3854158	0	1
2500 - 3000 EUR/month	.1963824	.3977753	0	1
3000 - 3500 EUR/month	.1447028	.3522564	0	1
3500 - 4000 EUR/month	.0904393	.2871813	0	1
4000 - 4500 EUR/month	.121447	.3270689	0	1
above 4500 EUR/month	.1576227	.3648586	0	1
Age: 18-29 years	.0077519	.0878167	0	1
Head of household characteristics:				
Age: 30-49 years	.3100775	.4631238	0	1
Age: above 50 years	.6821705	.4662355	0	1
Education: High-School and above	.5193798	.500271	0	1
Number of household members	2.821705	1.051396	1	8
Energy efficiency measures ($\vec{m}$)				
Type of en. eff. measure implemented:				
Roof or top story ceiling	.1317829	.3386925	0	1
Basement ceiling insulation	.0155039	.1237055	0	1
Outer walls insulation	.0594315	.2367366	0	1
Window replacement	.0775194	.2677599	0	1
Heating system replacement	.1111111	.3146765	0	1
Energy awareness ($\vec{a}$)				
Autom. spec. CO^2 emissions (SCE)	217.6331	96.0457	109	604
SCE^2	56565.1	57856.37	11881	364816
SCE^3	1.77E+07	3.02E+07	1295029	2.20E+08
SCE^4	6.54E+09	1.58E+10	1.41E+08	1.33E+11
Population density (PD)	746.5672	986.9007	14	4592
PD^2	1528819	3535677	196	2.11E+07
PD^3	4.44E+09	1.36E+10	2744	9.68E+10
PD^4	1.48E+13	5.50E+13	38416	4.45E+14
SCE × PD	177846.5	306968.3	2156	2459488

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Table A.5: Demand system estimation natural gas - summary statistics.

Continued from previous page

	Mean	Standard deviation	Min	Max
$SCE^2 \times PD^2$	1.26E+11	5.22E+11	4648336	6.05E+12
$SCE^3 \times PD^3$	1.64E+17	1.13E+18	1.00E+10	1.49E+19
$SCE^2 \times PD$	5.18E+07	1.39E+08	332024	1.49E+09
$SCE \times PD^2$	3.93E+08	1.12E+09	30184	1.00E+10
$SCE^3 \times PD$	1.84E+10	7.41E+10	5.11E+07	8.97E+11
$SCE \times PD^3$	1.19E+12	4.25E+12	422576	4.08E+13
$SCE^2 \times PD^3$	4.89E+13	2.85E+14	7.16E+08	3.65E+15
$SCE^3 \times PD^2$	4.00E+14	2.03E+15	6.51E+07	2.46E+16
Observations	387			

TABLE A.5: Demand system estimation natural gas - summary statistics.

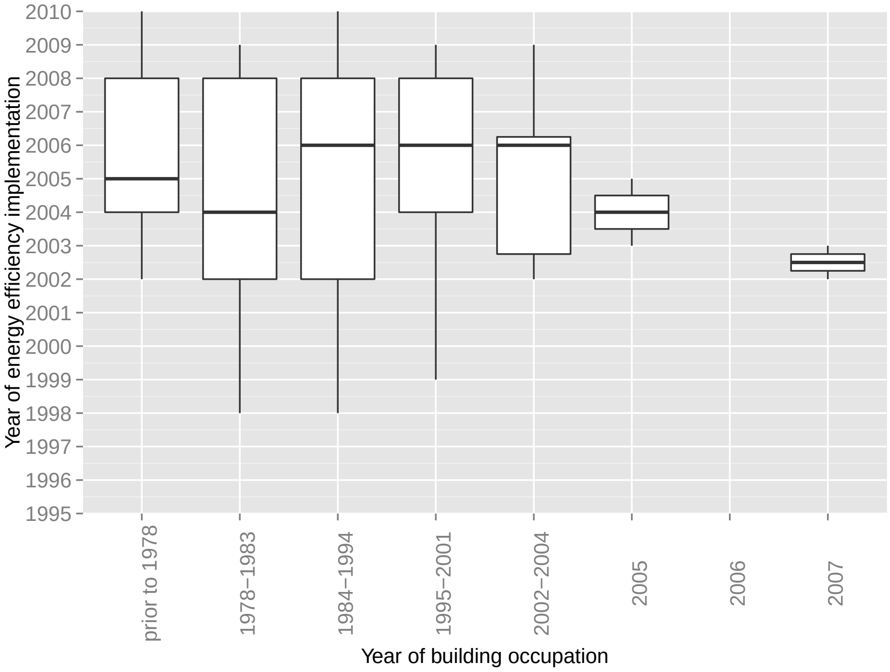

FIGURE A.1: Distribution of energy efficiency implementation years and years of building occupation.

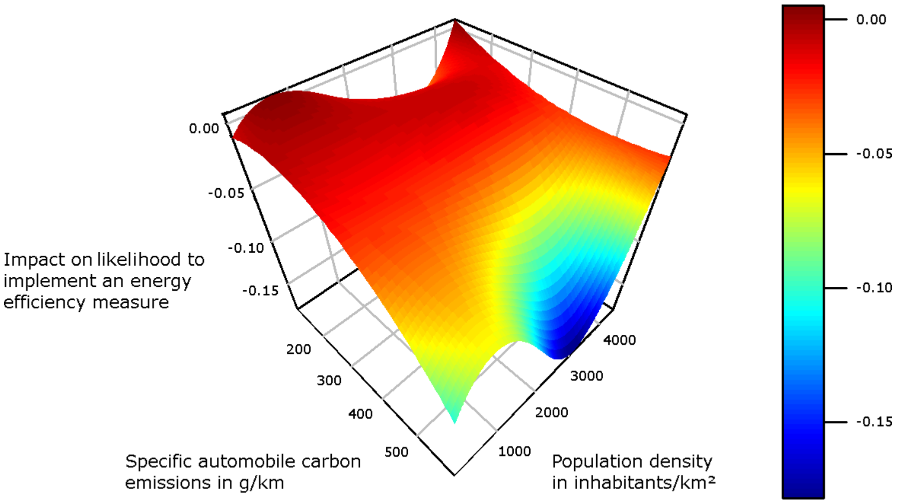

FIGURE A.2: First derivatives of the joint impact on the likelihood to implement an energy efficiency measure with respect to specific automobile carbon emissions.

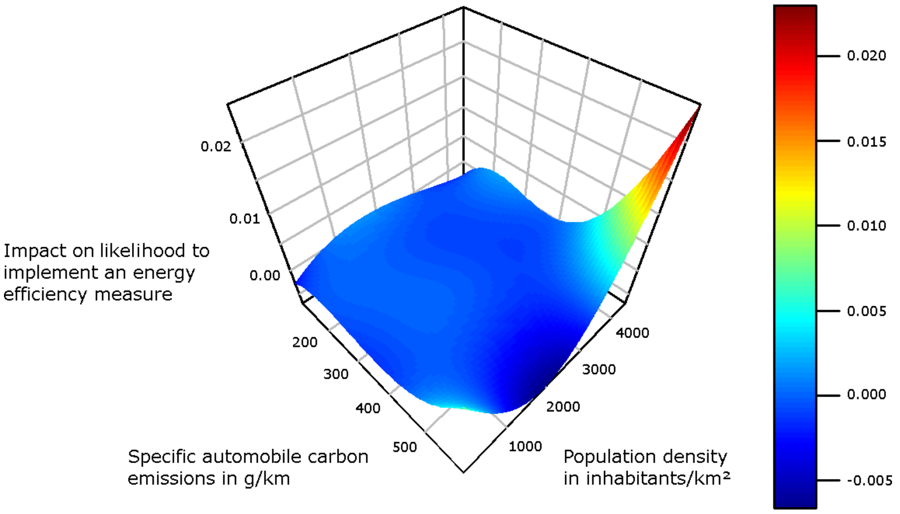

FIGURE A.3: First derivatives of the joint impact on the likelihood to implement an energy efficiency measure with respect population density.

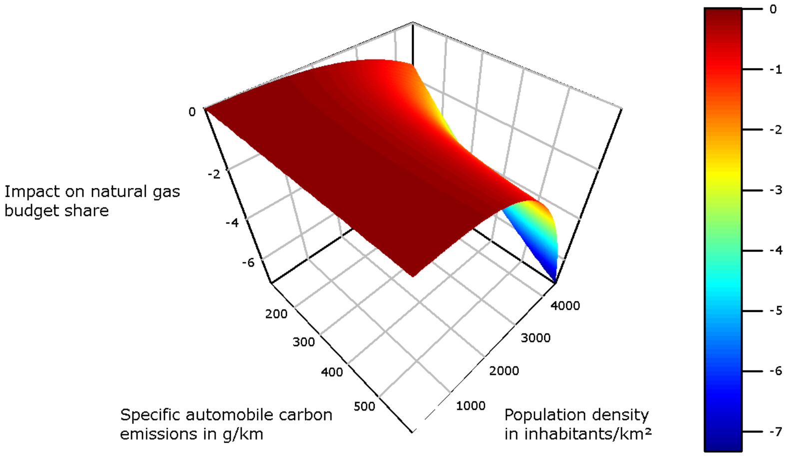

FIGURE A.4: First derivatives of the joint impact on budget share of natural gas with respect to specific automobile carbon emissions.

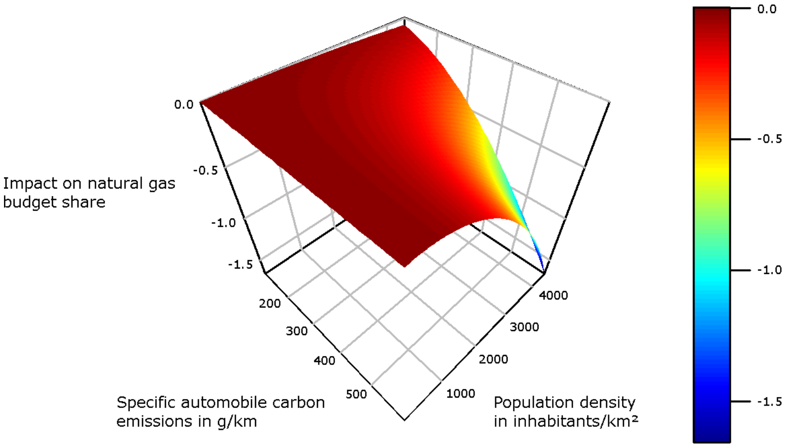

FIGURE A.5: First derivatives of the joint impact on budget share of natural gas with respect to population density.

Derivation of the demand system estimation equation

By assuming a quadratic form in logarithmized prices, the minimal log expenditure for households with the observed and unobserved characteristics (as specified in section 2.2.3), prices $\vec{p}$ and utility level u are given by the EASI cost function:

$$\ln C(\vec{p}, u, \vec{z}, m, \vec{a}, \vec{\varepsilon}) = u + \sum_{j=1}^{J} n^j(u, \vec{z}, m, \vec{a}) \ln p^j + \frac{1}{2}\sum_{j=1}^{J}\sum_{k=1}^{J} b^{jk}(\vec{z}, m, \vec{a}) \ln p^j \ln p^k + \sum_{j=1}^{J} \varepsilon^j \ln p^j \tag{A.1}$$

with $n^j(u, \vec{z}, m, \vec{a})$ representing the J-vector Hicksian budget share function and $b^{jk}(\vec{z}, m, \vec{a})$ being the Slutsky coefficients. Using Shepard's Lemma, we can derive Hicksian budget shares, by $\partial \ln C / \partial \ln p^j$. Denoting the Hicksian budget share by $\vec{v}$ it follows:

$$v^j(\vec{p}, u, \vec{z}, m, \vec{a}, \vec{\varepsilon}) = n^j(u, \vec{z}, m, \vec{a}) + \sum_{k=1}^{J} b^{jk}(\vec{z}, m, \vec{a}) \ln p^k + \varepsilon^j \tag{A.2}$$

From Equation (A.2) and due to the fact that the budget shares are observable in the data, it follows:

$$\sum_{j=1}^{J} w^j \ln p^j = \sum_{j=1}^{J} n^j(u, \vec{z}, m, \vec{a}) \ln p^j + \sum_{j=1}^{J}\sum_{k=1}^{J} b^{jk}(\vec{z}, m, \vec{a}) \ln p^j \ln p^k + \sum_{j=1}^{J} \varepsilon^j \ln p^j \tag{A.3}$$

Manipulating Equation (A.3) for $\sum_{j=1}^{J} n^j(u, \vec{z}, m, \vec{a}) \ln p^j$, replacing it in Equation (A.1), replacing $\ln C$ by $\ln x$ and rearranging the resulting equation for u gives the implicit utility function, y:

$$y = u = \ln x - \sum_{j=1}^{J} w^j \ln p^j + \frac{1}{2}\sum_{j=1}^{J}\sum_{k=1}^{J} b^{jk}(\vec{z}, m, \vec{a}) \ln p^j \ln p^k \tag{A.4}$$

Thus, substituting Equation (A.4) into Equation (A.2) results in the implicit Marshallian budget shares:

$$w^j = n^j(y, \vec{z}, m, \vec{a}) + \sum_{k=1}^{J} b^{jk}(\vec{z}, m, \vec{a}) \ln p^k + \varepsilon^j \tag{A.5}$$

From Equation (A.5) the first difficulty of the EASI demand system becomes obvious. Due to a possible non-linear dependency of n^j from y and the fact that y depends on $\vec{w}$, $\vec{p}$, $\vec{z}$, $\vec{m}$ and $\vec{a}$[51]. Therefore, we approximate Equation (A.4) in line with Lewbel and Pendakur (2009) by:

$$\tilde{y} = \ln x - \sum_{j=1}^{J} w^j \ln p^j \tag{A.6}$$

Under the assumption that $n^j(\tilde{y}, \vec{z}, m, \vec{a})$ is additively separable in $\tilde{y}$, $\vec{z}$, $\vec{m}$ and $\vec{a}$, the following linear specification for n^j results in:

$$n^j(\tilde{y}, \vec{z}, m, \vec{a}) = \sum_{e=1}^{E} \gamma_e^j \tilde{y}^r + \sum_{f=1}^{F} \delta_f^j z_f + \sum_{g=1}^{G} \tau_g^j m_g + \sum_{h=1}^{H} \psi_h^j a_h \tag{A.7}$$

Inserting Equation (A.7) and Equation (A.6) into Equation (A.5), the budget share equation to be estimated is as follows:

$$w^j = \sum_{e=1}^{E} \gamma_e^j \tilde{y}^r + \sum_{f=1}^{F} \delta_f^j z_f + \sum_{g=1}^{G} \tau^g m_g + \sum_{h=1}^{H} \psi_h^j a_h + \sum_{k=1}^{J} b^{jk}(\vec{z}, m, \vec{a}) \ln p^k + \varepsilon^j \tag{A.8}$$

---

[51] Lewbel and Pendakur (2009) provide some evidence that the nonlinearity is of relatively small relevance.

Endogeneity

The selection bias follows from the self-selection of households to implement an energy efficiency measure. Thus, the treatment (implementation of an energy efficiency measure $\vec{m}$) cannot be considered to be randomly assigned. If we do not control for the unobserved heterogeneity, as incorporated in $\vec{a}$, our estimation approach would suffer from endogeneity. When omitting the unobserved heterogeneity ($\sum_{h=1}^{H} \psi_h^j a_h + \varepsilon^j = \eta^j$) following the conditional expectation function (CEF) of Equation (2.6) results.

$$\begin{aligned} \mathbb{E}(w^j \mid \vec{z}, m) = & \sum_{e=1}^{E} \gamma_e^j \tilde{y}^e + \sum_{f=1}^{F} \delta_f^j z_f + \sum_{g=1}^{G} \tau_g^j m_g \\ & + \sum_{k=1}^{J} b^{jk}(\vec{z}, \vec{m}) \ln p^k + \mathbb{E}(\eta^j \mid \vec{z}, \vec{m}) \end{aligned} \tag{A.9}$$

We are interested in the difference in outcomes for those households that implement one or several energy efficiency measures and those who do not. For simplification, assume we are only interested in the effect of implementing one efficiency measure, i.e., $m = \{0, 1\}$. The CEF of households that choose to implement one energy efficiency measure is:

$$\begin{aligned} \mathbb{E}(w^j \mid \vec{z}, m = 1) = & \sum_{e=1}^{E} \gamma_e^j \tilde{y}^e + \sum_{f=1}^{F} \delta_f^j z_f + \tau_1^j \\ & + \sum_{k=1}^{J} b^{jk}(\vec{z}, m) \ln p^k + \mathbb{E}(\eta^j \mid \vec{z}, m = 1) \end{aligned} \tag{A.10}$$

For households that did not implement any energy efficiency measure m, following CEF results:

$$\begin{aligned} \mathbb{E}(w^j \mid \vec{z}, m = 0) = & \sum_{e=1}^{E} \gamma_e^j \tilde{y}^e + \sum_{f=1}^{F} \delta_f^j z_f \\ & + \sum_{k=1}^{J} b^{jk}(\vec{z}, m) \ln p^k + \mathbb{E}(\eta^j \mid \vec{z}, m = 0) \end{aligned} \tag{A.11}$$

Of our interest is the demand-reducing effect, i.e., the difference between both outcomes. Hence, it follows

$$\mathbb{E}(w^j \mid \vec{z}, m=1) - \mathbb{E}(w^j \mid \vec{z}, m=0) = \tau_1^j + \underbrace{\mathbb{E}(\eta^j \mid \vec{z}, m=1) - \mathbb{E}(\eta^j \mid \vec{z}, m=0)}_{\text{Selection bias}} \quad \text{(A.12)}$$

Following the ordered probit estimation results, the decision to implement an energy efficiency measure crucially depends on $\vec{a}$ that is omitted as an individual variable and hence, included in η^j. Therefore, the selection bias in this problem does not resolve to zero. However, with the introduction of $\vec{a}$ as control variables, i.e., proxy for the unobserved heterogeneity environmental awareness, the endogeneity problem can be resolved:

$$\mathbb{E}(w^j \mid \vec{z}, \vec{a}, m=1) - \mathbb{E}(w^j \mid \vec{z}, \vec{a}, m=0) = \tau_1^j + \underbrace{\mathbb{E}(\varepsilon^j \mid \vec{z}, \vec{a}, m=1) - \mathbb{E}(\varepsilon^j \mid \vec{z}, \vec{a}, m=0)}_{\text{Selection bias}} \quad \text{(A.13)}$$

With the unobserved heterogeneity excluded from the error term, the selection bias ($\mathbb{E}(\varepsilon^j \mid \vec{z}, \vec{a}, m = 1) - \mathbb{E}(\varepsilon^j \mid \vec{z}, \vec{a}, m = 0)$) is zero, as the decision to implement an efficiency measure should not be correlated to the error term. Thus, the incorporation of $\vec{a}$ as a proxy for the unobserved heterogeneity resolves the endogeneity issue.

Supplementary Material for Chapter 3

Notation

Abbr.	Explanation	Range
α	Naive fraction of the population	$0 < \alpha < 1$
$1-\alpha$	Sophisticated fraction of the population	$0 < 1-\alpha < 1$
ρ	Demand for energy after consumption of the efficiency service	$0 < \rho < 1$
Δ	Share of naive consumers that becomes informed (informed naive consumers)	$0 < \Delta < 1$
φ	Fraction of α that purchase the eff. service from firm A or B	$0 < \varphi < 1$
ϵ	Costs of offering and disclosing the efficiency service	$\epsilon \gtrapprox 0$
c	Marginal cost on the energy retail market	$c > 0$
t	Taste mismatch on the energy retail market	$t \geq 0$
x	Location in the linear city	$0 \leq x \leq 1$
U	Consumer utility	$-$
v	Utility from energy consumption	$-$
$p_{i,e,j}$	Price for energy of firm i in subgame j	$-$
$p_{i,s,j}$	Price for the efficiency service of firm i in subgame j	$-$
$\pi_{i,j}$	Period 2 profit of firm i in subgame j	$-$
Γ	Functions representing limiting values for ρ	$-$
CS_k	Consumer surplus	$-$
Λ_{CS} ,Λ_{TS}	Consumer and total surplus benefits from mandatory disclosure	$-$

TABLE B.1: Notation

Proofs

Proof of Lemma 1

From the firms' profits given in Equation (3.7), the first order conditions follow.

$$\begin{aligned}\frac{\partial \pi_{A,1}}{\partial p_{A,e,1}} =& \frac{\left((\alpha-1)\rho^2-\alpha\right)\left(2p_{A,e,1}-p_{B,e,1}\right)+c\left(\alpha+\rho^2-\alpha\rho^2\right)}{2t} \\ &+\frac{t(+\alpha+\rho-\rho\alpha)}{2t}, \qquad \text{(B.1)}\\ \frac{\partial \pi_{B,1}}{\partial p_{B,e,1}} =& \frac{\left((\alpha-1)\rho^2-\alpha\right)\left(2p_{B,e,1}-p_{A,e,1}\right)+c\left(\alpha+\rho^2-\alpha\rho^2\right)}{2t} \\ &+\frac{t(\alpha+\rho-\rho\alpha)}{2t}. \qquad \text{(B.2)}\end{aligned}$$

Solving the first order conditions for each firm's price, the reaction functions are:

$$p_{A,e,1} = \frac{\left((\alpha-1)\rho^2-\alpha\right)p_{B,e,1}+(\alpha-1)c\rho^2-\alpha(c+t)+(\alpha-1)\rho t}{2(\alpha-1)\rho^2-2\alpha}, \qquad \text{(B.3)}$$

$$p_{B,e,1} = \frac{\left((\alpha-1)\rho^2-\alpha\right)p_{A,e,1}+(\alpha-1)c\rho^2-\alpha(c+t)+(\alpha-1)\rho t}{2(\alpha-1)\rho^2-2\alpha}. \qquad \text{(B.4)}$$

Solving the reaction functions in Equation (B.3) and (B.4) for the equilibrium prices, results in (with $i \in \{A, B\}$)

$$p^*_{i,e,1} = c + \frac{t(\alpha+\rho-\rho\alpha)}{\alpha+\rho^2-\alpha\rho^2}. \qquad \text{(B.5)}$$

Plugging these equilibrium prices into Equation (3.7) gives the second period equilibrium profits of Lemma 1. □

Proof of Lemma 2

The first derivative of the equilibrium period 2 profits with respect to α is:

$$\frac{\partial \pi^*_{i,1}}{\partial \alpha} = \frac{(\rho-1)^2 t(\alpha(\rho-1)-\rho)((\alpha-1)\rho+\alpha)}{2\left(\alpha+\rho^2-\alpha\rho^2\right)^2}. \qquad \text{(B.6)}$$

It immediately follows that period 2 profits are at a minimum at $\partial\pi_{i,1}/\partial\alpha = 0$, i.e., $\bar{\alpha} = \rho/(1+\rho)$, as $\partial^2\pi_{i,1}/\partial\alpha^2|_{\bar{\alpha}=\rho/(1+\rho)} < 0$. With a maximum that is outside of the domain for α and ρ at $\acute{\alpha} = \rho/(\rho-1)$, it immediately follows that $\partial\pi_{u,1}/\partial\alpha$ is positive for $\alpha < \bar{\alpha}$ and negative for $\alpha > \bar{\alpha}$. □

Proof of Lemma 3

A naive consumer at location x in the linear city has utility $U_{\alpha(1-\Delta),A,x}$ buying the main good from firm A and utility $U_{\alpha(1-\Delta),B,x}$ buying from firm B.

$$U_{\alpha(1-\Delta),A,x} = v - p_{A,e,2} - tx \tag{B.7}$$

$$U_{\alpha(1-\Delta),B,x} = v - p_{B,e,2} - t(1-x) \tag{B.8}$$

A sophisticated or informed naive consumer at location x has utility $U_{1-\alpha(1-\Delta),A,x}$ buying energy from firm A and utility $U_{1-\alpha(1-\Delta),B,x}$ buying from firm B.

$$U_{1-\alpha(1-\Delta),A,x} = v - p_{A,e,2}\,\rho - tx \tag{B.9}$$

$$U_{1-\alpha(1-\Delta),B,x} = v - p_{B,e,2}\,\rho - t(1-x) \tag{B.10}$$

The firms' profits are given by Equation (B.11). From the existence of the competitive fringe it follows that $p_{i,s,2} = 0$. With $i \in \{A, B\}$:

$$\pi^*_{i,2} = q_{i,e,2}\left(p_{i,e,2} - c\right). \tag{B.11}$$

From the firm profits given in Equation (B.11), the following first order conditions result:

$$\frac{\partial \pi_{A,2}}{\partial p_{A,e,2}} = \frac{\left(\rho^2 - \alpha(\Delta-1)\left(\rho^2-1\right)\right)\left(2p_{A,e,2} - p_{B,e,2}\right)}{2t} \tag{B.12}$$

$$+\,\frac{c\rho^2(\alpha(\Delta-1)+1) - \alpha(\Delta-1)(c+t) + \rho t(\alpha(\Delta-1)+1)}{2t}, \tag{B.13}$$

$$\frac{\partial \pi_{B,2}}{\partial p_{B,e,2}} = \frac{\left(\rho^2 - \alpha(\Delta-1)\left(\rho^2-1\right)\right)\left(2p_{B,e,2} - p_{A,e,2}\right)}{2t} \tag{B.14}$$

$$+\,\frac{c\rho^2(\alpha(\Delta-1)+1) - \alpha(\Delta-1)(c+t) + \rho t(\alpha(\Delta-1)+1)}{2t}. \tag{B.15}$$

Thus, the reaction functions for the energy retail prices are

$$\begin{aligned} p_{A,e,2} =& \frac{\left(\alpha(\Delta-1)\left(\rho^2-1\right)+\rho^2\right)p_{B,e,2} + c\left(\alpha(\Delta-1)\left(\rho^2-1\right)+\rho^2\right)}{2\left(\alpha(\Delta-1)\left(\rho^2-1\right)+\rho^2\right)} \\ &+ \frac{t(\alpha(\Delta-1)(\rho-1)+\rho)}{2\left(\alpha(\Delta-1)\left(\rho^2-1\right)+\rho^2\right)}, \end{aligned} \tag{B.16}$$

$$\begin{aligned} p_{B,e,2} =& \frac{\left(\alpha(\Delta-1)\left(\rho^2-1\right)+\rho^2\right)p_{A,e,2} + c\left(\alpha(\Delta-1)\left(\rho^2-1\right)+\rho^2\right)}{2\left(\alpha(\Delta-1)\left(\rho^2-1\right)+\rho^2\right)} \\ &+ \frac{t(\alpha(\Delta-1)(\rho-1)+\rho)}{2\left(\alpha(\Delta-1)\left(\rho^2-1\right)+\rho^2\right)}. \end{aligned} \tag{B.17}$$

Solving the reaction functions in Equation (B.16) and (B.17) for the equilibrium prices, gives (with $i \in \{A, B\}$)

$$p^*_{i,e,2} = c + \frac{t(\alpha(\Delta - 1)(\rho - 1) + \rho)}{\alpha(\Delta - 1)\left(\rho^2 - 1\right) + \rho^2}, \tag{B.18}$$

$$p^*_{i,s,2} = 0. \tag{B.19}$$

Plugging these equilibrium prices into Equation (B.11) gives the second period equilibrium profits of Lemma 3. □

Proof of Proposition 1

Using the period 2 firms' profits in both settings as given in Equation (3.8) and (3.12), the conditions for the superiority introducing the efficiency service are given by the inequality ($i \in \{A, B\}$)

$$\pi^*_{i,2} = \frac{t}{2}\frac{(\alpha(\Delta - 1)(\rho - 1) + \rho)^2}{\alpha(\Delta - 1)\left(\rho^2 - 1\right) + \rho^2} \geq \pi^*_{i,1} = \frac{t}{2}\frac{(\alpha + \rho - \rho\alpha)^2}{\alpha + (1 - \alpha)\rho^2}. \tag{B.20}$$

This inequality is reduced using `Mathematica` computational software. The code is available from the author on request. The results in Proposition 1 follow. □

Proof of Corollary 1

Similar to Lemma 2, consider the simpler case of subgame 1. It was shown that at $\hat{\alpha}$ the firms' profits are minimized. To calculate the welfare maximum under a consumer surplus standard, consumer surplus needs to be calculated.

$$\begin{aligned}
CS_1 =& \alpha\Bigg[v\hat{x}_\alpha - {p^*}_{A,e,1}\hat{x} - \int_0^{\hat{x}_\alpha} tx\,dx && \text{(B.21)}\\
&+ v\left(1 - \hat{x}_\alpha\right) - {p^*}_{B,e,1}\left(1 - \hat{x}_\alpha\right) - \int_{\hat{x}_\alpha}^1 t(1 - x)\,dx\Bigg] && \text{(B.22)}\\
&+ (1 - \alpha)\Bigg[v\hat{x}_{1-\alpha} - \rho{p^*}_{A,e,1}\hat{x}_{1-\alpha} - \int_0^{\hat{x}_{1-\alpha}} tx\,dx && \text{(B.23)}\\
&+ v\left(1 - \hat{x}_{1-\alpha}\right) - \rho{p^*}_{B,e,1}\left(1 - \hat{x}_{1-\alpha}\right) - \int_{\hat{x}_{1-\alpha}}^1 t(1 - x)\,dx\Bigg] && \text{(B.24)}\\
=& v + \left(\alpha - \frac{5}{4}\right)t + \alpha c\rho - c(\alpha + \rho) + \frac{\alpha t(-2\alpha(\rho - 1) + 2\rho - 1)}{(\alpha - 1)\rho^2 - \alpha} && \text{(B.25)}
\end{aligned}$$

Taking the first derivative with respect to α and solving for α gives two possible solutions.

$$\breve{\alpha}_I = \frac{(\rho-1)^2\rho^2(c\rho+c+t) - \sqrt{(\rho-1)^4\rho^2 t(c\rho+c+t)}}{(\rho-1)^3(\rho+1)(c\rho+c+t)} \tag{B.26}$$

$$\breve{\alpha}_{II} = \frac{(\rho-1)^2\rho^2(c\rho+c+t) + \sqrt{(\rho-1)^4\rho^2 t(c\rho+c+t)}}{(\rho-1)^3(\rho+1)(c\rho+c+t)} \tag{B.27}$$

Evaluating both solutions at the second derivative illustrates that only $\breve{\alpha}_I$ is a maximum. Hence, $\breve{\alpha} = \breve{\alpha}_I$.

That $\breve{\alpha} < \hat{\alpha}$ follows directly from Lemma 5. □

Example Visualizations of Functions

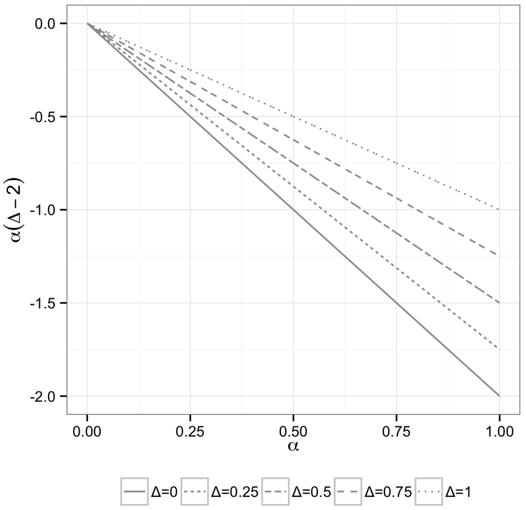

FIGURE B.1: Example visualization of $\alpha\,(\Delta - 2)$.

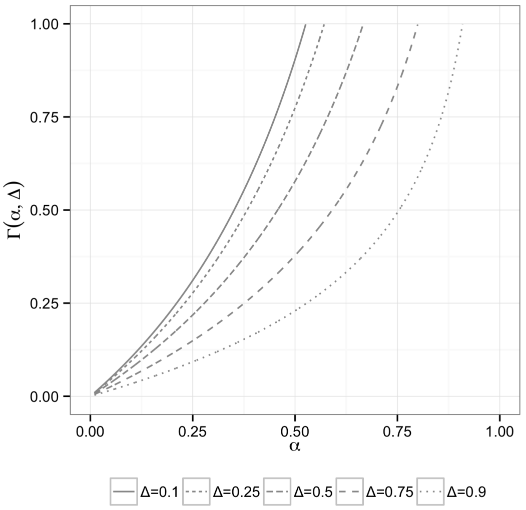

FIGURE B.2: Example visualization of $\Gamma(\alpha, \Delta)$.

Supplementary Material for Chapter 4

Notation

Abbreviation	Explanation
State variables	
χ	Cumulative resource additions
S	Amount of proven resources
Control variables	
E	Extraction rate
Q	Rate of final output
B	Exploration expenses
Parameters	
T	State of technology
P	Market price of final output
W	Market price of reproducible inputs (labor, capital)
X	Amount of reproducible inputs (labor, capital)
r	Real interest rate
λ_1	Shadow price of reserves (i.e., resource in situ)
λ_2	Shadow price of cumulative discoveries
Functions	
f	Exploration function
R	Revenue function
U	Utility function
V	Firm-specific factor prices of competing firms
Y	Exogenous global demand shifters
CR	Restricted cost function
FTC	Full total costs
FMC	Full marginal costs
Subscripts	
K	Capital
L	Labor
CAP	Global thermal capacity of nuclear power plants
MFM	Recycled warheads (“Megatons for Megawatts”)
INV	Changes in global uranium inventories
LAU, LKZ	Labor Australia, Kazakhstan
KAU, KKZ	Capital Australia, Kazakhstan
SAU, SKZ	Proven reserves Australia, Kazakhstan

Table C.1: Notation

Econometric Appendix

Wald test of perfect competition

As proposed by Ellis and Halvorsen (2002), we test our results regarding market power exertion against a null hypothesis of perfectly competitive price-taking behavior. Within our framework, perfect competition corresponds to $\beta_0 = \beta_1 = \beta_2 = \beta_3 = \beta_4 = 0$. We test the rejection of this null hypothesis using a Wald test. The resulting mean of the test statistic is found to be 36.492 (std. dev. 4.701). With a critical value 15.09, we reject the hypothesis of perfectly competitive behavior at the 1%-level.

Polynomial representation of $\beta(t)$

We estimate the Model 1 system of equations with five different polynomial representations of the time-varying mark-up. The specifications are as follows:

- Scalar representation: $\beta(t) = \beta_0$
- Linear representation: $\beta(t) = \beta_0 + \beta_1 T$
- Quadratic representation: $\beta(t) = \beta_0 + \beta_1 T + \beta_2 T^2$
- Cubic representation: $\beta(t) = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3$
- Biquadratic representation: $\beta(t) = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3 + \beta_4 T^4$

The estimation for the first four models are given in Table C.2 (scalar representation), Table C.3 (linear representation), Table C.4 (quadratic representation), Table C.5 (cubic representation) and Table 4.4 (biquadratic representation).

The results clearly show that the polynomial in $\beta(t)$ is only statistically significant for higher order approximations. Apart from that, almost all other estimates are relatively robust for different specifications. Therefore, we use the biquadratic specification as it reflects a higher order Taylor-approximation to the actual $\beta(t)$-function.

Parameter	*Estimate*		*p-value*		*Std. Error*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
α_0	20.719	0.034	7.35E-38***	4.01E-37	0.103	7.31E-3
α_Q	3.03E-8	3.20E-9	7.10E-10***	4.47E-10	2.98E-9	2.51E-10
$\alpha_K = 1 - \alpha_L$	0.102	1.32E-5	2.96E-54***	1.37E-54	1.08E-4	1.99E-6
α_E	2.144	0.100	2.53E-10***	7.34E-10	0.186	0.019
α_S	-0.187	0.136	0.195	0.228	0.114	0.038
$\gamma_{KK} = -\gamma_{LK}$ $= \gamma_{LL} = -\gamma_{LK}$	-6.43E-4	2.78E-4	0.133^{+}	0.141	3.39E-4	3.73E-5
γ_{QQ}	3.47E-8	2.72E-9	9.30E-4***	6.76E-4	8.96E-9	8.34E-10
γ_{EE}	1.208	0.266	0.077*	0.096	0.591	0.105
$\gamma_{KQ} = -\gamma_{LQ}$	-8.70E-9	2.74E-9	0.198	0.119	6.06E-9	5.78E-10
$\gamma_{KE} = -\gamma_{LE}$	2.33E-3	6.35E-5	9.04E-10***	1.23E-9	2.30E-4	9.38E-6
γ_{QE}	-4.17E-8	4.20E-9	3.50E-7***	2.33E-7	5.84E-9	5.03E-10
β_0	5.276	4.253	0.199	0.233	2.725	0.221
τ_{MFM}	26.427	8.941	0.567	0.124	44.715	2.824
τ_{CAP}	70.925	40.873	0.633	0.169	139.993	8.118
ϱ_{LAU}	18.112	1.778	0.028**	0.012	7.622	0.336
ϱ_{LKZ}	-9.679	4.604	0.279	0.200	7.603	0.408
ϱ_{KAU}	32.773	2.439	0.100^{+}	0.032	18.950	1.059
ϱ_{KKZ}	3.032	0.680	0.602	0.090	5.715	0.352
τ_{INV}	10.810	0.079	3.25E-16***	5.74E-16	0.508	0.030
ϱ_{SAU}	39.729	1.781	1.24E-3***	9.36E-4	10.627	0.638
ϱ_{SKZ}	-7.900	2.813	0.392	0.183	8.634	0.481

Observations	50×44
Adjusted R^2	Eq. (4.18): mean 0.54 std. dev. 0.05, Eq. (4.21): mean 0.62 std. dev. 0.1, Eq. (4.26): mean 0.27 std. dev. 0.22, Eq. (4.28): mean 0.54 std. dev. 0.05

*** $p < 0.01$,** $p < 0.05$,* $p < 0.1$,$^{+}$ $p < 0.15$

Table C.2: Scalar repr.: Estimation results for model without dynamic optimality condition.

Parameter	*Estimate*		*p-value*		*Std. Error*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
α_0	20.720	0.033	1.93E-36***	1.04E-35	0.103	7.22E-3
α_Q	2.92E-8	5.37E-9	1.06E-7***	1.44E-7	3.57E-9	3.84E-10
$\alpha_K = 1 - \alpha_L$	0.102	1.52E-5	3.97E-52***	1.70E-52	1.09E-4	2.00E-6
α_E	2.134	0.090	7.05E-10***	1.78E-9	0.194	0.016
α_S	-0.187	0.136	0.190	0.221	0.114	0.038
$\gamma_{KK} = -\gamma_{LK}$ $= \gamma_{LL} = -\gamma_{LK}$	-6.41E-4	2.73E-4	0.135^{+}	0.144	3.40E-4	3.71E-5
γ_{QQ}	3.25E-8	6.57E-9	5.59E-3***	4.72E-3	1.01E-8	1.11E-9
γ_{EE}	1.244	0.291	0.073*	0.091	0.596	0.103
$\gamma_{KQ} = -\gamma_{LQ}$	-8.09E-9	3.94E-9	0.273	0.173	6.26E-9	8.94E-10
$\gamma_{KE} = -\gamma_{LE}$	2.32E-3	6.09E-5	2.53E-9***	2.51E-9	2.38E-4	6.49E-6
γ_{QE}	-4.01E-8	7.36E-9	6.99E-6***	7.42E-6	6.56E-9	7.76E-10
β_0	3.991	6.864	0.341	0.324	3.419	0.337
β_1	-0.073	0.151	0.511	0.222	0.204	0.022
τ_{MFM}	26.308	8.868	0.565	0.127	44.434	3.545
τ_{CAP}	74.217	43.037	0.624	0.169	141.053	9.315
ϱ_{LAU}	17.868	1.996	0.031**	0.013	7.598	0.387
ϱ_{LKZ}	-9.040	6.017	0.328	0.239	7.570	0.480
ϱ_{KAU}	31.976	2.402	0.116^{+}	0.028	19.422	1.500
ϱ_{KKZ}	4.100	1.983	0.525	0.211	6.110	0.401
τ_{INV}	10.769	0.103	1.45E-15***	2.76E-15	0.515	0.034
ϱ_{SAU}	39.095	2.419	1.44E-3***	1.21E-3	10.546	0.792
ϱ_{SKZ}	-7.759	2.689	0.418	0.178	9.069	0.586
Observations	50×44					
Adjusted R^2	Eq. (4.18): mean 0.54 std. dev. 0.05, Eq. (4.21): mean 0.62 std. dev. 0.1, Eq. (4.26): mean 0.27 std. dev. 0.22, Eq. (4.28): mean 0.54 std. dev. 0.05					

*** $p < 0.01$,** $p < 0.05$,* $p < 0.1$,$^{+}$ $p < 0.15$

Table C.3: Linear repr.: Estimation results for model without dynamic optimality condition.

Parameter	*Estimate*		*p-value*		*Std. Error*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
α_0	20.729	0.037	7.48E-35***	4.25E-34	0.105	7.40E-3
α_Q	2.27E-8	3.73E-9	1.52E-8***	3.73E-8	2.42E-9	2.61E-10
$\alpha_K = 1 - \alpha_L$	0.102	1.89E-5	7.29E-50***	2.60E-50	1.11E-4	1.93E-6
α_E	1.894	0.130	9.09E-9***	2.04E-8	0.197	0.020
α_S	-0.214	0.149	0.197	0.275	0.116	0.041
$\gamma_{KK} = -\gamma_{LK}$ $= \gamma_{LL} = -\gamma_{LK}$	-4.94E-4	1.89E-4	0.214	0.163	3.46E-4	3.97E-5
γ_{QQ}	2.78E-8	3.92E-9	4.98E-4***	4.51E-4	6.50E-9	6.49E-10
γ_{EE}	1.556	0.316	0.046**	0.090	0.616	0.096
$\gamma_{KQ} = -\gamma_{LQ}$	-8.33E-9	1.38E-9	0.043**	0.036	3.62E-9	4.06E-10
$\gamma_{KE} = -\gamma_{LE}$	2.10E-3	9.00E-5	1.70E-8***	9.03E-9	2.37E-4	1.13E-5
γ_{QE}	-2.66E-8	3.34E-9	5.85E-6***	4.45E-6	4.35E-9	5.27E-10
β_0	-7.353	4.180	0.109^{+}	0.227	2.718	0.390
β_1	0.099	0.149	0.577	0.292	0.158	0.023
β_2	0.048	8.32E-3	5.33E-4***	8.43E-4	0.011	1.32E-3
τ_{MFM}	37.310	15.355	0.271	0.157	30.708	2.457
τ_{CAP}	71.237	18.597	0.508	0.119	104.568	6.159
ϱ_{LAU}	13.218	1.714	0.042**	0.037	5.824	0.373
ϱ_{LKZ}	2.280	4.014	0.530	0.237	5.575	0.348
ϱ_{KAU}	37.954	3.371	0.011**	6.59E-3	13.294	1.016
ϱ_{KKZ}	8.187	1.531	0.092*	0.075	4.328	0.307
τ_{INV}	10.577	0.172	2.49E-16***	5.99E-16	0.433	0.028
ϱ_{SAU}	21.975	3.417	0.016**	0.047	7.459	0.517
ϱ_{SKZ}	-9.784	2.305	0.180	0.117	6.643	0.465
Observations	50×44					
Adjusted R^2	Eq. (4.18): mean 0.54 std. dev. 0.05, Eq. (4.21): mean 0.62 std. dev. 0.1, Eq. (4.26): mean 0.27 std. dev. 0.22, Eq. (4.28): mean 0.54 std. dev. 0.05					

*** $p < 0.01$,** $p < 0.05$,* $p < 0.1$,$^{+}$ $p < 0.15$

Table C.4: Quadratic repr.: Estimation results for model without dynamic optimality condition.

Parameter	*Estimate*		*p-value*		*Std. Error*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
α_0	20.722	0.036	1.58E-33***	8.58E-33	0.105	7.50E-3
α_Q	2.36E-8	4.19E-9	9.80E-8***	3.76E-7	2.68E-9	3.10E-10
$\alpha_K = 1 - \alpha_L$	0.102	2.00E-5	8.78E-48***	2.81E-48	1.10E-4	1.84E-6
α_E	1.910	0.129	1.30E-8***	2.78E-8	0.198	0.020
α_S	-0.215	0.149	0.189	0.271	0.116	0.041
$\gamma_{KK} = -\gamma_{LK}$ $= \gamma_{LL} = -\gamma_{LK}$	-4.79E-4	1.85E-4	0.228	0.169	3.46E-4	3.97E-5
γ_{QQ}	2.79E-8	4.26E-9	1.37E-3***	1.05E-3	7.24E-9	8.20E-10
γ_{EE}	1.549	0.308	0.045**	0.082	0.616	0.096
$\gamma_{KQ} = -\gamma_{LQ}$	-8.05E-9	1.52E-9	0.072*	0.063	3.96E-9	5.42E-10
$\gamma_{KE} = -\gamma_{LE}$	2.13E-3	9.26E-5	2.53E-8***	1.36E-8	2.39E-4	1.16E-5
γ_{QE}	-2.80E-8	3.97E-9	1.14E-5***	8.09E-6	4.75E-9	7.02E-10
β_0	-6.516	4.643	0.126^{+}	0.234	2.969	0.439
β_1	0.219	0.172	0.392	0.250	0.209	0.033
β_2	0.047	8.44E-3	4.30E-3***	6.84E-3	0.014	1.81E-3
β_3	-5.09E-4	2.71E-4	0.581	0.171	8.99E-4	1.09E-4
τ_{MFM}	38.888	15.631	0.265	0.133	31.737	2.967
τ_{CAP}	71.533	21.270	0.517	0.135	106.829	7.661
ϱ_{LAU}	14.204	1.694	0.048**	0.036	6.491	0.376
ϱ_{LKZ}	1.615	4.604	0.564	0.254	5.994	0.507
ϱ_{KAU}	36.335	3.637	0.020**	0.011	14.085	1.316
ϱ_{KKZ}	7.150	1.544	0.152	0.109	4.505	0.375
τ_{INV}	10.644	0.187	1.63E-15***	5.33E-15	0.440	0.034
ϱ_{SAU}	22.509	3.909	0.026**	0.080	8.187	0.561
ϱ_{SKZ}	-9.100	2.692	0.238	0.157	6.994	0.586
Observations	50×44					
Adjusted R^2	Eq. (4.18): mean 0.54 std. dev. 0.05, Eq. (4.21): mean 0.62 std. dev. 0.1, Eq. (4.26): mean 0.27 std. dev. 0.22, Eq. (4.28): mean 0.54 std. dev. 0.05					

*** $p < 0.01$,** $p < 0.05$,* $p < 0.1$,$^{+}$ $p < 0.15$

TABLE C.5: Cubic repr.: Estimation results for model without dynamic optimality condition.

Additional tables for the estimation results of Model 1

Parameter	*Estimate*				
	Min	25%-quantile	Mean	75%-quantile	Max
α_0	20.651	20.695	20.715	20.734	20.865
α_Q	1.26E-8	1.41E-8	1.57E-8	1.69E-8	2.13E-8
$\alpha_K = 1 - \alpha_L$	0.102	0.102	0.102	0.102	0.102
α_E	1.906	2.062	2.116	2.173	2.314
α_S	-0.512	-0.252	-0.204	-0.126	0.083
$\gamma_{KK} = -\gamma_{LK} = \gamma_{LL} = -\gamma_{LK}$	-1.07E-3	-6.04E-4	-4.72E-4	-3.49E-4	-1.26E-4
γ_{QQ}	1.00E-8	1.14E-8	1.34E-8	1.48E-8	2.09E-8
γ_{EE}	0.700	1.526	1.665	1.890	2.284
$\gamma_{KQ} = -\gamma_{LQ}$	-1.29E-8	-9.95E-9	-9.39E-9	-8.45E-9	-5.81E-9
$\gamma_{KE} = -\gamma_{LE}$	2.12E-3	2.31E-3	2.35E-3	2.39E-3	2.47E-3
γ_{QE}	-2.57E-8	-2.04E-8	-1.93E-8	-1.80E-8	-1.62E-8
β_0	-21.208	-19.674	-18.297	-17.390	-12.319
β_1	-0.171	-0.014	0.038	0.093	0.212
β_2	0.090	0.098	0.112	0.116	0.158
β_3	-1.34E-3	-1.07E-3	-8.98E-4	-7.60E-4	-2.79E-4
β_4	-2.87E-4	-1.92E-4	-1.84E-4	-1.56E-4	-1.37E-4
τ_{MFM}	-2.020	8.774	14.216	17.448	42.922
τ_{CAP}	49.882	84.249	93.717	103.215	127.432
ϱ_{LAU}	12.322	13.657	14.580	15.169	17.976
ϱ_{LKZ}	5.684	9.059	10.609	12.322	13.639
ϱ_{KAU}	19.332	23.716	25.376	26.697	33.292
ϱ_{KKZ}	5.916	8.167	8.555	9.143	9.918
τ_{INV}	10.490	10.642	10.713	10.771	10.968
ϱ_{SAU}	15.600	18.387	19.788	21.273	26.506
ϱ_{SKZ}	-9.671	-6.181	-4.434	-2.917	0.379
Observations	50×44				

Table C.6: Estimation results for model without dynamic optimality condition: coefficients.

Parameter			*p-value*		
	Min	25%-quantile	Mean	75%-quantile	Max
α_0	6.29E-34	2.91E-33	3.14E-32	1.08E-32	1.07E-30
α_Q	1.98E-6	1.58E-5	3.25E-5	4.46E-5	8.68E-5
$\alpha_K = 1 - \alpha_L$	4.72E-46	1.02E-45	1.36E-45	1.66E-45	2.41E-45
α_E	8.55E-10	2.54E-9	9.23E-9	9.64E-9	9.57E-8
α_S	1.36E-4	0.020	0.174	0.234	0.956
$\gamma_{KK} = -\gamma_{LK}$ $= \gamma_{LL} = -\gamma_{LK}$	0.026	0.104	0.237	0.300	0.712
γ_{QQ}	0.020	0.065	0.104	0.142	0.248
γ_{EE}	7.03E-4	4.72E-3	0.031	0.023	0.326
$\gamma_{KQ} = -\gamma_{LQ}$	1.18E-3	8.75E-3	0.021	0.025	0.137
$\gamma_{KE} = -\gamma_{LE}$	9.33E-9	1.61E-8	2.89E-8	3.21E-8	1.55E-7
γ_{QE}	5.47E-5	2.38E-4	5.68E-4	7.31E-4	1.90E-3
β_0	8.94E-6	3.80E-5	7.66E-4	4.32E-4	0.013
β_1	0.365	0.626	0.741	0.907	0.994
β_2	5.35E-5	4.29E-4	1.11E-3	1.56E-3	5.05E-3
β_3	0.146	0.221	0.318	0.365	0.735
β_4	4.20E-4	4.05E-3	0.011	0.015	0.041
τ_{MFM}	0.150	0.530	0.617	0.727	0.933
τ_{CAP}	0.172	0.260	0.324	0.357	0.591
ϱ_{LAU}	7.60E-3	0.020	0.028	0.033	0.062
ϱ_{LKZ}	9.64E-3	0.022	0.076	0.112	0.330
ϱ_{KAU}	9.17E-3	0.032	0.049	0.049	0.144
ϱ_{KKZ}	0.012	0.025	0.041	0.046	0.134
τ_{INV}	1.84E-16	3.03E-16	3.66E-16	4.11E-16	6.38E-16
ϱ_{SAU}	3.37E-3	9.07E-3	0.016	0.020	0.040
ϱ_{SKZ}	0.136	0.341	0.513	0.666	0.999
Observations	50×44				

TABLE C.7: Estimation results for model without dynamic optimality condition: p-value.

Parameter	*Std. Error*				
	Min	25%-quantile	Mean	75%-quantile	Max
α_0	0.093	0.101	0.105	0.108	0.138
α_Q	2.54E-9	2.66E-9	2.82E-9	3.00E-9	3.30E-9
$\alpha_K = 1 - \alpha_L$	1.06E-4	1.10E-4	1.11E-4	1.13E-4	1.15E-4
α_E	0.184	0.200	0.211	0.218	0.261
α_S	0.060	0.085	0.116	0.132	0.259
$\gamma_{KK} = -\gamma_{LK}$ $= \gamma_{LL} = -\gamma_{LK}$	2.83E-4	3.11E-4	3.49E-4	3.83E-4	4.44E-4
γ_{QQ}	6.72E-9	7.09E-9	7.58E-9	8.07E-9	8.94E-9
γ_{EE}	0.468	0.534	0.606	0.687	0.840
$\gamma_{KQ} = -\gamma_{LQ}$	3.04E-9	3.20E-9	3.47E-9	3.72E-9	4.30E-9
$\gamma_{KE} = -\gamma_{LE}$	2.43E-4	2.54E-4	2.59E-4	2.64E-4	2.72E-4
γ_{QE}	3.90E-9	4.18E-9	4.53E-9	4.89E-9	5.59E-9
β_0	3.533	3.687	3.910	4.129	4.536
β_1	0.183	0.192	0.209	0.225	0.258
β_2	0.024	0.026	0.028	0.030	0.034
β_3	7.56E-4	7.93E-4	8.45E-4	8.99E-4	1.02E-3
β_4	5.30E-5	5.63E-5	6.13E-5	6.60E-5	7.53E-5
τ_{MFM}	23.666	24.987	26.319	27.623	30.055
τ_{CAP}	84.385	87.785	91.125	94.147	101.531
ϱ_{LAU}	5.753	5.935	6.012	6.051	6.356
ϱ_{LKZ}	4.739	4.957	5.183	5.387	5.898
ϱ_{KAU}	10.394	11.055	11.694	12.230	13.659
ϱ_{KKZ}	3.481	3.639	3.809	3.948	4.356
τ_{INV}	0.410	0.415	0.419	0.422	0.431
ϱ_{SAU}	6.883	7.054	7.268	7.457	8.009
ϱ_{SKZ}	5.828	6.146	6.446	6.724	7.362
Observations	50×44				

Table C.8: Estimation results for model without dynamic optimality condition: Std. Error.

Robustness Checks

Estimation without higher order transformations of exogenous variables as instrumental variables

As discussed in the econometric subsection, our system of equations will be nonlinear in endogenous variables due to transformations of the endogenous variables (e.g., interactions with other variables and squaring). To address potential endogeneity issues, we follow Wooldridge (2002) (Chapter 9.5) and use a set of squared and higher-order transformations of exogenous variables. To test our choice of variables, we estimate Model 1 and Model 2 with a reduced set of instrumental variables. Instead of using $\ln Q^3$, $\ln Q^4$, $\ln S^3$, $\ln S^4$, $\ln P^3$, $\ln P^4$, T, T^2, as well as the exogenous variables already used in our estimation equations, we use the exogenous variables already used in our estimation equations, as well as T, T^2. The estimation results are given in Tables C.9, C.10 and C.11.

Parameter	*Estimate*		*p-value*		*Std. Error*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
α_0	20.620	0.045	9.78E-31***	3.10E-30	0.126	0.010
α_Q	2.58E-8	1.47E-9	2.47E-3***	7.55E-4	7.34E-9	1.71E-10
$\alpha_K = 1 - \alpha_L$	0.102	3.10E-6	1.26E-44***	6.00E-45	1.25E-4	3.14E-6
α_E	2.473	0.170	3.05E-7***	1.04E-6	0.291	0.031
α_S	-0.134	0.264	0.293	0.312	0.154	0.057
$\gamma_{KK} = -\gamma_{LK}$ $= \gamma_{LL} = -\gamma_{LK}$	-2.41E-4	2.13E-4	0.588	0.245	4.26E-4	4.27E-5
γ_{QQ}	4.82E-8	2.44E-9	6.12E-3***	2.30E-3	1.55E-8	3.42E-10
γ_{EE}	2.667	0.688	0.043**	0.041	1.110	0.148
$\gamma_{KQ} = -\gamma_{LQ}$	-3.64E-8	1.40E-9	2.82E-4***	7.38E-5	8.17E-9	2.05E-10
$\gamma_{KE} = -\gamma_{LE}$	2.83E-3	9.84E-5	2.07E-7***	1.39E-7	3.55E-4	9.94E-6
γ_{QE}	-1.56E-8	1.12E-9	0.104^{+}	0.026	9.05E-9	3.02E-10
β_0	-5.547	1.514	0.545	0.107	8.955	0.207
β_1	0.927	0.097	0.122^{+}	0.028	0.567	0.020
β_2	0.131	0.019	0.017**	9.94E-3	0.047	1.61E-3
β_3	7.44E-3	3.74E-4	1.21E-3***	3.19E-4	1.95E-3	5.06E-5
β_4	1.00E-4	4.12E-5	0.352	0.181	1.02E-4	3.02E-6
τ_{MFM}	-44.119	13.153	0.570	0.118	75.759	3.626
τ_{CAP}	281.212	53.205	0.269	0.083	241.570	10.473
ϱ_{LAU}	19.536	1.396	0.135^{+}	0.026	12.442	0.525
ϱ_{LKZ}	-31.898	3.518	0.044**	0.015	14.613	0.556
ϱ_{KAU}	106.437	8.349	0.038**	8.41E-3	47.374	1.901
ϱ_{KKZ}	-0.874	2.442	0.874	0.101	11.755	0.491
τ_{INV}	10.264	0.205	1.77E-10***	1.72E-10	0.822	0.039
ϱ_{SAU}	13.419	5.194	0.458	0.113	17.881	0.790
ϱ_{SKZ}	0.025	2.372	0.921	0.072	17.088	0.592
Observations	50×44					
Adjusted R^2	Eq. (4.18): mean 0.47 std. dev. 0.08, Eq. (4.21): mean 0.43 std. dev. 0.07, Eq. (4.26): mean 0.57 std. dev. 0.04, Eq. (4.28): mean 0.47 std. dev. 0.08					

*** $p < 0.01$,** $p < 0.05$,* $p < 0.1$,$^{+}$ $p < 0.15$

Table C.9: Simplified instruments: Estimation results for model without dynamic optimality condition.

Interest rate	χ^2 *test statistic*		*p-value*	
	Mean	Std. Dev.	Mean	Std. Dev.
0.01	1684.117	5006.961	0.018**	0.094
0.02	2438.72	10266.476	0.022**	0.128
0.03	2723.209	10845.397	0.054*	0.222
0.04	1553.409	4537.783	0.03**	0.167
0.05	721.678	2178.448	0.076*	0.253
0.06	1544.614	6129.165	0.041**	0.181
0.07	529.064	1133.182	0.057*	0.232
0.08	685.74	1673.32	0.057*	0.231
0.09	545.404	869.724	0.057*	0.23
0.1	571.335	893.317	0.026**	0.149
0.11	443.77	694.349	0.022**	0.12
0.12	429.996	623.075	0.035**	0.139
0.13	462.302	601.057	0.009***	0.047
0.14	386.714	481.56	0.041**	0.174
0.15	399.879	537.441	0.037**	0.161
0.16	444.773	802.049	0.033**	0.169
0.17	1208.095	4948.531	0.03**	0.169
0.18	519.925	1117.688	0***	0
0.19	431.879	617.551	0***	0
0.2	569.918	1132.179	0***	0
0.21	503.458	979.483	0***	0
0.22	816.422	2648.744	0***	0
0.23	689.117	1424.815	0***	0
0.24	1376.555	5656.499	0.008***	0.045
0.25	356.417	508.363	0.033**	0.138

*** $p < 0.01$,** $p < 0.05$,* $p < 0.1$,$^{+}$ $p < 0.15$

The critical value (CV) for p=0.01 is at 37.566

Table C.10: Simplified instruments: Hausman test results for constant interest rates.

Interest rate	χ^2 *test statistic*		*p-value*	
	Mean	Std. Dev.	Mean	Std. Dev.
$r \cdot 0.25$	2806.53	9795.993	0.017^{**}	0.101
$r \cdot 0.5$	4210.452	123.101	0.032^{**}	0.147
$r \cdot 0.75$	1783.073	105.781	0.037^{**}	0.169
$r \cdot 1$	854.059	100.271	0.049^{**}	0.186
$r \cdot 1.25$	1135.411	96.706	0.04^{**}	0.178
$r \cdot 1.5$	537.023	98.237	0.029^{**}	0.167
$r \cdot 1.75$	524.807	99.078	0.028^{**}	0.166
$r \cdot 2$	502.346	104.862	0.027^{**}	0.156
$r \cdot 2.25$	479.99	96.347	0.021^{**}	0.125
$r \cdot 2.5$	425.095	96.835	0.042^{**}	0.175
$r \cdot 2.75$	399.722	98.238	0.013^{**}	0.053
$r \cdot 3$	373.576	104.687	0.033^{**}	0.169
$r \cdot 3.25$	420.606	108.966	0.038^{**}	0.173
$r \cdot 3.5$	868.896	105.875	0.002^{***}	0.01
$r \cdot 3.75$	507.577	131.428	0^{***}	0
$r \cdot 4$	443.043	109.229	0^{***}	0

$^{***}\ p < 0.01,^{**}\ p < 0.05,^{*}\ p < 0.1,^{+}\ p < 0.15$

The critical value (CV) for p=0.01 is at 37.566

Table C.11: Simplified instruments: Hausman test results for proportional variations of the actual Canadian interest rate r.

As can be clearly seen from Tables C.10 and C.11 the results of the Hausman tests are robust. However, while we find that most coefficient estimates are robust, we find implausible results for ϱ_{LKZ}. A statistically significant negative estimate would mean that with increasing labor costs, as a supply shifter, would lead to lower prices. This however is economically implausible and hence, illustrates biased estimates and the importance of using higher order instruments.[52]

Estimation with dummy variables controlling for potential shocks

The observation period used within our estimation, includes two time periods that might have potential impact on the global uranium market. First, the global financial crisis of 2008 might have led to a demand reducing shocks. Second, the Fukushima nuclear disaster and the subsequent shut down of several nuclear power plants could have had an impact on market price setting. To test whether such effects are observable in the

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[52] We find that out of the 2050 estimates of Model 2 (50 subsamples times 41 different interest rates) 631 face near singular matrices during estimation, exceeding the number of near singular matrices in our main model by far.

data, we replace the inverse residual demand function, as given in Equation (4.25), with the following equation:

$$P = \beta \ln Q + \sum_{k} \varrho_k \ln V_k + \sum_{l} \tau_l \ln Y_l + \sum_{i=1}^{3} \delta_i D_i. \tag{4.25$'$}$$

Equation (4.25′) includes three time dummy variables to capture the above mentioned potential shocks. The definition of the dummy variables is based on the findings of spikes in Figure 4.1. D_1 equals one for the third quarter of 2008 and zero for any other time step. D_2 equals one for the first quarter of 2012 and zero for any other time step. D_3 equals one for the second quarter of 2012 and zero for any other time step. The estimation results are given in Tables C.12, C.13 and C.14.

Parameter	*Estimate*		*p-value*		*Std. Error*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
α_0	20.710	0.034	6.11E-28***	2.26E-27	0.107	7.60E-3
α_Q	9.96E-9	2.11E-9	0.032**	0.104	3.65E-9	1.74E-10
$\alpha_K = 1 - \alpha_L$	0.102	1.30E-5	4.71E-39***	1.46E-39	1.14E-4	2.22E-6
α_E	2.141	0.102	7.02E-8***	7.51E-8	0.224	0.017
α_S	-0.188	0.144	0.238	0.256	0.119	0.041
$\gamma_{KK} = -\gamma_{LK}$ $= \gamma_{LL} = -\gamma_{LK}$	-5.10E-4	2.00E-4	0.212	0.149	3.51E-4	4.28E-5
γ_{QQ}	4.72E-9	2.74E-9	0.643	0.137	1.03E-8	6.48E-10
γ_{EE}	1.683	0.299	0.031**	0.051	0.616	0.089
$\gamma_{KQ} = -\gamma_{LQ}$	-1.01E-8	8.82E-10	0.026**	9.66E-3	4.07E-9	2.95E-10
$\gamma_{KE} = -\gamma_{LE}$	2.36E-3	7.63E-5	2.53E-7***	1.41E-7	2.75E-4	7.96E-6
γ_{QE}	-9.62E-9	1.94E-9	0.178	0.099	6.59E-9	4.73E-10
β_0	-25.179	2.065	2.78E-4***	3.57E-4	5.116	0.262
β_1	-0.256	0.146	0.336	0.222	0.224	0.016
β_2	0.128	0.024	9.95E-3***	0.038	0.038	2.79E-3
β_3	-7.12E-5	4.44E-4	0.784	0.171	8.99E-4	5.35E-5
β_4	-2.26E-4	5.15E-5	0.036**	0.108	8.66E-5	6.41E-6
τ_{MFM}	-32.149	20.166	0.455	0.146	38.613	2.475
τ_{CAP}	114.394	42.163	0.448	0.140	140.722	4.889
ϱ_{LAU}	15.328	1.576	0.040**	0.013	6.753	0.279
ϱ_{LKZ}	10.536	2.609	0.146^{+}	0.120	6.451	0.460
ϱ_{KAU}	24.879	5.490	0.249	0.146	20.145	0.838
ϱ_{KKZ}	13.239	1.112	0.017**	6.36E-3	4.944	0.371
τ_{INV}	10.490	0.152	1.44E-11***	9.75E-11	0.486	0.040
ϱ_{SAU}	18.266	2.181	0.054*	0.023	8.580	0.598
ϱ_{SKZ}	-0.295	2.846	0.853	0.153	8.592	0.448
δ_1	-7.866	4.733	0.454	0.133	10.942	1.023
δ_2	7.383	5.645	0.613	0.102	17.296	1.149
δ_3	-25.681	7.019	0.222	0.118	19.515	1.615
Observations	50×44					
Adjusted R^2	Eq. (4.18): mean 0.54 std. dev. 0.05, Eq. (4.21): mean 0.62 std. dev. 0.1, Eq. (4.26): mean 0.27 std. dev. 0.22, Eq. (4.28): mean 0.54 std. dev. 0.05					

$^{***}\ p < 0.01, ^{**}\ p < 0.05, ^{*}\ p < 0.1, ^{+}\ p < 0.15$

TABLE C.12: Shock dummy variables: Estimation results for model without dynamic optimality condition.

Interest rate	χ^2 *test statistic*		*p-value*	
	Mean	Std. Dev.	Mean	Std. Dev.
0.01	737.217	1149.548	0.103^{+}	0.28
0.02	674.936	1181.231	0.067^{*}	0.234
0.03	810.951	1295.165	0.104^{+}	0.302
0.04	765.694	1271.562	0.104^{+}	0.239
0.05	951.724	2030.274	0.084^{*}	0.261
0.06	950.824	1549.972	0.067^{*}	0.241
0.07	1105.71	2070.77	0.094^{*}	0.282
0.08	813.206	1301.175	0.061^{*}	0.211
0.09	868.01	1303.886	0.044^{**}	0.187
0.1	940.62	1464.42	0.078^{*}	0.251
0.11	832.355	1211.427	0.06^{*}	0.223
0.12	937.656	1677.771	0.047^{**}	0.191
0.13	993.898	1716.678	0.064^{*}	0.241
0.14	782.812	1308.535	0.049^{**}	0.191
0.15	804.457	1407.83	0.05^{*}	0.189
0.16	5234.076	27117.246	0.083^{*}	0.271
0.17	763.876	1175.537	0.064^{*}	0.223
0.18	937.014	1621.986	0.05^{*}	0.211
0.19	704.424	1186.1	0.05^{*}	0.21
0.2	681.163	1157.198	0.077^{*}	0.258
0.21	776.816	1303.854	0.064^{*}	0.221
0.22	727.61	1183.675	0.074^{*}	0.249
0.23	671.346	1104.346	0.046^{**}	0.188
0.24	638.071	1084.896	0.051^{*}	0.186
0.25	755.862	1307.389	0.045^{**}	0.175

$^{***}\ p < 0.01,^{**}\ p < 0.05,^{*}\ p < 0.1,^{+}\ p < 0.15$

The critical value (CV) for p=0.01 is at 37.566

TABLE C.13: Shock dummy variables: Hausman test results for constant interest rates.

Interest rate	χ^2 *test statistic*		*p-value*	
	Mean	Std. Dev.	Mean	Std. Dev.
$r \cdot 0.25$	710.523	1143.932	0.072^{*}	0.216
$r \cdot 0.5$	655.868	56.58	0.065^{*}	0.205
$r \cdot 0.75$	1325.145	50.632	0.102^{+}	0.25
$r \cdot 1$	1217.06	64.829	0.047^{**}	0.19
$r \cdot 1.25$	924.326	135.989	0.067^{*}	0.242
$r \cdot 1.5$	863.447	102.821	0.064^{*}	0.235
$r \cdot 1.75$	864.167	100.167	0.049^{**}	0.196
$r \cdot 2$	1225.145	133.792	0.052^{*}	0.192
$r \cdot 2.25$	844.23	132.805	0.068^{*}	0.244
$r \cdot 2.5$	983.449	111.341	0.067^{*}	0.248
$r \cdot 2.75$	871.569	120.222	0.072^{*}	0.243
$r \cdot 3$	796.647	110.794	0.037^{**}	0.166
$r \cdot 3.25$	1068.129	127.346	0.081^{*}	0.264
$r \cdot 3.5$	804.02	127.107	0.103^{+}	0.266
$r \cdot 3.75$	777.663	120.227	0.05^{*}	0.211
$r \cdot 4$	703.321	123.534	0.051^{*}	0.21

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, $^{+}$ $p < 0.15$

The critical value (CV) for p=0.01 is at 37.566

Table C.14: Shock dummy variables: Hausman test results for proportional variations of the actual Canadian interest rate r.

Again, Tables C.13 and C.14 illustrate the results of the Hausman tests to be robust even under the alternative specification of the inverse residual demand curve. Further, we find all coefficient estimates to be robust. Noticeably, no dummy variable coefficient is statistically significant. Therefore, showing that shock effects on the world market should not be the factors explaining the negative Lerner index at these points in time.[53]

Data Appendix

Summary Statistics

Quantity of uranium extracted, E

Extraction volumes are taken from Cameco (2012b). Missing statements for the fourth quarter of the years 2008-2012 are calculated using first to third quarter values from

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[53] Out of the 2050 estimates of Model 2 (50 subsamples times 41 different interest rates) 723 models had near singularity issues during estimation, exceeding the number of near singular matrices in our main model by far.

Series	*Mean*	*Maximum*	*Minimum*	*Std. Dev.*	*Observations*
B	1.274332	4.070614	0.264269	1.029772	44
$\ln CR$	20.84144	22.94147	19.08893	1.150019	44
$\ln E$	0.022724	1.175044	-1.206911	0.460854	44
$\ln P$	3.333787	4.049799	2.470928	0.520859	44
$\ln Q$	-0.054477	0.807969	-1.11201	0.278829	44
$\ln S$	-0.042334	1.299977	-5.909206	0.665293	50×44
$\ln W_K$	0.00044	0.662086	-0.359989	0.223815	44
$\ln W_L$	0.00641	0.294694	-0.570092	0.203949	44
M_K	0.102294	0.103997	0.099066	0.001333	44
P	31.75191	57.38593	11.83343	14.49644	44
$\bar{r}$	0.033211	0.048234	0.012374	0.009906	44
T	0	21.5	-21.5	12.58251	44
$\ln V_{KAU}$	-0.041982	0.134903	-0.29417	0.13467	44
$\ln V_{KKZ}$	0.137492	0.61845	-0.446492	0.315771	44
$\ln V_{LAU}$	0.061223	0.502522	-0.432324	0.258745	44
$\ln V_{LKZ}$	-0.085882	0.288374	-0.742886	0.301522	44
$\ln V_{SAU}$	-0.044462	0.217286	-0.318706	0.222694	44
$\ln V_{SKZ}$	-0.049702	0.18477	-0.298063	0.124974	44
$\ln Y_{CAP}$	-0.003819	0.012031	-0.031199	0.00964	44
$\ln Y_{INV}$	2.98131	3.926857	2.093219	0.502895	44
$\ln Y_{MFM}$	0.001745	0.054552	-0.029454	0.027657	44

Table C.15: Summary Statistics

Cameco (2012b) and annual values from Cameco (2012a).

Quantity of final output, Q

Sales volumes are taken from Cameco (2012b). Missing statements for the fourth quarter of the years 2008-2012 are calculated using first to third quarter values from Cameco (2012b) and annual values from Cameco (2012a).

Exploration expenditures, B

Exploration expenditures are given in Cameco (2012b). Quarterly expenditures are directly stated for the 4th quarter of the following years: 2008, 2009, 2010, 2011, 2012. Using information on annual exploration expenditures (Cameco, 2012a), quarterly values are calculated. In Cameco (2012b) and Cameco (2012a), monetary values are expressed in Canadian dollar. Real (2012) values are calculated using the U.S. Consumer price index (CPI) (U.S. Department of Labor, 2013) (converted to quarterly values by weighting by the number of days per month) and Canadian to U.S. dollar exchange rates. Exchange rates are expressed in Cameco (2012b). Missing data for the 4th quarter 2002 are substituted with data from Bank of Canada (2014a).

Additional exploration expenditure information for Canada used for estimating the exploration function, f, is taken from Nuclear Energy Agency (2006). Nominal values are converted to real (2012) values using Canadian Consumer Price Indices (OECD, 2013).

State of the technology, T

The state of the technology is expressed as a mean-adjusted linear trend.

Market price of final output, P

Data for the first three quarters of each year are taken from Cameco (2012b) using information on average realized prices. The market price for the final quarter of each year is calculated from annual data (Cameco, 2012b) weighted by sales volumes. Nominal values given in Canadian dollar are converted to real (2012) U.S. dollar using Canadian to U.S. dollar exchange rates (Bank of Canada, 2014a, Cameco, 2012b) and Canadian Consumer Price Indices (OECD, 2013).

Market price of reproducible input labor, W_L

The market price of reproducible input labor in Canada is based on two data sources. Average weekly wage rates for Saskatchewan for forestry, fishing, mining, quarrying, oil and gas (North American Industry Classification System) (Statistics Canada, 2013a) are converted using Canadian to U.S. dollar exchange rates (Bank of Canada, 2014a, Cameco, 2012b) and U.S. Consumer Price Indices (OECD, 2013). Supplementary benefits are received by calculating the share of supplementary benefits in monthly wages from Statistics Canada (2012) and scaling the converted average weekly wage rates accordingly.

Quantity of labor, X_L

Annual data for direct employment in uranium mining operations in Canada is taken from Nuclear Energy Agency (2011). Data for Cameco are obtained by scaling total numbers using ownership shares for mining operations and assuming an equal distribution of changes among seasons.

Market price of reproducible input capital, W_K

Following Ellis and Halvorsen (2002), we calculate the price of capital as the product of the producer price index (PPI, for the mining industry if available), the sum of the depreciation rate (assumed to be at 10%) and the real rate of interest. We derive market prices for capital for Canada using the Machinery and Equipment Price Index (MEPI) for mines, quarries and oil wells (Statistics Canada, 2013b) as well as real interest rates calculated from data for selected Canadian 10-year bond yields (Bank of Canada, 2014b) and Canadian consumer price indices (OECD, 2013).

Quantity of capital, X_K

Quantity of capital is derived via the perpetual inventory method. Year-end net value of property for the year 1996 as well as quarterly capital expenditures are taken from Cameco (2012a) and Cameco (2012b). Depreciation rates are assumed to be 10% and the producer price index is the Machinery and Equipment Price Index (MEPI) for mines, quarries and oil wells (Statistics Canada, 2013b). Exchange rates are from ABS (2014a) and X-RATES (2014).

Proven reserves, S

There are numerous classification schemes for uranium reserves and resources. We utilize definitions used by Nuclear Energy Agency (2011) and Cameco (2012a) and focus on proven reserves. Cameco (2012a) covers annual data for uranium reserves and resources. Quarterly values are imputed as described in the data section.

Recycling of military warheads, Y_{MFM}

Annual data for the “Megatons to Megawatts” quantities are given by Centrus (2014). We assume an equal distribution of quantities among quarters.

Global thermal capacity of nuclear power plants, Y_{CAP}

Global thermal capacity of nuclear power plants are calculated from plant characteristics, and commissioning and decommissioning dates taken from International Atomic Energy Agency (2013).

Global inventories, Y_{INV}

Inventory data is, generally speaking, not publicly available. Nuclear Energy Agency (2011) includes graphical information on global uranium production and demand from 1945 (i.e., approximately ten years prior to the commissioning of the first nuclear reactor) up to 2011. The difference between total production and demand approximates global uranium inventories. Quarterly values are obtained from annual data from Nuclear Energy Agency (2011) using cubic splines.

Australian market prices for capital, V_{KAU}

Australian capital prices are obtained using PPI for the (coal) mining industry from ABS (2014d). Real (2012) rate of interest results from data for Commonwealth Government 10-year bonds (Reserve Bank of Australia, 2014) and inflation rates are calculated using ABS (2014c).

Kazakh market prices for capital, V_{KKZ}

Capital prices for Kazakhstan are based on the general PPI data from UNECE (2014). Using the Kazakh corporate bonds index KASE_BY (KASE, 2014b) and CPI data from UNECE (2014), real (2012) interest rates are calculated.

Australian market prices for labor, V_{LAU}

Data for Australian mining operations is taken from ABS (2014b). In order to convert the data to real (2012) U.S. dollar values, exchange rates from ABS (2014a) are used for January 2002 to March 2012. April 2012 to December 2012 are covered by X-RATES (2014). Both time series are weighted for quarterly values and adjusted using ABS (2014c).

Kazakh market prices for labor, V_{LKZ}

Kazakh mining industry monthly wage data for the years 2008 to 2012 is obtained from the Agency of Kazakhstan of Statistics (2014a). As sector-specific data is unavailable for years prior to 2008, we approximate mining wage data using changes in average wage statistics (Agency of Kazakhstan of Statistics, 2014c). Correlation between both series is shown via OLS estimation for overlapping observations (values in brackets represent t-values):

$$\text{avg. wage mining industry} = \underset{(-1.951)}{-1.128 \times 10^4} + \underset{(27.924)}{1.993}\ \text{avg. wage.}$$

Assuming strong correlation between GDP and wage growth (Warner et al., 2006, e.g.) and further decreasing unemployment with growth in GDP, we approximate mining sector wage data for Kazakhstan using Kazakh labor statistics for changes in unemployment (Agency of Kazakhstan of Statistics, 2014b). Again, correlation between both series is shown via OLS estimation for overlapping observations (values in brackets represent t-values):

$$\text{avg. wage mining industry} = \underset{(32.64)}{4.901 \times 10^5} \underset{(-25.91)}{-671.36}\ \text{unemployed population in thousands.}$$

Real (2012) values are obtained by conversion using KASE (2014a) and UNECE (2014).

Australian proven reserves, V_{SAU}

Australian annual data is taken from Australia (2013). Quarterly values are assumed to be identical to annual values.

Kazakh proven reserves, V_{SKZ}

Rempel et al. (2013) include annual data on Kazakh uranium reserves. Quarterly values are assumed to be identical to annual values.

Canadian interest rate, $\tilde{r}$

See *Market price of reproducible input capital.*

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Refereed Journal Publications

Knaut, A., Tode, C., Lindenberger, D., Malischek, R., Paulus, S., Wagner, J., 2016. The Reference Forecast of the German Energy Transition – An Outlook on Electricity Markets. Energy Policy, Vol. 92, pp. 477-491, *in press.*

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