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ABSTRACT

Over the last decade, publicly funded investments in energy efficiency have skyrocketed as a result of policies aimed at reducing energy consumption and mitigating the harmful effects of global climate change. Furthermore, supplementing the energy needs of the poor has been suggested as a direct and effective means for improving energy security in the developed world. In this paper, we present a unique theoretical model based on the theory of household production, which allows us to capture a household’s demand for and production of energy services and thus energy security. We then apply a stochastic production frontier approach to empirically measure the extent of a household’s level of energy security. Using principal component analysis, we construct a residential survey-based index measure for household energy security and then estimate two models to examine how making energy efficiency improvements in the home impacts the presence of household energy security.

Keywords: Energy Security, Energy Efficiency, Fuel Poverty
Over the last decade, publicly funded investments in energy efficiency have skyrocketed as a result of policies aimed at reducing energy consumption and mitigating the harmful effects of global climate change. From taking advantage of utility sponsored in-home energy audits, to replacing home appliances with more efficient models, becoming a more energy efficient household is easier now than ever before. Furthermore, supplementing the energy needs of the poor has been suggested as a direct and effective means for improving energy security in the developed world (Reames 2016). The objective of this paper is to develop a theoretical model and empirical procedure for examining how improvements in energy efficiency impact household energy security.

To be energy secure, we assume a household must have physical and economic access to a sufficient, safe, and affordable energy supply that meets their most basic daily energy service needs. Consistent with the literature, we assume the term “energy services” can be used to describe any function performed inside the household that uses energy (e.g. electricity or natural gas) as an input to produce a desired output (Fell 2017). Examples of household energy services include maintaining comfortable indoor room temperatures, access to cold or hot food and beverages, and sufficient room lighting for indoor leisure activities such as reading. Energy services are generated from household appliances such as air conditioners, refrigerators, and stoves – and the operation of these appliances by members of the households. ¹

Maintaining energy security is becoming increasingly more difficult for many of the world’s most vulnerable populations including the elderly, the disabled, and persons with low or impoverished incomes (Wilkinson et al. 2001; Hernández 2013; O’Mera 2016). A recent report by

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¹ Households that are unable to access these energy services due to poor housing conditions, financial constraints, and/or high energy costs are not considered energy secure (Middlmiss and Gillard 2015; Hernández 2016; O’Mera 2016).
the U.S. Energy Information Administration (EIA) indicated that nearly 31% of households in the United States struggled to pay for energy services in 2015 (EIA 2016). Furthermore, the EIA found only minor differences among respondents from different geographical regions, suggesting that a household's ability to afford energy services could be more related to structural features of the household (e.g. number of square feet, number of bedrooms) or lower levels of thermal energy efficiency (e.g. inadequate insulation level, type of windows, or type of appliances) rather than weather. Rodriguez (2016) suggested similar reasons why households may be energy insecure.

In this paper we further examine the relationships between household energy efficiency and energy security by presenting a unique theoretical model based on household production theory that allows us to capture a household’s demand for and production of energy services. Under this framework, we assume the objective of each household is to obtain the highest level of household energy security possible. Therefore, we use a stochastic production frontier approach to relate “shortfalls” in production to a lack of household energy security. Additionally, we propose an economically robust index for measuring household energy security using responses from the 2015 Residential Energy Consumption Survey (RECS).

The remainder of this paper is organized as follows. We first provide some additional background on the energy security issue including a discussion of the primary measures historically used to examine household energy security. We then present a theoretical model that allows us to determine household demand for energy services and establish the connection between energy services and energy security. We then briefly discuss the data and the methods used to construct the index for energy security. We follow this discussion with an outline of our empirical strategy and some preliminary results of our analysis, which we plan to extend as more data

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2 Additionally, they find that households with children, who had residents that identified with a minority racial group or as Hispanic, or were low income on average, were more likely to be energy insecure (EIA, 2016).
becomes available this year. \(^3\) Finally, the last section provides some concluding remarks and policy recommendations based on results to date.

**ENERGY SECURITY BACKGROUND**

Energy efficiency programs for low-income households have become the second most common type of U.S. electric energy efficiency program based on total expenditures (Massey 2017). From an economics point of view, low-income households may struggle to achieve energy security for three main reasons. First, due to inadequate credit, many low-income households are renters or temporary residents. Thus, they may lack the financial incentives to invest in any structural improvements that could increase the energy efficiency of their home over the long-run. Secondly, even if low-income households are motivated to invest in energy efficiency improvements, many are unable to afford the high upfront costs associated with purchasing or financing such improvements. \(^4\) In other words, the high upfront costs associated with making energy efficient upgrades create a barrier for adoption (Kapur et al. 2011). Third, low-income households may not invest in energy efficiency upgrades due to lack of information about energy efficiency opportunities (Scott et al. 2008).

In this paper we examine the connections between energy security and energy efficiency for low-income households as suggested in the literature by (Hernandez 2013). Such connections have largely been ignored in previous energy security studies and papers with the exception of Fowlie et al. (2015) who analyzed one of the nation’s largest initiatives for reducing domestic energy insecurity, the Weatherization Assistance Program (WAP). This program is specifically designed to reduce energy costs for low income households by increasing the level of energy

\(^3\) The anticipated release date for the remaining 2015 RECS data is summer 2018.

\(^4\) Examples of improvements could include buying more efficient appliances or replacing their current house windows with more efficient ones.
efficiency within the home. Using a randomized controlled trial, their results revealed that investments in energy efficiency, particular those sponsored by the WAP, reduced monthly energy consumption by 10-20% on average. However, their analysis only focuses on households in Michigan, and is primarily motivated by the presence of the energy efficiency gap.  

MEASURING HOUSEHOLD ENERGY SECURITY

Historically, energy security has been measured using three main approaches: the expenditure approach, the predication approach, and the subjective survey approach (O’Mera 2016). The expenditure approach is directly linked to the amount of money a household spends on fuel. Households are considered to be energy insecure when they spend more than 10% of their disposable income on fuel (Boardman 1991). However, as suggested by Hills (2012) this method directly excludes low-income households that might end up spending less than 10% of their income because they are simply unable to spend more. In some cases, the threshold beyond which energy ceases to be “affordable” has been reported to be as low as 6% of a household’s disposable monthly income (Chandler 2016).

In contrast, the prediction approach estimates how much a household would need to spend on fuel to achieve a “livable” indoor air temperature. If spending the forecasted amount leaves the household with a remaining income below the designated poverty line, then the household is considered to be energy insecure (Omera 2016; DECC 2013). While this method directly avoids excluding households who spend less than 10% of their income on fuel costs, it still assumes one

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5 The energy efficiency gap refers to the difference between the cost-minimizing level of energy efficiency achieved and the level of energy efficiency actually realized (Allcott and Greenstone 2012).

6 Livable indoor air temperatures as suggested by the World Health Organization are 21°C (69.8°F) in the living room and 18°C (64.4°F) in the any other occupied rooms.

7 The forecasted required amount is based on the size and demission of the dwelling, the price of fuel inputs, the household’s income, and the median level of fuel expenditures for a household of a similar size.
uniform level of comfort exists across households of a similar size and make-up. This assumption is unrealistic, given that tastes and preferences usually vary by household.

The third measure of energy security, and the method most similar to the one we employ in this paper, is the subjective survey approach wherein respondents answer questions related to their household’s level of energy security. Previously, large scale surveys such as the European Union’s Survey on Income and Living Conditions (SILC), the Spanish Living Conditions Survey (SLCS), and the Residential Energy Consumption Survey (RECS) conducted by the U.S. Energy Information Agency (EIA), have included a subset of questions that specifically target household energy behavior and security. These questions ask respondents to report whether or not they have had to go without heating or cooling within the last year, whether or not they have been unable to afford their energy bills, and/or whether or not they have received energy assistance to restore heating or cooling in the household.  

However, as Watson and Maitre (2015) point out, an issue with the subjective survey approach is it relies on an individual’s perception of their own, personal current energy security situation. This type of subjective indicator could lead to households with higher incomes reporting a low level of energy security, even though they do not necessarily lack the financial resources to afford their energy bills. For example, higher income households may still experience difficulty affording necessary fuel expenses due to other income constraints such as debt payments (i.e. car payments, mortgages), higher household maintenance costs, and healthcare expenditures (O’Mera

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8 A complete list of the questions from the 2015 RECS can be found in Table 1 in the Appendix.
9 In addition, whatever the cause, some people just naturally do not feel as secure as others. For example, from an objective perspective a person may actually have adequate food, water and shelter, but still he or she does not feel secure from a personal subjective perspective.
2016). Which begs the question, if a household identifies as energy insecure, does that also mean
they will identify as being economically vulnerable or vice versa? This is an interesting
relationship and one that has yet to be explored in the literature.

While the definition of energy security has been discussed and debated in the literature for
some time now (Boradman 1991; Hills 2012; Watson and Maitre 2015; O’Mera 2016; Chandler
2016), the lack of a single, comprehensive index measure continues to be one of the major
roadblocks to eliminating its presence in the developed world. We are only aware of one other
previous attempt that defines a specific index used to measure energy security in the United States.
In this study, Cook et al. (2008), developed an energy security index, using responses to a set of
four questions from a household survey administered as part of the ongoing Children’s Sentinel
Nutrition Assessment Program (C-SNAP). Households who answered “yes” to only the first listed
question were considered to be moderately energy insecure, whereas households who answered
yes to any additional question(s) were categorized as severely energy insecure. 11

The basis for the index construction by Cook et al. (2008) is modeled after the Rasch
scoring model used by the United States Department of Agriculture (USDA) to develop the food
security index. However, as Gundersen (2008) points out, because an index of this type is
constructed solely based on the number of affirmative responses, it neglects to take full advantage
of information available in each specific question asked. Additionally, it disregards several other
key factors that can strongly indicate the presence of energy insecurity in the household. For
example, households who are energy insecure may keep indoor air temperatures at unsafe levels
in order to avoid high electrical utility bills, and as a result may be forced to seek medical attention

10 Based on their available assets, higher income households are unable to receive federal financial support to pay for fuel
expenses or make energy efficiency upgrades. For example, to be eligible for the Low-Income Home Energy Assistance Program
(LIHEAP), a household’s income must be below 150% of the federal poverty line.
11 Households who responded “No” to all questions were considered energy secure (Cook et al., 2008).
as a result of heat exhaustion or severely cold temperatures. Affirmatively responding to a question of this nature should bear more weight than responding “yes” to whether or not you have received a shut-off notice within the past year. To address this need, we propose a unique and economically robust measure for household energy security using principal component analysis. This index is described in detail later in the empirical section of this paper.

THEORETICAL FOUNDATION

To develop a theoretical framework that allows us to address the determinants of household energy security, we first establish a set of assumptions about the structure of and operations within the household. Similar to Becker (1981) we assume households seek to maximize utility through their consumption of energy services. That is, demand for energy, is derived indirectly rather than directly, from the demand for a warm house, lit room, or cooked food, and can be specified using the basic framework of household production theory as first proposed by Becker (1965) and Muellbauer (1974) and developed further by Burnett and Madariaga (2017) Davis et al. (2014), and Filippini (1999).

To apply this framework, we assume households are both consumers and producers, who in order to produce goods and services use a set of inputs purchased from the market (Becker 1965; Bockstael and McConnell 1983; LaFrance 2001; Huffman 2010). In our specific case, the household combines electricity input $E$ with capital technology input $K$ and labor input $L$ to produce an energy service, which we label as $ESERV$. An example of an energy service produced by a household, as mentioned previously, might include a comfortable room temperature, cooked

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$^{12}$ We also used cluster analysis to construct the index for energy security. For this paper we chose to use the principal component analysis results since this method generates an energy security for each household which is consistent with our household production theoretical model.
food, cold or hot beverage, or sufficient room lighting. The production function of these energy services, can be generally expressed according to the following household production function:

(1) \( E_{SERV} = E_{SERV}[E,K,L], \)

where \( L \) is household labor (or time), \( E \) is electricity, and \( K \) represents the current stock of capital technology.

To examine how energy efficiency impacts the production of energy services inside the household, we assume that the stock of capital technology \( K = f(k \cdot \gamma) \) where \( k \) represents the specific capital inputs owned by the household (e.g. heating and/or air conditioning unit, refrigerator, stove, lamp) and \( \gamma \) represents the specific capital technology input’s corresponding “efficiency level.” We assume increasing the value of \( \gamma \) leads to increase in the amount of output per unit of energy input (e.g. an increase in energy efficiency). Additionally, we allow the value of \( \gamma \) to be continuous and exist within the interval \([0, \gamma_{max}]\), where \( \gamma_{max} \) represents the maximum obtainable level of efficiency (Sanstad 2011).

For simplicity, we assume households obtain utility from the consumption of only two commodities, the energy related services \( E_{SERV} \) discussed previously, and a composite commodity representative of all other non-energy related goods and services, which we label as \( X \) (Becker 1981; Li 2011). Therefore, a household’s utility can be generically summarized by a strictly concave utility function of the form

(2) \( U = U(X, E_{SERV}; HC) \)

where \( HC \) represents a vector of both demographic and physical household characteristics (e.g. square footage, number of bedrooms, number of bathrooms, or geographical location) that could

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13 We allow the interval to be continuous to reflect the continuous changes of efficiency ratings of a household appliances from year to year.
potentially influence household demand for energy services (i.e. fuel or electrical input), as well as preferences for other goods purchased on the market (Li 2011).

In the present application of this basic framework we assume each household wishes to maximize utility in equation (2) subject to the following budget constraint,

\[ M - P_S \cdot ESERV - P_X \cdot X = 0 \]

where \( M \) is money income, \( P_S \) is the price of energy services, \( P_X \) is the price of composite commodity \( X \), and all other terms are defined previously. For simplicity we normalize the price of composite commodity \( X \) to 1. We can now set up the household’s decision as a two-stage optimization problem (Deaton and Muellbauer 1980; Filippini 1999; Feleke, Kilmer, and Gladwin 2005). Within this framework, we view demand for energy services as a consumption demand function. Additionally, since energy is a derived demand, households do not necessarily seek to consume the most energy possible in order to maximize utility; but rather, a household’s demand for energy is constrained by the costs of providing such services (Scott 2008).

Thus, in the first stage we can assume the household acts as a firm whose objective is to minimize the cost of producing the energy service, \( ESERV \). We can write this problem simply as

\[ \text{Min } C = (P_E \cdot E) + (P_K \cdot K) \]

subject to the following production function

\[ ESERV = ESERV[E, (k \cdot \gamma), L] \]

where \( P_E \) is the price of electricity input \( E \) and \( P_K \) is the price of the capital technology input \( K \) chosen by the household. To simply things further, we assume the production function \( ESERV \) exhibits constant returns to scale.

The result of the optimization problem above generates the corresponding cost function

\[ C = C(P_E, P_K, ESERV) \]
with the following properties: homogenous of degree one in $ESERV$ and prices, increasing in $ESERV$, and non-decreasing and concave in prices (Varian 1992). We apply Shepherd’s Lemma and derive the following input demand functions for electricity input $E$ and stock of capital technology input $K$:

\[
(7) \quad E = \frac{\partial C(P_E, P_K, ESERV)}{\partial P_E} = E(P_E, P_K, ESERV)
\]

\[
(8) \quad K = \frac{\partial C(P_E, P_K, ESERV)}{\partial P_K} = K(P_E, P_K, ESERV).
\]

In the second stage of the optimization problem the household maximizes utility in (2) subject to the following budget constraint,

\[
(9) \quad M - C(P_E, P_K, S) - X = 0.
\]

Here we have simply replaced the price of producing energy services with the cost function associated with producing the energy services. The corresponding Lagrangian function for this second stage optimization problem is as follows

\[
(10) \quad L = U(X, ESERV; HC) + \lambda (M - C(P_E, P_K, ESERV) - X).
\]

The solution to equation (10) yields the following demand functions

\[
(11) \quad X^* = X^*(P_E, P_K, M; HC)
\]

\[
(12) \quad ESERV^* = ESERV^*(P_E, P_K, M; HC)
\]

for the composite commodity $X$ and corresponding energy services $ESERV$, which are both a function of the input prices faced by the household, $P_E$ and $P_K$, income $M$, and household characteristics $HC$. These two solutions involve the decision for the quantity of market goods and the level of energy services consumed by the household.

We can also substitute equation (12) into equations (7) and (8) to obtain the following input demand functions
for electricity $E$ and stock of capital technology $K$. These solutions reflect the long-run equilibrium decision of the household and assume any instantaneous shifts in prices or income will result in an adjustment to either the utilization rate or the physical stock of capital itself within the household. This gives us a full picture of the economic behavior of the household as both a producer and consumer of energy services.

**EMPIRICAL METHODOLOGY**

*Stochastic Production Frontier Function and Household Energy Security*

Currently, there are many different definitions of household energy security. All of which refer to a level of energy consumption that is insufficient to meet daily energy service needs demanded by a household. As discussed previously, households produce energy services following the household production process. Therefore, using the theoretical framework above, energy security, which we denote as $ESECURE$, can generally be written as a function of energy services, $ESERV$:

$$ESECURE = f(ESERV).$$

Following the literature on food security, we could determine a household’s level of energy security by first calculating the number of kilowatt-hours (kWh) of electricity necessary to provide a standard level of energy services. Then, to determine the extent of a household’s level of insecurity (i.e. lack of security), we could calculate the difference between the number of kWh consumed and the number of kWh necessary to provide this pre-determined standard level of

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14 In the literature, a household’s level of food insecurity is typically measured by comparing the number calories consumed with a fixed number of required of calories believed to indicate an adequate level of nutrition. For further information see Gundersen (2008) or Feleke Kilmer and Gladwin (2005).
household energy services. However, it is only possible to observe the number of kWh actually consumed by a household, and not the number necessary to provide a standard level of services.

Furthermore, as shown by equation (5), household production of energy services is a function of more than just electricity input. Ultimately, a household combines kWh of electricity with a stock of capital technology and labor to produce energy services. This can be shown conceptually by substituting equation (5) into equation (15) which produces:

\[
E_{SECURE} = f[E, (k \cdot \gamma), L].
\]

We assume the basic objective of the household, as a producer of energy services, and thus energy security, is to obtain the highest level of household energy security possible. The extent of a household’s ability to produce energy security could then be determined by the difference between the “optimal” level of energy security a household should be able to achieve given its fixed set of inputs and the level energy security actually achieved. For the purposes of this study, we assume any shortfall from maximum output is defined as a measure of household energy “insecurity.”

Therefore, to empirically model the production of household energy security, we rely on a stochastic production frontier approach. Under this framework, we define the stochastic production function for energy security generally as

\[
E_{SECURE_i} = f[E, (k \cdot \gamma), L] - \varepsilon_i + \nu_i,
\]

where the key difference between equation (17) and the standard production function lies in the appearance of the two distinct error terms. The error term \(\varepsilon_i\) terms captures “insecurity”, or shortfall from maximal output dictated by the production function of energy security, while the

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15 It should be noted that shortfall from maximum output is normally referred to as “inefficiency” in production. However, because our research question is motivated by energy efficient capital technology, we use the term “insecurity.”
error term $v_i$ captures outside influences beyond the control of the producer (e.g., things beyond the control of the household that impact their ability to provide adequate energy security). Figure 1 illustrates this gap between the optimal and observed levels of energy security (see Appendix).

The extent of each household $i$’s energy “insecurity” (defined previously as $\epsilon_i$) could then be determined by the difference between the “optimal” level of energy security a household should be able to achieve and the actual level of energy security achieved by the household. We can define this simply as

\[ E_{\text{INSECURE}}_i = E_{\text{SECURE}}_* - E_{\text{SECURE}}_i \]

where $E_{\text{SECURE}}_*$ represents the optimal level of household energy security, $E_{\text{SECURE}}_i$ represents the level of energy security achieved by the household, and $E_{\text{INSECURE}}_i$ measures the energy “insecurity” of each household $i$.

**Household Energy Security Index**

It is difficult for a researcher to directly observe the level of energy services produced by the household. Additionally, because the optimal level of energy services (e.g. a “comfortable” room temperature, “adequately lit” room, “cold” beverage, or “hot” meal) depends on each household’s preferences; it is also difficult to measure each household’s level of energy security. As a result, we are not able to quantify the specific level of energy “insecurity” (i.e. lack of energy security) being experienced by each household. Therefore, in an attempt to accurately gauge each household’s level of energy “insecurity” we use a proxy, a unique and economically robust energy security index based on self-reported indictors of energy security described below.

**Data Description**

Data for constructing our energy security index comes from the 2015 Residential Energy Consumption Survey (RECS). The RECS is a national multi-phase survey administered by the
U.S. Energy Information Administration (EIA) that solicits information on energy consumption and expenditures from households across the United States. While data collection for each RECS completion cycle spans multiple years, each set of observations are treated as a single cross-section. The survey data was collected over three phases: the household survey phase, the energy use collection phase, and the end-use consumption and expenditure estimates phase. Currently, only data from the 2015 household survey phase has been released to the public by the EIA.

The 2015 RECS was administered using a combination of in-person computer assisted interviews, mailed paper surveys, and web-based questionnaires. A total of 5,686 responses were collected from the 2015 RECS, indicating a response rate of about 44%. For the purposes of our study, we focus only on single family detached homes. After controlling for missing variables, we were left with approximately 3,707 total observations. We specifically use the 2015 RECS survey because it asks participants to reveal information about the energy use patterns within their household. Additionally, each survey collected information about the physical characteristics of each individual’s home including the age of the dwelling, the number of bedrooms, the number of bathrooms, and the type of heating and ventilation equipment used.

**Index Construction**

To construct our energy security index, we first let $n = \{1,2,\ldots,N\}$ denote a set of households, such that $n$ is equivalent to the total number of households within a given set. We assign $EINDEXSECURE_i$ to denote the “energy security status” of each household $i \in N$, such

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16 To create a general, representative sample of all U.S. households, the EIA used a multistage area probability sample design. This design begins by dividing the United States into different geographical areas by randomly selecting public use micro data areas (PUMAs). Each PUMA was then divided into several different census block groups (CBGs), resulting in a total of 800 total CBGs, four per each PUMA. In the third and final stage randomization, households are randomly chosen from an overall list of households in each of the selected CBGs. In most of the CBGs, the list of households is created from the United States Postal Service Delivery Sequence File (DSF).

17 These energy use patterns include information such as, whether or not the household has received an in-home energy audit within the past year, made any energy efficiency upgrades, or had been the recipient of funding from an energy assistance program.
that lower values of $EINDEXSECURE_i$ correspond with more favorable energy circumstances within the household. For the purposes of this study, we assume the term energy circumstances refer to any circumstances that affect the household’s ability to receive adequate energy services. In this case, households who are able to “produce” more energy services are considered more energy secure than households who “produce” less.

To gauge each household $i$’s ability to provide energy services, we construct the energy security index using individual responses to a subset of questions from the 2015 RECS. 18 We assume each household’s energy security index (i.e. measure of energy insecurity) can be expressed using the following general form

\[ EINDEXSECURE_i = f(a_1, a_2, ..., a_7, h_1, ..., h_5) \]

where $EINDEXSECURE_i$ is the energy security index of each household $i$, $a_1, a_2, ..., a_7$, are a set of indicators equal to one if the household answered yes to any of the questions listed in Table 1 (see Appendix) and $h_1, ..., h_5$ are a set of household characteristics including household size measured in square feet, number of bedrooms, number of bathrooms, number of household members, and ownership status believed to influence household energy security. 19

To construct the energy security index we use principal component analysis. 20 Principal component analysis (PCA) considers how the questions included in Table 1, and the additional information considered from the survey, can be linked together to measure household energy security. Using the covariance/variance matrix, PCA attempts to capture the correlation among the

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18 A complete list of the questions asked can be found in Table 1 of the Appendix.
19 Currently, we do not yet have data on the energy prices faced by the household, but plan to add those data as they become available in the future.
20 We also use cluster analysis to generate an energy security index from the data. The results from applying this method can be found in Table 3 (see Appendix).
variables of interest to create a set of weights that can be used to determine a household’s level of energy security. Once a principal component has been chosen, a dependent variable, representative as each household i’s energy “score,” can be constructed. To generate an index using the results from the PCA, we could either establish a set of cut points that allow us to differentiate households into separate energy security categories or separate households using quintiles. The preliminary results from applying this method can be found in Table 4 (see Appendix).

**EMPIRICAL MODEL**

We now present the two empirical models used to examine how improvements in energy efficiency impact the presence of household energy security. Using only the index results produced by the PCA technique, we first establish a single cut point that allows us to separate households into two mutually exclusive categories: not energy secure households \((Z_i = 1)\) and energy secure households \((Z_i = 0)\). Using this method of partitioning, the energy security model can be cast as a qualitative response model, where \(\phi_i\) is the probability that a household does not identify as energy secure, which can be written generally as

\[
\phi_i = Prob(Z_i = 1) = Prob\left(\sum_{j=1}^{k} \beta_j X_i + \mu_i\right).
\]

The standard parametric approach to analyze the data would be a logistic regression. The logistic model of energy insecurity (e.g. not energy security) could then be specified as

\[
\ln\left(\frac{\phi_i}{1-\phi_i}\right) = \beta_0 + \sum_{i=1}^{n=9} \beta_k X_i + \mu_i
\]

where \(\phi_i\) is the conditional probability of energy insecurity; the \(\beta_k\)’s are the parameters to be estimated; \(X_1\) is median household income; \(X_2\) is a binary variable equal to one if the head of household is employed; \(X_3\) is a binary variable equal to one if the household has a programmable thermostat; \(X_4\) and \(X_5\) correspond to the average number of cooling degree days (CDD) and heating degree days (HDD) over the past 30 years; \(X_6\) is a binary variable equal to one if the household
received an in-home energy audit, $X_7$ is a binary variable equal to one if the household made changes as a result of receiving the in-home energy audit, $X_8$ is a binary variable equal to one if the household has triple and/or double pane windows, $X_9$ is a variable equal to one if the household has adequate insulation, and $X_{10}$ is continuous variable equal to the number of energy star appliances owned and operated by the household. Energy star appliances considered include: washers, dryers, dishwashers, refrigerators, freezers, light bulbs, and hot water heaters.

For the purposes of this study $\mu_i$ is assumed to be a random disturbance term. As stated earlier, at this point in time, cross sectional data on energy prices are not yet available. However, because energy prices faced by households are relatively constant throughout the year, they can be regarded as constant and excluded from the model without causing any bias in the estimation (Halvorsen 1975). However, our data also currently excludes information on the number kWh of electricity consumed by the household. We recognize this as an issue that could lead to bias in our results and plan to adjust our analysis accordingly as more data becomes available this summer.

Rearranging equation (19), where the dependent variable is in log form, the results of the logistic regression can also be expressed in terms of conditional probabilities

$$
(22) \quad \phi_i = \frac{e^{(\beta_0 + \sum_{i=1}^{n=10} \beta_k X_{ik})}}{1+e^{(\beta_0 + \sum_{i=1}^{n=10} \beta_k X_{ik})}}.
$$

Here, the “partial” effects for any continuous variables believed to impact household energy insecurity can be calculated using

$$
(23) \quad \frac{\partial \phi_i}{\partial X_{ik}} = \phi_i (1 - \phi_i) \beta_k
$$

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21 Once these prices become available, we will be able to test this assumption.
while the partial effects of any categorical variables can be calculated as the change in the probability that a household identifies as energy insecure as the categorical variable changes from 0 to 1, holding all other variables constant.

As a method to test the sensitivity of our results from the logistic regression using the original index results produced by the PCA technique, we establish a different cut point and separate households into two new categories of energy security. In this case we assume any index value less than or equal to zero produced by the PCA is an indication of household energy security. Conversely, households with positive index values (i.e. index values greater than zero) produced by the PCA are considered as energy “insecure.” In this case, the degree of insecurity is determined by distance between the index value and zero.

Under this framework, we can separate households again into two mutually exclusive energy security categories: energy insecure households \((Z_i > 0)\) and energy secure households \((Z_i = 0)\). Using this method, where the dependent variable is censored, the model for household energy security can be cast as a Tobit. The general formulation will be given in terms of the index function,

\[
EINDEXSECURE_i = \sum_{k=1}^{n} \beta_k X_i + \mu_i
\]

where \(EINDEXSECURE_i = 0\) if \(EINDEXSECURE_{pca,i} \leq 0\) and \(EINDEXSECURE_i = EINDEXSECURE_{pca,i}\) if \(EINDEXSECURE_{pca,i} > 0\).

In this case, \(EINDEXSECURE_{pca,i}\) is the energy security index result produced for household \(i\) from the results of PCA, \(\beta_k\) are parameters to be estimated, and \(X_i\) are the set of factors believed to impact household energy security as discussed previously, and \(\mu_i\) is the random disturbance term. In this case the partial effect of each \(X_i\) variable considered can be decomposed into two parts:
Equation (25) can be interpreted as the partial effect of each $X_i$ on the expected value of the energy security index for the cases when the index value is fully observed, while equation (26) is the partial effect of each $X_i$ on the probability that the energy security index is fully observed.

**ESTIMATION RESULTS**

The estimated maximum-likelihood parameters from the estimation of equations (21) and (24) are presented in Table 5 (see Appendix). The majority of the estimated coefficients have conceptually expected signs, with the exception of Employment. To keep our results general, we specified a household as employed if either full-time or part-time employment was reported in the survey. However, nearly 10% of our sample indicated they only work part time. As a result, lumping together full-time and part-time employment may have influenced the unexpected sign on the Employment variable. Additionally, almost all the estimated coefficients are statistically significant at the 1% level; with the exception of Audit and Audit Change. Because the dependent variable in both models is a latent class variable used to measure household energy insecurity, we can interpret the estimated coefficients broadly as the likelihood that a household will identify as energy insecure (i.e. not energy secure).

The results from both regressions suggest that households with higher incomes are less likely to identify as energy insecure, which makes sense from a budget constraint standpoint. For instance, households with higher incomes spend less of their disposable income on fuel expenditures and are probably less likely to become negligent on energy bills, given available financial credit. Additionally, households who have a programmable thermostat are 35% less
likely to identify as energy insecure, based on the results of the logistic regression. Programmable thermostats are unique in that they are designed to automatically adjust to a certain temperature depending on the time of the day and the settings put in place by the household. Thus, a programmable thermostat enables a household to reduce energy costs by automatically reducing energy consumption when household members are away from the home (e.g. at work or on vacation).

To examine how improvements in energy technical efficiency affect household energy security, we focus on the estimated coefficients of three primary variables: Energy Star, Windows, and Insulation. The results indicate that households who reported adequate levels of insulation ($Insulation = 1$) were statistically less likely to identify as energy insecure. Improving the insulation of a home is one of the keys ways to reduce heat and cooling loss through walls, ceilings, and floors. Thus, insulation helps to reduce energy consumption and lower fuel expenditures enabling households to produce a higher level of energy security.

A similar result was observed for the windows variable which showed that households who had either double or triple pane windows ($Windows = 1$) were 47% less likely to identify as energy insecure. The magnitude of this effect is the same across models. Every household included in our sample had a least one, Energy Star certified appliance, and many had more than one. Estimation results for the continuous variable measuring the number of Energy Star appliances in a household ($Energy Star$) indicated that as the number of energy star certified appliances increases in the household, the probability the household identifies as energy insecure decreases significantly. Again, results are consistent across the two models.
SUMMARY AND CONCLUSIONS

In this study, we examine the theoretical and empirical relationships between household energy efficiency and energy security. Our theoretical model is based on the theory of household production and depicts households as both consumers and producers of energy services. Households produce energy services such as hot, cooked foods, cold beverages, comfortable room temperatures by combining time (labor), fuel (electricity), and capital technology (e.g., a washer, dryer, stove) inputs. Based on our theoretical framework, we are able to show that energy security is a direct function of the energy services produced by the household.

However, while the definition of energy security has been discussed and debated in the literature for some time now, the lack of a single, comprehensive index measure continues to be one of the major roadblocks to qualitatively examining how the purchase of energy efficient technology impacts a household’s ability to achieve energy security. We empirically measure the extent of each household’s level of energy security using a stochastic production frontier approach. Additionally, we propose an economically robust index-measure for household energy security using principal component analysis (PCA).

Results from the PCA indicate that about 41% of single family households in the United States identified as being energy insecure to some extent in 2015. Using this index, we explore the relationship between making energy efficient upgrades in the home and household energy security. Our empirical analysis results are based on two models based on the stochastic production frontier approach, an estimated logistic regression and a general Tobit model specification. In these models, a household’s current stock of energy efficient capital technology is represented by three primary variables; adequate insulation, double- or triple-paned windows, and the number of Energy Star certified appliances in the household. Our estimation results indicate that all three of
these variables have a positive and statistically significant relationship with a household’s self-reported level of energy security. The implication, consistent with our theoretical model, is that energy efficient capital inputs enable household to “produce” more energy services and therefore achieve higher levels of energy security, *ceteris paribus*. Additionally, we find households with higher incomes are also statistically more likely to self-identify as energy secure which is also consistent with our theoretical model.

A limitation of our analysis is the lack information not yet available in the data, including the number of kWh of electricity consumed by the household. However, we plan to add this information to our analysis as more of the 2015 RECS survey data is made publicly available by the EIA this summer. Additionally, as more data becomes available we will be able to further check the robustness of our index results by comparing between the expenditure approach, the principal component results we have now, and two other methods to measure household energy security: (1) cluster analysis and (2) the method suggested by Cook et al. (2008) that involves focusing on only four questions from the RECS. We plan to extend this work even further by exploring the work of Gundersen (2008) who explores the outcomes of using different aggregation rules to determine the extent of aggregate food insecurity in the United States.

Furthermore, once more data becomes available, we will also be able to judge the accuracy of our index and estimation results using content and construct validity measures. More specifically, in terms of content validity, we are interested in exploring whether or not individual responses to the nine questions listed in section L of the 2015 RECS actually represent an individual household’s level of energy security/insecurity. To examine the content validity of these questions, we plan to compare the PCA results and the Cluster Analysis results to the results produced by the expenditure approach. To examine the construct validity of our index and
estimation results, we plan to compare the index results from the four separate measures discussed to see how highly correlated the different measures are. We can also estimate the same empirical model using different index results as the dependent variable and examine how the results vary by model.

We suggest that future research should further consider the role of energy prices faced by the household as determinants of household energy security. Electricity prices vary greatly by state, with states in the Northeast United States paying almost three times what those in the Southeast pay. We were not able to explore the impact of prices on energy security due to current limitations of the survey data. However, in the future, we plan to extract average energy price data from the different censuses listed in the data and to include this information in our model. In addition, it would be interesting to explore the impacts of the different fuel sources used to produce energy services and determine how each influences household energy security.
APPENDIX

Table 1. 2015 RECS Energy Assistance Question

<table>
<thead>
<tr>
<th>Variable</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsafe</td>
<td>In the last year, has your household keep your home at a temperature that you felt was unsafe or unhealthy?</td>
</tr>
<tr>
<td>Reduce</td>
<td>In the last year, has your household reduced or foregone other expenses for basic household necessities, such as medicine or food, in order to pay an energy bill?</td>
</tr>
<tr>
<td>Notice</td>
<td>In the last year, has your household received a disconnection notice, shut off notice, or non-delivery notice for an energy bill?</td>
</tr>
<tr>
<td>HVAC</td>
<td>In the last year, was there ever a time your household was unable to use your main source of heat or air conditioning because equipment was broken and you couldn’t afford to pay to repair or replace.</td>
</tr>
<tr>
<td>Disconnect</td>
<td>In the last year, was there ever a time your household was unable to use your main source of heat or air conditioning because you could not afford to restore your main source of fuel and it was disconnected.</td>
</tr>
<tr>
<td>Medical</td>
<td>In the last year, has anyone in your household needed medical attention because your home was too hot or too cold?</td>
</tr>
<tr>
<td>Assistance</td>
<td>In the past year, has your household applied for and received home energy assistance to help restore your heating or cooling?</td>
</tr>
</tbody>
</table>

*Note: This subset of questions was taken from section L of the 2015 Residential Energy Consumption Survey. In some cases questions were modified and combined.*
Table 2. Summary Statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Mean</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Income</td>
<td>Median Household Income ($)</td>
<td>71,901.80</td>
<td>(697.2391)</td>
</tr>
<tr>
<td>Employed</td>
<td>=1 if Head of Household is Employed</td>
<td>0.6903</td>
<td>(0.0105)</td>
</tr>
<tr>
<td>ProTherm</td>
<td>=1 if Household has a Programmable Thermostat</td>
<td>0.5892</td>
<td>(0.0081)</td>
</tr>
<tr>
<td>Cdd</td>
<td>Average Number of Cooling Degree Days</td>
<td>1,439.03</td>
<td>(16.5639)</td>
</tr>
<tr>
<td>Hdd</td>
<td>Average Number of Heating Degree Days</td>
<td>4,158.84</td>
<td>(35.1923)</td>
</tr>
<tr>
<td>Audit</td>
<td>=1 if Household Received an In-Home Energy Audit</td>
<td>0.0966</td>
<td>(0.0049)</td>
</tr>
<tr>
<td>Audit Change</td>
<td>=1 if Household made Changes Suggested by the Audit</td>
<td>0.0782</td>
<td>(0.0044)</td>
</tr>
<tr>
<td>Energy Star</td>
<td>Number of Energy Efficiency Appliances</td>
<td>3.4157</td>
<td>(0.0326)</td>
</tr>
<tr>
<td>Windows</td>
<td>=1 if Household has Double or Triple Pane Windows</td>
<td>0.6787</td>
<td>(0.0077)</td>
</tr>
<tr>
<td>Insulation</td>
<td>=1 if Household has Adequate Insulation</td>
<td>0.8581</td>
<td>(0.0057)</td>
</tr>
<tr>
<td>Total Sq. Ft</td>
<td>Total Square Feet</td>
<td>2,565.05</td>
<td>(20.8702)</td>
</tr>
<tr>
<td>Bedrooms</td>
<td>Number of Bedrooms</td>
<td>3.2827</td>
<td>(0.0148)</td>
</tr>
<tr>
<td>Bathrooms</td>
<td>Number of Bathrooms</td>
<td>1.9245</td>
<td>(0.0127)</td>
</tr>
<tr>
<td>Ownership</td>
<td>=1 the Household is Owned</td>
<td>0.8870</td>
<td>(0.0052)</td>
</tr>
<tr>
<td>HH Members</td>
<td>Number of Household Members</td>
<td>2.7518</td>
<td>(0.0237)</td>
</tr>
<tr>
<td>Reduce</td>
<td>=1 if the Household has Reduced or Forgone Expenses</td>
<td>0.1629</td>
<td>(0.0061)</td>
</tr>
<tr>
<td>Unsafe</td>
<td>= 1 if the Household has kept Home at an Unsafe Temperature</td>
<td>0.0774</td>
<td>(0.0044)</td>
</tr>
<tr>
<td>Notice</td>
<td>=1 if the Household has Received a Disconnection Notice</td>
<td>0.1184</td>
<td>(0.0053)</td>
</tr>
<tr>
<td>Assistance</td>
<td>=1 if the Household Applied for Energy Assistance</td>
<td>0.0156</td>
<td>(0.0020)</td>
</tr>
<tr>
<td>Disconnect</td>
<td>=1 if the Household’s Fuel Source was Disconnected</td>
<td>0.0003</td>
<td>(0.0003)</td>
</tr>
<tr>
<td>HVAC</td>
<td>=1 if Household could not Afford to Repair or Replace HVAC System</td>
<td>0.0089</td>
<td>(0.0015)</td>
</tr>
<tr>
<td>Medical</td>
<td>=1 if a Household Member has Needed Medical Attention</td>
<td>0.0011</td>
<td>(0.0005)</td>
</tr>
<tr>
<td>Observations</td>
<td></td>
<td></td>
<td>3,707</td>
</tr>
</tbody>
</table>
Table 3. Energy Security Index Results: Cluster Analysis

<table>
<thead>
<tr>
<th>Cluster Analysis</th>
<th>Energy Security Measure</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very Low Energy Security</td>
<td>664 Households</td>
</tr>
<tr>
<td></td>
<td>Low Energy Security</td>
<td>1 Households</td>
</tr>
<tr>
<td></td>
<td>Marginal Energy Security</td>
<td>631 Households</td>
</tr>
<tr>
<td></td>
<td>High Energy Security</td>
<td>2,411 Households</td>
</tr>
</tbody>
</table>

Table 4. Energy Security Index Results: Principal Component Analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Comp 1</th>
<th>Comp 2</th>
<th>Comp 3</th>
<th>Comp 4</th>
<th>Comp 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Sq. Ft.</td>
<td>-0.3682</td>
<td>0.3417</td>
<td>-0.0013</td>
<td>0.0487</td>
<td>0.2093</td>
</tr>
<tr>
<td>Bedrooms</td>
<td>-0.3599</td>
<td>0.4444</td>
<td>-0.0318</td>
<td>0.0224</td>
<td>-0.0703</td>
</tr>
<tr>
<td>Bathrooms</td>
<td>-0.4070</td>
<td>0.3436</td>
<td>0.011</td>
<td>0.0359</td>
<td>0.0942</td>
</tr>
<tr>
<td>Ownership</td>
<td>-0.2980</td>
<td>-0.0891</td>
<td>0.2525</td>
<td>0.2724</td>
<td>0.4983</td>
</tr>
<tr>
<td>Number of Household Members</td>
<td>-0.0350</td>
<td>0.4354</td>
<td>-0.1291</td>
<td>-0.1596</td>
<td>-0.4994</td>
</tr>
<tr>
<td>Reduce</td>
<td>0.3926</td>
<td>0.3007</td>
<td>-0.0186</td>
<td>0.1028</td>
<td>0.1307</td>
</tr>
<tr>
<td>Unsafe</td>
<td>0.3132</td>
<td>0.2478</td>
<td>0.1555</td>
<td>0.0498</td>
<td>0.4171</td>
</tr>
<tr>
<td>Notice</td>
<td>0.3733</td>
<td>0.3192</td>
<td>-0.2030</td>
<td>0.0822</td>
<td>0.0490</td>
</tr>
<tr>
<td>Assistance</td>
<td>0.2413</td>
<td>0.2773</td>
<td>-0.1874</td>
<td>-0.0379</td>
<td>0.2454</td>
</tr>
<tr>
<td>Disconnect</td>
<td>0.0463</td>
<td>0.0031</td>
<td>-0.0496</td>
<td>0.9335</td>
<td>-0.2946</td>
</tr>
<tr>
<td>HVAC</td>
<td>0.1467</td>
<td>0.1601</td>
<td>0.6258</td>
<td>-0.005</td>
<td>0.0034</td>
</tr>
<tr>
<td>Medical</td>
<td>0.0758</td>
<td>0.1179</td>
<td>0.6508</td>
<td>-0.0588</td>
<td>-0.3303</td>
</tr>
<tr>
<td>Proportion</td>
<td>0.2009</td>
<td>0.1581</td>
<td>0.0844</td>
<td>0.0812</td>
<td>0.0725</td>
</tr>
<tr>
<td>Cumulative Observations</td>
<td>0.2009</td>
<td>0.3590</td>
<td>0.4630</td>
<td>0.5474</td>
<td>0.6286</td>
</tr>
<tr>
<td>Observations</td>
<td>3,707</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5. Regression Results

<table>
<thead>
<tr>
<th></th>
<th>Logistic</th>
<th>Tobit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Income</td>
<td>$-2.14 \times 10^{-5}$ ***</td>
<td>$-2.20 \times 10^{-5}$ ***</td>
</tr>
<tr>
<td></td>
<td>(1.08 $\times 10^{-7}$)</td>
<td>(1.06 $\times 10^{-6}$)</td>
</tr>
<tr>
<td>Employment</td>
<td>0.2017***</td>
<td>0.3105***</td>
</tr>
<tr>
<td></td>
<td>(0.0594)</td>
<td>(0.0543)</td>
</tr>
<tr>
<td>ProTherm</td>
<td>-0.3521***</td>
<td>-0.2899***</td>
</tr>
<tr>
<td></td>
<td>(0.0782)</td>
<td>(0.0692)</td>
</tr>
<tr>
<td>CDD</td>
<td>-0.0002***</td>
<td>-0.0002***</td>
</tr>
<tr>
<td></td>
<td>(0.0001)</td>
<td>(0.0001)</td>
</tr>
<tr>
<td>HDD</td>
<td>-0.0001***</td>
<td>-0.0001***</td>
</tr>
<tr>
<td></td>
<td>(0.0000)</td>
<td>(0.0000)</td>
</tr>
<tr>
<td>Audit</td>
<td>0.3460</td>
<td>0.3569</td>
</tr>
<tr>
<td></td>
<td>(0.2949)</td>
<td>(0.2310)</td>
</tr>
<tr>
<td>Audit Change</td>
<td>-0.2139</td>
<td>-0.1803</td>
</tr>
<tr>
<td></td>
<td>(0.3222)</td>
<td>(0.2601)</td>
</tr>
<tr>
<td>Energy Star</td>
<td>-0.0693***</td>
<td>-0.0770***</td>
</tr>
<tr>
<td></td>
<td>(0.0203)</td>
<td>(0.0181)</td>
</tr>
<tr>
<td>Windows</td>
<td>-0.4779***</td>
<td>-0.4702***</td>
</tr>
<tr>
<td></td>
<td>(0.0851)</td>
<td>(0.0750)</td>
</tr>
<tr>
<td>Insulation</td>
<td>-0.9863***</td>
<td>-1.1021***</td>
</tr>
<tr>
<td></td>
<td>(0.1145)</td>
<td>(0.0956)</td>
</tr>
<tr>
<td>Log-Liklihood</td>
<td>-2.062.90</td>
<td>-4.018.29</td>
</tr>
<tr>
<td>Observations</td>
<td>3707</td>
<td>3707</td>
</tr>
</tbody>
</table>

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
Figure 1. Stochastic Frontier Production Function for Energy Security

Output (Y) “Energy Security”

Energy Secure

Deterministic Production Function

\[ y = f(x; \beta) \]

\( \epsilon_i \): Level of Insecurity

Energy Insecure

Inputs, X

0
References


