

THREE ESSAYS ON SUBSTITUTION
IN CLEAN ENERGY
APPLICATIONS

by
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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Mineral and Energy Economics).

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ABSTRACT

This dissertation presents three essays that deal with the measurement of substitutability in different contexts pertaining to clean energy. The first two essays deal with material substitution in permanent magnets used in wind turbines that rely on rare earth elements for the provision of certain essential properties. These two chapters use two somewhat nontraditional approaches to measuring price responsiveness, since quality data on uses of rare earth elements is scarce. These are followed by an essay on substitution between programs offered by electric utilities to satisfy preferences for clean energy production. This third essay uses more traditional econometric techniques.

The first essay evaluates the role increased and uncertain material costs play in inducing different material substitution types in the short to medium term. Specifically, it uses an expert survey to evaluate the extent to which magnet and wind turbine manufacturers substituted materials in response to the rapid and significant rare earth element price increases that occurred in 2010 and 2011. The second essay assesses the potential ability of producers to respond to future sustained cost increases of material inputs—specifically the ability of rare earth magnet manufacturers to respond to future heavy rare earth price increases. Since sufficient disaggregated data is not available for the use of more traditional methods, this question is answered by estimating long-run demand curves and price elasticities using data gathered from an expert elicitation survey. The third essay evaluates the substitutability between two types of clean energy programs offered by electric utilities. It analyzes whether participation in green pricing programs acts as a substitute for net metering programs.

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CHAPTER 1

INTRODUCTION

Substitution is among the most fundamental concepts in economics. Even basic ideas such as the laws of supply and demand would be incomplete without some notion of how changes in the price of a good affect its use relative to other available goods. That is to say, the ability to substitute between goods, whether for direct consumption or for use as inputs to a production process, directly determines the shapes of supply and demand. At its most basic level of understanding, a substitute good is one which can be used in place of another. However, the concept applies broadly to many situations. Some of these are obvious, such as the ability to produce a final good using different amounts of material inputs, but others are less so, such as the ability produce a good using alternate production techniques. Given the foundational nature of the concept, the study and measurement of substitutability makes up a large literature, both within and outside of economics. Measurements are important for understanding consumer and producer responses to various taxes and policies, as well as for estimating impacts associated with exogenous shocks to specific markets and entire economies. They are also used in assessments of material criticality, system resilience, and climate change modeling.

This dissertation deals with the measurement of substitutability in different contexts pertaining to clean energy. The first two essays deal with material substitution in permanent magnets used in wind turbines that rely on rare earth elements for the provision of certain essential properties. These two chapters use two somewhat nontraditional approaches to measuring price responsiveness, since quality data on uses of rare earth elements (as with many highly disaggregated industries) is scarce. These are followed by an essay on substitution between programs offered by electric utilities to satisfy preferences for clean energy production. This third essay uses more traditional econometric techniques. The following paragraphs summarize these essays in more detail.

Chapter 2 elucidates the role increased and uncertain material costs play in inducing different material substitution types in the short to medium term. Environmental technologies, such as wind turbines and solar panels, depend on raw materials, some of which are subject to volatile costs and availability concerns. One way to address these concerns is through different types of substitution. An important form of substitution in the short term is adopting a more expensive yet more efficient production process, yielding a material with the same functional properties with less material input. In effect, technology substitutes for material. This essay evaluates the extent to which magnet and wind turbine manufacturers substituted materials in response to the rapid and significant rare earth element price increases that occurred in 2010 and 2011.

The analysis uses an expert survey to determine the relative importance of eight specific industry responses between 2011 and 2016. Statistical tests show adopting an existing production process for magnets was the most important response, followed by cost passthrough, using an alternate magnet grade in a redesigned generator system, and using alternate systems altogether.

Chapter 3 assesses the potential ability of producers to respond to future sustained cost increases of material inputs—specifically the ability of rare earth magnet manufacturers to respond to future heavy rare earth price increases. Since sufficient disaggregated data is not available for the use of more traditional methods, this question is answered by estimating long-run demand curves and price elasticities using data gathered from an expert elicitation survey. This appears to be the first study to use such techniques to calculate price elasticities of demand, providing a potential method for quantifying forward-looking price responsiveness for highly disaggregated industries with poor data availability. Results indicate that significant increases in material costs would induce reductions in heavy rare earths in permanent magnets over the following five years, though the response is inelastic. Manufacturers would be most responsive to a doubling of material costs, but demand is almost perfectly inelastic for more substantial increases.

Moving away from materials, Chapter 4 discusses a completely different aspect of substitution. It evaluates the substitutability between two types of clean energy programs offered by electric utilities. The electricity sector has undergone drastic changes in the last decade. One of the main causes of this change is the reduced price, and increased installation, of renewable energy. Utilities and policymakers use two different programs to encourage residential investment in renewables: net metering and green pricing programs. This essay analyzes whether participation in green pricing programs acts as a substitute for net metering programs using a proportional hazards model framework as well as a reduced-form fixed effects model. Results indicate that the presence of a popular green pricing program, defined as a high share of customers enrolled, leads to a delay in the start of a net metering program. Similarly, there is also less customer sign up for net metering programs if there are many customers in the green power program in states with no state-wide mandatory green pricing option.

These three essays provide a survey of some of the different ways substitution can be viewed as well as assessed quantitatively. Perhaps the largest contribution of this work is in its treatment of disaggregated industries with virtually no data. Decision makers, modelers, and analysts alike often require detailed knowledge of disaggregated economic processes to inform their assumptions, yet economists often neglect such questions due to their difficulty and lack of data. Further analysis in such situations could provide a potential avenue for future research.

CHAPTER 2

MATERIAL SUBSTITUTION THROUGH TECHNOLOGY ADOPTION: EVIDENCE FROM RARE EARTH MAGNETS IN WIND TURBINES

A paper revised and published in *Environmental Science & Technology*.¹

Braeton J. Smith² and Roderick G. Eggert³

Abstract: Environmental technologies depend on raw materials, some of which are subject to volatile costs and availability concerns. One way to address these concerns is through substitution, of which there are many types. An important form of substitution in the short term is adopting a more-efficient production process, yielding a material with the same functional properties with less material input. In effect, technology substitutes for material. This study elucidates the role increased and uncertain material costs play in inducing different material substitution types in the short to medium term. Specifically, this paper determines the extent magnet and wind turbine manufacturers substituted materials in response to the 2010/2011 rare-earth price spike. It uses an expert survey to determine the relative importance of eight specific industry responses between 2011 and 2016. Statistical tests show adopting an existing production process for magnets was the most important response, followed by cost passthrough, using an alternate magnet grade in a redesigned generator system, and using alternate systems altogether. The paper also provides specific findings for the magnet and wind turbine industries with respect to each substitution type.

2.1 Introduction

Modern technologies depend on raw materials. Less obvious is that some raw-material supply chains are risky, and some raw materials prices are especially volatile – discouraging development and adoption of otherwise promising technologies. Risky supply chains and volatile material costs are among the challenges to the widespread proliferation of clean energy technologies [1, 2]. The ability to reduce the amount of certain raw materials in environmental technologies through substitution would alleviate these concerns and increase the likelihood of successfully meeting climate change and pollution goals.

The substitutability of material inputs is an important consideration for all cost-minimizing firms, particularly when faced with supply constraints and unpredictable price fluctuations. The ability to substitute

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directly affects one’s dependence on material markets and supply disruptions, and thus, the ability to compete in a crowded marketplace. Accordingly, understanding substitutability is paramount to addressing material criticality and energy system resilience concerns [3, 4] as well as performing climate change policy and scenario analysis [5, 6, 7, 8]. Unfortunately, material substitution is often poorly understood and difficult to quantify, largely due to a lack of quality data at the detailed level. This paper explains how permanent magnet and wind turbine manufacturers substituted materials in response to the significant and rapid rare earth element price increases in 2010-2011.

There is some debate about what induces material substitution as well as what is technically feasible. Graedel et al.[9] and Nassar [10], for example, find that direct elemental substitution does not exist for most elements in their major applications. By contrast, both Tilton [11, 12] and Schlabach [13] identify several more general substitution types from economic and technological perspectives, respectively, that can arise from many potential influences. Economists are especially interested in the role of material costs, which have generally been shown to induce substitution in the long run for highly-aggregated materials and end-uses [12, 14]. While the same result has held for some disaggregated studies with shorter time periods and specific materials in specific end-uses [15, 16, 17, 18], it has not been consistent [19, 20, 21, 22]. This leads Tilton [23] to assert an “alternative” view of substitution which occurs indirectly through technological innovations, which may or may not have been induced by high or volatile material costs. High input costs and environmental policy are among the key drivers of technological advances in environmental technologies [24, 25, 26].

Most significant innovations happen in the long run, making manufacturers reliant on existing technologies and small engineering refinements in the short run [27]. Much attention has been given to the optimal timing [28, 29] of technology adoption and the factors that induce it [30], yet the influence of material costs has been largely overlooked. Still, changes in relative material costs have been shown to induce material substitution indirectly through the adoption of alternative existing production technologies [21, 22].

The purpose of this paper is to elucidate the role increased and uncertain material costs play in inducing material substitutions in the short term. Specifically, it examines the different ways permanent magnet and wind turbine manufacturers responded to the 2010/2011 rare-earth price spike through 2016. The price spike, during which prices of certain rare earth elements increased by over 3,000 percent in a matter of months, was a rare extreme event providing an uncommon opportunity to evaluate the responsiveness of material users to severe price swings. Due to substantial data limitations for quantities of specific elements used in specific applications over time, this study uses quantitative and qualitative data from an expert survey (first described by Smith and Eggert [31]) which asked experts to assess the degree to which companies implemented different strategies. It uses Smith and Eggert’s unique substitution “taxonomy” for permanent

magnets in wind turbines and substantially extends and interprets their findings for a different audience.

The contributions of this work lie in the intersection of economics and industrial ecology. First, it provides an ex-post case study (in an application with virtually no data) of the ways manufacturers respond over a relatively short time period to rampantly increasing and uncertain material costs. Second, it refines Tilton’s alternative view of substitution, arguing that high material costs can induce substitution through the adoption of existing technology in the short run. Third, it argues that being explicit about the nature of substitution communicates specific ideas with experts of different disciplines. This study differs from previous case studies in this specific application, which are mostly performed from engineering and industrial ecology perspectives [4, 32, 33, 34], in its historical emphasis on how high material costs induced actual changes in material and technology use. Further, the Supporting Information (SI)⁴ provides specific and novel findings about the ways permanent magnet and wind turbine industries responded to the rare earth price spike.

2.1.1 Rare Earth Elements, Magnets, and Wind Turbines

Rare earth elements (REEs) are essential inputs in many modern technologies, such as smart phones, televisions and monitors, hard drives, lighting, electric vehicles, and many others. They comprise the group of 15 lanthanide metals (with scandium and yttrium sometimes included) and tend to occur in the same deposits as they are chemically similar [35]. REEs are divided into two groups: light rare earth elements (LREEs) have atomic numbers 57 to 64 while heavy rare earth elements (HREEs) have atomic numbers 65 to 71 [35]. While not actually “rare” in the earth’s crust, REEs tend to be rarely found in deposits which are economical to exploit.

Prior to 2012, China accounted for over 95 percent of global REE production [36]. In mid-2010, the announcement of a drastically reduced export quota for REEs caused panic worldwide among end-users, governments, and other stakeholders, leading to rapid and extreme price increases (by over 3,000 percent for some elements) over the following 12 months [31]. The “price spike” lasted through early 2012, when prices of most REEs fell substantially, though many remain well above their pre-2010 levels.

One of the most important uses of REEs is in permanent magnets (PMs) used in wind turbines, electric vehicles, and many other products across many industries. The four major PM types are ferrite, alnico, samarium-cobalt, and neodymium-iron-boron (NdFeB). While NdFeB magnets, which contain the LREEs neodymium (Nd) and praseodymium (Pr), are the most powerful magnets available at room temperature, they demagnetize at high temperatures. Adding HREEs, usually dysprosium (Dy) and occasionally terbium (Tb), improves temperature stability [37]. NdFeB grades with higher temperature resistance almost always have a higher HREE content. As NdFeB has roughly 32 percent total REE content by weight (most of which

⁴The Supporting Information is available from the American Chemical Society at <https://dx.doi.org/10.1021/acs.est.7b05495>.

is Nd), magnets with more HREE contain less Nd [31].

Wind turbines contain an electric generator, traditionally a PM-free doubly-fed induction generator (DFIG) coupled with a gearbox. Despite decades of use, DFIGs often break down, requiring expensive maintenance. Direct drive generators, most of which use PMs, are more efficient and require less maintenance [34]. PM generators (PMGs) are especially useful in offshore turbines, where the maintenance required in a DFIG configuration is prohibitive. PMG turbines require substantial quantities of NdFeB material, often well over one ton per turbine [38]. Despite their small market share, PMG use is expected to grow, especially as the first offshore windfarm in the U.S. began supplying power with PMG turbines in 2016 [39].

2.2 Responding to the Price Spike

There are several responses that firms might undertake when facing increasing or volatile material costs. Broadly, these include either passing through or absorbing costs or pursuing substitution of some type. Schlabach [13] and Tilton [11, 12] define several substitution types from technological and economic perspectives, respectively, ranging from narrow to broad. Although they define them slightly differently with various subcases, there are five general substitution types which reduce material inputs.

The first way to substitute materials is the direct substitution of certain materials for others, which Tilton calls “material-for-material” substitution and includes Schlabach’s “physical” material substitution. Examples include substituting plastic for glass in beverage containers or aluminum for copper in electrical wiring. The second is by adopting an alternative production process which reduces the quantity of one or more materials. Schlabach refers to this simply as “process” substitution, however, Tilton’s “other-factors-for-material” substitution reflects the idea that it requires increases in other inputs, such as labor or energy. The third is by altering the product itself to require less material, either by reengineering its design (Schlabach) or reducing its quality (Tilton). The fourth (and most general) involves meeting the product’s function in a different way, which Schlabach and Tilton call “functional” and “inter-product” substitution, respectively, reflecting the idea that an end-use is met by changing the mix of goods and services used to achieve it. The last way to substitute materials is through an advance in technology (distinct from process and redesign substitutions) which reduces material requirements without increasing other inputs. Tilton calls this “technological” substitution and includes Schlabach’s “quantitative” material substitution.

The subtle terminology differences for similar substitutions suggest that perceived disparities in the ways economists and engineers view substitution are largely semantic. Accordingly, when working with experts from different disciplines it is imperative to communicate effectively without sacrificing precision. For disaggregated studies, then, it is necessary to explicitly define substitution types along the relevant supply chain in a way that makes sense to both economists and the experts.

Smith and Eggert [31] define eight specific responses that PM and wind turbine manufacturers could have had in response to the REE price spike, including six specific substitution types resulting in the reduction of HREEs. Table 2.1 provides definitions and specific examples for each response. The first two, cost pass-through and cost absorption, are not substitution at all. In both cases, manufacturers essentially do nothing either because they can (low cost-share, high demand for their product, etc.) or because they expect prices to fall in the future. Focusing on PMs and wind turbines, the six substitution types fall loosely into the categories above and range from specific (element-for-element) to broad (system-for-system and improved manufacturing efficiency).

2.3 Survey Method

Expert consultation is a common approach for disaggregated material substitution studies. Holmes [41] argues for formal questionnaires performed via personal interviews with industry experts when obtaining data for empirical investigations and that such data should be analyzed through subjective and judgmental techniques. Eastin et al. [15] and Eastin et al. [16] also perform formal surveys (via mail), asking experts to rate their level of (dis)agreement with several statements about material use and the underlying reasons behind any substitutions on a Likert-type rating scale. They use t-tests and factor analysis to analyze the results.

Other recent studies have also investigated HREE and PM substitution in wind turbines using less-formal expert consultation [4, 33, 34]. Smith and Eggert [31] also provide an informal discussion of REE substitution in PMs and wind turbines, based on several interviews pertaining to the categories in Table 2.1. This paper offers a more formal approach and a significantly updated and expanded discussion for a different audience.

A formal questionnaire was constructed to elicit expert views on the reaction of PM and wind turbine manufacturers to the 2010/2011 REE price spike. The survey introduces the project and explicitly defines the eight responses in Table 2.1 before asking experts to rate the extent to which they observed each response on a four-point rating scale with the values zero (“Not at all”), one (“Somewhat”), two (“Moderate”), three (“Significant”), and “Unsure”. It then asks experts to rate the extent each response was driven by the price increases versus other factors. The remainder asks specific qualitative and quantitative questions to better understand the answers to the initial rating scale questions. These include before-and-after questions about the elemental compositions of various NdFeB grades, which grades are used in wind turbines, the ability of other magnet types to be used in turbines, and many others. The survey was emailed to participants in advance and the questions were completed via phone interview.

Table 2.1: Price Response Categories [31]

<i>Response</i>	<i>Definition</i>	<i>Example</i>	<i>Other Literature</i>
Cost Pass-through	Pass increased material costs through to end-user by increasing sales price of final product	Increase magnet sales price by the same amount as materials cost increase	--
Cost Absorption	Absorbing increased material costs by not increasing the sales price of final product	Magnet sales price remains the same	--
Element-for- Element Substitution	Replace one element with another without significantly changing the properties of the magnet; does not include substitutions which result in a magnet with significantly different properties	Substitute Tb for Dy in NdFeB magnet of the same grade	Material-for-material subst. [12]; Physical material subst. [13]
Process-for- Element Substitution	Reduce one or more elements by using an alternate production process to produce a magnet with the same properties; involves increasing other inputs, such as energy or labor	Use grain boundary modification rather than powder metallurgy process to produce NdFeB magnet of the same grade	Technology-for-element subst. [31]; Other-factors-for-material subst. [12]; Process subst. [13]
Grade-for- Grade Substitution	Use a magnet (of the same type) with different properties in place of another; could result from system redesign or initial over-specification	Use NdFeB magnet with less temperature resistance in a direct drive generator	Quality-for-material subst. [12]; Design subst. [13]; Grade optimization [4]
Magnet-for- Magnet Substitution	Use a different magnet type in place of the magnet in the original design in a re-engineered system	Use ferrite instead of NdFeB magnets in a direct drive generator	Material-for-material subst. [12]; Design subst. [13]; Material subst. [4]
System-for- System Substitution	Meet the end-use in an entirely different way; most broad type of substitution	Use an induction generator with no PMs instead of a direct drive generator	Functional subst. [13], [40]; Inter-product subst. [12]; Invisible material subst. [13]; Technological subst. [4]
Improved Manufactur- ing Efficiency	Using purchased materials more efficiently by reducing waste or reusing materials, in effect, substituting more efficient methods in place of materials	Reduce material waste by using thinner separating saws	Technological subst. [12]; Quantitative material subst. [13]

As with any study involving surveys and interviews, there are biases which can affect the results. Most notably, a possible lack of randomness exists in responses associated with consenting, declining, and non-responsive experts. For this reason, requests were sent to many individuals involved with different segments of the PM industry. A similar bias could arise from the choice of whom to contact to participate in the study (convenience sampling). Interviewees were thus asked to refer others who might partake in the study.

2.4 Results and Discussion

Starting with a description of expert selection and a profile of the experts, this section discusses the relative importance of the ratings received by each response type as well as more specific information relevant to each response. It discusses each response in relation to its temporal and technological considerations. The section concludes by making comparisons to other literature and pointing out some limitations in the analysis.

2.4.1 Profile of Experts

Experts were selected from the PM and wind turbine industries, academia, and U.S. national laboratories. Most of the experts are materials scientists employed as magnet sales and purchasing managers with many years of experience. The initial list included industry and research partners with the Critical Materials Institute (an energy innovation hub funded by the U.S. Department of Energy) and contacts from industry conferences and was expanded by asking each interview subject for additional references. The list was exhausted until all relevant references were those who had already been interviewed, declined, or did not respond to three email requests. Interviews were conducted over the phone and lasted between roughly 30 minutes and two hours, with the average lasting about one hour.

There were 22 experts interviewed in total, 17 of whom were from the PM and electric motor industries, three researchers from national laboratories, and two academic researchers. Of the industry participants, four were magnetics industry consultants with previous experience in various segments of the market, six were from sales departments of NdFeB manufacturing companies, five were from NdFeB suppliers, and two were from research and development departments at major wind turbine manufacturing companies. To ensure candid conversations with experts about their experiences during the 2010/2011 price spike and protect them from undue risk, their names and affiliations have been kept confidential.

2.4.2 Relative Importance of Responses

Experts rated the extent to which PM and wind turbine manufacturers implemented the responses defined in Table 2.1 between 2010 and 2016 on a four-point scale (zero to three). Figure 2.1 shows the medians and 90 percent confidence intervals of the distributions for each response. The experts rated process-for-element substitution as the most significant response, followed by cost pass-through, grade-for-grade substitution,

and system-for-system substitution. Improved manufacturing efficiency, element-for-element substitution, and cost absorption all have medians of one, while magnet-for-magnet substitution happened the least or not at all.

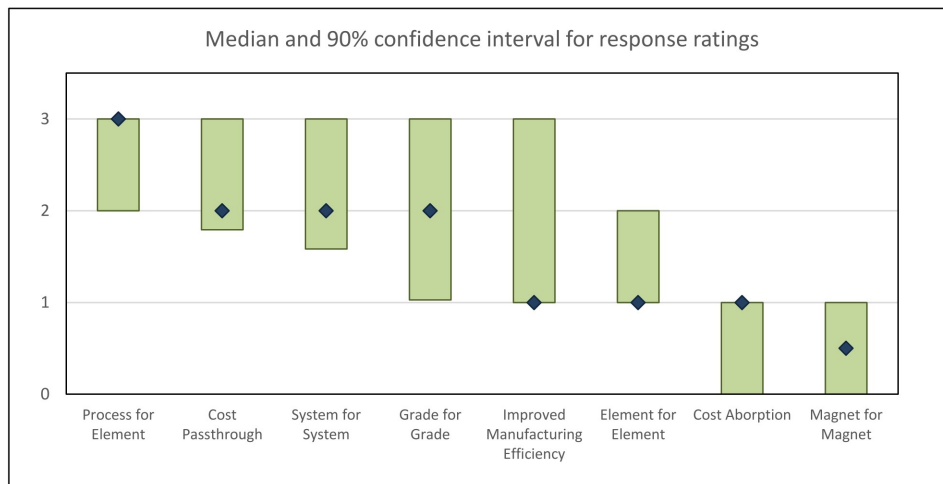


Figure 2.1: Median and 90% confidence interval of response ratings for responses to 2010/2011 rare earth price increases; 0 = “Not at all”, 1 = “Somewhat”, 2 = “Moderate”, 3 = “Significant”

Non-parametric statistical tests, such as the Sign test, provide several advantages over traditional t-tests when dealing with discrete ordered (non-normal) data [42]. The Sign test examines whether two distributions have the same median and makes no assumptions about the shape of the underlying distribution, degrees of freedom, nor variance [42]. Performing this test for each pair of response distributions allows for the inference of a rank ordering. Figure 2.2 shows the results from the paired Sign tests, where the shaded cells indicate statistically different responses at different significance levels.

The experts consistently ranked process-for-element substitution as having occurred more than every other response, although it is not statistically different from cost pass-through, grade-for-grade, or system-for-system substitution, which make up a clear second grouping of responses at the 0.10 significance level. Improved manufacturing efficiency is significantly different from process-for-element substitution at the 0.05 significance level, placing it in its own group since it also differs from cost absorption and magnet-for-magnet substitution. Element-for-element substitution follows improved manufacturing efficiency and is significantly different from the first four distributions at the 0.10 level. Last are cost absorption and magnet-for-magnet substitution, which the experts clearly ranked as having occurred least. Further nonparametric tests (with results provided in the SI) indicate the same ordering.

One- and two-sided Sign tests against discrete values indicate experts rated process-for-element substitution as at least a moderate response (greater than two) at the 0.10 significance level (i.e. reject that

Relative Ranking of Responses and Statistically Similar Distributions - Sign Test										
90% Rank	95% Rank	Response	PE	CPT	GG	SS	IME	EE	CA	MM
1	1	Process-for-Element Subst. (PE)								
3	2.5	Cost Pass-through (CPT)								
3	2.5	Grade-for-Grade Subst. (GG)								
3	4	System-for-System Subst. (SS)								
5	5	Improved Manufacturing Efficiency (IME)								
6	6	Element-for-Element Subst. (EE)								
7.5	7.5	Cost Absorption (CA)								
7.5	7.5	Magnet-for-Magnet Subst. (MM)								





<i>H0: The medians of each distribution are equal.</i>	 $p > 0.10$	 $p < 0.10$	 $p < 0.05$	 $p < 0.01$
--	--	--	--	--

Figure 2.2: Results of pairwise Sign tests of response ratings for responses to 2010/2011 rare earth price increases

the median is equal to two in favor that it is greater than two with a p-value of 0.09). Similarly, there is insufficient evidence to reject that the medians for cost passthrough, grade-for-grade substitution, and system-for-system substitution are two (moderate). The median for improved manufacturing efficiency is between one and two (inclusive) at the 0.05 significance level. There is also insufficient evidence to reject that the medians for element-for-element substitution, cost absorption, and magnet-for-magnet substitution are different from one, and insufficient evidence to indicate that magnet-for-magnet substitution is less than one.

2.4.3 Timing and Technological Change

The eight responses are clearly differentiated by time-scale as well as the amount of technological innovation required. Doing nothing and passing costs through was the easiest and swiftest response but was not tenable longer term. Substitutions involving the adoption of pre-existing processes or methods already under development occurred rather quickly, whereas more significant improvements took longer. Much of what happened between 2011 and 2016 was technological adoption and modest improvements rather than innovation—but not entirely. Since the REE price spike was relatively short-lived, lasting from June 2010 to the end of 2011 (about 18 months), many experts asserted that there was simply not enough time for certain responses to take place.

2.4.3.1 Cost Pass-through and Absorption

The most immediate response to the REE price spike by PM manufacturers was to pass costs through as much as possible without making changes to the production process. Most experts ascertained that there was little choice involved, since most producers were already producing near the margin and Dy accounted for as much as 95 percent of the total magnet cost in some cases. One expert estimated that prices of some NdFeB grades increased by over 600 percent between January 2010 and August 2011 [31]. Many experts noted that magnet producers absorbed costs as much as possible and passed through the remainder, however, absorbing costs was an unrealistic strategy for most producers (especially those with smaller volume). Passing costs through had disadvantages, particularly in the early stages of the price spike before magnet customers were fully aware of the REE supply situation. After several months, magnet producers were forced to look to other options as they faced pressure to keep magnet prices low.

Longer term, magnet producers negotiated agreements within existing quarterly contracts called “metal clauses”, which allowed the negotiated magnet sales price to vary for specified deviations in material costs and exchange rates. Producers absorbed increased material costs for increases less than the specified amount but could pass additional costs over the specified amount to the customer. Consequently, magnet producers both absorbed and passed costs through over the duration of an existing contract.

2.4.3.2 Technological Adoption

Changes in technology were behind significant reductions in the HREE content of both magnets and wind turbines following the price spike. The extent to which the price spike influenced these changes varies by the level of technological change.

Most of the material substitutions which took place during and following the price spike were those for which (approximate) solutions already existed. Both PM and wind turbine manufacturers adopted (rather than innovated) alternative manufacturing processes and product specifications fairly quickly.

Process-for-element substitution was the most significant response to the REE price spike by PM manufacturers due to two known production processes which reduced the HREE content of magnets with high temperature resistance by 40 to 50 percent. The first process involves improving the microstructure of the magnet by modifying the grain boundaries of the magnet, namely through the grain boundary diffusion (GBD) process, which allows magnet manufacturers to microscopically place the required HREEs around individual magnet grains rather than dispersing it throughout [43]. The second process is “dual-alloying” technology, which consists of using unseparated ferro-dysprosium alloy (DyFe) to economize on Dy rather than inserting it separately [44]. There is also a third, though less prevalent, process, called powder refinement technology, which consists of using finer grain sizes in the magnets [37].

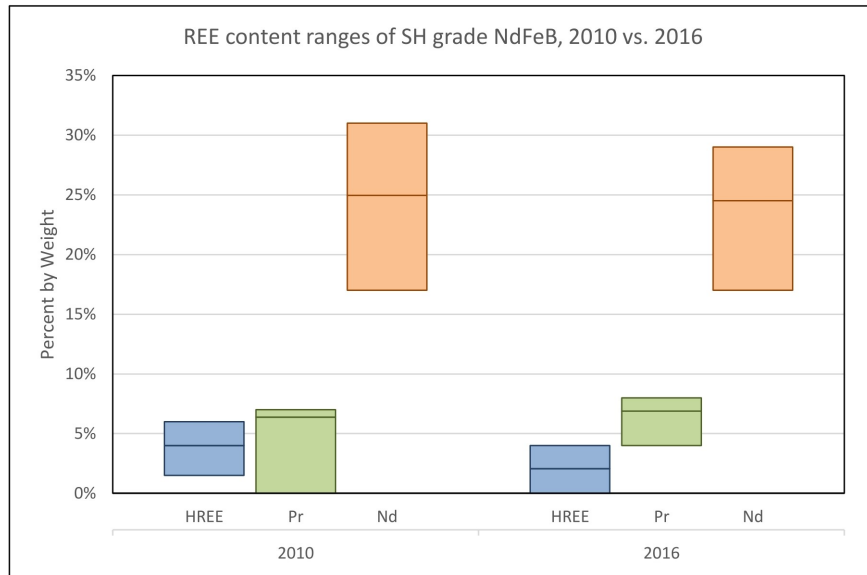


Figure 2.3: Nd, Pr, and HREE content range of SH grade NdFeB in the N40-N45 range, 2010 vs. 2016 (Note: horizontal lines represent maximum, median, and minimum; based on responses from six experts)

Most experts pointed to the adoption of the GBD process as the magnet industry’s main response to the price spike, representing a major change from traditional sintering with the powder metallurgy method. They noted that although the GBD process for HREEs was known prior to the price spike (having been developed by Sumitomo in 2002), it is time-intensive and requires expensive equipment and labor, so it did not see widespread adoption until material cost increases forced producers to economize on Dy. Different (but related) methods of grain boundary modification were used and patented by the major Japanese producers, which license their processes to a select group of companies worldwide [45].

Despite the relatively small number of licensed companies, one expert asserted that “more than 75 percent” of the industry now uses the GBD process. Similarly, an expert from a major Chinese manufacturer indicated that introducing the dual-alloying process allowed their company to “remove Dy from half their grades” while another indicated that almost all companies now purchase pre-alloy metals. Despite consistently rating element-for-element substitution as less important, the experts mentioned a few important developments. The most notable elemental substitution in NdFeB magnets was the increased use of didymium (unseparated NdPr), which reduces the Nd content while increasing the Pr content. Some companies used didymium prior to the price spike (circa 2007), but in 2011 the practice became widespread. The experts estimated that the Pr content range in a typical magnet was zero to seven percent before the price spike and three to eight percent after. Figure 2.3 shows ranges for estimates of the REE content of NdFeB by element in 2010 and 2016.

Substitution between HREEs is also possible to achieve the same temperature properties. Tb can completely substitute for Dy and, according to several experts, is more effective [31]. The experts mentioned that some companies may have tried to use Tb in the short run, however, Tb prices are kept high due to its use in phosphors [31, 34]. One expert noted that some NdFeB magnets contain both elements, estimating that Tb decreased relative to Dy as the total HREE content decreased.

System-for-system substitution was the simplest solution for wind turbine manufacturers and project planners, especially for onshore systems. More accurately, the price spike impeded the widespread adoption of PMG systems since DFIGs already dominated the market [34, 38]. Several experts mentioned industry decisions to pursue DFIG designs, such as General Electric’s decision in 2012 to quit using PMGs and return to DFIG for their onshore turbine designs (although magnet cost was a single factor of this decision) [46].

2.4.3.3 Technological Improvement

Actual technological improvements also occurred in response to the REE price spike through continued innovation, though they were less immediate, and, as several experts mentioned, might have been more significant had prices remained high for a longer period. In economics, technological (or “technical”) improvement strictly implies the ability to produce the same amount of output using less of an input without increasing other inputs, as with Tilton’s view of technological substitution [23].

Technical improvements via improved manufacturing efficiency at least somewhat occurred after the REE price spike, though many experts pointed out that well-managed firms continuously improve the efficiency of their processes regardless of material costs. Still, others thought the price spike hastened the speed of improvements. In the words of one expert, “everything that could be done was done” to economize on expensive REE components.

There are two ways to use materials more efficiently: either reduce material waste, or reuse scrap material from the manufacturing process. According to the experts, most improvements were accomplished through waste reduction, though the degree of improvement varies by magnet size. Using slimmer separating saws reduced waste for thinner magnets and, for larger magnets, manufacturing the magnet closer to its final shape reduced the amount of grinding necessary. One expert noted that waste reduction techniques allowed producers to reduce total purchased REE content in a typical magnet by about five percent. Another stated that since 2011 Chinese companies reduced the separation saw size from about one mm to 0.4 mm, while Japanese companies pursued near net-shape manufacturing. Because large magnets (like those used in wind turbines) tend to be manufactured near their final dimensions, one expert noted that material yield is over 95 percent. More significant improvements were made in smaller magnets, however, as experts noted yields that were between 30 and 60 percent are now 70 to 85 percent with near net-shape manufacturing. Reusing

material in the production process is difficult and less common.

There was also some improvement for wind turbine manufacturers. Experts indicated that some companies responded in the short run via grade-for-grade substitution where magnets were over-specified according to their turbine designs (Sprecher et al. [4] call this “grade optimization”). Once some of the larger manufacturers realized their systems were not optimized for cost, they substituted magnets with reduced HREE content. One expert also mentioned that some companies switched to less expensive, lower quality versions of the same magnet grade.

2.4.3.4 Technological Innovation

Despite the brevity of the REE price spike, a small number of actual technological breakthroughs reduced HREE use in wind turbines. One notable innovation occurred via grade-for-grade substitution. Many experts pointed to Siemens, which developed a system to cool the PMG, allowing for magnets with reduced HREE contents [31, 47]. One expert also mentioned that some companies experimented with different magnet shapes to isolate different parts of the magnet from demagnetization, which also allowed them to use lower-grade magnets.

There were also some longer-term innovations via system-for-system substitution. Experts mentioned that manufacturers sought alternatives to PMGs and DFIGs for both onshore and offshore turbines, but that most solutions were less efficient than PMGs. These experts stated that manufacturers have been returning to PMGs in recent years since REE prices have fallen. There are also designs which substantially reduced the amount of REEs, such as Enercon’s low-speed direct drive generator with no PMs [34] and mid-speed “hybrid” generators by manufacturers like Gamesa and Vestas, which contain a smaller PMG coupled with a gearbox.

While the price spike caused magnet-for-magnet substitution in other applications [4], the experts ranked it as the least significant response for wind turbine manufacturers and most indicated it was not feasible. The major advantage of NdFeB is its high energy product, implying it takes less material to generate a comparable magnetic field. A system with less powerful magnets necessarily uses more magnetic material, leading to larger (and more expensive) systems overall. One expert noted that switching to less powerful magnets was not worth investigating since it would require years of additional testing and REE prices declined within a fairly short period.

2.4.4 Comparisons to Other Literature

Except for improved manufacturing efficiency and grade re-optimization, the experts indicated that most responses occurred directly because of the price spike. The price spike caused material substitutions fairly

quickly via technological adoptions, providing a refinement to Tilton’s [23] alternative view of material substitution which occurs through technological improvement and innovation in the long run. This is indeed the case for process-for-element substitution, where manufacturers switched to two previously-known production technologies that were cost-prohibitive prior to the price spike. Holmes similarly finds that technological adoption was important for material substitutions in battery electrodes [22] and windows [21] in the 1980s, but notes that the nature of final demand and technical attributes of new materials were more significant drivers than material prices.

As both Holmes and Tilton point out, introducing new technology raises an important point about the relationship between substitution and material prices. It is generally assumed that demand is continuous and reversible, implying that if prices decline the quantity demanded returns to its previous level. Changing production processes, however, can permanently shift the demand curve inwards for a given material. The findings from this study indicate that demand for HREEs in magnets is not continuous (material costs changed by thousands of percentage points to induce a discrete 40 to 50 percent change), and possibly not reversible. REE prices have since fallen and producers continue to use technology implemented during and after the price spike. Were REE prices to fall substantially, there might be a return to previous technology.

While this study differs in purpose and scope from Graedel et al.’s [9] and Nassar’s [10] work in quantifying elemental substitution, it finds it is at least somewhat possible in NdFeB magnets. Specifically, substitution of different HREEs is possible (though impractical since Tb is several times more expensive than Dy), as is substitution of non-REE components of the magnet [48]. Further, the ability to introduce unseparated metal (in the cases of both NdPr and DyFe) also alters the elemental composition and lowers material costs. This study does, however, corroborate Nassar’s assertion that substitution is more likely to occur in other areas than at the elemental level.

While other studies [4, 33, 34, 49] have analyzed potential substitution strategies for PMs in wind turbines and electric vehicles, they tend to be from engineering perspectives and are less interested in the influence of material costs on firm behavior. This study is explicit in its focus on how PM and turbine manufacturers actually responded to the rampant material price increases of the REE price spike. It also provides general insight into how industries facing substantial increases or uncertainty in material costs might respond in the shorter term. In the end, it appears the actual impact of the price spike was improvements in the way materials and technology are used.

2.4.5 Limitations and Future Research

There are limitations to this study. Most notable are the relatively small number of observations and the biases inherent in the survey interview. The conclusions are drawn from the collective opinion and

knowledge of industry experts, rather than actual price-quantity data. Still, the method employed provides an advantage over statistical regression models in its recognition of the actual ways manufacturers respond to material price increases, rather than simply providing a numerical estimation of this relationship.

While the findings indicate that demand for HREEs in PMs is price inelastic and non-zero (between zero and minus one), it is difficult to ascertain how much so. There was an observed increase in material costs of about 3000 percent and an accompanying decrease in HREE content by many manufacturers by 40 to 50 percent, yet it is unknown at what price level PM manufacturers would have initiated this change. Demand is inelastic for any price increase over 100 percent (by definition), so the true estimate is likely closer to zero than minus one. It also appears demand shifts in discrete jumps as production technology changes. Future research could investigate where these jumps occur. Furthermore, demand for HREEs in wind turbines is highly elastic at high REE prices, since low-HREE technologies already exists.

Finally, this study assumes that responses to the REE price spike were in fact linked to material costs. While a reasonable assumption, geopolitical factors (perhaps induced by the price spike) arising from the geographic concentration of REE production may have influenced manufacturers in certain countries.

CHAPTER 3

QUANTIFYING FUTURE PRICE RESPONSIVENESS TO MATERIAL INPUTS IN DISAGGREGATED INDUSTRIES: THE CASE OF RARE EARTH MAGNETS

A paper prepared for journal submission.

Braeton J. Smith⁵

Abstract: Manufacturing processes for clean energy technology require materials with risky supply chains due to a variety of reasons. The ability to reduce dependence on these inputs through substitution alleviates such concerns. This study assesses the potential ability of producers to respond to future sustained cost increases of material inputs—specifically the ability of rare earth magnet manufacturers to respond to future heavy rare earth price increases. Since sufficient disaggregated data is not available for the use of more traditional methods, this question is answered by estimating long-run demand curves and price elasticities using data gathered from an expert elicitation survey. To the knowledge of the authors, this is the first study to use such techniques to calculate price elasticities of demand, providing a potential method for quantifying forward-looking price responsiveness for highly disaggregated industries with poor data availability. Results indicate that significant increases in material costs would induce reductions in heavy rare earths in permanent magnets over the following five years, though the response is inelastic. Manufacturers would be most responsive to a doubling of material costs, but demand is almost perfectly inelastic for more substantial increases.

3.1 Introduction

Clean energy technology is expected to play a larger role in the coming century, however, many manufacturing processes for clean energy equipment require materials with risky supply chains due to concerns arising from geopolitical challenges, physical availability, and severe price volatility. The ability to substitute away from inputs with risky supply chains alleviates such concerns. Quantitative indicators of substitutability are necessary for material criticality assessments [3], scenario analysis [4], and informing policy [7], but are difficult to obtain for specific materials in specific end-uses. This study quantifies the ability of manufacturers to respond to increasing material costs in the future, without relying on historical data and events to make inferences. Specifically, it uses expert elicitation techniques to provide a forward-looking assessment of the ability of permanent magnet manufacturers to respond to future rare earth element price increases.

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Other literature has investigated material substitution in various contexts. Much recent work focuses on the substitutability of critical and strategic materials used in modern technology applications, particularly as regards material criticality assessments [3, 33], life cycle analysis [8, 50], and system resilience concerns [4]. Graedel et al. [9] and Nassar [10] provide perhaps the most quantitative and reproducible assessments of physical material substitution to date for most metals, finding that acceptable substitute materials generally do not exist for their primary uses. This leads them to conclude that prices do not generally influence the ability of manufacturers to substitute material inputs. Disaggregated (material and application-specific) case-studies have taken a broader approach, noting that dependence on certain materials can be reduced by substitution at different levels and for different reasons which include material costs, geopolitical factors, and technological adoption and innovation [12, 13, 21, 22, 31, 51, 4]. As Holmes [41] suggests, most of these have employed some combination of expert consultation and quantitative analysis due to a lack of sufficient data on material consumption in specific end-uses for traditional quantitative economic models. To date, none have calculated forward-looking long-run elasticities of demand and substitution, which capture the price responsiveness of manufacturers to price changes.

The purpose of this paper is to assess the potential ability of producers to respond to future sustained cost increases of material inputs. Specifically, it asks how producers of rare earth permanent magnets would respond to future heavy rare earth price increases either by substituting materials or passing through or absorbing costs. This question is answered by estimating long-run demand curves and elasticities using data gathered from an expert elicitation survey [52]. This is a novel application of expert elicitation techniques, and one of the first uses of the method in economics outside of health economics [53, 54, 55] and several works forecasting future energy technology costs and efficiencies [56, 57, 58, 59, 60, 61]. As such, an additional purpose of this work is to propose expert elicitation techniques as a potential tool for economists when there is insufficient data available to use more common methods.

The contributions of this work lie within the materials substitution literature and the economics discipline more generally. Perhaps most importantly, this is (to the knowledge of the authors) the first study to use expert elicitation techniques to calculate elasticities of demand, showing that it is possible for economists to estimate long-run substitutability of inputs for highly disaggregated industries where data is sparse or nonexistent. These elasticities are not estimated using historical data and capture the current thinking by industry participants without embodying the implicit assumption that industry will respond to future price changes the same as in the past. This study also contributes to the growing literature of material criticality studies, showing that materials are potentially more substitutable than is often assumed.

Results indicate that significant increases in material costs would induce reductions in heavy rare earths in permanent magnets over the following five years, though the response is inelastic and not wholly due

to material costs. On average, the experts estimate that heavy rare earth content would fall by about 18 percent due to improvements in technology alone and by about 43 percent if prices were to double. For extreme increases in material costs, the experts indicate on average that heavy rare earth content could be reduced by about 55 percent. This indicates that demand for heavy rare earths in permanent magnets, while inelastic at all price levels, is most elastic for a doubling of material costs, but almost perfectly inelastic for more substantial increases.

The remainder of this paper is organized as follows. The following short section provides some brief background on rare earth elements and their uses in magnets and clean energy technology. Section 3.2 provides some theoretical background to differentiate between technological improvement and substitution of technological processes. Section 3.3 discusses expert elicitation techniques and how they are used to estimate demand curves and elasticities, as well as experimental and survey design. Section 3.4 then discusses the results in detail. Section 3.5 concludes the paper and discusses some limitations to the work.

3.1.1 Background

Rare earth elements (REEs) are metallic elements comprised of the group of 15 lanthanide elements (atomic numbers 57-71) and scandium and yttrium, which are chemically similar [35]. They are divided into two groups: light REEs (LREEs), which have atomic numbers 57-64; and heavy REEs (HREEs), which have atomic numbers 65-71. Prior to 2012, over 95 percent of production came from China [36]. In mid-2010, the announcement of a new, more restrictive export quota on REEs by the Chinese government led to panic among users, causing REE prices to increase by over 3000 percent for some individual REEs [31]. The price shock lasted through the beginning of 2012, when prices fell substantially, yet still remained about double their pre-quota levels. Currently about 80 percent of all REE production comes from China, with the remainder coming from the Mount Weld mine in Australia and small projects in Russia, Brazil, and a few other countries [62]. The term “rare earth” is something of a misnomer, as REEs have a fairly high crustal abundance, though they are rarely concentrated in deposits which are economical to exploit. While REE prices are currently somewhat stable, they are still subject to demand-related price swings as production is low relative to other metals.

REEs are essential inputs to many modern technologies, particularly those used in clean energy technologies such as offshore wind turbines, electric vehicles, and batteries for energy storage. Permanent magnets (PMs), the strongest of which contain REEs, are necessary components of direct (low-speed) and hybrid (mid-speed) drive wind turbines [34]. Such turbines are preferred for their better efficiency and lower maintenance costs, especially for use offshore [38]. The four major PM types are ferrite, alnico (containing aluminum, nickel, and cobalt), samarium-cobalt (SmCo), and neodymium-iron-boron (NdFeB). The latter

two types are called rare earth PMs, since they contain REEs. NdFeB magnets are the strongest available at room temperature (in terms of energy product) and contain the LREEs neodymium (Nd) and praseodymium (Pr). Because NdFeB magnets demagnetize fairly rapidly at high temperatures (above 100 degrees C), manufacturers add small quantities of HREEs, namely dysprosium (Dy) and terbium (Tb), which improve their resistance to demagnetization.

There is some evidence that magnet manufacturers are able to reduce material requirements through substitution. Prior to the REE price spike in 2010/2011, NdFeB magnets with an operating temperature up to 150 degrees C contained between two and six percent HREE content by weight, which manufacturers were able to half through the substitution of alternative production processes after the shock [51]. Determining the extent to which manufacturers would be able to respond similarly in the future is one of the main questions of this paper.

3.2 Conceptual Framework

There are a number of ways manufacturers can respond to an increase in the price of a material input. They can pass increased costs on to their downstream customers if demand is sufficiently high for their product to allow them to do so. They can also absorb increased costs for a period or substitute inputs in several different ways, such as those defined by Tilton [12] and Schlabach [13]. Smith and Eggert [51] similarly define several specific ways PM manufacturers responded to the REE price increases in 2010 and 2011. Those relevant to the present study are:

1. *Cost passthrough/absorption*: Either pass increased material costs through to end-users by increasing the sales price of the final product or absorb them to some extent.
2. *Element-for-element substitution*: Replace one element with another without significantly changing the properties of the magnet.
3. *Process-for-element substitution*: Reduce the amount used of an element by using an alternate production process to produce a magnet with the same properties; involves increasing other inputs, such as energy or labor.
4. *Improved manufacturing efficiency*: Use purchased materials more efficiently by reducing waste or reusing materials, in effect, substituting more efficient methods in place of materials.

The first two responses are relatively straightforward, but the other two are less-so. While similar, process-for-element substitution is distinct from improved manufacturing efficiency: the former specifically involves the ability to reduce the amount of a material through the adoption of an alternate production process

while being accompanied by increases in other inputs, whereas the latter implies an actual improvement in technology that reduces material use without increases in other inputs [51]. Smith and Eggert [51] show that both occurred, at least to some extent, in PMS following the REE price shock in 2010/2011.

To economists, such distinctions are clear, and can be shown both graphically and mathematically with isoquants and cost minimization. An isoquant describes all possible combinations of inputs $i = 1, \dots, n$ that can be used to produce a given amount of some manufactured good y . Isoquants take on different shapes depending upon the characterization of technology in the underlying production function $y = f(x_1, \dots, x_n)$ and the elasticity of substitution σ_{ij} , which measures the substitutability between two inputs at different relative prices $P = p_i/p_j$. When $\sigma_{ij} \rightarrow \infty$, two inputs are perfect substitutes and the isoquant is represented by a negatively-sloped straight line. When $\sigma_{ij} = 0$, there is no ability to substitute between the two inputs at all, and the technology is characterized by fixed proportions of the two inputs, yielding L-shaped isoquants with “Leontief” technology (see Leontief’s work on input-output modelling [63]). An isoquant’s shape determines the shape of the factor demand curves $x_i(p_i, \dots, p_n)$, which describe the optimal amount x_i of input i required to produce the good at different price levels. Inward shifts of the isoquant (and demand curves) represent improvements in technology, implying more efficient production that uses less of an input to produce the same level of output.

Isoquants are typically depicted as smooth curves convex to the origin, but specific production processes are often characterized by fixed proportions with limited substitutability between inputs. Activity analysis models incorporate several production processes with Leontief technology that produce the same output [64]. Production process A_k is defined by the ratio x_j^k/x_i^k . Panel *a* of Figure 3.1 shows an activity analysis isoquant for good Y , which has three production processes depicted as rays A_1 through A_3 . A firm producing Y_0 units of good Y via process A_2 will produce at point e_2 , which uses x_i^2 units of input i . If input i becomes more expensive relative to input j (i.e. $P = p_i^0/p_j^0$ becomes $P' = p_i^1/p_j^0$), at some point it will become more efficient to switch to production process A_3 and produce at point e_3 , which uses less of input i and more of j . If, on the other hand, technology improves for all production processes (e.g., if firms produce less waste), the isoquant shifts toward the origin to Y'_0 , which requires less of both i and j to produce Y_0 for all production processes. Process for element substitution is the movement from e_2 to e_3 , whereas improved manufacturing efficiency is the movement from e_2 to e'_2 .

In addition to the elasticity of substitution σ , price responsiveness is measured by the price elasticity of demand $\epsilon_i^d = dx_i(P)/dP * P/x_i$, the ratio of the percentage change in demand to the percentage change in price. The price change from p_i^0 to p_i^1 in the previous example is accompanied by a decrease in the consumption of input i from x_i^2 to x_i^3 , as depicted in panel *b* of Figure 3.1. The elasticity between these points is then $(x_i^3 - x_i^2)/(p_i^1 - p_i^0) * (p_i^0)/(x_i^2)$. To calculate price responsiveness in material inputs, one needs

the percentage change in the use of the input $((x_i^3 - x_i^2)/(x_i^2))$ associated with given percentage changes in the price level $((p_i^1 - p_i^0)/(p_i^0))$. If the values of p_i^0 and x_i^2 are known (or given), then one can simply elicit x_i^3 for a given p_i^1 to calculate ϵ_i^d .

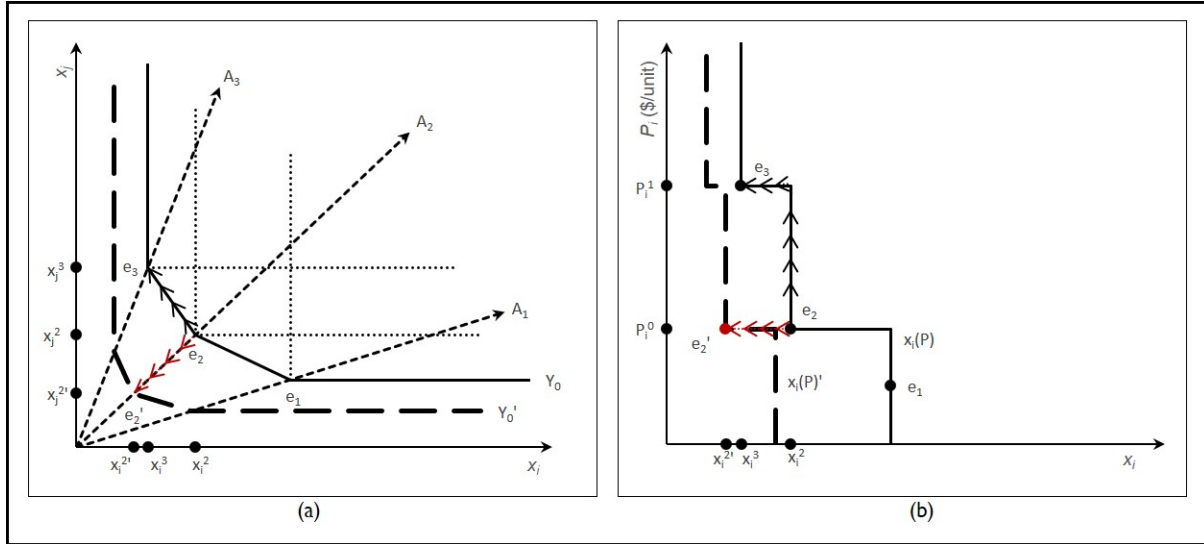


Figure 3.1: Activity Analysis Model of Production

3.3 Expert Elicitation and Survey Design

Expert elicitation, also known in decision and risk analysis as probability encoding, is the practice of capturing an individual's beliefs about unknown and uncertain quantities. It was developed in the 1960s as a means for quantifying prior distributions in Bayesian analysis when sufficient data is unavailable [65]. The elicitation process typically involves acquiring a cumulative distribution function (CDF) from an individual that reflects their beliefs and uncertainty about an unknown quantity before new data becomes available [66].

Spetzler and von Holstein [66] identify three common methods for eliciting CDFs from experts: one) elicit a cumulative probability estimate associated with a fixed value of a variable (FV); 2) elicit an estimate of the value associated with a fixed probability (FP), usually a percentile; or 3) a mixture of the two. Given some event E , the FV method asks the expert to give the probability p_i that the true value of a variable V is less than or equal to a specific value v_i , or $p_i = P(V \leq v_i | E)$. For example, one could ask for the probability that the highest temperature tomorrow will be 50 degrees F or less, given it is the middle of winter. By contrast, the FP method asks experts to give the value v_i associated with a given probability p_i . Using the same example, one could ask for a person's 90th percentile guess for the highest temperature tomorrow (worded differently, the temperature they are 90 percent sure it will not go above). While both methods

are used in practice, the FV method is more natural and tends to be slightly faster and more accurate [67], however, using multiple mProfile of Experts methods can improve the accuracy and consistency of an expert’s estimates [68, 69].

Experts have been shown to exhibit several types of conscious and unconscious cognitive biases in probability elicitation, namely overconfidence, availability, anchoring, and representative biases [66, 70]. To minimize these cognitive biases (as well as motivational biases), a short primer on basic probability and elicitation concepts was provided to each expert a week in advance of the interview. In particular, the primer reviewed basic probability concepts, alerted the experts to the major biases (providing contextual examples of each), and explained the elicitation process in detail [52, 53, 71, 72]. The interviewer reviewed the primer with each expert at the start of the interview and performed several practice exercises in both FP and FV formats for which the true answers were known. These exercises elicited known quantities both within and outside of the expert’s expertise, such as Ludwig van Beethoven’s year of birth, the number of summits in Colorado between 13,000 and 13,999 feet, and the atomic number of Dy. These questions served to familiarize experts with the elicitation process as well as how to reflect their uncertainty about unknown values.

This study uses both FP and FV methods to estimate the ability of NdFeB producers to respond to high HREE prices by reducing the amount of HREEs in the magnet. Different NdFeB grades require substantially different amounts of HREE depending on their maximum operating temperature and vary significantly by manufacturer and production process. For this reason, a reference magnet was defined as a control with given material composition and magnetic properties. In addition to maintaining consistency, using a reference magnet also avoided asking the experts to divulge proprietary or confidential information. Defining a control and definitions is common practice in expert elicitation studies [56, 60, 61]. The reference magnet was defined as a N42SH grade NdFeB magnet (maximum operating temperature of 150 degrees Celsius) for use in a 2.5 MW wind turbine with the material contents shown in Table 3.1 along with the initial market conditions. The specification of the reference magnet was largely based on the findings of Smith and Eggert [51].

Table 3.1: Reference N42SH NdFeB magnet for use in a 2.5 MW wind turbine and initial market conditions (November 2016)

<i>Element</i>	<i>Material Composition</i>	<i>Metal Price (\$/kg)</i>
Neodymium (Nd)	25%	\$50
Praseodymium (Pr)	3%	\$50
Dysprosium (Dy)	4%	\$250
Terbium (Tb)	0%	\$550

Experts were asked, via both FV and FP methods, to quantify the amount to which the Dy and Tb contents of the reference magnet would change (if at all) within five years for several different levels of future sustained price changes for the two elements (both together and individually). For the FV questions, experts were given a specified price change for one or both elements and an associated maximum material content and asked to give the probability of such an outcome. For each price change, they were asked to give a probability for several levels of material content change ranging from a content increase to a total elimination of the element from the magnet. That is, CDFs of Dy content estimates were elicited for Dy and joint Dy/Tb price level changes of -50 percent (\$125/kg), 0 percent (\$250/kg), 50 percent (\$375/kg), 100 percent (\$500/kg), 500 percent (\$1,500/kg), and 1000 percent (\$2,750/kg) and for Tb price decreases of 25 percent (\$413/kg), 50 percent (\$275), and 75 percent (\$138/kg). For example, one question asked was “if Dy/Tb prices permanently increased by 100 percent tomorrow, what is the probability the Dy content of the reference magnet would be less than or equal to three percent five years from now?” In total, 15 CDFs were elicited from each expert using the FV method.

For the FP questions, experts were given specified price changes for one or both elements and asked directly for their 10th, 50th, and 90th percentile estimates (that is, values associated with fixed probabilities of 0.1, 0.5, and 0.9) for what the material content would be in five years. The corresponding FP distributions were elicited as for those described for the FV method, with the addition of several questions pertaining to changing Tb content (as opposed to just Dy). In total, 25 distributions were elicited using the FP method. Between both methods, a total of 40 distributions were elicited from each expert.

One of the most useful aspects of expert elicitation techniques is the ability to either reach consensus or identify different schools of thought with a small sample size. Keeney [73] notes that most common biases are eliminated with as few as three experts and Winkler and Clemen [69] show that the marginal benefit of adding experts decreases rapidly after five experts, though additional experts generally improve accuracy. Elicitation studies differ widely in the number of experts interviewed. Baker et al. [74] report that between three and 31 experts were interviewed for 13 elicitation studies related to future costs of low-carbon energy technologies, with an average of about 12 experts (all but two used fewer than 20 experts). They point to an ongoing question in the literature which considers whether elicitation should contain highly detailed, resource-intensive interviews with fewer experts or simpler, lower cost surveys with a larger number of experts.

In the present study, interviews were conducted individually via telephone with screen sharing software so that experts were able to view their distributions as they were given for both methods. Individual interviews (as opposed to group interview methods such as the Delphi process) allow experts to form and give opinions that are not influenced or distorted by the voice of a single confident expert or social pressure [61]. The

personal interview process used in this study, versus other methods such as online or mail surveys, allowed the elicitation exercise to incorporate significantly more detail. The distribution elicited from an expert is not always the complete answer, as it is important to understand the logic (i.e. qualitative data) behind an expert's responses [75]. The tradeoff for better information, of course, is that the number of experts included in the study is necessarily lower than it might be had other methods been used.

The eight experts included in this study were selected from a subsample of 22 experts who participated in a previous study of PM producer and user responses to the REE price spike in 2010/2011 [51]. The experts selected for the present study were those who were able to provide particularly detailed responses for that study and who were available to participate. Of the eight experts, only five completed the probability questions. These consisted of three major industry consultants with extensive previous industry experience, one business manager at a prominent NdFeB production company with extensive knowledge of the PM and REE industries, and one engineer from a major European NdFeB supplier. Collectively, the five experts possess over 120 years of PM industry experience. The names and affiliations of the experts have been kept confidential in order to ensure candid conversations and avoid confidentiality concerns. A maximum of three attempts were made to contact each potential expert. The interviews ranged from one and a half to five hours, with the average interview lasting about two and a half hours.

Expert elicitation techniques are widely used in risk and decision analysis. While they have been used to some extent in the economics literature, applications have to a large extent been focused on estimating returns to research and development spending and future efficiency and costs for emerging energy technologies (as mentioned) and within health economics [55, 61, 74]. To the knowledge of the authors, this is the first study to use expert elicitation to study price responsiveness. As such, it provides an alternative to more traditional econometric techniques with substantial data requirements. This reliance on historical data inhibits their ability to be forward-looking, as even forecasts relying on historical data assume the past is a good predictor of the future. Expert elicitation incorporates expert views of the present as well as future expectations (which are informed by, but not necessarily dependent upon, what has happened in the past) and is perhaps the best way to gain an opaque view of the future based on the most current knowledge. Another common (though not strictly necessary) assumption of most econometric models is that demand for inputs is continuous and that elasticities are constant. The method employed here does away with these assumptions.

3.4 Results and Discussion

This section discusses the main findings, discusses results for process-for-element substitution and element-for-element substitution, and price elasticity of demand calculations. It concludes with a comparison of results for the FP and FV methods and a comparison to other works.

3.4.1 Main Findings

There is consensus among the experts that HREE reductions in NdFeB are indeed possible within the next five years in the event of significant material cost increases, although there was some disagreement about the degree as well as the influence of price. That is, some experts were more optimistic about the industry than others, and some thought some degree of technological improvement (improved manufacturing efficiency) was more important than material costs. Regardless, the aggregated demand curves are downward sloping, indicating that overall the experts expect increased material costs to have some effect on material composition in the long run.

Figure 3.2 and Figure 3.3 show the CDFs and probability mass functions (PMFs) given by the experts for a 1000 percent increase in the price of HREEs (both Dy and Tb) for the FV method. With the exception of Expert 1, the experts estimate a fairly substantial decrease in HREE content, assigning a probability of at least 0.50 to a 75 percent HREE decrease (from four to one percent by weight). The experts can be easily grouped by their perspective within the magnetics industry. Experts 1, 2, and 3 are highly-regarded consultants to the magnetics industry with many years of previous experience in the industry. Experts 4 and 5 are employed within the industry, one by a prominent NdFeB manufacturer and the other by a prominent supplier and components manufacturer. Overall, the industry consultants appear to be slightly less optimistic compared to those employed directly by the industry, who predict fairly rapid HREE content decreases at much lower price levels. In fact, Expert 5 fairly confidently estimated substantial decreases in HREE content independent of any price movements.

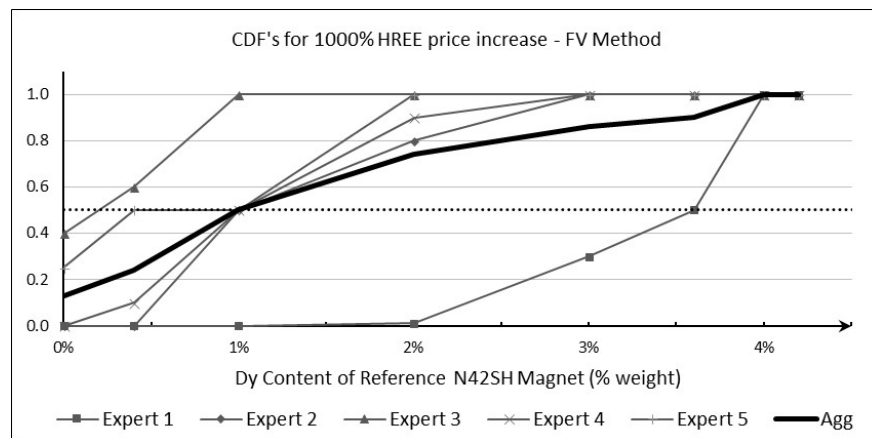


Figure 3.2: Cumulative distribution functions elicited via the fixed variable method for a 1000% increase in the price of HREEs

There is much debate in the expert elicitation literature about how to aggregate probability distributions from experts, or whether or not to aggregate them at all [76, 77]. Cooke [78], for example, advocates for

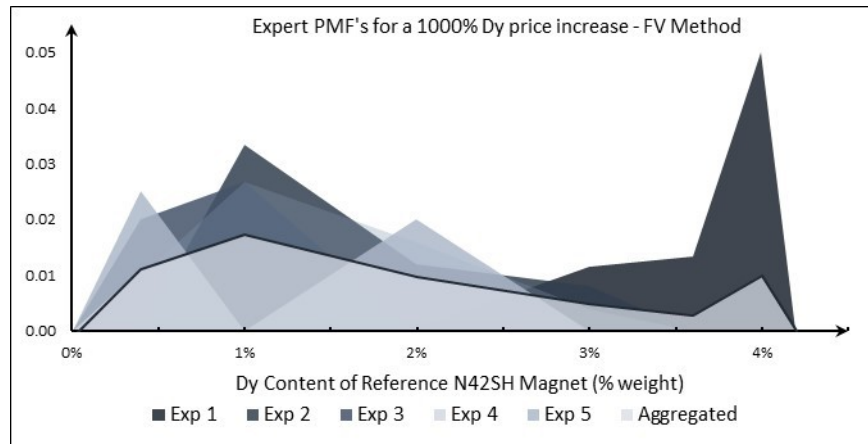


Figure 3.3: Probability distribution functions elicited via the fixed variable method for a 1000% increase in the price of HREEs

weighting experts based on information and calibration scores received on “seed” questions. Several studies have shown, however, that while Cooke’s “classical” method is theoretically rigorous, it adds a great deal of complexity to the elicitation process and does not generally perform better than equal weights (i.e. a simple average) [76, 79, 80]. Despite the best efforts of many scientists over the past several decades, Clemen and Winkler [76] reach the conclusion that simpler aggregations methods generally perform better than more complex methods in practice. Among the most commonly applied methods is the linear opinion pool [81], referred to by some as “Laplacean mixing” [74]. The linear opinion pool, which satisfies several necessary properties for aggregation, is essentially a weighted linear combination of probabilities, which amounts to a simple average when equivalent weights are used [76]. In this study the experts’ distributions are aggregated using a simple linear opinion pool with equal weights for both the FV and FP methods.

Figure 3.4 and Figure 3.5 show the aggregated CDFs and PMFs for the FV method and Figure 3.6 and Figure 3.7 show the CDFs and probability density functions (PDFs) for the FP method. The distributions for the FP method are aggregated using a combination of the equal-weighted linear opinion pool and piecewise cubic splines fitted between the 0th, 10th, 50th, 90th, and 100th percentiles (x_0, x_{10}, x_{50} , etc.). Since the x_0 and x_{100} were not elicited, they are assumed to satisfy the ratios $x_0/x_{10} = x_{10}/x_{50}$ and $x_{100}/x_{90} = x_{90}/x_{50}$, as proposed by Baker et al. [74]. The minimum was also restricted to be positive.

The aggregated distributions from both methods show the experts expect reductions in the Dy content of the reference magnet as HREE prices increase. The FV distributions show that for a 50 percent decrease in HREE prices, the median remains near four percent, with a small probability that the content would either decrease or increase slightly. As the price level reaches 1000 percent, the median moves to one percent Dy content, however the distribution encompasses the entire range from zero to over four percent. In the FP

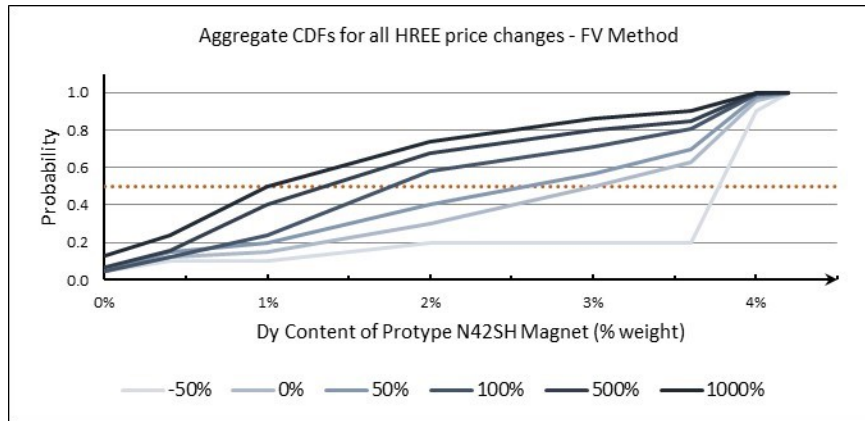


Figure 3.4: Aggregated cumulative distribution functions elicited via the fixed variable method for different levels of HREE price change

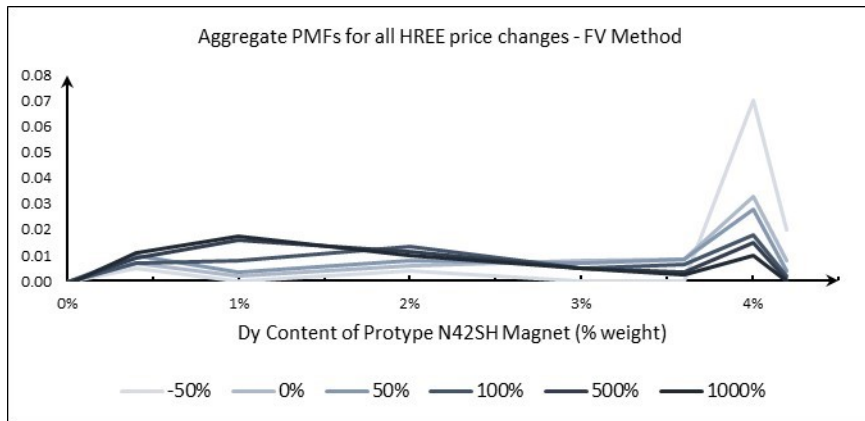


Figure 3.5: Aggregated probability mass functions elicited via the fixed variable method for different levels of HREE price change

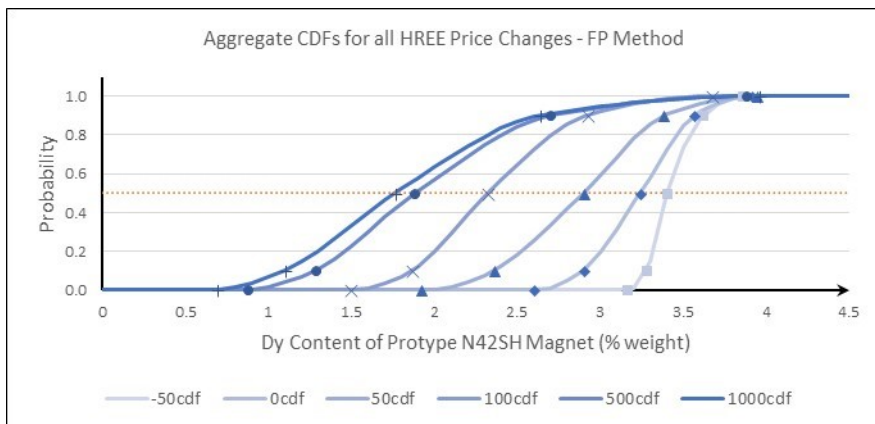


Figure 3.6: Aggregated cumulative distribution functions elicited via the fixed probability method for different levels of HREE price change

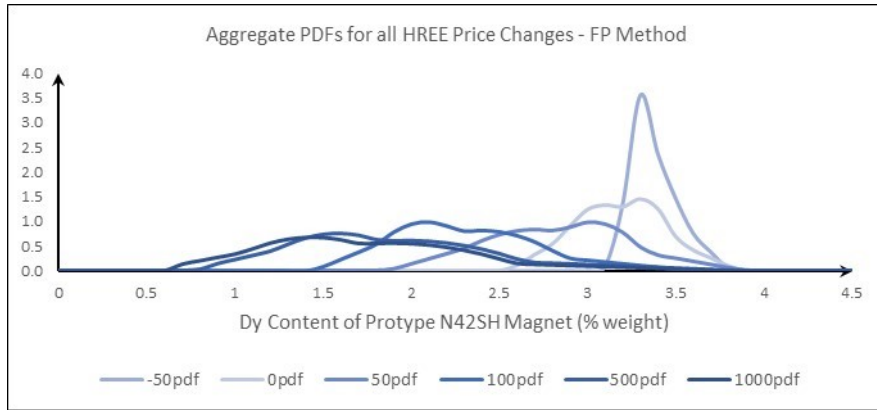


Figure 3.7: Aggregated probability distribution functions elicited via the fixed probability method for different levels of HREE price change

distributions, the experts appear to have estimated somewhat more modest material content decreases but with slightly more certainty. For a 1000 percent increase in the price level, the experts predict a decrease in Dy content to about 1.8 percent. Interestingly, in the event of a price decrease, the median estimate for the FP distributions decreases to 3.4 percent. Overall, the distributions elicited with the FP method indicate tighter bounds and a higher degree of confidence, despite being slightly less optimistic.

The aggregated PMFs and PDFs are bimodal for both methods (especially for the FV method), largely due to the estimates provided by Expert 1, who was substantially more pessimistic than the others and more accepting of potential Dy content increases. Baker et al. [74] note that while multimodal distributions arising from the aggregation of opinions of experts from different schools of thought might reflect the multimodal distribution of opinions, it is more likely they result from overconfidence by some of the experts. Keith [77], on the other hand, argues that aggregating distributions of experts with opposing views potentially misrepresents amount of uncertainty, since consensus does not necessarily imply correctness. Note the bimodal distribution provided by Expert 5 (depicted in Figure 3) is deliberate, as this expert insisted that, regardless of material costs, there was an equal probability (0.5) that manufacturers would either be able to reduce the Dy content of the reference magnet to one percent through the grain boundary diffusion process, or to 0.4 percent or less if efforts to reduce impurities from the manufacturing process are successful in the future.

Figure 3.8 shows the inferred long run demand curves for Dy in the reference magnet using the experts' 50th percentile estimates from the FP method. On average, the experts estimate it would take a Dy price of \$1,500/kg (an increase of 500 percent) to see a halving of the HREE content in the reference magnet to 1.9 percent weight. Much of this reduction is due to process-for-element substitution, but not entirely. On average, the experts estimate nearly a 25 percent reduction in total HREE content even if prices remain

the same due to technological improvements and improved efficiency. They estimate a Dy reduction to 3.2 percent if the Dy price remains near \$250/kg and a reduction to 3.4 percent even if the Dy price falls by 50 percent. According to the model described in Section 2, this is evidence of technological change (improved manufacturing efficiency) combined with substitution. In the event of a substantial price increase of 1000 percent to \$2,750/kg, the experts collectively believe manufacturers would be able to reduce the HREE content in the reference magnet to between 1.1 and 2.6 weight percent over the following five years (representing their 10th and 90th percentile estimates, respectively).

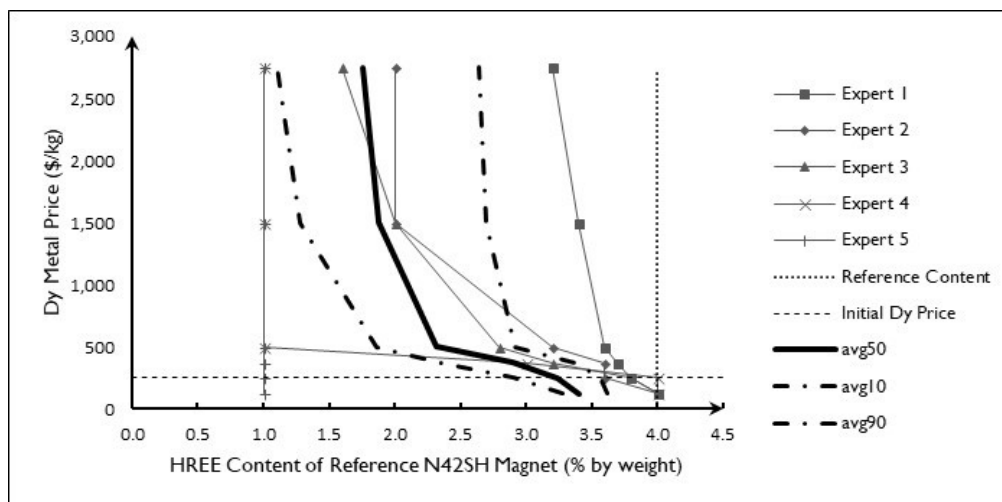


Figure 3.8: Inferred long run conditional demand curves for Dy in the reference magnet for different HREE price levels (elicited via the FP method)

Clearly experts 4 and 5 both believe NdFeB manufacturers would be able to reduce the total HREE content of the reference magnet from four percent to one percent without substantial price increases such as those in 2010-2011. Expert 4 believes it would take a doubling in HREE prices, whereas Expert 5 believes there is a 50 percent chance the content would decrease to one percent though technological improvements alone, independent of price changes. Experts 2 and 3, while less optimistic than experts 4 and 5, believe in a more modest 50 percent decrease to two percent weight if the Dy price increased to \$1,500/kg (500 percent increase). Expert 1, clearly the most pessimistic of the experts, asserted that the Dy prices would have to increase by 1000 percent (to \$2,750/kg) to observe an HREE content reduction of 20 percent to 3.2 percent weight over the next five years.

3.4.2 Process- vs. Element-for-Element Substitution

Up to this point, the discussion has focused solely on joint movements in HREE prices; that is, it has assumed that both Dy and Tb prices have increased together and reductions in HREE content occur mostly

through process-for-element substitutions and improvements in manufacturing efficiency. While a reasonably realistic assumption, it is nonetheless possible that prices of the two elements could become disentangled. For example, if demand for Tb in phosphors for fluorescent lighting decrease due to transformations to solid state lighting [82], Tb may become substantially less expensive in the future. In such a case, Tb could become a potential substitute for Dy in high grade NdFeB magnets if it were less expensive. As expected, when evaluating the influence of Dy and Tb prices separately, the demand for Dy in the reference magnet becomes somewhat more responsive to price changes since Tb is considered a perfect substitute for Dy [51].

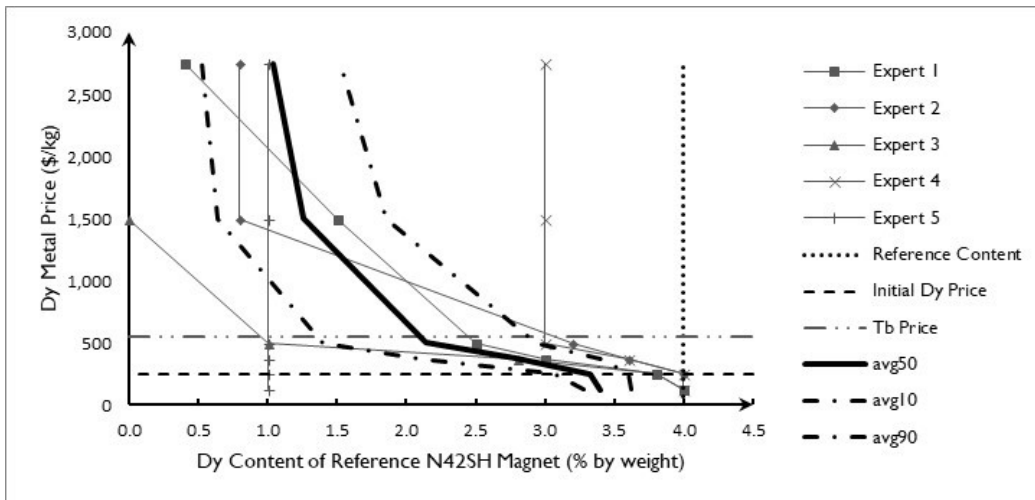


Figure 3.9: Inferred long run demand curves for Dy in the reference magnet for different Dy price levels (elicited via the FP method)

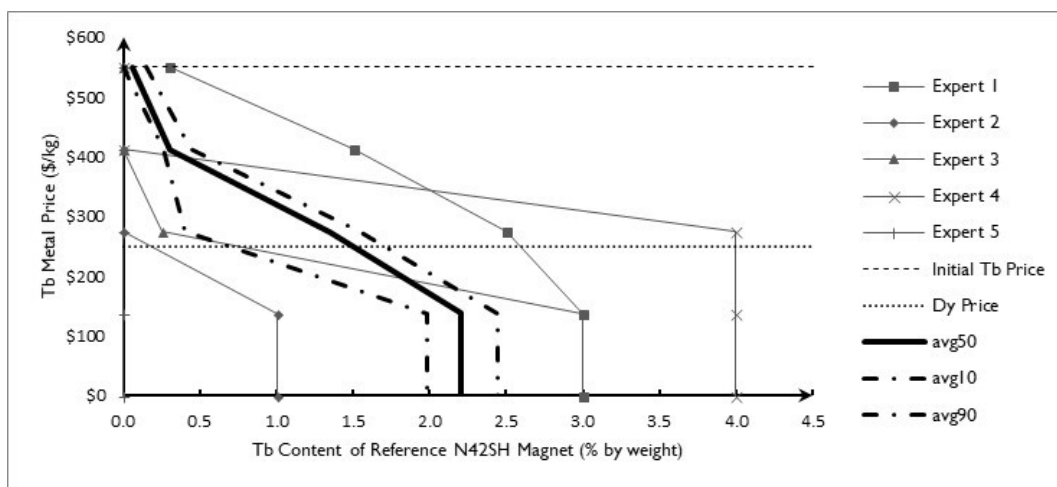


Figure 3.10: Inferred long run demand curves for Tb in the reference magnet for different Tb price levels (elicited via the FP method)

Figure 3.9 and Figure 3.10 show the long run demand curves for Dy and Tb (respectively) in the reference magnet. For Dy price increases where the Tb price remains constant at \$550/kg (Figure 3.9), demand for Dy in the reference magnet falls to almost two percent as the Dy price approaches \$500/kg. For a substantial price increase, Dy content falls to about one percent. There is a fairly wide range of opinion among the experts as to the degree of Tb substitution that would take place. Expert 3 believes Tb would completely replace Dy in the reference magnet if Dy is more expensive, while experts 1, 2, and 4 think Tb would replace some, but not all, of the Dy. Expert 1 remains steadfast in the belief that the Dy content of the magnet will fall to one percent and Tb will remain at 0 percent, regardless of Dy and Tb prices.

3.4.3 Price Elasticities of Demand

As discussed in Section 2, the price elasticity of demand measures the price responsiveness of users of a good. As shown in Figure 3.8, the long run demand curve for HREEs based on the experts' 50th percentile estimates is downward sloping and nonlinear. The price elasticity of demand is not constant as is often assumed in simulation models. The demand curve is clearly much less elastic at higher prices, with only minor reductions in HREE possible above a Dy price of about \$1,500/kg. The elasticities were indirectly elicited from each expert by asking for the price quantity pairings. Since there is evidence that it is generally better to aggregate expert's responses earlier rather than later [83], the FP responses were used to calculate elasticity distributions for each expert before aggregating them (rather than calculating the elasticities for the aggregate long run demand curve shown in Figure 3.8). The 10th, 50th, and 90th percentile elasticity estimates for each price interval are shown in Table 3.2 and the values evaluated from the initial point (as provided by the experts) are shown in Table 3.3.

Table 3.2: Elasticity estimates by Dy price interval

<i>Dy price (\$/kg)</i>	<i>10th percentile</i>	<i>50th percentile</i>	<i>90th percentile</i>
\$125-\$250	-0.10	-0.04	-0.01
\$250-\$375	-0.29	-0.17	-0.09
\$375-\$500	-0.67	-0.56	-0.38
\$500-\$1,500	-0.11	-0.07	-0.03
\$1,500-\$2,750	-0.14	-0.06	-0.02

The estimated elasticities evaluated at both each interval and from the initial point are inelastic at all price levels, however, they are more elastic for price changes between 50 and 100 percent. For both very small and very large price changes, Dy demand is almost perfectly inelastic. According to these estimates, the experts seem to indicate that magnet manufacturers will be most responsive to Dy prices near \$500/kg but will respond fairly modestly for smaller price increases. Furthermore, for large increases above 500 percent,

Table 3.3: Elasticity estimates by level of price change from initial Dy price of \$250

<i>Dy price (\$/kg)</i>	<i>% Change</i>	<i>10th percentile</i>	<i>50th percentile</i>	<i>90th percentile</i>
125	-50%	-0.23	-0.09	-0.03
375	+50%	-0.29	-0.17	-0.09
500	+100%	-0.28	-0.24	-0.16
1,500	+500%	-0.09	-0.07	-0.04
2,750	+1000%	-0.05	-0.04	-0.02

their ability to respond is limited. As any doubling of prices guarantees an inelastic demand response by definition [51], it is possible these results are somewhat driven by the elasticity equation itself. However, this mostly pertains to the estimates in Table 3.3, as those in Table 3.2 are calculated for each price step.

Future work in elasticity quantification could involve constructing a large dataset of pseudo price/quantity responses based on the distributions obtained from the experts to be used in a regression model. That is, the pseudo dataset could be constructed to represent a population of price/quantity responses where the distribution is known. A sample could then be randomly drawn with replacement. A regression model could be estimated on the new dataset to determine own and cross price elasticity estimates which incorporate the expert data obtained from both FP and FV methods.

3.4.4 Comparison of Methods

Both the FP and FV methods reflect similar results, though there are some important differences, and each has important advantages and disadvantages for elasticity estimation. Interestingly, despite both methods being used as a consistency check for the experts, the experts reflected differing degrees of uncertainty between the two. The FP method yielded less uncertainty, while the FV method results showed uncertainty encompassing nearly the entire range of responses. It is not immediately clear why this is the case. The FV method is the more natural of the two in terms of how people generally assess uncertain situations yet relies on the ability of the experts to accurately reflect their beliefs as probabilities. The FP method, while less natural, encourages the experts to think carefully about the bounds around the quantity as well as the shape of the distribution. Both suffer from some degree of anchoring bias: the FV method could lead experts to anchor on the values provided in the survey, while the FP method could lead them to anchor on the median they provide themselves.

The FP method allowed for questions about material reduction to be asked in two different ways, which allowed for flexibility with the experts but may also have created some variation between responses. The first way is to ask directly for the expert's p th percentile guess for what the actual material content would be under various prices (e.g. three percent, rather than four percent, material content). The second way is

to ask for the percentage change from the initial material content (e.g. decrease of 25 percent, indicating a material content of three percent). The latter method was used in most cases, except where it was easier for the expert to answer in the former.

In terms of estimating demand curves and calculating elasticities, the FP method is more direct in that it allows distributions to be compared consistently across experts. That is, it allows for the creation of Figure 3.8, Figure 3.9, and Figure 3.10 and for the calculation of the elasticities in Table 3.2 and Table 3.3. The FV estimates are more conducive to the linear opinion pool to obtain an aggregate distribution, as shown in Figure 3.2 through Figure 3.5. Overall, the FV method was far simpler to explain to the experts and was easier to conduct from an elicitation perspective, while the results from the FP method were more tractable. An additional advantage of the FV method is the ability to incorporate deliberate bimodal distributions from the experts. Such was the case for Expert 5, who believed in a 50/50 chance of two specific outcomes. The FP method was not able to incorporate this belief.

3.4.5 Comparisons to Other Work

While there are a large number of both material substitution and expert elicitation studies, there are few which are directly comparable to this work. As far as expert elicitation studies, this appears to be the first which uses these techniques to estimate demand and price elasticities. Interestingly, the elasticity estimates for HREEs in the reference magnet are reasonably close to most elasticity estimates in the economics literature, which are generally near -0.5 [84].

As far as disaggregated material substitution studies are concerned, this study differs in its direct estimation of forward looking price elasticities of demand. Most disaggregated studies, including this one, rely on formal expert consultation as they are not able to use econometric methods due to a lack of data at the detailed level [22, 21, 41, 51]. Other studies in the industrial ecology literature have attempted to quantify material substitutability in critical and strategic materials [4, 9, 10, 85], but have defined substitution more narrowly and have not attempted to estimate elasticities of demand. These studies provide useful estimates for use in material criticality studies, but their usefulness in simulation models (such as computable general equilibrium, systems dynamics, and agent-based models) is limited [4]. The elasticities estimated in this work are better suited to use in such models.

3.5 Conclusions and Limitations

This paper assesses the potential ability of producers to respond to future sustained cost increases of material inputs—specifically the ability of rare earth magnet manufacturers to respond to heavy rare earth price increases in the future. This question is answered by applying expert elicitation techniques to esti-

mate long-run demand curves and elasticities. To the knowledge of the authors, this is the first study to use such techniques to calculate price elasticities of demand, providing an example of price responsiveness quantification for highly disaggregated industries with poor data availability. Furthermore, the elasticities are forward-looking and not based on estimates using historical data.

The results indicate that significant increases in heavy rare earth prices would induce reductions in the heavy rare earth content in NdFeB magnets over the following five years, though the response is inelastic and would not solely occur through substitution. According to the experts, manufacturers are most responsive to price changes between 50 and 100 percent, where manufacturers may be able to reduce heavy rare earth content by about 43 percent but are limited for more significant price changes. For such changes, the experts indicate on average that heavy rare earth content could be reduced by about 55 percent. If dysprosium and terbium prices were to become disentangled, manufacturers could substitute some terbium (or some other heavy rare earth) for dysprosium if dysprosium were to become relatively more expensive.

While providing some evidence that materials are potentially more substitutable in their end-uses than is often assumed, there are several limitations to this work. Most obvious is small sample size and the biases associated with conducting expert elicitation studies. Rather than relying on actual data, findings are drawn from the collective opinion of prominent industry experts. Care was taken to minimize expert bias through the probability primer and practice questions as well as through the definition of the reference magnet and using multiple elicitation techniques. While providing a consistent benchmark, the reference magnet is also somewhat limiting in that all expert responses pertain to this singular model. In spite of these limitations, the results generally reflect the leading opinions of industry stakeholders for how the industry would attempt to respond to sustained material cost increases in the future.

CHAPTER 4

DOES PARTICIPATION IN UTILITY GREEN PRICING PROGRAMS DELAY OR REDUCE THE ADOPTION OF NET METERS?

An paper prepared for journal submission.

Braeton J. Smith⁶ and Ian A. Lange⁷

Abstract: The electricity sector has undergone large changes in the last decade. One of the main causes of this change is the reduced price, and increased installation, of renewable energy. Utilities and policymakers utilizes two different programs to encourage residential investment in renewables: net metering and green pricing programs. This research analyzes whether the presence of green pricing programs acts as a substitute for net metering programs. Results indicate that the presence of a popular green pricing program, defined as a high share of customers enrolled, leads to a delay in the start of a net metering program. Similarly, less customer’s sign up for net metering programs if there are many customers in the green power program in states with no state-wide mandatory green pricing option.

4.1 Introduction

Clean energy technologies emit fewer life-cycle emissions than fossil fuel-based technologies, reducing pollution from electricity production. Yet despite becoming relatively cheap in recent years [86], these technologies still place certain burdens on electric utilities and are debated heavily in state politics. Renewable standards can be met through the deployment of either grid-scale “macro” projects or through distributed generation, such as residential solar or microgrids. These options impose different costs on electric utilities, which in turn influences the availability and attractiveness of policies offered by utilities to their customers. Customers with preferences for clean energy have the option in many states to install residential solar through a net metering program or participate in green pricing programs to ensure the amount of electricity they consume comes from renewable sources. This paper evaluates how participation in green pricing programs influences the adoption of net meters (that is, customers with residential solar) by households in a utility’s service area.

Net metering programs allow customers to sell power back to the utility at set prices to help offset the costs of electricity purchased from the utility. Several studies have investigated the impact of distributed micro renewables, namely residential solar, on utility and social costs. Schmalensee [87] and colleagues at the

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MIT Energy Initiative [88] conclude that distributed solar is relatively inefficient compared to grid-scale solar, as the levelized costs for the latter are much lower. Due to the difference in wholesale and retail electricity prices, they note that net metering customers are paid a much higher price than grid-scale generators, which subsidizes residential solar over other technologies and shifts system costs to customers without net meters. Borenstein [89, 90] likewise finds that residential solar is more costly, even after accounting for the social cost of carbon, and that, generally speaking, more affluent customers reap most of the benefits associated with net metering programs. Satchwell et al. [91], however, estimate that even a large penetration of residential solar would have a relatively modest impact on retail rates paid by ratepayers in aggregate. They find that residential solar reduces utility (and shareholder) revenue but can also decrease overall system costs. Additionally, there is the potential resiliency benefit of a distributed grid that comes from micro-renewables that would not occur with grid-scale renewables.

Green pricing programs, by contrast, provide customers a way to support utility investment in renewable energy through a voluntary premium on their electric bill. Where they exist, these programs provide (in some sense) an alternative to net meters for customers and place an emphasis on large grid-scale projects rather than distributed generation. Green pricing, described by Moskovitz [92], allows for private citizens to internalize the extra costs of their environmental preferences without imposing them on others. Not all green pricing programs are created equal, however, as program participation rates vary considerably [93]. Such programs also capture the willingness-to-pay for renewable energy by customers [94].

The purpose of this paper is to examine how participation in green pricing programs influences the adoption of net meters. It is concerned with how customers “substitute” between multiple options to meet their consumption of environmental goods. The paper evaluates the effects of green pricing on net metering at both the extensive and intensive margins—that is, the rate at which participation in green pricing programs influences the first customer to adopt net metering at the utility as well as total net metering customers per utility. To measure the extensive margin, the study uses a proportional hazard model, akin to those employed by Knittel [95], Lyon and Yin [96], and Jenner et al. [97], to determine if the time to first net metering customer is impacted by the presence and/or popularity of a green pricing program. For the intensive margin, the analysis relies on the use of a more traditional reduced-form fixed effects model to determine whether the number of households in a utility’s net metering program is related to the number of customers in their green pricing program. A two-part model is also estimated to supplement the main results.

This work contributes to the energy economics literature on energy policy adoption. It evaluates the substitution effects associated with the presence of two policies with similar goals, but with drastically different implications. Rather than focusing on utility and social costs, policy incidence, distributional

impacts, or policy effectiveness, this work is concerned with quantifying trade-offs. This is of potential value to both regulatory agencies with specific policy goals in mind and to utilities trying to meet policy obligations while keeping costs just and reasonable. This study is also among the first studies to evaluate which factors lead to the adoption of net metering in addition to the influence of green pricing.

An important aspect of the tradeoff between green pricing and net metering programs is that they facilitate a different scale of renewable electricity generation. Green pricing programs provide support for macro- or utility- scale renewables. These generally have a lower cost of generation per MWh than the micro-renewables installed with a net metering program. Thus, if one is concerned about providing green electricity at the lowest cost, a green pricing program would be preferred. However, green pricing programs work through the utility and generally support centralized electricity generation while net metering programs help decentralize the grid by having smaller sources available at more local levels. Green pricing programs also rely on those with a high willingness-to-pay to provide a positive externality and are thus subject to free-riding [98, 99, 100].

The results show that there is both an extensive and intensive margin effect of participation in green pricing programs on net metering programs. For utilities with a large share of households enrolled in a green pricing program, the year in which households first adopt net meters statistically increases. On the intensive margin, the number of customers enrolled in a utility’s green pricing program reduces the number of customers enrolled in that utility’s net metering program, though the number only holds for utilities in states with no mandatory green pricing policy. While the mechanism that leads to this reduced availability and participation in net metering programs is unclear, the results reveal that green pricing programs generally do “crowd-out” net metering when there is significant enrollment.

The next section provides a background on net metering and green pricing programs and gives a conceptual framework as to how the two programs act as substitutes for a household’s desire for green electricity. Section 4.3 discusses the empirical methods and data. Section 4.4 provides the results of the analysis while Section 4.5 concludes and provides a discussion of the limitations of the work.

4.2 Conceptual Framework

Green pricing programs began as a way for utilities to provide their consumers a choice of electricity attributes. In these programs, customers pay an extra fee per kWh per month and are ensured that this money goes to purchasing energy from macro-renewables sources. Generally, green pricing programs began in states that deregulated their electricity sector and offered some form of retail choice to their citizens. The popularity of these programs spread and by 2005 there were about 450,000 customers on a green pricing program, accounting for about 0.89% of total residential electricity sales [101].

Net metering’s genesis is in the Public Utilities Regulatory Policies Act (PURPA) of 1978 [102]. As states began to implement aspects of PURPA, they saw net metering as a way to encourage new sources of energy onto the electricity grid [103]. For many years, the cost of renewable technologies was prohibitive for households to install themselves with net metering. This changed in the late 2000s as the falling price of solar panels, along with state and federal incentives, made it economical for households to install micro-renewables with net metering. The popularity of net metering programs increased considerably in the early 2010s such that states started to restrict the terms allowed in net metering contracts in order to curb the growth in participation.

If budget constrained households have a preference for green electricity, then green pricing and net metering programs are substitutes to fulfill those preferences. Households may hold other preferences like an aversion to up-front costs due to hyperbolic discounting or preference for independence from the grid, but the basic premise of the argument remains unchanged—the household’s preferences simply tilt towards one of the options. Given this substitutability, one would expect that the presence of one of the programs would detract from the interest and participation in the other program.

Figure 4.1 shows the total number of U.S. customers enrolled in net metering and green pricing programs between 2002 and 2012. By 2012, over 2.1 million households in the U.S. were enrolled in some type of green pricing program, while there were only about 300 thousand net meters nationwide. Figure 4.2 shows the proportions of U.S. utilities that had at least one net metering customer and at least one green pricing customer between 2002 and 2012. Interestingly, while green pricing programs were substantially more popular among customers, more utilities had customers with net meters from 2010 onward. This suggests that net metering programs were becoming increasingly widespread, if not popular.

As the figures and discussion above show, green pricing programs became widespread before net metering programs did. Thus, this work hypothesizes that the presence and popularity of existing green pricing programs can delay the onset and utilization of net metering programs. The presence of a green pricing program can allow a utility to delay the onset of a formal net metering program if the green pricing program limits customer interest in net metering or provides energy regulators with a reason to put less pressure on the utility (an extensive margin effect). Alternatively, an intensive margin effect may occur if the presence or popularity of a green pricing program limits the number of households who sign up for net metering due to their demands for green electricity being satisfied. The goal of this analysis is to empirically test whether the popularity of green pricing programs delays the onset of a formal net metering program and whether their popularity reduces the number of households who sign up for net metering.

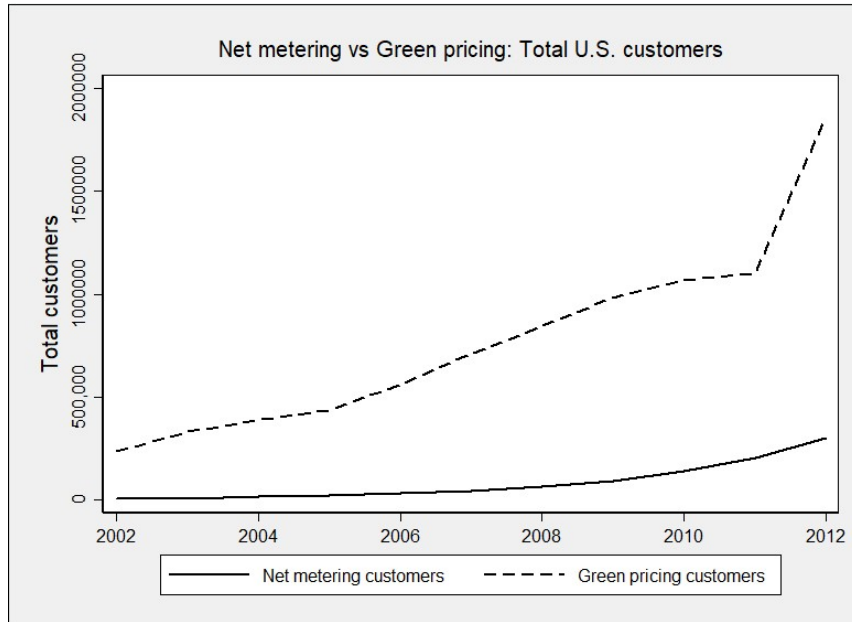


Figure 4.1: Total U.S. customers enrolled in net metering and green pricing programs, 2002-2012

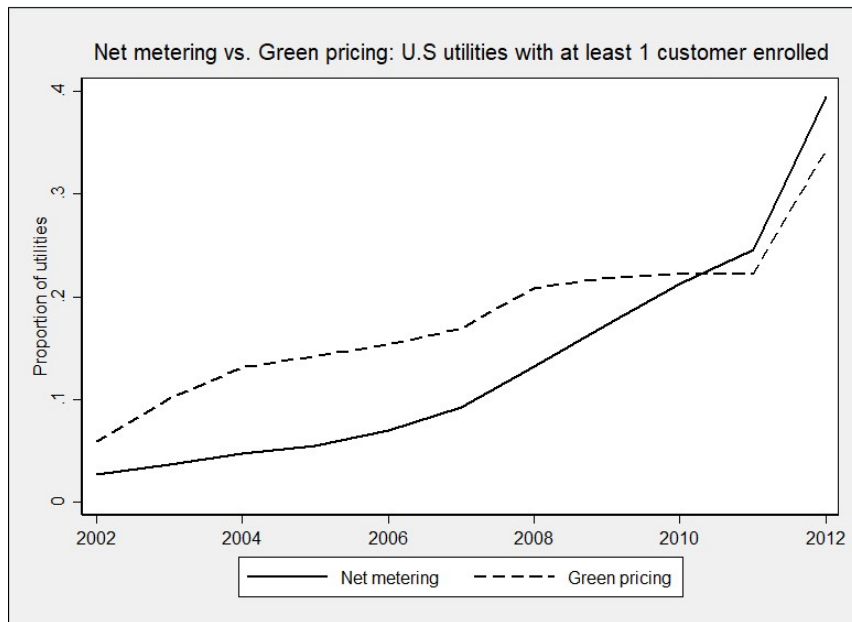


Figure 4.2: Proportion of U.S. utilities with at least one customer enrolled in net metering and green pricing programs, 2002-2012

4.3 Empirical Methods

The modeling framework allows for the measurement of both the extensive and intensive margins, as with the work of Davis and Gertler [104] on air conditioner adoptions and climate change and works in the international trade literature [105]. In this case, the extensive margin examines how participation in green pricing programs (and other factors) drives or delays the adoption of net meters by customers in a service area. The intensive margin examines the extent (i.e. the impact on the number of customers). The two measures are modeled separately as a proportional hazards model and a fixed effects model, respectively.

4.3.1 Extensive Margin: Proportional Hazards Model

Modeling the extensive margin follows from the work of Kiefer [106], who introduced hazard models for use with economic duration data. As with the energy policy adoption work of Knittel [95], Lyon and Yin [96], and Jenner et al. [97], the data used in this analysis is grouped annually with a large number of ties for the first adoption of a net meter. Thus, this study uses the commonly used proportional odds model for grouped data and follows a similar approach to those works.

The adoption of net metering by at least one customer in utility i 's service area is modeled as a discrete event which occurs in year t , given no customers had net meters in year $t - 1$. Utilities with net metering customers prior to the initial year $t = 0$ are not included in the sample, and utilities are not included in the sample for years after the first customer in their service area installs a net meter. The proportional hazards model tests the effect of explanatory variables X_{it} on the relative odds of utility i to have at least one net meter in year t , given it had zero net metering customers in the previous year (also known as the hazard function $\lambda_{it}(t, X_{it})$), and is expressed as:

$$\frac{P(t, X_{it})}{1 - P(t, X_{it})} = \frac{P_0(t)}{1 - P_0(t)} * \exp(\beta' X_{it} + \varepsilon_{it}) \quad (4.1)$$

Where $P(t, X_{it})$ is the conditional probability of utility i to have at least one net meter in year t and $P_0(t)$ is the baseline conditional probability of initial net meter adoption when the explanatory variables are equal to zero. This expression implies that the relative odds of a customer in utility i 's service area adopting net metering is equal to a baseline relative odds ratio (or baseline hazard) that is constant across all utilities in the sample multiplied by a utility-specific scaling factor. The exponential scaling factor applied in this instance is a commonly used specification in research using duration data [97]. Taking the log of the above expression yields:

$$\log\left(\frac{P(t, X_{it})}{1 - P(t, X_{it})}\right) = \log\left(\frac{P_0(t)}{1 - P_0(t)}\right) + \beta' X_{it} + \varepsilon_{it} \quad (4.2)$$

$$\text{logit}(P(t, X_{it})) = \gamma_t + \beta' X_{it} + \varepsilon_{it} \quad (4.3)$$

Where $\gamma_t = \text{logit}(P_0(t))$. In practice, γ_t takes form as the natural log of the survival time t , yet the results are consistent across different specifications. It is also possible to fit a non-parametric specification that allows the baseline hazard to vary across time intervals (assumed to be constant within a single time period) by using year fixed effects [95]. The effect of X_{it} on the “hazard” of net metering adoption $\lambda_{it}(t, X_{it})$ is equal to β :

$$\frac{\delta \log\left(\frac{P(t, X_{it})}{1-P(t, X_{it})}\right)}{\delta X_{it}} = \beta \quad (4.4)$$

That is, a one-unit change in the value of X_{it} changes the probability of at least one household in utility i 's service area installing residential solar in a given year by β .

4.3.2 Intensive Margin: Fixed Effects Model

The intensive margin is more straightforward, as it simply measures the size of the effect. That is, it is concerned with the overall effect the total number of green pricing customers has on the number of net meters. In keeping with the logic laid out in Section 2, one might expect more green pricing customers to be associated with fewer net metering customer as household it is reasonable to assume that customers who choose to enroll in a green pricing program will not feel the need to enroll in a net metering program, and vice-versa, and will exercise their preference for clean energy by choosing one option or the other. The intensive margin is modeled as a reduced-form fixed effects model which estimates the effect of participation rates in green pricing programs on total net meters. It takes the form:

$$\ln(NMC_{ust_{it}}) = \alpha + \psi_1 \ln(GPC_{ust_{it}}) + \psi_2 \ln(C_{ust_{it}}) + \psi_3 \ln(p_{it}) + \beta' Z_{it} + a_i + \mu_t + \varepsilon_{it} \quad (4.5)$$

Where $NMC_{ust_{it}}$ is the number of net metering customers served by utility i in year t , $GPC_{ust_{it}}$ is the number of customers enrolled in a green pricing program with utility i in year t , $C_{ust_{it}}$ is the total number of customers, p_{it} is the average residential electricity price, Z_{it} is a vector of control variables (discussed in greater detail below), a_i is a utility-specific fixed effect that does not vary over time (e.g. if the utility is regulated for the duration of the sample), μ_t is a year-specific fixed effect that affects all utilities equally, and ε_{it} is the idiosyncratic error. If green pricing is a substitute for net metering, ψ_1 , which serves as a type sort of elasticity of substitution between the two programs, will be negative. The coefficients on log of total customers and electricity price are expected to be positive.

4.3.3 Variables and Data

The dataset is comprised of an unbalanced annual panel of all electric utilities in the U.S. that provided delivery service over the period from 2002 to 2012 for which there is a complete series (that is, only utilities with no reporting gaps). The full dataset consists of 33,157 observations total.

4.3.3.1 Explanatory Variables

Data for utility revenue, sales, total customers, net-metering customers, and green pricing customers are from the U.S. Energy Information Administration's (EIA) Annual Electric Power Sales, Revenue, and Energy Efficiency Data series (Form 861). All data are for the residential sector at the utility level and excludes utilities that do not provide delivery and billing services (data are aggregated for each utility reporting on Form 861 Schedule 4 parts A, C, and D; B is excluded). Because the EIA discontinued collecting data on participation in green pricing programs after 2012, it is the final year in the dataset (data for green pricing and net metering customers begins in 2002). Additionally, the EIA introduced the optional 861 Short Form (Form 861S) in 2012, which does not distinguish between customers of different sectors. About 1,100 utilities drop out of the dataset in 2012 as they opted to complete Form 861S instead.

Several variables were created from the EIA Form 861 data. The dependent variable in the extensive margin model (*DNM*) is an indicator variable equal to one for a given utility and year if the utility had at least one net metering customer in that year and zero otherwise. A similar indicator variable was created for green pricing customers (*DGP*). The share of green pricing customers (*GPSHare*), the main explanatory variable of interest in the extensive margin model, is green pricing customers for each utility and year divided by the utility's total customers in that year. Lastly, the average residential electricity price (*Price*) for each utility in each year was calculated by dividing each utility's annual residential revenue by that year's residential sales. The natural log was taken of both *GPSHare* and *Price*, adding one to each before the log transformation to avoid negative and missing values.

The main explanatory variables for the extensive margin model (i.e. the proportional hazards model) are the natural log of *GPSHare*, *DGP*, and the natural log of *Price* (included in both models). The sign on *GPSHare* is expected to be negative, reflecting the central thesis of this paper: that the more popular a green pricing program, the longer it takes for net meters to be adopted. The sign on *DGP* is unknown, as a negative sign would provide further evidence of a possible substitution effect between net metering and green pricing, while a positive one might provide a control for the underlying political beliefs of the utility's customer base. Clearly price is expected to have a positive coefficient in both models, under the assumption that higher electricity prices would encourage customers to reduce their electric bill through net metering.

As discussed in the previous section, the main explanatory variables for the intensive margin model (i.e. the fixed effect model) are the natural logs of $GPCust$ (the number of green pricing customers), $Cust$ (the total number of customers), and residential electricity price. The sign on $GPCust$, if negative, would provide evidence of a substitution effect between popular green pricing programs and the prevalence of net metering. $Cust$, as a simple measure of population for the utility, is expected to be positive, since more households in an area naturally implies there will be more households with net meters.

4.3.3.2 Control Variables

In addition to the main explanatory variables discussed above, there are also several control variables included in both models. The controls used in this analysis are related to those that have been found to be significant in literature examining the determinants of renewable portfolio standard (RPS) adoption. Some typical determinants of RPS adoption include personal income [96, 97, 107], some measure of the political makeup of the region [96, 97, 108], renewable energy potential [96, 97, 109], previous fossil fuel and renewables capacity [96, 108], years of existence of local solar energy advocacy group [96, 97], unemployment rate [96, 97, 110], and others. In this work, measures for the first three factors are used since data are readily available and they are directly relevant to a household's choice to install a rooftop solar.

Annual median household income by state was collected from the U.S. Census Bureau. To capture political factors which might explain the environmental preferences of the residents of each state, annual partisan composition of state legislature data was collected from the National Conference of State Legislatures (NCSL) for 2002-2012. The variable Dem is equal to one if the legislature (both houses where relevant) was controlled by Democrats in a given state and year (as defined by NCSL), and 0 otherwise. Data for solar intensity measured by direct normal irradiance (DNI) was collected from the National Renewable Energy Laboratory (NREL). Annual averages are used for each state and are constant over time (since data for Alaska are not available, the national average was assumed). NREL does provide estimates for DNI by county which could be potentially mapped to each utility's service area. This is time-intensive, however, and may only marginally improve the power of this control variable. The signs on all three variables are expected to be positive in both models.

In addition to the three controls discussed, this analysis also includes three policy indicator variables which might have an impact on net metering adoption. These include the state-wide existence of an RPS, a state-wide mandate to utilities to offer a green pricing program (of which there are currently only eight), and a state-wide net metering policy. Policy data were collected from the North Carolina Clean Energy Technology Center's Database of State Incentives for Renewable Energy (DSIRE). For each policy type, the indicator variable is equal to one if the policy existed at the state level in a given year, and 0 otherwise. For the net

metering policy, many states defer to PURPA, which requires utilities to allow net metering installations, while others have more targeted policies. For assignment of the net metering policy variable, this analysis defers to DSIRE’s assigned “created” date. Table 4.1 provides the abbreviations and descriptions of all variables.

Table 4.1: Variable names and descriptions

<i>Variable Name</i>	<i>Description</i>	<i>Variable Name</i>	<i>Description</i>
DNM	Equal to 1 if utility has > 1 net metering customer (by utility and year)	Income	Median household income (\$2016) (by state)
DGP	Equal to 1 if utility has > 1 green pricing customer (by utility and year)	DNI	Average annual direct normal irradiance (kWh/m ² /day) (by state); measure of solar energy potential
NM Cust	Number of net metering customers (by utility and year)	Dem	Equal to 1 if state legislature control by Democratic party (by state and year)
GP Cust	Number of green pricing customers (by utility and year)	PNM	Equal to 1 if state-wide net metering policy (by state and year)
Cust	Total number of residential customers (by utility and year)	PGP	Equal to 1 if state-wide mandatory green pricing option (by state and year)
GP Share	Share of customers enrolled in green pricing program (by utility and year)	PRPS	Equal to 1 if state-wide renewable portfolio standard (by state and year)
Price	Average residential electricity price (\$/kWh) (by utility and year); (Revenue/Sales)		

4.4 Results and Discussion

The estimation results generally confirm the hypothesis that the popularity of green pricing programs hinders the initiation of net metering customers. A one percent increase in the share of green pricing customers decreases the odds (i.e. the hazard) of net metering adoption in a given year by 12.1% to 12.5%, other things equal. That is, it increases the amount of time until first net metering customers. Similarly, an increase in the total number of green pricing customers in general decreases the total number of net meters in states where there is no requirement for utilities to offer a green pricing program.

4.4.1 Extensive Margin Results

Implementation of the proportional hazards model requires that the data be censored in order to not bias the coefficients. Specifically, any utilities that had net metering customers prior to 2002 were dropped from the sample. Observations were also dropped for years following their exposure to net metering. The sample size for the proportional hazards models in this case is 29,551 (down from 33,157).

The results from the proportional hazards models (shown in Table 4.2) show that there is indeed evidence of an extensive margin effect. Results are robust across specifications, including parametric and non-parametric specifications. Models 1 through 3 are non-parametric models in that they make no assumption about the shape of the baseline hazard function and instead assume discrete year fixed-effects (and no constant term). The parametric models (models 4 and 5) assume the baseline hazard function takes form as the natural log of failure time and are nearly identical to specifications with other assumptions about the shape of the baseline hazard (not shown). In all cases the explanatory variables of interest consistently have the same sign and are highly significant, regardless of the inclusion of the control variables or state fixed effects. Furthermore, the results are also consistent under the assumption of a complementary log-log model and the Cox proportional hazards model for continuous time data. They are also consistent with the continuous variables in levels instead of logs and The main results are also consistent when data for 2012, which is incomplete, is excluded. All standard errors are clustered at the utility level, and the coefficients are consistent when clustered at the state level.

Table 4.2: Proportional Hazard Model Results (Model Coefficients)

Explanatory Variables	(1) DNM	(2) DNM	(3) DNM	(4) DNM	(5) DNM
DGP	1.618*** (0.082)	1.729*** (0.091)	2.033*** (0.106)	1.685*** (0.090)	1.996*** (0.105)
ln(GP Share)	-7.494*** (2.666)	-16.420*** (4.637)	-13.295*** (4.502)	-16.565*** (4.686)	-12.855*** (4.502)
ln(Price)	1.861*** (0.462)	1.574*** (0.520)	5.644*** (1.954)	1.830*** (0.515)	5.978*** (1.981)
Controls?	No	Yes	Yes	Yes	Yes
Year FE?	Yes	Yes	Yes	No	No
State FE?	No	No	Yes	No	Yes
Parametric?	No	No	No	Yes	Yes
Model	Logit	Logit	Logit	Logit	Logit
Observations	29,551	29,551	29,551	29,551	29,551

Standard errors in parentheses, clustered at utility level. Controls include: PNM, PGP, PRPS, ln(DNI), ln(Income), Dem, and ln(Yr) and a constant for the parametric specifications.

* p<0.10, ** p<0.05, *** p<0.01

The most interesting result is clearly the effect of the share of green pricing customers on the rate of first net metering adoption. The negative coefficients imply that as the share of households enrolled in green pricing programs in a utility's service area increases, the year in which a utility begins a net metering

program statistically increases. That is to say, the higher the share of green pricing customers, the lower is the “hazard” of net metering adoption occurring in a given year. Models 3 and 5 contain all controls as well as state fixed effects, so the remainder of the discussion will focus on these models.

Models 3 and 5 imply that for a one percent increase in the share of green pricing customers, the odds of net metering adoption in a given year decrease by 12.1% and 12.5%, respectively, other things equal. This implies that increases in the share of green pricing customers generally delays the onset of net metering by the utility’s customers. *DGP*, by contrast, is positive and significant in all of the models, implying that if a utility has at least one green pricing customer, they are more likely to also have net metering customers. At first glance this result appears to contradict the main finding; however, the significance of *DGP* may imply that utilities in areas with strong environmental preferences tend to offer (and have customers enrolled in) both programs. The odds of a utility offering a green pricing program to have a net metering adopter (versus a utility with no green pricing program) is between 7.35 (for Model 5) and 7.64 (for Model 3). This implies that utilities with green pricing programs are around 650% more likely to have net metering adopters in a given year than utilities with no green pricing program (other things equal).

Taken together, these results imply that a utility with a green pricing program is substantially more likely to have at least one net metering customer, however, if the program is reasonably popular, the likelihood of net metering adoption decreases. Evaluated together (and under the assumption that all other variables are zero), on average utilities must have over 16.5% of their total customer base participating in their green pricing program in order to delay the adoption of net metering according to Model 3 (solving for the point where $\lambda_t = 0$, *GPShare* must be equal to $\exp(-\beta_0/\beta_1)$ when only accounting for only these two variables). Thus, a green pricing program must be reasonably popular to inhibit the adoption of net meters, but not prohibitively so. For utilities with under 16.5% enrollment, the existence of a green pricing program actually decreases the time to adoption of the first net meter by their customer base.

The influence of the average residential electricity price charged by the utility is positive and statistically significant. A one percent increase in the electricity price increases the hazard of net metering adoption by between 5.8 and 6.2% in the two models, while a 10% increase in the price increases the hazard by between 75.8 and 81.8%. This is to be expected. Other control variables not shown in the table either have the expected sign or are not significant. Unsurprisingly, utilities in states with higher solar power potential experience net metering adoptions much sooner.

4.4.2 Intensive Margin Results

For the intensive margin models, only those utilities with positive net metering or green pricing customers were included in the analysis, since the existence of at least one program is necessary for participation. For

this reason, the sample size was reduced to 7,830 for these models.

Results for the intensive margin models are shown in Table 4.3. Generally speaking, the number of customers enrolled in a utility’s green pricing program has a negative effect on the number of customers with net meters, although the effect is imprecisely estimated when accounting for utility-level fixed effects. When accounting for state- and year-level fixed effects (as in Model 2), the effect of green pricing customers on net metering customers is statistically significant and negative, suggesting a 10% increase in the number of green pricing customers is associated with a 0.52% decrease in the number of net metering customers. When accounting for utility-level fixed effects rather than state-level effects (Model 3), the point estimate remains negative but decreases substantially while the standard error increases, making it statistically insignificant. In this model, the utility fixed effects account for most of the variation in the number of net metering customers, as the number of total customers and the average residential electricity price are also insignificant.

Table 4.3: Intensive Margin Model Results

Explanatory Variables	(1) ln(NM Cust)	(2) ln(NM Cust)	(3) ln(NM Cust)	(4) ln(NM Cust)
ln(GP Cust)	-0.065*** (0.020)	-0.052*** (0.016)	-0.030 (0.022)	
ln(Cust)	0.548*** (0.027)	0.596*** (0.027)	0.277 (0.241)	0.299 (0.242)
ln(Price)	17.540*** (1.516)	7.656*** (1.392)	2.091 (2.904)	1.684 (2.834)
PGP		0.680*** (0.134)	0.738*** (0.155)	
ln(GP Cust) if PGP = 0				-0.054** (0.023)
ln(GP Cust) if PGP = 1				0.084*** (0.027)
Controls?	No	Yes	Yes	Yes
Year FE?	No	Yes	Yes	Yes
State FE?	No	Yes	No	No
Utility FE?	No	No	Yes	Yes
Observations	7,830	7,830	7,830	7,830

Standard errors in parentheses, clustered at utility level. Controls include: PNM, PRPS, ln(DNI), ln(Income), Dem, and a constant.
* p<0.10, ** p<0.05, *** p<0.01

Table 4.3 also includes the estimates for the indicator variable PGP, which is both positive and highly significant in both the models with state- and utility-level fixed effects. States with a mandatory green power purchasing option have on average over twice as many net metering customers as states without such a policy ($\exp(0.738) - 1 = 109\%$). Mandatory green power purchasing options are mandated by the state regulatory agency that utilities of a certain size must offer their customers a green pricing option to their customers. The eight states with such policies include Colorado, Iowa, Maine, Montana, New Mexico, Oregon, Virginia, and Washington. One possible explanation for this large effect is that the existence of these policies in certain states exhibits a higher than average skew in preferences for clean energy by electricity customers in those states. All eight states were also relatively early adopters of net metering policies.

Because the effect of a state-wide green pricing policy is so strong (but only present in a small minority of states), Model 4 explicitly controls for an interaction effect between green pricing customers and the existence of a state-wide mandatory green pricing option. According to this model, a 10% increase in the number of green pricing customers is associated with a 0.84% increase in the number of net metering customers in states with a green pricing policy in place; however, the same 10% increase in green pricing customers is associated with a statistically significant decrease in net metering customers of 0.54% in states with no green pricing policy, which describes utilities in 42 states. This result indicates that green pricing programs are net substitutes for net metering in most states (without a state-wide green pricing policy) but are net complements in states with such policies. Both results are highly inelastic, however, so regardless of what state a utility is located in, it would need to add a substantial amount of green pricing customers before it saw any reduction/addition in its net metering customer base. This result is consistent when Model 4 is estimated under the assumption of a Poisson distribution using both logs and levels for the continuous variables.

4.4.3 Two-Part Model (Combined Model)

It is also possible to model both the extensive and intensive margins using a single model. Two-part models are common approaches to modeling variables with separate distributions for zero and non-negative outcomes [111, 112], These typically involve estimating a model for a binary indicator variable, such as a logit or probit model, followed by a model for the continuous variable given it is non-negative, usually a linear or Poisson model for count data. Such models are often used in applications where a substantial portion of the observations take on a zero value or where observations are only observed above (or below) some threshold value. Models such as the hurdle model [113] and the zero-inflated Poisson (ZIP) model [114] were further extensions to two-part models developed for such purposes.

In the present study, the first part of the model estimates the probability that at least one customer in utility i 's service area installs a net meter in year t :

$$P(NMCust_{it} > 0) = \exp(\beta' X_{it} + \varepsilon_{it}) \quad (4.6)$$

$$\text{logit}(P(NMCust_{it} > 0)) = \beta' X_{it} + \varepsilon_{it} \quad (4.7)$$

Where X_{it} is the same vector of control variables as in the proportional hazards model (the extensive model) above. This model differs, however, in that it does not use a censored dataset and makes no assumptions about a baseline hazard function.

The second part of the model estimates the number of net metering customers served by utility i in year t , given the number of net metering customers is positive [115]:

$$E(NMCust_{it}|Z_{it}) = P(NMCust_{it}|X_{it}) * E(NMCust_{it}|Z_{it}, NMCust_{it} > 0) \quad (4.8)$$

Where

$$E(NMCust_{it}|Z_{it}, NMCust_{it} > 0) = \alpha + \beta' Z_{it} + a_i + \mu_t + \varepsilon_{it} \quad (4.9)$$

Where Z_{it} is a vector of control variables which includes all of the same variables as the intensive model above (specifically, Model 4 from Table 4.3). The second part is estimated both using natural logs for all continuous variables for the linear model (with fixed effects) and levels for a Poisson model. This model differs from the intensive model in that it is run on a more restricted sample; that is, only utilities with at least one net metering customer (the intensive model above includes utilities with either net metering or green pricing customers).

Results for the two-part models are shown in Table 4.4. While the effects of DGP and $GPShare$ are similar across specifications for the selection models (and for the most part consistent with the discussion above), the estimates for the full models are not consistent. Models 1 through 4 are two-part models with a logit for the selection model. Models 1 and 2 use a linear specification for the full model, while models 3 and 4 use a Poisson distribution and levels for the continuous variables. When applying utility-level fixed effects to the selection models (models 2 and 4), the effect of $GPShare$ becomes statistically insignificant, though still negative. The effect of $GPCust$ in states with no mandatory green pricing requirement remains negative across all four specifications for the full model, though is only significant in the zero-adjusted Poisson specifications. The effect for models 3 and 4 implies that for every 1,000 green pricing customers, the incidence rate of an additional net metering customer decreases by about two percent in states with no mandatory green pricing option and increases by the same amount in states with the policy. For states with a mandatory green pricing option, green pricing customers is associated with more net metering customers in all specifications (the effect is also statistically significant across specifications).

Table 4.4: Two-Part, Hurdle, and Zero-Inflated Poisson Model Results

Explanatory Variables	(1) ln(NM Cust)	(2) ln(NM Cust)	(3) NM Cust	(4) NM Cust	(5) ln(NM Cust)	(6) NM Cust	(7) NM Cust
1st Equation: Selection/Inflation Model							
DGP	2.336*** (0.109)	2.028*** (0.252)	2.330*** (0.109)	2.028*** (0.251)	1.287*** (0.059)	1.287*** (0.059)	-2.330*** (0.113)
GP Share	-6.492*** (2.290)	-2.125 (3.633)	-5.867*** (2.263)	-1.912 (3.042)	-3.223*** (1.235)	-3.223*** (1.235)	5.919*** (2.294)
Price	9.542*** (2.679)	7.170 (6.933)	6.761*** (2.466)	4.010 (5.919)	2.942*** (0.990)	2.942*** (0.990)	-6.840*** (2.480)
1 st Eq. Model	Logit	Logit	Logit	Logit	Probit	Probit	Logit
Year FE?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State FE?	Yes	No	Yes	No	Yes	Yes	Yes
Utility FE?	No	Yes	No	Yes	No	No	No
Observations	33,155	8,889	33,155	8,889	33,155	33,155	33,155
2nd Equation: Full Model							
GP Cust if PGP = 0	-0.001 (0.021)	-0.001 (0.021)	-0.00002* (0.000)	-0.00002* (0.000)	0.039** (0.018)	0.00008*** (0.000)	0.00004*** (0.000)
GP Cust if PGP = 1	0.055** (0.026)	0.055** (0.026)	0.00002** (0.000)	0.00002** (0.000)	0.094*** (0.025)	0.00008*** (0.000)	0.00007*** (0.000)
Cust	1.257*** (0.376)	1.257*** (0.376)	-0.000001 (0.000)	-0.000001 (0.000)	0.825*** (0.035)	0.000002*** (0.000)	0.000001*** (0.000)
Price	3.909 (3.490)	3.909 (3.490)	5.820** (2.263)	5.820** (2.263)	14.098*** (1.354)	1.243 (1.828)	0.291 (3.568)
2 nd Eq. Model	Linear	Linear	Poisson	Poisson	Linear	Poisson	Poisson
Year FE?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State FE?	No	No	No	No	No	Yes	Yes
Utility FE?	Yes	Yes	Yes	Yes	No	No	No
Observations	4,187	4,187	4,087	4,087	-	-	-
Model Type	2-Part	2-Part	2-Part	2-Part	Hurdle	Hurdle	ZIP
Standard errors are in parentheses and are clustered at the utility level. Controls include: PNM, PGP, PRPS, DNI, Income, Dem, and a constant.							
* p<0.10, ** p<0.05, *** p<0.01							

Models 5 and 6 estimate Cragg's hurdle models under linear and Poisson assumptions, respectively, while Model 7 estimates a ZIP model with a logit for the selection model. The main difference between these two types of models from a philosophical perspective is the assumption about what constitutes a zero value for total net metering customers. While the hurdle models assume a zero is simply a decision to not install a net meter, the ZIP model assumes that zeros can arise both due to a decision not to install a net meter, as well as a decision to install but an inability to do so. Note that the opposite coefficients in the ZIP's inflation model reflect the prediction of excess zeros, rather than positive net metering customers. All three models find that the amount of green pricing customers has a significantly positive effect on total net metering customers in states both with and without mandatory green pricing options; however, none of these specifications incorporates utility-level fixed effects. Further research could look at the effects of green pricing customers on net metering after accounting for fixed effects.

While the two-part models discussed in this section provide perhaps a more elegant model formulation that includes the entire dataset, they also have some important drawbacks in the present study. Most notable is the exclusion of data for all utilities in the full model that do not have any net metering customers, which includes utilities that may have a substantial amount of green pricing customers but zero net metering customers (which are included in the intensive margin models). This could be an important exclusion for customers in restructured electricity markets who select retail energy providers based on the provision of green electricity. For future research, a ZIP model with utility-level fixed effects may be able to address these concerns since the existence of such utilities leads to the existence of excess zeros. It is also worth noting that the two-part models are not able to incorporate the proportional hazards model at present, since it relies on a censored dataset.

4.5 Conclusion and Limitations

Over the past several years, use of micro-renewables has increased greatly, partially facilitated by utility net metering programs. Net metering programs are one way for households to express their preference for green electricity, which is also possible through enrollment in a green pricing program. Since green pricing programs were widespread before net metering programs became popular, this research hypothesizes that the presence and popularity of a green pricing program may have delayed the initiation of net metering and reduced the total number of households enrolled in net metering. This hypothesis is tested using data from 2002-2012, when net metering programs were becoming popular. The results show that the time to first net metering customer was statistically delayed by the presence of a popular green pricing program with at least 16.5% of its customer base enrolled. For those utilities with smaller shares of their customer base enrolled in a green pricing program, however, the first net metering adoptions occurred more quickly than

otherwise. For utilities with both net metering and green pricing customers, more green pricing customers leads to fewer net metering customers in states with no state-wide green pricing policy in place but leads to more net metering customers in states with such a policy.

The implication of this analysis is that utilities and state regulators should consider the relationship between programs offered and their potential to be in conflicts with each other. Green pricing programs support the development of utility scale renewables, which generally have a lower levelized cost of energy. Additionally, potential benefits and costs of customers to each program fall on different entities. Utilities may prefer green pricing programs as it keeps customers using and paying for other services provided by the utility. This research reveals that utilities may have and potentially could still limit customer interest in net metering through the type of green pricing program it offers.

One limitation is the use of aggregate data for each utility and the lack of access to household-level data. With the current data, it is impossible to know if a given household is enrolled in one or both programs. Other details about the household which might allow one to predict their participation in various programs are also not included. Thus, it is currently somewhat ambiguous which agent's behavior is being captured in this analysis, as decisions by individual households, electric utilities, and state regulators all play a role. Additionally, the demographic data are not geographically distributed enough to form a detailed understanding of a utility's customer base. For example, net metering programs may be more likely to be adopted by households residing in unattached dwellings that they own, rather than attached units that they rent. Thus, one might expect net metering programs to be more popular among customers residing in suburban and rural areas rather than urban ones.

Another potential limitation of the study is the lack of availability of comparable economic data on net metering and green pricing programs for the duration of the sample. This study relies on data available from the EIA Form 861, which contains data on the number of customers enrolled in each program for the full sample period from 2002 to 2012. Thus, it defines substitution between the two programs as customer participation. A slightly better measure might be generated by comparing the total sales from green pricing programs with total energy displacement from net metering. Neither of these data series is consistent over the period in question.

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