# THREE ESSAYS ON ENERGY POLICIES AND THEIR DISTRIBUTIONAL IMPACTS

by

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# ABSTRACT

This thesis consists of three individual chapters that deal with various energy policies and their distributional impacts i.e. their impacts on different income groups of consumers. It includes energy policies such as energy taxes, energy efficiency standards, and energy efficiency subsidies.

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# LIST OF SYMBOLS

| | |
|---|---|
| Capital | $K$ |
| Cash transfers | $trn$ |
| Elasticity of substitution between energy use and efficiency capital | $\sigma$ |
| Energy | $E$ |
| Energy services | Y |
| Kilo Watt Hours | kWh |
| Labor | $L$ |
| Lighting energy services | $S$ |
| Other goods | X |
| Tera Watt Hours | TWh |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| Air Conditioner | AC |
| Bureau of Economic Analysis | BEA |
| Coarsened Exact Matching | CEM |
| Compact Fluorescent | CFL |
| Database of State Incentives for Renewables and Efficiency | DSIRE |
| Ideal Demand System | AIDS |
| Instrumental Variable | IV |
| Light-Emitting Diodes | LED |
| Residential Electricity Consumption Survey | RECS |
| Square feet | sqft |
| U.S. Energy information Administration | EIA |
| US. Congressional Budget Office | CBO |
| US. Dollars | USD |

# ACKNOWLEDGMENTS

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This thesis is dedicated to Mohammad, my better half, who has been so supportive and helpful.

# CHAPTER 1
# INTRODUCTION

There have been various types of energy policies to reduce energy consumption and the associated emissions. These policies are expected to have different impacts on different income groups of consumers in terms of their behavioral impacts as well as their welfare impacts. This thesis tries to shed lights on this area, and it provides more information about the potential distributional impacts of different energy policies that can be useful to economists and policy makers. The thesis includes three individual chapters that deal with topics in energy policies and their distributional impacts. The three chapters are as follows:

- Chapter 2: Distribution and the Rebound Effect: Evidence from Efficient Lighting Subsidies
- Chapter 3: Distributional Impacts of Energy Efficiency Standards vs. Energy Taxes
- Chapter 4: Efficiency vs Equity: an Alternative to Energy Efficiency Subsidies

Rebound effect is a term that has been widely used to describe the increase in energy consumption from an energy efficient durable good, which stems from lower operating costs after the energy efficiency improvement. In Chapter 2, I investigate heterogeneity in the rebound effect of energy efficiency subsidies across different income and home-size categories. I exploit variation in household-level uptake of residential energy efficiency programs in lighting using instrumental variables for program awareness as well as exact coarsened matching. This research shows evidence of economically meaningful rebound effects that are created by energy efficient lighting subsidies. This paper contributes to the existing literature by establishing evidence of a policy-oriented rebound effect that differs by income and home-size categories. The results show that the effects mainly stem from households that have low incomes or small homes. I also show that there is no backfire in the rebound effect of the policy which would be the case if the rebound effect were very high resulting in an increase in energy consumption. I discuss these empirical findings in the context of distributional implications for energy policy.

In Chapter 3, the distributional impacts of energy efficiency standards versus direct energy taxes are quantified by incorporating non-homothetic preferences in a general equilibrium framework. Compared to an equivalent energy efficiency standard policy, the results show that an energy tax policy is not only more efficient, it also can be progressive depending on how the tax revenue is distributed back to the economy.

Market-based policies such as energy taxes are economically efficient but they are associated with distributional concerns. Energy efficiency subsidies might result in rebound effects which are privately welfare enhancing even if they reduce social welfare (by raising pollution). These programs, however, are not economically efficient since they subsidize households in a constrained way. Building upon Chapter 2 which finds that the rebound effect is created by low-income households, Chapter 4 compares the distributional impacts of energy efficiency subsidies versus energy taxes combined with cash transfers. I employ non-homothetic preferences in a general equilibrium framework where the low/high income consumers are distinguished, not only by different total wealth endowments, but also by different factor production ownership including labor and capital. The results show that the welfare differences after the two policy instruments are highly dependent on the elasticity of substitution between energy use and efficiency capital.

# CHAPTER 2

# DISTRIBUTION AND THE REBOUND EFFECT: EVIDENCE FROM EFFICIENT LIGHTING SUBSIDIES

Rebound effect is a term that has been widely used to describe the increase in energy consumption from an energy efficient durable good, which stems from lower operating costs after the energy efficiency improvement. This paper investigates heterogeneity in the rebound effect of energy efficiency subsidies across different income and home-size categories. I exploit variation in household-level uptake of residential energy efficiency programs in lighting using instrumental variables for program awareness as well as exact coarsened matching. This research shows evidence of economically meaningful rebound effects that are created by energy efficient lighting subsidies. This paper contributes to the existing literature by establishing evidence of a policy-oriented rebound effect that differs by income and home-size categories. The results show that the effect mainly stems from households that have low incomes or small homes. I also show that there is no backfire in the rebound effect of the policy which would be the case if the rebound effect were very high resulting in an increase in energy consumption. I discuss these empirical findings in the context of distributional implications for energy policy.

## 2.1 Introduction

There is a vast literature examining the efficiency and total cost effectiveness of energy efficiency subsidies, but the incidence and distributional impacts are much less known. In general, energy efficiency is associated with private benefits such as reducing energy bills for consumers, as well as social benefits such as emissions reduction goals, avoided energy infrastructure, and national security. However, the environmental benefits might not be fully achieved due to market failures. One goal of energy efficiency subsidies is to address two types of market failures: 1) energy use externalities and 2) investment inefficiencies in energy efficiency, which stem from factors such as incomplete information [4]. Nonetheless, few studies investigate the distributional impacts of these policies.

Distributional impacts mainly arise from the fact that low-income consumers usually spend a higher share of their income on energy, so that any energy related policy could impact their behavior differently in comparison to high-income consumers. Distinguishing the distributional impacts is important for policy makers and economists, and analyzing the distributional impacts of these policies helps them find an economically efficient solution that does not create pressure on the poor.

The purpose of this paper is to establish evidence of a direct rebound effect caused by energy efficiency subsidies that differs by income and home-size categories. The identification strategies are employing instrumental variables (IV) and matching algorithm to address the associated self-selection in policy participation. Evidence for rebound effects of the programs has been considered by examining the main factors that affect the adoption of the assistance program and then analyzing the impact of the policy adoption on demand for energy services. Policy participation is voluntary and is expected to be endogenous to household level unobservables such as preferences and information [1]. As a measure of information, I use the availability of energy efficiency incentives and the number of people who receive the assistance as instrumental variables influencing the participation in an energy efficiency program. Then I investigate the heterogeneous impacts of the policy adoption by income level and home-size groups.

The results show that policy adoption creates a significant rebound effect which is mainly created by consumers who have low incomes or small homes. Additionally, I examine the existence of a backfire rebound effect which would be the case if the rebound effect were too high so that it offsets all of the expected energy use reduction after the energy efficiency improvement. In order to assess the existence of a backfire case, a proxy variable for electricity consumption in lighting is used as the outcome variable. Based on the results, the policy participation has a negative impact on electricity use for lighting both on average and also at each income and home-size quintile, which implies that there is no backfire effect. Succinctly, there is an increase in hours of use, but there is a decrease in total electricity consumed so that there are net savings.

Ultimately, I explore the distributional and policy implications by examining an alternative policy option that might be employed to address the associated efficiency and distributional concerns. The alternative policy would be energy taxes combined with cash transfers to low-income groups. This policy is expected to reduce electricity consumption since electricity is more expensive to use, whereas low-income households are expected to have improved well-being since they receive rebates which can be used for either paying their energy bills or purchasing other goods. However, the amount of electricity use reduction after each policy, and the well-being of high-income groups are unknown. A thorough comparison of the two policy options in terms of their impacts on total welfare, energy use, and required funding will be examined in the future by employing general equilibrium modelling.

The remainder of this article is as follows. Section 2.2 reviews some related previous works and Section 2.3 gives an account of the theoretical motivation of this study. Then the empirical analysis is presented in Section 2.4, followed by the results in Section 2.5. Section 2.6 explores some policy implications and finally, Section 2.7 includes the conclusion of this paper.

## 2.2 Literature Review

Energy efficiency subsidies are politically easier to implement than other policies, but they are associated with some limitations such as not achieving the efficient level of consumption [15]. Thus, the energy reduction goal might not be fully accomplished due to some unintended consequences of the policy called rebound effects. Total rebound effect consists of direct and indirect rebound effects. The direct rebound effect term implies that after energy efficiency improvement, energy consumption of the efficient goods might increase since they are cheaper to use. The indirect rebound effect indicates the increase in consumption of other goods that require energy use. These impacts cause the actual energy saving to be less than the ex-ante

[85].

There is a vast literature on different forms of rebound effects (i.e. direct, indirect, and total economy-wide rebound effects). The direct rebound effect can be measured using either quasi-experimental or econometric approaches. The former measures the energy demand before and after an energy efficiency improvement [31]. This approach, however, is associated with some weaknesses such as selection bias [50, 67]. Due to different weaknesses of this approach, the econometric approach is widely employed by economists to measure the direct rebound effect in different sectors and using different durable goods such as passenger vehicles [5, 16, 47, 47, 82] and various types of appliances [17, 43, 49, 57]. The indirect rebound effect can be measured by employing methods such as input-output analysis [78] and Almost Ideal Demand System (AIDS) models [23]. Economy-wide impacts of energy efficiency improvements are usually analyzed by employing general equilibrium modeling.

Although the existence of rebound effects does not imply inaction to move towards energy efficiency improvement [42], it is important to understand who creates the rebound effect for distributional considerations. In addition, energy efficiency subsidies lower the high up-front cost of energy-efficient goods which helps the low-income consumers relatively more. These subsidies would result in income redistribution [79] no matter whether the up-front cost outweighs the expected energy saving [29] or the cost is less. Although these programs create income redistribution, they might not be economically efficient to create maximum total welfare. There is usually a trade-off between equity and efficiency impacts of a particular energy policy. For example, Borenstein [13] shows that although increasing-block pricing has distributional benefits for low-income groups, it is not economically efficient and creates substantial deadweight loss.

In this paper, I test the existence of a direct rebound effect that might be created by energy efficiency programs. By showing the existence of rebound effects, I do not intend to conclude that the energy efficiency programs are not useful. Although rebound effect is important in strategic energy planning, it does not imply government/utility companies inaction which is mainly due to little evidence for the backfire case [42]. Backfire is the case where the rebound effect is too high (100% or more) where all of the expected energy savings is offset. This study also shows that energy efficiency policies in lighting do not create a backfire rebound effect. The size of rebound effects, however, is vital for evaluation of energy efficiency policies in terms of both energy savings and welfare impacts [41].

Heterogeneity in rebound effect could be examined from different aspects such as consumer income [48, 69], energy use intensity of the consumer [32], and different features of the durable good as well as geographical features [40, 77, 84]. Frondel et al. [32] show that households with low vehicle mileage are expected to be less price elastic so the rebound effect would be lower for them (Germany and vehicle use). Milne and Boardman [69] also show higher rebound effects for low-income households . The mentioned papers, however, focus on price and income elasticities to calculate the rebound effect. The main contribution of this study is that it investigates the heterogeneous impacts of a policy shock on the rebound effect and energy services consumption for different income and home-size quintiles. This information will be mainly helpful for policy implications.

Informational failures are influential in determining how consumers respond to participating in an energy efficiency program [70, 72]. Fowlie et al. [27] show that increasing the level of information significantly affects the adoption of energy efficiency programs. Therefore, the households are not randomly treated and there is a selection bias issue. In this paper, I address this issue by using policy availability and intensity as instruments for policy participation which takes into account the effect of information on respondents.

### 2.2.1 Energy Efficiency in Lighting

Light-emitting diodes (LED), and Compact Fluorescent (CFL) are the new generations of light bulbs that save energy and improve light quality, performance, and service. Compared to conventional lighting sources, they are capable of offering high quality and cost-effective performance. An energy efficient light bulb uses less energy than a comparable incandescent light bulb having the same amount of lumens or brightness, and has a longer life span. These features have the potential to significantly lower the operating cost of lighting in terms of using less electricity to provide the same amount of lighting energy services.

In the United States as an example, energy consumption for lighting in the residential sector is expected to decrease from 173 TWh in 2010 to 153 TWh in 2030 [21]. Energy savings from using these energy efficient light bulbs are estimated to be around 2,700 TWh or approximately $250 billion at 2012's energy prices during 2010-2030 in the United States [21]. These expected cost savings (assuming no behavioral changes) justify the economic aspect of applying energy efficient lighting. In addition, they have environmental protection impacts which are approximately equivalent to a reduction of 1,800 million metric tons of carbon emissions [21].

The cost effectiveness feature of energy efficient light bulbs, however, has changed the lighting application culture towards indoor and outdoor decorating which could raise the per-capita number of bulbs [12]. This impact is part of the rebound effect. These new applications are the main reasons why energy efficiency incentives might result in a substantial rebound effect.

In general, consumer behavior in lighting is associated with two sets of questions. First, what factors can motivate the consumers to adopt the energy efficient light bulbs? Second, how much will the consumption be after the technology adoption. Adoption of energy efficient bulbs has been faced by several barriers such as lower lighting quality and/or a warm-up period requirement before achieving the full brightness [30, 81]. Mills and Schleich [68] point out that since energy efficient light bulbs are usually more expensive to buy, it may not be economically rational to replace the light bulbs with energy efficient ones for rooms with low usage.

Assistance programs try to reduce the high initial costs of energy efficient bulbs to motivate the consumers to use them. The lighting consumption after adoption of the technology, however, might increase due to lower operating costs. Using engineering methods and employing a household survey in Germany, Schleich et al. [74] calculated the expected total direct rebound effects for an average bulb at about 6%. In economic literature, rebound effect in lighting has been estimated for Pakistan which shows that the lower operating cost of energy efficient light bulbs reduces potential energy savings by 23% to 35% due to increased brightness and extended hours of use [20]. This paper focuses only on the hours of use as a measure of lighting services consumption and contributes to the existing economic literature by estimating the impacts of policy on the energy services consumption of lighting while taking into account any potential heterogeneity.

## 2.3 Theoretical Motivation

In order to show the theoretical intuition behind the potential rebound effect caused by the policy, I start with a simple utility maximization problem by a representative household. The consumer's goal is maximizing the utility, subject to the budget constraint, where the household's utility is a function of lighting energy services ($S$) and a numaire for all other goods ($X$).

$$U = f(S, X)$$

The lighting energy services increase by using either more electricity or more effective capital stock. Increase in $S$ as a result of policy adoption implies the existence of a rebound effect. Figure 2.1 is a particular example that can show this concept. The technology is assumed to be constant. The green budget line shows the case where the household adopts energy efficient light bulbs which are more expensive to buy but cheaper to use. The former causes the line to shift down compared to the initial red line and the latter makes it flatter. $U_0$ shows the initial utility for a household who would not buy energy efficient bulbs without receiving the assistance since the utility will be lower on the green budget line. The initial utility will be to the right corner for the households who would buy energy efficient light bulbs even without receiving any assistance.

If the household receives energy efficient lighting assistance, the line shifts up and Figure 2.1 shows a case when the amount of incentive is such that the household is indifferent to adopt energy efficient light bulbs. The policy increases energy efficiency which requires less electricity use. Compared to the level of energy services on the green line (it is not shown on the figure), the new consumption of energy services after adopting the policy will increase if there is a rebound effect. The reason is that on both green and dashed lines, the household is using energy efficient light bulbs so that the difference between the level of energy services stems from the change in electricity use. In this paper, I empirically analyze this rebound effect as a result of the policy shock by considering any potential heterogeneity based on income and home-size categories.

## 2.4 Empirical Analysis

### 2.4.1 Data

In this research I use cross sectional data from the 2009 Residential Electricity Consumption Survey (RECS). The data is a national sample survey collected by the U.S Energy Information Administration (EIA) and includes 27 reportable domains in which households are located. Reportable domain provides the geographical information and is an index of 21 individual states or group of states. That includes various energy related data of housing units such as lighting, appliances, electronics, space heating, air conditioning, water heating, energy programs, energy bills, energy suppliers, housing unit characteristics, and household characteristics. The survey includes a random sample of 12,083 households in the United States. In addition, the data on the number of different energy efficiency programs for residential sector in lighting comes from the Database of State Incentives for Renewables and Efficiency (DSIRE).

The RECS survey consists of information about the number of total and energy efficient light bulbs that were turned on for 1 to 4 hours, 4 to 12 hours, and more than 12 hours during a summer day. This information was used to calculate the outcome variables including total hours of lighting use and hours of energy efficient lighting use according to the formula $y_i = \sum_j h_j N_{ij}$. $h_j$ stands for the average hours that light bulbs were turned on and $N_{ij}$ represents the number of total or energy efficient bulbs that were turned on by household $i$

during that time.

A summary of variables used in this paper is shown in Table 2.1. Assistance for energy efficient light bulbs (treatment variable) is a binary variable which is one if the household receives assistance for energy efficient light bulbs and is zero otherwise. kWh used for lighting is a proxy variable for electricity use in lighting which is calculated using the $kWh_i = \beta_1 y_{in} + \beta_2 y_{ie}$ formula. $y_{in}$ and $y_{ie}$ represent 1) energy inefficient and 2) energy efficient hours of lighting use respectively where the former is calculated by subtracting the energy efficient hours from the total. $\beta_1$ and $\beta_2$ are the average kWh used in an hour by 1) an energy inefficient and 2) an energy efficient light bulb respectively (i.e. 0.060 and 0.014). Policy intensity is a measure of the number of people who received lighting assistance one year before a household adopts the policy and before 2009 if the household did not receive any lighting assistance. It has been calculated using the treatment variable, the lighting assistance time, and the reportable domain information.

Policy availability shows the number of residential energy efficiency programs for lighting in the reportable domain where the household lives one year before the household adopts the policy. It has been calculated using the DSIRE database, the lighting assistance time, and the reportable domain information in the survey. The estimation also includes other variables such as annual income (USD), home size (sqft), state electricity price, household size (the number of household members), gender (one if female and zero otherwise), electricity bill payment (one if the household pays the electricity bills and zero otherwise), age of household head, and home ownership status.

### 2.4.2 Methodology

To analyze the potential heterogeneous rebound effect in lighting, total hours of lighting consumption is regressed on policy adoption and a vector of control variables. Policy adoption is a dummy variable of receiving assistance for energy efficient lighting in the form of manufacturer or retailer rebate, utility or energy supplier rebate, and/or weatherization assistance.

I use an instrumental variables strategy that leverages variation in knowledge about the programs. The intuition behind my approach is that in areas with more energy efficiency subsidies historically and more recent adopters of those policies, any individual household is more likely to be aware of the policies and therefore more likely to adopt the policy. This approach is similar to that of Si et al. [75]. Participating in these policies may be endogenous to household level unobservables such as preferences and information that affect the hours of lighting use. In order to address the endogeneity, a two stage instrumental variable (IV) regression is employed. I use two variables named policy intensity and policy availability as instruments for the policy adoption variable. The former is defined as the sum of the households who received the assistance in the same reportable domain that the household $i$ lives except for the household $i$, one year before the household $i$ adopts the policy or before 2009 if household $i$ did not receive any lighting assistance. The latter is the number of energy efficiency incentives in lighting at the residential sector in each reportable domain, one year before the household $i$ adopts the policy or before 2009 if household $i$ did not receive any efficient lighting assistance.

The two instrumental variables are time lagged. My main assumption is that the time lagged instruments have no impact on a household's lighting use except through their impact on the household's current policy adoption, conditional on the control variables. This assumption is reasonable, because variables such as household size, income, home size, and home ownership control for unobservable factors such as preferences and needs that may be correlated across households. Therefore, conditional on control variables, the time lag of policy adoption by other households and the time lag of available incentives should not affect the lighting use by household $i$, except through their impact on the household's current policy adoption. Therefore, instruments are correlated with policy adoption by household $i$ at time t and do not influence the lighting consumption by household $i$ at time t except through their impact on the policy adoption by household $i$ at time t.

The predicted policy adoption variable comes from the first stage regression, regressing this variable on policy intensity and policy availability as instrumental variables as well as all other explanatory variables. I also consider the heterogeneity by choosing different sub-samples based on income level and home size.

In the IV regression, the following equation is estimated for the whole sample as well as sub-samples by income and home size quintiles.

$$y_i = \beta_0 + \beta_1 treat_i + X_i \alpha_x + \epsilon_i \tag{2.1}$$

where the outcome variable is the log of total hours of lighting use during a summer day. $treat_i$ is the treatment effect of receiving assistance for energy efficient lighting. Control variables include electricity price, income level, home ownership dummy, assistance year, lighting bill payment dummy, state dummy variables, age, home size, number of household members, and so on. All variables other than the binary variables are in log form. I assume that electricity prices are exogenous due to regulated electricity prices.

In order to assess the existence of a backfire rebound effect, the same set of equations but with a different outcome variable are estimated where the outcome variable is the electricity use in lighting. The outcome variable is a proxy for actual electricity use for lighting which is calculated by multiplying the hours of energy efficient and inefficient light bulb use by the average electricity use of an energy efficient and inefficient light bulb and then adding them up together.

### 2.4.3 Coarsened Exact Matching

In addition to using the IV estimator, I use Coarsened Exact Matching (CEM) algorithm as another identification strategy to control for a set of pre-treatment variables and address the selection-bias issue. The algorithm is used to match each adopter of energy efficiency assistance to similar non-adopters and drop non-matched observations. This method is preferred to other types of matching methods due to some features such as requiring fewer assumptions, reducing the degree of model dependence, and reducing the estimation error of causal impact [60]. It reduces any potential imbalance between treated and control groups [54] which helps me to improve the estimation of causal effects.

The matching is done using covariates such as household size, employment status, and a binary variable of receiving assistance for home energy audit. In order to evaluate the quality of matching, a summary of the CEM matching as well as the level of imbalance between treated and control groups before and after the matching are shown in Table 2.2. The global imbalance, which was first introduced by Iacus et al. [54], is shown by the multivariate $L_1$ statistics. The goal is to reduce this global imbalance which is the difference between the multivariate empirical distribution of the pre-treatment covariates for the treated $p(X|T = 1)$ and matched control $p(\tilde{X}|T = 0)$ groups [54]. The matching results demonstrate that the level of imbalance decreases, after the matching, compared to the unmatched data.

### 2.5 Results

The results of the first stage regressions, including the whole sample, are shown in Table 2.3. They demonstrate that both instruments have a significant effect on the endogenous policy adoption variable and the instruments are correlated with the endogenous variable while controlling for all explanatory variables. As the result shows, income level does not have a statistically significant effect on policy adoption which implies that the major policy adopters are not necessarily the low-income households. Figure 2.2 also shows that the income distribution for policy participants is similar to non-participants. The spike on the right tail of each distribution mainly stems from the top-censored income question for privacy purposes. The figure implies that although policy adoption might have heterogeneous impacts on energy services consumption at different income level groups, policy adoption, however, is not dependent on income level. The results of the Kolmogorov-Smirnov test [63, 76] for equality of distribution functions show that the two distributions are not the same.

Table 2.3 also shows that both policy intensity and policy availability variables (IVs) have a positive significant impact of policy participation. In order to test the quality of the instrumental variables, statistical tests such as under-identification (Kleibergen-Paap LM statistic) and over-identification (Hansen J statistic) tests [8] have been implemented. In addition, the Montiel-Pflueger robust weak instrument test [71] has been done for all instrumental variable regressions which is preferred to the regular non-robust first stage F test due to using a correction factor for non-homoskedasticity [7]. The F statistics of this test have been shown on IV regression results.

Since each reportable domain has a different population, I use population weights for the instrumental variables. The results of the naive and IV regressions with/without matching for the whole sample are shown in Table 2.4. They show that the policy adoption has positive and significant impact on hours of lighting use. Other explanatory variables also have the expected impacts. Gender is a binary variable for being female. Lighting assistance time, that is the number of years since adopting the policy, has a negative sign which implies that the impact of policy adoption decreases during time. The coefficient of electricity bill payment implies that households who do not pay the electricity bills for lighting and other appliances intend to have more hours of lighting use.

I investigate the heterogeneous impacts of policy participation by running the regression for various sub-samples which are shown in Table 2.5 and Table 2.6 for each income quintile and Table 2.7 and Table 2.8 for each home-size quintile. The results show that the impact of policy adoption on hours of lighting use is positive only for households who have either very low incomes or very small homes.

Based on the empirical results, although income level does not impact policy participation, people who have a very low income would use more hours of lighting after receiving energy efficiency assistance for lighting. So, the rebound effect of energy efficiency policy in lighting is mainly created by people who have a very low incomes or have small homes.

Furthermore, a similar set of regressions has been estimated while using the electricity use in lighting as the outcome variable, and the results for the whole sample as well as the subsamples by income and home size quintiles are shown in Table 2.9, Table 2.10, and

Table 2.11, respectively. The negative and significant impacts of the policy adoption on the electricity use for lighting on average and also for all income and home-size groups imply that there is no backfire rebound effect. In other words, although there is a rebound effect, it is not too high to completely offset the expected electricity use reduction due to the policy.

## 2.6 Policy Implication

As a form of income redistribution, energy efficiency subsidies create welfare gains for low-income groups, but they are economically inefficient because they subsidize households in a constrained way. Therefore, they probably are not the first-best policy option to reduce energy use. For example, a low-income household who has an inefficient air conditioner (AC), receives energy efficiency subsidy to get an energy efficient AC. The new energy efficient AC creates energy and money saving which could help the household to receive more energy services from the new AC by turning it on for a longer time and having more comfortable temperature (direct rebound effect); this impact will create welfare gain. The program, however, does not give that much flexibility to the household to be used for other needs.

Although energy efficiency subsidies might result in the rebound effect, they create welfare gains for households. These welfare gains can be seen in Figure 2.3 where the utility on the green budget line (not shown on graph) would be lower than the $U_0$ assuming the technology is held constant. This figure shows a household who would not buy an energy efficient light bulb if the household does not receive any assistance. As I showed before, the rebound effect is created by low-income groups. These subsidies address the distributional issues by creating welfare gain for these low-income groups, but they create the welfare gains in a constrained way and they are economically inefficient. They also require government/utility companies funding. Energy taxes instead create a revenue, but they are associated with distributional issues and they are regressive. It means that the burden of tax on low-income groups is relatively higher because low-income groups spend a higher share of their income on energy bills.

One potential alternative policy is using energy taxes and rebating some of the tax revenue to low-income groups in a form of cash transfers. This policy could address distributional concerns. It also needs less government funding, but its impact on total welfare is ambiguous. Cash transfers to low-income groups help them to have similar welfare gain as from subsidies. In addition, the household can spend the rebate not only on energy but also on other necessary goods. One example is shown in Figure 2.3 where the amount of cash transfer is such that it makes the household indifferent between the two policies. Point 3 also shows a case where the size of the subsidy is such that it makes the household indifferent compared to the initial point. Since the household uses energy efficient bulbs at both points 2 and 3, higher energy services at point 3 are associated with more energy use; this implies the existence of a direct rebound effect. By employing energy tax, the budget line gets steeper and cash transfers shift the line up. Since the alternative policy makes the household less constrained, the household uses fewer energy services compared to the subsidy and spends the cash transfer on other goods. If a utility company implements the policy, the alternative could be raising electricity prices for everyone and rebating based on income.

Based on the mentioned intuition, future work can benefit from comparing the two policy options in the form of answering two types of questions. First, what is the cheapest way for the government/utility companies to reduce energy use and not leave all households worse off? Second, what is the most efficient way for the government/utility companies to reduce energy use and not leave low-income groups worse off? These two questions can be answered by employing a partial or general equilibrium modelling.

## 2.7 Conclusion

I investigated the distribution and the rebound effects of energy efficiency subsidies by using efficient lighting subsidies in the residential sector. I showed that despite having no impact of income level on policy adoption, income level creates heterogeneous effect on hours of lighting use. The direct rebound effect is mainly created by households that are at the lowest income group and at the lower home-size groups. I also showed that these rebound effects are not too large to completely offset the policy's expected electricity use reduction.

Since the associated rebound effect creates welfare gain for low-income households due to the increase in energy services, we can use an alternative policy that could have similar welfare gain for these low-income consumers. The policy option would be in the form of energy taxes as well as cash transfers to the lowest income group, such that it does not make these households worse-off compared to the receiving energy efficiency subsidy.

Future work might benefit from employing general equilibrium modeling to compare these two types of policies in the form of answering two types of questions. First, what is the cheapest way for the government/utility companies to reduce energy use and not leave all households worse off? Second, what is the most efficient way for government/utility companies to reduce energy use and not leave low-income groups worse off? The amount of cash transfers should be such that it makes the low-income households indifferent after each policy. Then, the change in welfare of other households as well as the amount of government funding would help us to compare the two policy options.

Lastly, there might be some concerns about endogeneity of the policy availability instrument, which can be addressed using the state party affiliation as an instrument for the policy availability variable.

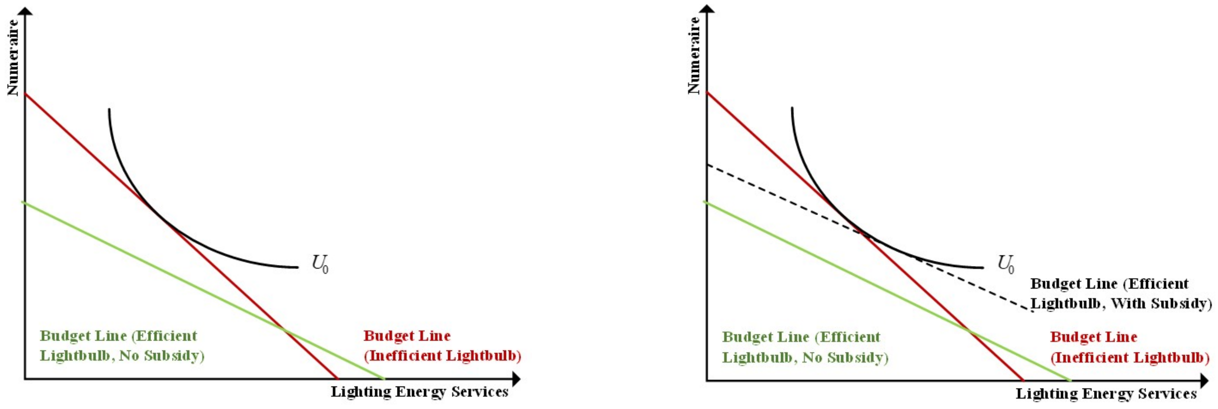

Figure 2.1: Energy Efficiency With and Without Assistance

Table 2.1: Summary Statistics

| VARIABLES | (1)<br>N | (2)<br>mean | (3)<br>sd | (4)<br>min | (5)<br>max |
|---|---|---|---|---|---|
| Hours of lighting use | 11,042 | 27.35 | 28.77 | 2.500 | 505 |
| Hours of efficient lightbulb use | 11,042 | 14.02 | 20.98 | 0 | 362.5 |
| Assistance for EE light bulbs | 11,042 | 0.0389 | 0.193 | 0 | 1 |
| kWh used for lighting | 11,042 | 0.996 | 1.335 | 0.0350 | 30.30 |
| Income (USD) | 11,042 | 55,803 | 36,532 | 2,000 | 120,000 |
| Home size (sqft) | 11,042 | 2,204 | 1,469 | 100 | 16,122 |
| Lighting assistance time | 10,978 | -1.857 | 0.790 | -2 | 5 |
| Policy availability | 11,042 | 2.290 | 6.765 | 0 | 76 |
| Policy intensity | 11,042 | 0.861 | 3.347 | 0 | 50 |
| Electricity price (cents/kwh) | 10,629 | 12.37 | 2.737 | 8.450 | 17.50 |
| Employment status | 11,042 | 0.626 | 0.484 | 0 | 1 |
| Household size | 11,042 | 2.678 | 1.514 | 1 | 14 |
| Gender | 11,042 | 0.527 | 0.499 | 0 | 1 |
| Electricity bill payment | 11,042 | 0.946 | 0.226 | 0 | 1 |
| Age (years) | 11,042 | 49.62 | 16.71 | 16 | 85 |
| Home ownership | 11,042 | 0.682 | 0.466 | 0 | 1 |

Table 2.2: Coarsened Exact Matching

Number of strata: 289
Number of matched strata: 119

|  | 0 | 1 |
|---|---|---|
| All | 10613 | 429 |
| Matched | 9637 | 408 |
| Unmatched | 976 | 21 |

| Imbalance (L1 distance) | Before matching | After matching |
|---|---|---|
| Household size | .053 | .002 |
| Employment status | .027 | 3.7e-15 |
| Energy audit assistance | .084 | -4.9e-16 |
| Hours of lighting use | .174 | .128 |
| **Multivariate L1 distance** | **.365** | **.284** |

Note: The table shows the number of matched and unmatched observations for treated and untreated groups. Additionally, the level of univariate and multivariate imbalances decreases after the matching.

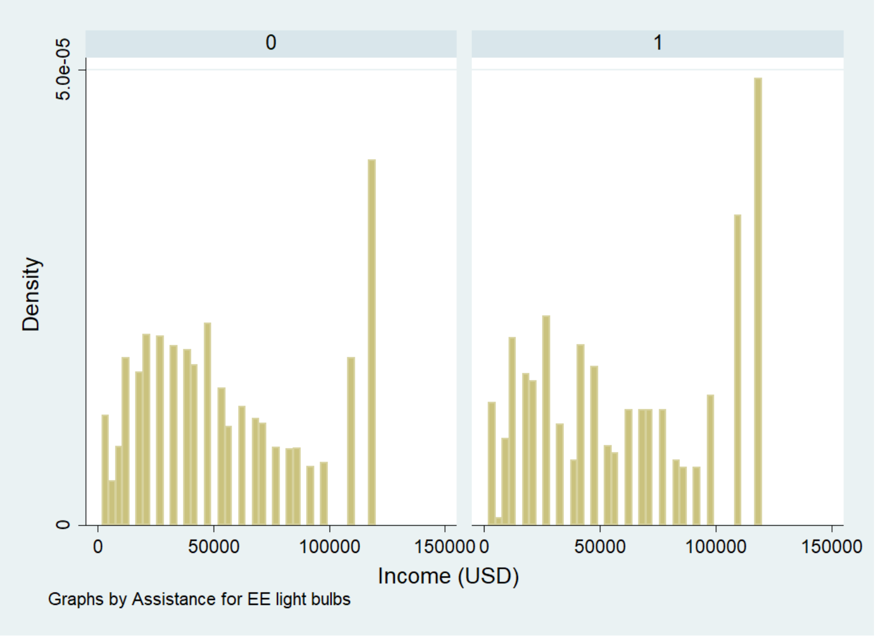

Figure 2.2: Income Distribution by Policy Participation

Note: The figure shows a comparison of income distributions for policy participants versus nonparticipants which implies that policy participation is not dependent on the income level.

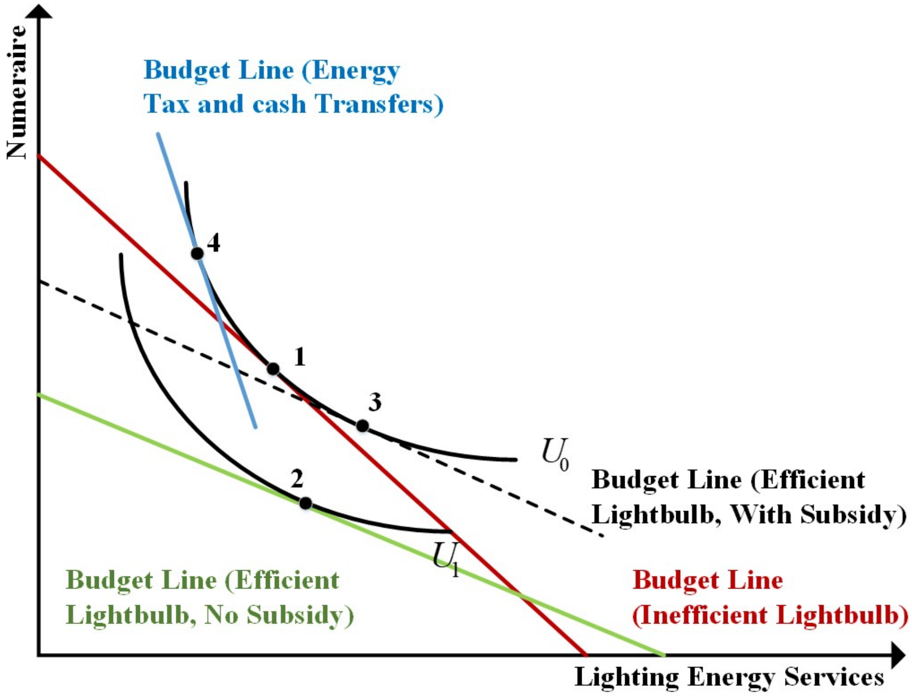

Figure 2.3: Policy Alternative

Table 2.3: First Stage Regression

| VARIABLES | (1)<br>Lighting assistance | (2)<br>Lighting assistance |
|---|---|---|
| Policy intensity | 0.00690*** | 0.00680*** |
| | (0.000737) | (0.000732) |
| Policy availability | 0.00400*** | 0.00403*** |
| | (0.000292) | (0.000300) |
| Electricity price | 0.000906 | 0.000278 |
| | (0.00411) | (0.00414) |
| Home size | 0.000805 | 0.000808 |
| | (0.000856) | (0.000914) |
| Income | -0.000826 | -0.000922 |
| | (0.000616) | (0.000639) |
| Gender | 0.000496 | 0.000410 |
| | (0.000852) | (0.000893) |
| Lighting assistance time | 0.192*** | 0.192*** |
| | (0.00419) | (0.00429) |
| Employment status | -0.000529 | |
| | (0.00109) | |
| Household size | -0.00116 | |
| | (0.000804) | |
| Home ownership | 0.000381 | -0.000774 |
| | (0.00124) | (0.00129) |
| Electricity bill payment | -0.00143 | 0.000710 |
| | (0.00199) | (0.00164) |
| Age (years) | -7.26e-05** | -4.96e-05* |
| | (3.34e-05) | (2.76e-05) |
| Observations | 10,570 | 9,711 |
| CEM matching | NO | YES |
| Census division dummy | YES | YES |

Note: Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1. The impacts of policy availability and policy intensity instrumental variables on the lighting assistance are positive while the income level does not influence the policy participation.

Table 2.4: Lighting Consumption Regression

| VARIABLES | (1)<br>Naive | (2)<br>IV | (3)<br>IV |
|---|---|---|---|
| Lighting assistance | 0.171 | 0.786** | 0.942*** |
| | (0.163) | (0.347) | (0.330) |
| Electricity price | -0.00108 | -0.000891 | -0.00406 |
| | (0.00802) | (0.00802) | (0.00820) |
| Home size | 0.203*** | 0.203*** | 0.206*** |
| | (0.0195) | (0.0195) | (0.0194) |
| Income | 0.105*** | 0.106*** | 0.108*** |
| | (0.0127) | (0.0127) | (0.0124) |
| Gender | -0.127*** | -0.126*** | -0.113*** |
| | (0.0189) | (0.0189) | (0.0193) |
| Lighting assistance time | -0.00754 | -0.144* | -0.168** |
| | (0.0369) | (0.0777) | (0.0745) |
| Employment status | 0.00726 | 0.00787 | |
| | (0.0231) | (0.0232) | |
| Household size | 0.193*** | 0.193*** | |
| | (0.0194) | (0.0194) | |
| Home ownership | 0.0485* | 0.0469* | 0.0717*** |
| | (0.0259) | (0.0259) | (0.0268) |
| Electricity bill payment | -0.151*** | -0.149*** | -0.125*** |
| | (0.0434) | (0.0435) | (0.0445) |
| Age (years) | -0.000814 | -0.000760 | -0.00358*** |
| | (0.000712) | (0.000712) | (0.000600) |
| Observations | 10,570 | 10,570 | 9,711 |
| CEM matching | NO | NO | YES |
| Census division dummy | YES | YES | YES |
| F_eff | | 141.5 | 131.2 |

Note: Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1. F_eff represents the F statistics from Montiel-Pflueger robust weak instrument test. The impact of lighting assistance on the hours of lighting use is positive on average which implies the existence of a direct rebound effect.

Table 2.5: Lighting Consumption Regression (Income Quintile Subsamples)

| VARIABLES | (1)<br>q1 | (2)<br>q2 | (3)<br>q3 | (4)<br>q4 | (5)<br>q5 |
|---|---|---|---|---|---|
| Lighting assistance | 1.281** | 0.890 | 1.361 | -0.277 | 0.783 |
| | (0.569) | (1.193) | (0.911) | (0.650) | (0.626) |
| Electricity price | 0.0300 | -0.00680 | 0.000568 | -0.00826 | -0.0229 |
| | (0.0198) | (0.0184) | (0.0166) | (0.0164) | (0.0192) |
| Home size | 0.199*** | 0.122** | 0.118*** | 0.122*** | 0.268*** |
| | (0.0455) | (0.0477) | (0.0383) | (0.0452) | (0.0491) |
| Income | -0.0121 | 0.00376 | 0.235* | 0.297** | 0.602 |
| | (0.0325) | (0.149) | (0.132) | (0.135) | (0.535) |
| Gender | -0.0961** | -0.0315 | -0.159*** | -0.105*** | -0.203*** |
| | (0.0484) | (0.0445) | (0.0367) | (0.0396) | (0.0459) |
| Lighting assistance time | -0.248* | -0.163 | -0.264 | 0.0839 | -0.137 |
| | (0.129) | (0.266) | (0.194) | (0.146) | (0.150) |
| Employment status | 0.0520 | -0.0230 | -0.00139 | -0.0278 | -0.0128 |
| | (0.0524) | (0.0526) | (0.0450) | (0.0527) | (0.0612) |
| Household size | 0.120** | 0.188*** | 0.224*** | 0.205*** | 0.215*** |
| | (0.0475) | (0.0424) | (0.0362) | (0.0431) | (0.0519) |
| Home ownership | -0.0398 | 0.0589 | 0.0695 | 0.0606 | 0.175** |
| | (0.0566) | (0.0573) | (0.0507) | (0.0593) | (0.0754) |
| Electricity bill payment | -0.0933 | -0.233*** | -0.0157 | -0.1000 | -0.130 |
| | (0.0710) | (0.0886) | (0.0931) | (0.131) | (0.187) |
| Age (years) | -0.00186 | -0.000426 | 0.000606 | 0.000509 | -0.00162 |
| | (0.00152) | (0.00160) | (0.00139) | (0.00169) | (0.00201) |
| Observations | 1,892 | 1,909 | 2,627 | 2,304 | 1,838 |
| CEM matching | NO | NO | NO | NO | NO |
| IV | YES | YES | YES | YES | YES |
| Census division dummy | YES | YES | YES | YES | YES |
| F_eff | 44.34 | 29.23 | 25.96 | 24.91 | 29.81 |

Note: Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1. F_eff represents the F statistics from Montiel-Pflueger robust weak instrument test. The impact of lighting assistance on the hours of lighting use is positive only for the lowest income quintile which implies the existence of a direct rebound effect by the lowest income quintile.

Table 2.6: Lighting Consumption Regression with Matching (Income Quintile Subsamples)

| VARIABLES | (1)<br>q1 | (2)<br>q2 | (3)<br>q3 | (4)<br>q4 | (5)<br>q5 |
|---|---|---|---|---|---|
| Lighting assistance | 1.331** | 1.563 | 1.469 | -0.246 | 0.852 |
| | (0.589) | (1.184) | (0.919) | (0.627) | (0.607) |
| Electricity price | 0.0384* | -0.00961 | -0.00263 | -0.0215 | -0.0310 |
| | (0.0199) | (0.0191) | (0.0169) | (0.0167) | (0.0194) |
| Home size | 0.207*** | 0.151*** | 0.126*** | 0.150*** | 0.208*** |
| | (0.0445) | (0.0489) | (0.0386) | (0.0452) | (0.0469) |
| Income | -0.0256 | -0.0522 | 0.301** | 0.312** | 0.266 |
| | (0.0328) | (0.153) | (0.135) | (0.138) | (0.545) |
| Gender | -0.0752 | -0.0401 | -0.154*** | -0.0931** | -0.155*** |
| | (0.0488) | (0.0460) | (0.0378) | (0.0404) | (0.0456) |
| Lighting assistance time | -0.273** | -0.307 | -0.275 | 0.0879 | -0.126 |
| | (0.138) | (0.264) | (0.195) | (0.141) | (0.145) |
| Home ownership | -0.0445 | 0.0683 | 0.116** | 0.0656 | 0.231*** |
| | (0.0575) | (0.0600) | (0.0527) | (0.0620) | (0.0786) |
| Electricity bill payment | -0.0464 | -0.243*** | -0.0414 | -0.0933 | -0.0127 |
| | (0.0726) | (0.0898) | (0.0971) | (0.139) | (0.199) |
| Age (years) | -0.0041*** | -0.0021 | -0.0024** | -0.002 | -0.005*** |
| | (0.00125) | (0.00132) | (0.00121) | (0.00144) | (0.00177) |
| Observations | 1,751 | 1,775 | 2,430 | 2,100 | 1,655 |
| IV | YES | YES | YES | YES | YES |
| Census division dummy | YES | YES | YES | YES | YES |
| F_eff | 39.93 | 23.81 | 25.43 | 24.28 | 30.09 |

Note: Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1. F_eff represents the F statistics from Montiel-Pflueger robust weak instrument test. The impact of lighting assistance on the hours of lighting use is positive only for the lowest income quintile which implies the existence of a direct rebound effect by the lowest income quintile.

Table 2.7: Lighting Consumption Regression (Home Size Quintile Subsamples)

| VARIABLES | (1)<br>q1 | (2)<br>q2 | (3)<br>q3 | (4)<br>q4 | (5)<br>q5 |
|---|---|---|---|---|---|
| Lighting assistance | 1.652** | 1.075* | 0.929 | 0.190 | 0.627 |
| | (0.738) | (0.627) | (0.715) | (0.625) | (0.848) |
| Electricity price | -0.00735 | -0.00867 | 0.0126 | 0.0172 | -0.0163 |
| | (0.0194) | (0.0166) | (0.0180) | (0.0191) | (0.0171) |
| Home size | 0.152* | 0.257* | 0.0508 | 0.0848 | 0.476*** |
| | (0.0777) | (0.151) | (0.208) | (0.215) | (0.0892) |
| Income | 0.0549** | 0.117*** | 0.174*** | 0.105*** | 0.0902*** |
| | (0.0251) | (0.0259) | (0.0317) | (0.0329) | (0.0301) |
| Gender | -0.103** | -0.0913** | -0.0977** | -0.0406 | -0.288*** |
| | (0.0429) | (0.0398) | (0.0424) | (0.0424) | (0.0434) |
| Lighting assistance time | -0.334** | -0.188 | -0.185 | -0.0250 | -0.104 |
| | (0.160) | (0.136) | (0.168) | (0.139) | (0.197) |
| Employment status | -0.0398 | 0.0189 | -0.0723 | -0.000794 | 0.117** |
| | (0.0534) | (0.0474) | (0.0527) | (0.0549) | (0.0517) |
| Household size | 0.144*** | 0.210*** | 0.180*** | 0.214*** | 0.264*** |
| | (0.0417) | (0.0382) | (0.0449) | (0.0471) | (0.0488) |
| Home ownership | -0.00579 | 0.0114 | 0.0768 | 0.238*** | 0.204** |
| | (0.0549) | (0.0449) | (0.0569) | (0.0841) | (0.0944) |
| Electricity bill payment | -0.0530 | -0.175** | -0.0790 | -0.149 | -0.142 |
| | (0.0606) | (0.0787) | (0.163) | (0.212) | (0.242) |
| Age (years) | -0.00154 | 0.000780 | -0.00270* | -0.00288 | 0.00286 |
| | (0.00140) | (0.00143) | (0.00160) | (0.00180) | (0.00195) |
| Observations | 2,081 | 2,121 | 2,099 | 2,111 | 2,158 |
| CEM matching | NO | NO | NO | NO | NO |
| IV | YES | YES | YES | YES | YES |
| Census division dummy | YES | YES | YES | YES | YES |
| F_eff | 17.32 | 21.87 | 22.67 | 62.82 | 36.74 |

Note: Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1. F_eff represents the F statistics from Montiel-Pflueger robust weak instrument test. The impact of lighting assistance on the hours of lighting use is positive only for the lower home quintiles which implies the existence of a direct rebound effect by the lowest home-size quintile.

Table 2.8: Lighting Consumption Regression with Matching (Home Size Quintile Subsamples)

| VARIABLES | (1)<br>q1 | (2)<br>q2 | (3)<br>q3 | (4)<br>q4 | (5)<br>q5 |
|---|---|---|---|---|---|
| Lighting assistance | 1.546** | 1.113* | 1.116* | 0.185 | 1.052 |
| | (0.774) | (0.665) | (0.655) | (0.628) | (0.760) |
| Electricity price | -0.00779 | -0.0109 | 0.00335 | 0.0171 | -0.0238 |
| | (0.0202) | (0.0171) | (0.0184) | (0.0193) | (0.0173) |
| Home size | 0.207*** | 0.278* | -0.0461 | 0.0945 | 0.394*** |
| | (0.0793) | (0.159) | (0.214) | (0.217) | (0.0877) |
| Income | 0.0447* | 0.125*** | 0.175*** | 0.101*** | 0.103*** |
| | (0.0236) | (0.0253) | (0.0306) | (0.0318) | (0.0305) |
| Gender | -0.0907** | -0.0972** | -0.0881** | -0.0472 | -0.257*** |
| | (0.0439) | (0.0417) | (0.0437) | (0.0432) | (0.0431) |
| Lighting assistance time | -0.311* | -0.190 | -0.220 | -0.0193 | -0.176 |
| | (0.173) | (0.143) | (0.159) | (0.139) | (0.178) |
| Home ownership | 0.00159 | 0.0376 | 0.0897 | 0.243*** | 0.196* |
| | (0.0563) | (0.0472) | (0.0591) | (0.0860) | (0.103) |
| Electricity bill payment | -0.0369 | -0.194** | -0.104 | 0.0585 | -0.123 |
| | (0.0609) | (0.0819) | (0.172) | (0.214) | (0.284) |
| Age (years) | -0.0025** | -0.0024* | -0.004*** | -0.0068*** | -0.0034** |
| | (0.00118) | (0.00126) | (0.00136) | (0.00141) | (0.00162) |
| Observations | 1,973 | 1,955 | 1,930 | 1,942 | 1,911 |
| IV | YES | YES | YES | YES | YES |
| Census division dummy | YES | YES | YES | YES | YES |
| F_eff | 16.25 | 23.11 | 20.98 | 61.59 | 34.37 |

Note: Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1. F_eff represents the F statistics from Montiel-Pflueger robust weak instrument test. The impact of lighting assistance on the hours of lighting use is positive only for the lower home quintiles which implies the existence of a direct rebound effect by the lowest home-size quintile.

Table 2.9: Electricity Consumption for Lighting

| VARIABLES | (1)<br>Naive | (2)<br>IV | (3)<br>IV |
|---|---|---|---|
| Lighting assistance | -0.108 | -3.420*** | -3.021*** |
| | (0.201) | (0.569) | (0.570) |
| Electricity price | -0.0201** | -0.0212** | -0.0207** |
| | (0.00991) | (0.00994) | (0.00978) |
| Home size | 0.217*** | 0.220*** | 0.186*** |
| | (0.0241) | (0.0243) | (0.0234) |
| Income | 0.0938*** | 0.0933*** | 0.0962*** |
| | (0.0157) | (0.0158) | (0.0150) |
| Gender | -0.112*** | -0.114*** | -0.0962*** |
| | (0.0233) | (0.0235) | (0.0233) |
| Lighting assistance time | -0.0185 | 0.714*** | 0.658*** |
| | (0.0461) | (0.128) | (0.129) |
| Employment status | 0.0203 | 0.0170 | |
| | (0.0281) | (0.0284) | |
| Household size | 0.160*** | 0.158*** | |
| | (0.0237) | (0.0240) | |
| Home ownership | -0.0776** | -0.0689** | -0.0464 |
| | (0.0315) | (0.0319) | (0.0321) |
| Electricity bill payment | -0.175*** | -0.183*** | -0.136*** |
| | (0.0524) | (0.0526) | (0.0514) |
| Age (years) | -0.000319 | -0.000610 | -0.00286*** |
| | (0.000870) | (0.000882) | (0.000727) |
| Observations | 10,570 | 10,570 | 9,610 |
| CEM matching | NO | NO | YES |
| Census division dummy | YES | YES | YES |
| F_eff | | 141.5 | 127.3 |

Note: Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1. F_eff represents the F statistics from Montiel-Pflueger robust weak instrument test. The impact of lighting assistance on the electricity use for lighting is negative on average which implies that the direct rebound effect is not too high to increase the electricity consumption.

Table 2.10: Electricity Consumption for Lighting (Income Quintile Subsamples)

| VARIABLES | (1)<br>q1 | (2)<br>q2 | (3)<br>q3 | (4)<br>q4 | (5)<br>q5 |
|---|---|---|---|---|---|
| Lighting assistance | -2.694*** | -3.468** | -7.475*** | -4.684*** | -1.467** |
| | (0.790) | (1.743) | (2.371) | (1.125) | (0.710) |
| Electricity price | 0.00300 | -0.0412* | -0.0189 | -0.00896 | -0.0465* |
| | (0.0239) | (0.0234) | (0.0205) | (0.0206) | (0.0241) |
| Home size | 0.189*** | 0.102* | 0.105** | 0.138** | 0.293*** |
| | (0.0563) | (0.0576) | (0.0507) | (0.0568) | (0.0602) |
| Income | -0.0624 | -0.109 | 0.231 | 0.291* | 0.836 |
| | (0.0402) | (0.184) | (0.173) | (0.167) | (0.675) |
| Gender | -0.0799 | -0.0143 | -0.137*** | -0.0651 | -0.219*** |
| | (0.0593) | (0.0556) | (0.0481) | (0.0491) | (0.0567) |
| Lighting assistance time | 0.481*** | 0.731* | 1.545*** | 1.016*** | 0.333** |
| | (0.175) | (0.397) | (0.505) | (0.266) | (0.168) |
| Employment status | 0.0559 | -0.0526 | -0.000516 | 0.0192 | -0.00521 |
| | (0.0630) | (0.0623) | (0.0608) | (0.0652) | (0.0732) |
| Household size | 0.108* | 0.163*** | 0.145*** | 0.179*** | 0.192*** |
| | (0.0569) | (0.0528) | (0.0476) | (0.0528) | (0.0648) |
| Home ownership | -0.0918 | -0.0957 | -0.0214 | -0.0905 | 0.105 |
| | (0.0697) | (0.0677) | (0.0672) | (0.0717) | (0.100) |
| Electricity bill payment | -0.108 | -0.292*** | 0.00539 | -0.193 | -0.0707 |
| | (0.0818) | (0.111) | (0.118) | (0.164) | (0.280) |
| Age (years) | -0.00263 | -0.000199 | 0.000584 | 0.00202 | -0.000309 |
| | (0.00181) | (0.00196) | (0.00190) | (0.00212) | (0.00245) |
| Observations | 1,892 | 1,909 | 2,627 | 2,304 | 1,838 |
| IV | YES | YES | YES | YES | YES |
| Census division dummy | YES | YES | YES | YES | YES |
| F_eff | 44.34 | 29.23 | 25.96 | 24.91 | 29.81 |

Note: Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1. F_eff represents the F statistics from Montiel-Pflueger robust weak instrument test. The impact of lighting assistance on the electricity use for lighting is negative for all income quintiles which implies that the direct rebound effect is not too high to increase the electricity consumption.

Table 2.11: Electricity Consumption for Lighting (Home Size Quintile Subsamples)

| VARIABLES | (1)<br>q1 | (2)<br>q2 | (3)<br>q3 | (4)<br>q4 | (5)<br>q5 |
|---|---|---|---|---|---|
| Lighting assistance | -4.370*** | -3.533*** | -3.654** | -3.780*** | -2.906** |
| | (1.406) | (1.019) | (1.671) | (0.894) | (1.132) |
| Electricity price | -0.0263 | -0.0319 | -0.0140 | -0.00685 | -0.0160 |
| | (0.0233) | (0.0211) | (0.0218) | (0.0238) | (0.0218) |
| Home size | 0.111 | 0.241 | 0.140 | 0.273 | 0.527*** |
| | (0.101) | (0.181) | (0.258) | (0.266) | (0.104) |
| Income | 0.0346 | 0.130*** | 0.140*** | 0.110*** | 0.0881** |
| | (0.0318) | (0.0312) | (0.0398) | (0.0395) | (0.0389) |
| Gender | -0.0931* | -0.0640 | -0.0693 | -0.0277 | -0.280*** |
| | (0.0527) | (0.0501) | (0.0531) | (0.0529) | (0.0542) |
| Lighting assistance time | 0.840*** | 0.730*** | 0.795** | 0.781*** | 0.651** |
| | (0.301) | (0.231) | (0.390) | (0.201) | (0.271) |
| Employment status | -0.0733 | -0.0297 | -0.0306 | 0.000173 | 0.217*** |
| | (0.0645) | (0.0588) | (0.0637) | (0.0670) | (0.0643) |
| Household size | 0.144*** | 0.143*** | 0.122** | 0.179*** | 0.260*** |
| | (0.0516) | (0.0476) | (0.0564) | (0.0582) | (0.0605) |
| Home ownership | -0.0186 | -0.0775 | -0.102 | 0.156 | 0.0603 |
| | (0.0676) | (0.0559) | (0.0689) | (0.101) | (0.122) |
| Electricity bill payment | -0.0245 | -0.352*** | -0.0277 | -0.197 | -0.0427 |
| | (0.0716) | (0.0943) | (0.212) | (0.261) | (0.313) |
| Age (years) | -0.00238 | -0.00183 | -0.00162 | -0.00177 | 0.00653*** |
| | (0.00167) | (0.00181) | (0.00199) | (0.00228) | (0.00240) |
| Observations | 2,081 | 2,121 | 2,099 | 2,111 | 2,158 |
| IV | YES | YES | YES | YES | YES |
| Census division dummy | YES | YES | YES | YES | YES |
| F_eff | 17.32 | 21.87 | 22.67 | 62.82 | 36.74 |

Note: Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1. F_eff represents the F statistics from Montiel-Pflueger robust weak instrument test. The impact of lighting assistance on the electricity use for lighting is negative for all home-size quintiles which implies that the direct rebound effect is not too high to increase the electricity consumption.

# CHAPTER 3

# DISTRIBUTIONAL IMPACTS OF ENERGY EFFICIENCY STANDARDS VS. ENERGY TAXES

This study compares the distributional impacts of energy efficiency standards versus direct energy taxes employing non-homothetic preferences. I find that compared to an equivalent energy efficiency standard policy, an energy tax policy is the most efficient instrument from an economy-wide perspective. However, the distributional impacts mainly depend on how the tax revenue is distributed back to the economy. Low-income consumers receive more welfare gains under energy efficiency standards than energy taxes if the tax revenue is distributed across income groups proportional to their income level.

## 3.1 Introduction

There has always been a debate on how to reduce energy consumption. Policymakers suggest several instruments by which energy consumption could decrease. These policy options can be ranked based on different criteria such as flexibility, economic efficiency, and distributional equity [33]. Many economists are in favor of market-based energy policies, particularly a tax on energy consumption. Meanwhile, in practice, reductions are also achieved by enforcing other tools such as energy efficiency standards. An energy tax influences consumer behavior by directly affecting energy prices, whereas, energy efficiency standards set a maximum threshold on energy used per unit of energy services. An energy efficiency standard instrument implies an implicit tax on energy use as well as an implicit subsidy on energy services [36] since more efficient goods are cheaper to operate. The main difference between the two instruments is that the latter generates an implicit subsidy due to the energy efficiency improvement which could create a rebound effect.

One of the reasons why energy efficiency standards could raise consumers' welfare is the increase in quality [53]. Energy efficiency standards could also raise welfare when there are some other distortions in the factor market [45]. Most economists, however, argue that market-based policies are more economically efficient for two reasons: First, market-based policies do not create a rebound effect while energy standards do. An increase in the energy efficiency of a particular durable good reduces the cost of using the good and creates an implicit subsidy which could result in an increase in the consumption of energy. This impact is called the rebound effect which could happen in different markets such as automobiles, appliances, lighting, and etc. [4]. The rebound effect may cause total energy savings compared to upfront efficiency investment costs to be low [28]. The second reason is the frequency of using energy-consuming goods and/or facing low energy prices. In the residential sector, for instance, some consumers do not use their appliances frequently or they face low electricity prices; therefore, using inefficient appliances and paying taxes will be more beneficial for them [3].

The debate over which policy is the most economically efficient option neglects the other criteria which I use to rank policy instruments. Energy efficiency standards may be less efficient than taxes but still be preferred if energy taxes are particularly regressive. For instance, some authors find that the relative cost of the Clean Air Act for low-income consumers in the United States is more than the relative cost for high-income groups [39]. Low-income consumers spend a higher share of their income on energy services, and the implicit subsidy emerging from efficiency standards would generate some welfare gains for them [55]. So, although energy taxes are the most cost effective way to reduce energy use, the distributional impacts associated with taxes remain a concern. There is always a trade-off between efficiency and equity impacts of the policies. The distributional effects are different depending upon how the additional revenues from the tax increase are recycled, and this revenue distribution can reduce the severity of the trade-off [10, 46, 61].

In terms of comparing two types of policies, Levinson [65] employs a partial equilibrium model and shows that energy efficiency standards can be more regressive. However, he assumes that the change in income after each policy is the same. However, I employ non-homothetic preferences in a general equilibrium framework and allow income and consumption to change after the two policies. I compare the two policy options in an equivalent way where both policies result in the same amount of energy use reduction. In addition, energy use and efficiency are not perfect substitutes in our model.

The purpose of this paper is to compare the two policy instruments by measuring the distributional consequences of energy taxes versus energy efficiency standards followed by a numerical exercise using residential sector data and incorporating non-homothetic preferences. By using non-homothetic preferences, the consumption side in the general equilibrium framework is not neutralized anymore [66]. The same amount of reduction in energy use is set after each policy while the tax and implicit subsidy rates are endogenous in the model. I use the theoretical model to quantify the welfare impacts of each policy on consumers. In terms of equity, these policy instruments could have different welfare impacts on the whole economy and different consumers. In order to compare them, I measure the welfare effects of each policy instrument as well as their distributional impacts on the whole economy, and then choose the appropriate policy. Since energy taxes create tax revenues, the associated tax revenue redistribution is expected to highly impact the welfare of each income group. I redistribute the revenue in three ways: First, the revenue is distributed such that it provides the high-income consumer the same amount of welfare after the two policies. Second, the revenue is distributed evenly across low-income and high-income groups, and third, the tax revenue is recycled back to the two income groups proportional to their income levels. Then I compare the welfare gains for each income group after each policy and each tax revenue scenario.

The contribution of this research compared to the literature is that I quantify the distributional impacts of two policy instruments using non-homothetic preferences in a general equilibrium framework where both policies result in the same amount of energy use reduction. The advantage of using non-homothetic preferences is that the ratio of goods demanded by each consumer depends not only on relative prices but also on income level.

I find that total welfare after implementing energy taxes is always higher than the total welfare after implementing efficiency standards. However, employing non-homothetic preferences, I see that even with no preexisting distortions, the welfare impacts on each income group heavily depend upon tax revenue recycling. Low-income households are better off using energy taxes compared to efficiency standards if the tax revenue distribution is such that the high-income group has the same welfare gain after each policy and if the tax revenue is distributed evenly. In the case of proportional tax revenue distribution, the low-income group is better off under the standard policy and the high-income group is better off under the tax policy.

The remainder of this study is organized as follows. Section 3.2 gives an account of the theoretical model used in this paper in a static general equilibrium framework. Section 3.3 involves a numerical exercise that is used to compare the two policies by using residential sector and appliance market, and then the results are interpreted followed by some sensitivity analyses. Finally, Section 3.5 presents the conclusions.

## 3.2 Theoretical Model

In this paper, a simple model is employed. I use a representative household who has preferences for appliance energy services such as cooling, heating, lighting, and etc., and an index for all other goods. The household utility is assumed to have a nested Stone-Geary functional form as a function of energy services ($Y$) and consumption level of all other goods ($X$) where the elasticity of substitution between energy services and other goods is unity. I assume that the subsistence level for all other goods is zero, and the minimum consumption level of energy services is $\bar{Y}$. The representative household maximizes its utility subject to its budget constraint.

$$Max \;\; U = \phi(Y - \bar{Y})^{\alpha} X^{(1-\alpha)} \tag{3.1}$$

$$s.t. \;\; P_l L + trn = P_e E + P_a A + P_x X \tag{3.2}$$

The parameter $\alpha$ represents the expenditure share of energy services in discretionary income for the representative household which is equal to $\frac{P_Y Y - P_Y \bar{Y}}{M_0 - P_Y \bar{Y}}$, where $M_0$ shows the benchmark income level. $L$ is the production factor, and the consumer's income includes the production factor income plus cash transfers from tax revenue distribution ($trn$).

The advantage of using the Stone-Geary function is that it allows us to have a non-homothetic function where the expenditure share of energy services is not constant. The share has the following form:

$$\frac{P_Y Y}{I} = \frac{\alpha I + (1-\alpha) P_Y \bar{Y}}{I} \tag{3.3}$$

If $\bar{Y}$ is zero, I will have a homothetic utility function, and the share is equal to $\alpha$; if $\bar{Y}$ is more than zero, the function will be non-homothetic and the derivative of the share respect to income will be negative. In reality, lower income groups spend a higher share of their budget on energy services, and this functional form allows us to add that feature to the model.

Energy service is a function of energy consumption ($E$) and efficiency capital ($A$), and is assumed to have a CES (Constant Elasticity of Substitution) functional form. The calibrated share form of the function and corresponding cost function($P_Y$) have the following forms:

$$Y = Y_0 \left[ \theta \left( \frac{E}{E_0} \right)^{\rho} + (1-\theta) \left( \frac{A}{A_0} \right)^{\rho} \right]^{\frac{1}{\rho}} \tag{3.4}$$

$$P_Y = P_{Y_0} \left[ \theta \left( \frac{P_E}{P_{E_0}} \right)^{(1-\sigma)} + (1-\theta) \left( \frac{P_A}{P_{A_0}} \right)^{(1-\sigma)} \right]^{\frac{1}{1-\sigma}} \tag{3.5}$$

where a zero subscript signifies a benchmark value, and $\sigma$ is the elasticity of substitution between energy use and efficiency capital. The calibrated parameter, $\theta$, stands for the value share of energy consumption at the benchmark point which is equal to $\frac{P_{E_0} E_0}{P_{Y_0} Y_0}$.

Employing Shephard's lemma, as well as assuming unit benchmark prices, I find compensated demand functions for energy consumption and efficiency capital as shown below:

$$E = Y\theta \left(\frac{P_Y}{P_E}\right)^{\sigma} \tag{3.6}$$

$$A = Y(1-\theta) \left(\frac{P_Y}{P_A}\right)^{\sigma} \tag{3.7}$$

Going back to the utility function and minimizing the expenditures subject to a specific level of utility ($U$), I obtain the following unit expenditure and compensated demand functions:

$$exp = P_Y\bar{Y} + UP_Y^{\alpha}P_X^{1-\alpha} \tag{3.8}$$

$$Y = U\alpha \left(\frac{P_X}{P_Y}\right)^{1-\alpha} + \bar{Y} \tag{3.9}$$

$$X = U(1-\alpha) \left(\frac{P_Y}{P_X}\right)^{\alpha} \tag{3.10}$$

On the production side, I keep the model as simple as possible so that there is no heterogeneity across consumers based on their production factor ownership. I assume that there is one endowment factor ($L$) that could be allocated to production of electricity, efficiency capital, and other goods in a competitive market. The producer's goal is maximizing profit subject to the following production functions:

$$Max \;\; \pi = P_eE + P_aA + P_xX - P_lL \tag{3.11}$$

$$s.t. \;\; E = \phi_E L^{\tau} \tag{3.12}$$

$$A = \phi_A L^{\tau} \tag{3.13}$$

$$X = \phi_X L^{\tau} \tag{3.14}$$

The aggregate supply function is assumed to have a Constant Elasticity of Transformation ($CET$) functional form. The calibrated share form of the aggregate supply of these goods, called $Q$, is shown below while benchmark prices are designated to be one.

$$Q = Q_0(\phi_x X^{1+\frac{1}{\tau}} + \phi_a A^{1+\frac{1}{\tau}} + \phi_e E^{1+\frac{1}{\tau}})^{\frac{\tau}{1+\tau}} \tag{3.15}$$

$\tau$ is the elasticity of transformation, and $\phi$ represents the $Q$ primal share parameters.

Finally, by employing Hotelling's lemma and finding the derivatives of the profit function, I obtain the supply functions for each good:

$$X = \phi_x^{-\tau}\, Q \left(\frac{P_X}{P_L}\right)^{\tau} \tag{3.16}$$

$$E = \phi_e^{-\tau}\, Q \left(\frac{P_E}{P_L}\right)^{\tau} \tag{3.17}$$

$$A = \phi_a^{-\tau}\, Q \left(\frac{P_A}{P_L}\right)^{\tau} \tag{3.18}$$

### 3.2.1 Welfare Impacts

I use Equivalent Variation (EV) to measure the household's welfare. The general form of the total expenditure (equation 3.8) is as follows.

$$exp(P, U) = a(P) + Ub(P), \tag{3.19}$$

where $a(P)+Ub(P)$ is a price index, $a(P) = P_Y \bar{Y}$, and $b(P) = P_Y^{\alpha} P_X^{1-\alpha}$. Using the definition of Money Metric Utility functions [80], I have:

$$EV \equiv \; exp(P_0, U_1) - exp(P_0, U_0) \tag{3.20}$$

$$EV \equiv \; U_1\, b(P_0) - U_0\, b(P_0) \tag{3.21}$$

By calculating the proportional change in welfare and using equation 3.19, I obtain the following form of relative welfare after each policy.

$$W = \frac{\frac{M_1 - a(P_1)}{b(P_1)}}{U_0} \tag{3.22}$$

### 3.2.2 Tax versus Standard

Market-based policies are associated with imposing taxes on energy consumption, and efficiency standards are associated with energy efficiency requirements of durable goods such as appliances, cars, and etc. The former make energy consumption more expensive and could stimulate consumers to reduce their energy use. The latter force producers to increase energy efficiency of durable goods which raises their production costs. These companies might transfer all or part of the cost increase to consumers by raising durable good prices depending upon their market power [52]. In this paper, I assume the market is competitive; however, the prices are endogenous and could change. In addition, standard policies could result in a rebound effect due to an implicit subsidy that stems from higher energy efficiency.

As mentioned before, in order to achieve an energy reduction goal, two types of policies can be implemented: either a price policy in the form of imposing a tax on energy consumption ($E$) or an energy efficiency standard where both policies result in the same amount of energy use reduction. The standard policy is in the form of setting an energy efficiency goal ($\frac{Y}{E}$). The intuition that energy efficiency standards subsidize energy service consumption is from [51], but our setting is not a perfectly straightforward extension of their work. In this study, the increase in energy efficiency is achieved by implicitly subsidizing $Y$ and implicitly taxing $E$.

### 3.2.3 Poor versus Rich

Employing income data from Table 3.1, the economy is divided into two groups of consumers, the poor (the lowest income quintile) and the rich (the rest of the economy). The question is which policy eventuates in more welfare gains for each group as well as for the whole economy.

One of the key assumptions in the model is how the tax revenue is distributed across these income groups. I assume three scenarios for tax revenue recycling. The first scenario is that the tax revenue is distributed back to consumers so that the high-income group receives the same amount of welfare after the two policies. The second and third scenarios are distributing the tax revenue evenly and proportionally to the initial income level. The size of the government does not change in our model, and the whole tax revenue is recycled.

### 3.3 Numerical Simulation

In order to empirically quantify the welfare impacts of each policy, I look at the appliance market in residential sector and use the 2013 United States national data which are summarized in Table 3.1. Electricity prices and consumption are from the U.S. Energy Information Administration (EIA) data. Income data are from the Bureau of Economic Analysis and Congressional Budget Office. Multiplying electricity consumption by average electricity price, we obtain electricity expenditures which represent $E_0$ in the model, where all benchmark prices are set to be one. The table also provides benchmark values for energy efficiency capital ($A_0$) and total income ($W_0$). The benchmark energy service consumption is calculated by summing $A_0$ and $E_0$. Energy service subsistence level, $\bar{Y}$, is calculated by using the following formula. Other parameters such as $\theta$ and $\alpha$ are calculated using their formulas in 3.2 and their values are summarized in Table 3.2.

$$\bar{Y} = \frac{W_0 - \sqrt{W_0^2 - 4\eta W_0(1-\eta)Y_0}}{2\eta} \tag{3.23}$$

Income elasticity of residential demand for electricity ($\eta$) in the United States has been estimated by different studies which ranges between $0.1 - 0.5$ [24][2]; I assume $\eta$ is equal to 0.3 in our analysis and use it to calculate the energy service subsistence level. I set the elasticity of substitution between electricity use and efficiency capital ($\sigma$) to be equal to 0.5 and then check the results assuming different values for it. A standard policy is considered to achieve a 10% increase in energy efficiency. Then a tax policy is implemented which gives us the same amount of electricity use reduction as the standard policy does.

Table 3.3 shows the welfare impacts after each policy for each tax revenue recycling scenario. They demonstrate that in the case of distributing the tax revenue such that the high-income group gains the same amount of welfare after each policy, the low-income group's welfare is higher from the tax policy than the welfare from the efficiency standard policy. Under an equal tax revenue distribution scenario, the poor are better off after the tax compared to after the standard policy while the rich are worse off. When the tax revenue is

Table 3.1: U.S. 2013 Data

| Variable | Sector | Amount |
|---|---|---|
| Personal Consumption Expenditures for household appliances (billion USD) | Residential | 46.1 |
| Sales and Direct Use of Electricity to Ultimate Customers (MWh) | Residential | 1,394,812,129 |
| Average Price of Electricity to Ultimate Customers (¢/kWh) | Residential | 12.13 |
| After-Tax Income (2013 billion USD) | Lowest Quintile | 612,500 |
| | Second Quintile | 1,054,620 |
| | Middle Quintile | 1,495,680 |
| | Fourth Quintile | 2,075,010 |
| | Highest Quintile | 4,784,850 |
| | Total | 10,022,660 |

Sources: EIA, BEA, CBO

Note: The U.S. data reflecting residential sector and national income data

Table 3.2: Summary of the Model parameters

| Parameter | Value | Definition |
|---|---|---|
| $E_0$ | 169.19 | Energy use |
| $A_0$ | 46.1 | Energy efficiency capital |
| $Y_0$ | 215.29 | Total energy service consumption |
| $W_0$ | 10022.66 | Total income |
| $\alpha$ | 0.006 | Expenditure share of energy services in discretionary income |
| $\theta$ | 0.786 | Value share of energy in energy services |
| $\bar{Y}$ | 151.389 | Energy service subsistence level (split equally among five income groups) |

Note: Benchmark values and parameters calculated by the author recycled proportional to the initial income level, low-income households benefit more from the standard policy while high-income households benefit more from the tax policy. The total economy is always better off under the energy tax policy compared to under the energy efficiency standard policy.

Table 3.3: The Base Case Results

| Policy Scenario | Poor | % change | Rich | % change | Total | % change |
|---|---|---|---|---|---|---|
| | Conditional tax revenue distribution | | | | | |
| Standard | 566 | -0.96 | 9,280 | -0.21 | 9,846 | -0.26 |
| Tax | 582 | 1.93 | 9,280 | -0.21 | 9,863 | -0.09 |
| | Even tax revenue distribution | | | | | |
| Standard | 564 | -1.32 | 9,274 | -0.29 | 9,837 | -0.35 |
| Tax | 620 | 8.60 | 9,239 | -0.66 | 9,859 | -0.12 |
| | Proportional tax revenue distribution | | | | | |
| Standard | 564 | -1.32 | 9,274 | -0.29 | 9,837 | -0.35 |
| Tax | 556 | -2.65 | 9,303 | 0.03 | 9,859 | -0.12 |

Note: The numbers show the welfare changes (in $ billions) and percentage changes compared to the benchmark values after each policy and tax revenue distribution scenario.

## 3.4 Sensitivity Analysis

In order to check the consistency of our results, I calibrate the model by changing the amount of some parameters in the model including: 1) the elasticity of substitution between electricity consumption and efficiency capital and 2) energy service subsistence level. The results are for the each tax revenue distribution case.

### 3.4.1 Welfare Sensitivity to Substitution Elasticity

I check the results of various tax revenue distribution scenarios via different values for the elasticity of substitution between electricity consumption and efficiency capital ($\sigma$). The simulation results are shown in Figure 3.1, Figure 3.2, and Figure 3.3 for the conditional, evenly and proportionally distributed tax revenue scenarios, respectively. As shown in the figures, the results are consistent compared to the base case results. In consequence, no matter how the tax revenue is distributed back to the economy, the total surplus will be higher under the tax policy. However, the welfare of each income group highly depends on how the tax revenue is recycled. Low-income households prefer standards if the tax revenue is distributed proportionally to their initial income shares.

### 3.4.2 Welfare Sensitivity to Energy Service Subsistence Level

Figure 3.4, Figure 3.5, and Figure 3.6 show the simulation results for each income group at the conditionally, evenly and proportionally distributed tax revenue scenarios, respectively. The results are robust to different amounts of energy service subsistence levels where the low-income group is better off under the standard policy compared to under the tax policy when the tax revenue is distributed proportionally to their initial income share. It should be noted that we do not have the same energy use reduction at different energy service subsistence levels, because the first policy improves energy efficiency by ten percent and then the tax policy provides the same energy use reduction as the first policy. By increasing the energy service subsistence levels, the required energy efficiency improvement comes from a different allocation of energy use and energy services. At higher subsistence levels, the required tax rate is higher and the energy use reduction is lower such that they create higher tax revenues. These higher tax revenues are the reason why the welfare gains for each income group change substantially at high subsistence levels when the tax revenue is distributed evenly or proportionally.

As mentioned earlier in the paper, if the energy service subsistence level is zero, I end up having homothetic preferences which cause the income groups to be different only based on their initial income share. In this case, the relative consumption of goods does not change at different income levels. This is shown in Figure 3.7 when the subsistence level, $\bar{Y}$, is equal to zero. The welfare values are normalized into one in this figure. By increasing the subsistence level, the low-income group's welfare decreases substantially, which is one channel through which the distributional impacts arise.

To sum up, the conditional tax revenue distribution provides maximum rebates to the poor where the rich are not worse off. In addition, distributing the tax revenue evenly grants high rebates to the poor which make the rich even worse off. Since the poor receive high transfers which are more than what they contribute to the economy under these two scenarios, it is reasonable for them to have higher welfare gains under the tax policy. On the other hand, when the poor receive rebates that are proportional to their initial income and what they contribute to the economy, energy taxes are not preferred by them anymore. In this case, the implicit subsidy stemming from energy efficiency improvements makes them better off under the standard policy.

## 3.5 Conclusion

Taking into account the potential rebound effects emerging from energy efficiency improvements, I compare the distributional impacts of two types of energy policy instruments. Energy taxes and efficiency standards are two instruments that could be employed to reduce energy consumption. Using the 2013 residential electricity data for households in the United States, I compare two policy instruments where both policies result in the same amount of change in electricity consumption. To evaluate the distributional impacts of these energy policies, I incorporate non-homothetic preferences by employing a nested Stone-Geary utility function.

First, our results for the total welfare resemble other research where the whole economy is better off using an energy tax policy compared to using an energy efficiency standard policy.

Second, I find that the low-income households will have higher surplus from energy taxes compared to from efficiency standards while the tax revenue is allocated such that the two policy options create the same welfare for the high-income group. Under energy taxes policy compared to the alternative policy, distributing the tax revenue evenly across consumers provides the poor with more benefits and the rich with fewer. If the tax revenue allocation is proportional to their initial income share, the low-income group is better-off under energy efficiency standards.

This study contributes to the previous literature on energy policies by measuring the distributional impacts of direct price policies versus energy efficiency standards by employing non-homothetic preferences where both policies result in the same amount of energy use reduction. I conclude that the distributional impacts of the two types of energy policies depend importantly on how the tax revenues are distributed back to the economy; furthermore, energy taxes can be progressive, depending on how the tax revenue is distributed back to the economy.

I simplified the model to focus on the research question, but there are some interesting extensions that could be done in the future. For instance, one of the model simplifications is assuming one factor of production. If I assume there are more factors of production, the production factor endowments are different across different income groups, and factor intensities differ for producing different goods, which would provide some income-side distributional effects. For instance, I can assume that there are two production factors, labor and capital. The electricity sector is capital-intensive, and other sectors are assumed to be relatively labor-intensive. The capital endowment distinguishes low and high income groups by different factor ownership. A tax on the capital-intensive energy sector reduces returns to capital which is primarily supplied by high-income groups. So the welfare gains for high-income groups are expected to be relatively lower after the tax policy. If this impact is high enough, low-income households might not prefer energy taxes anymore.

There are some other policy options, such as using energy taxes combined with lump-sum transfers to poor households. This is expected to reduce the burden of energy taxes on low-income groups. Another interesting policy option could be using the tax revenue to subsidize energy efficiency.

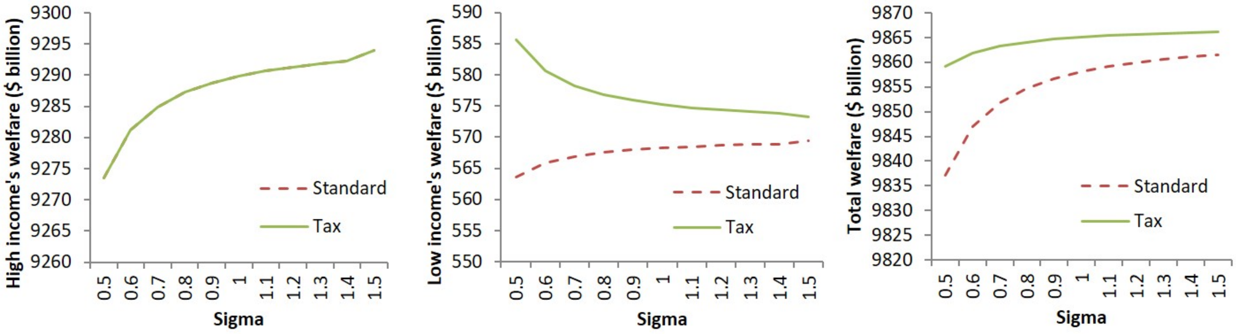

Figure 3.1: Welfare sensitivity to substitution elasticity ($\sigma$): conditional tax revenue distribution

Note: The graphs show the welfare levels at different substitution elasticities between energy use and efficiency capital when the tax revenue is distributed such that it provides the same amount of welfare for high-income consumers after the two policy options.

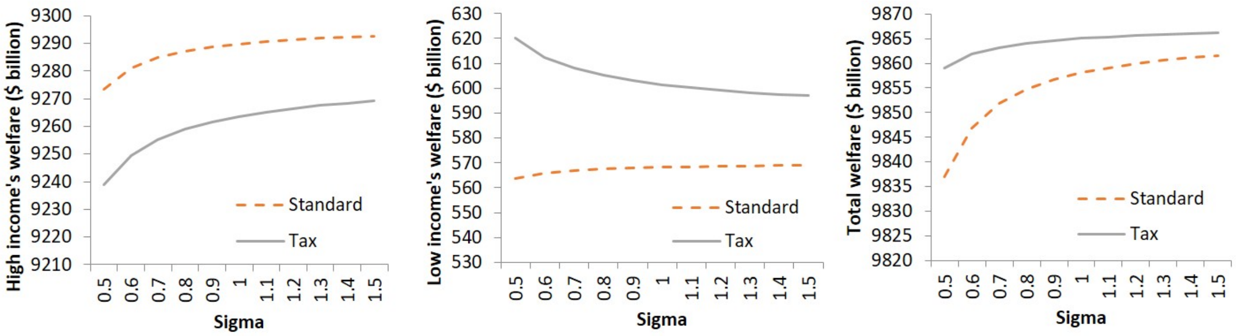

Figure 3.2: Welfare sensitivity to substitution elasticity ($\sigma$): even tax revenue distribution

Note: The graphs show the welfare levels at different substitution elasticities between energy use and efficiency capital when the tax revenue is distributed evenly across the income groups.

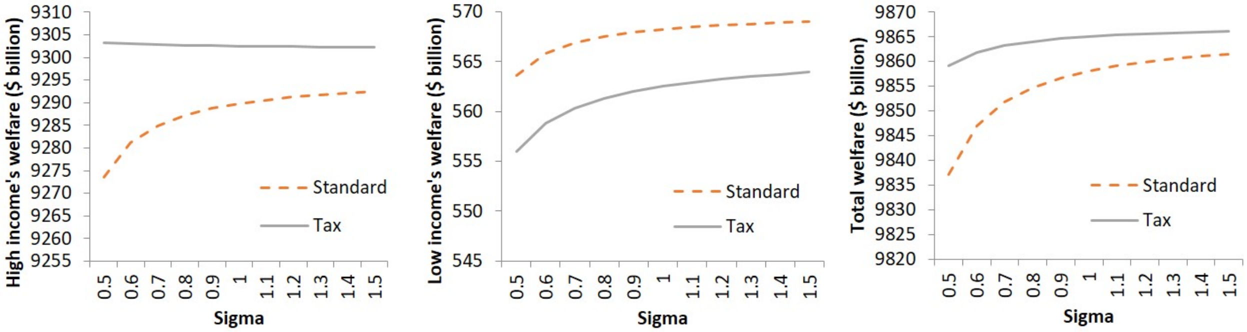

Figure 3.3: Welfare sensitivity to substitution elasticity ($\sigma$): proportionally distributed tax revenue

Note: The graphs show the welfare levels at different substitution elasticities between energy use and efficiency capital when the tax revenue is distributed across income groups proportional to their initial income share.

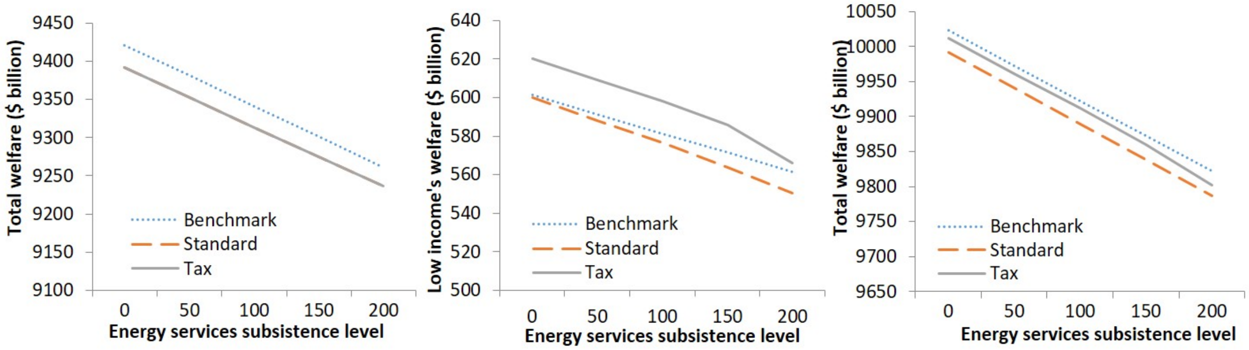

Figure 3.4: Welfare sensitivity to energy service subsistence levels: conditional tax revenue distribution

Note: The graphs show the welfare sensitivity to energy service subsistence levels when the tax revenue is distributed such that the high-income group obtains the same welfare the two policy options.

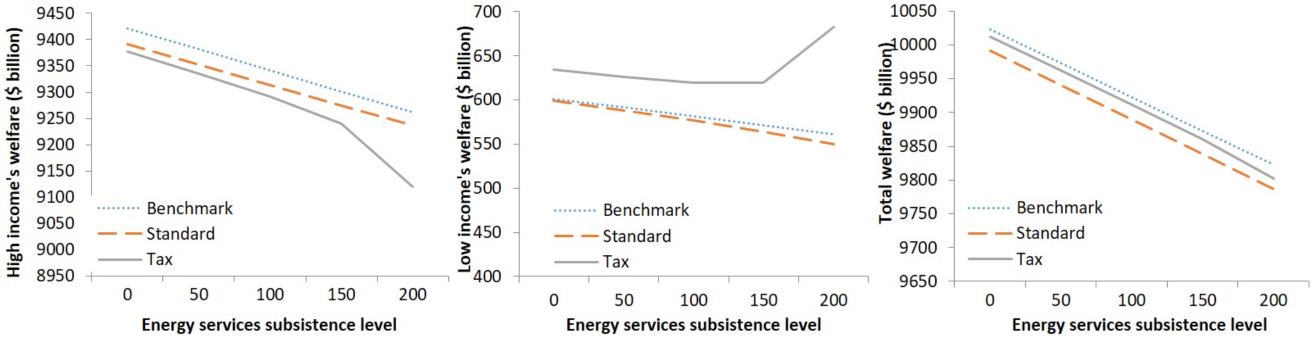

Figure 3.5: Welfare sensitivity to energy service subsistence levels: even tax revenue distribution

Note: The graphs show the welfare sensitivity to energy service subsistence levels when the tax revenue is distributed evenly across the income groups.

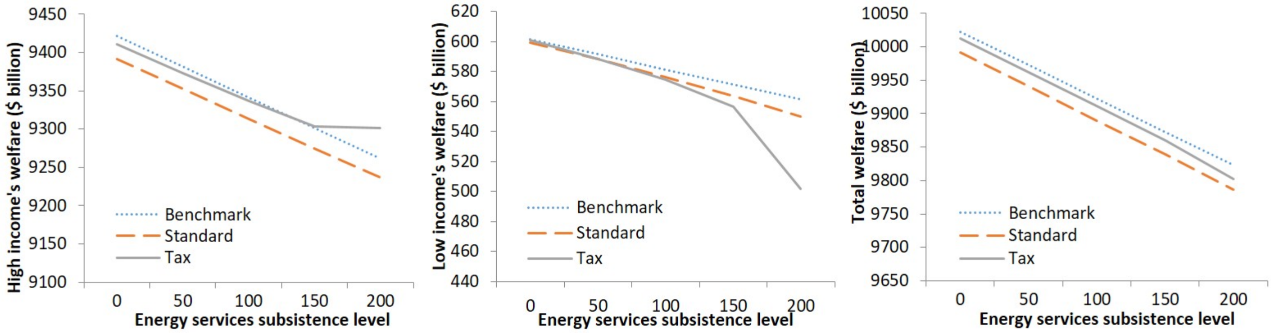

Figure 3.6: Welfare sensitivity to energy service subsistence level: proportional tax revenue distribution

Note: The graphs show the welfare sensitivity to energy service subsistence levels when the tax revenue is distributed across income groups proportional to their initial income share.

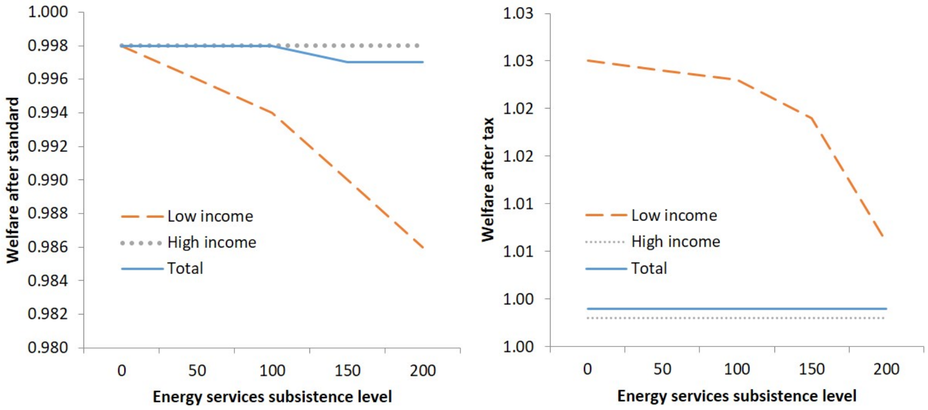

Figure 3.7: Homothetic versus Non-homothetic

Note: The graphs show welfare sensitivity to energy services subsistence levels when the welfare gains are normalized to one and the tax revenue is distributed such that the high-income group receives the same welfare after the two policy options. Zero-level subsistence level shows the welfare for homothetic preferences while other values represent non-homothetic preferences.

# CHAPTER 4

# EFFICIENCY VS EQUITY: AN ALTERNATIVE TO ENERGY EFFICIENCY SUBSIDIES

Market-based policies such as taxes are economically efficient, but they are associated with distributional concerns. On the other hand, energy efficiency subsidies might result in rebound effects which enhance individual households welfare even if they reduce social welfare (by raising pollution). These programs, however, are not economically efficient since they subsidize households in a constrained way. Building upon Chapter 2, which finds that the rebound effect is created by low-income households, this chapter compares the distributional impacts of energy efficiency subsidies versus energy taxes combined with cash transfers. The results show that energy taxes create higher welfare for the whole economy, and the distributional concerns associated with energy taxes can be addressed by allocating cash transfers across income groups.

## 4.1 Introduction

National energy security and emissions reduction are the main rationals for employing various energy policies to reduce energy consumption. Notwithstanding, there is always a trade-off between efficiency and equity impacts of different policy instruments[25]. Energy/Pollution taxes are considered a first-best policy and they also create tax revenues. However, taxes are politically hard to implement, and they are associated with distributional concerns; they have a relatively higher burden on low-income groups, which stems from a higher expenditure share of energy for these low-income groups [19, 58]. On the other hand, energy efficiency subsidies, as a form of income redistribution, create welfare gains particularly for low-income groups but they require government and/or utility company spending. These programs might result in rebound effects, which are privately welfare enhancing even if they reduce social welfare (by raising pollution). Energy efficiency subsidies, however, are not economically efficient since they subsidize households in a constrained way. Therefore, the question is: is there a solution that could minimize this trade-off? This chapter compares these two policy instruments while showing cases where the trade-off severity could be minimized.

There is an extensive scholarly work on the efficiency and equity impacts of energy and environmental taxes [11, 22]. While energy/carbon taxes are the least-cost tool to reduce energy use or emissions, they are known to have distributional concerns. Depending on how tax revenues are recycled back to the economy, some authors show that energy tax policy can be progressive in some cases [9, 18, 37, 38]. Many factors affect distributional equity beyond the tax revenue recycling, including, but not limited to, factors such as higher energy/carbon prices, heterogeneous benefits from improved environmental quality [44], change in relative returns to production factors such as labor and capital [35], privately sub-optimal investment in efficiency [73], capitalization effects [34], and competition between appliance manufacturers[6]. However, none of these studies capture the potential change in relative demand as a result of income effects. Klenert and Mattauch conceptually show that subsistence consumption has a significant role in making the tax policy progressive via tax revenue recycling [62]. In this study, I employ non-homothetic preferences by setting a subsistence level for energy use to evaluate the distributional impacts of two alternative energy policies.

The purpose of this chapter is to compare the distributional impacts of two energy policies (i.e. energy taxes combined with cash transfers to the consumers) versus energy efficiency subsidies. Since fossil fuels dominate US. energy consumption by 60% [26], it is deduced that energy taxes are proportionally equivalent to pollution taxes. The economy is divided into two groups: the poor (the lowest income quintile) and the rich (rest of the economy). Both policies are constrained to have the same amount of energy use reduction. The cash transfers are such that they create the same level of welfare for the rich. Then the welfare impacts on the poor as well as the whole economy are evaluated.

The contribution of this work, relative to prior literature, is that it quantifies the distributional impacts of energy efficiency subsidies versus an alternative policy option. It also shows an example of minimized trade-off between efficiency versus equity. This study also employs non-homotheic preferences which implies that the expenditure share of energy is not constant and it is dependent on income level. So, rich and poor households will consume different consumption bundles. This provides a new channel from which the distributional impacts arise.

The results show that the whole economy is better off under energy taxes. The distributional impacts depend on how the cash transfers are distributed across income groups. If these cash transfers are such that they create the same welfare gains for the high-income group after the two policies, the tax policy is preferred for the low-income group. These results imply that while energy taxes are more efficient than energy efficiency subsidies for the economy as a whole, they can also be progressive, depending on how the cash transfers are allocated. The welfare differences are sensitive to the elasticity of substitution between energy use and efficiency capital. If this elasticity is low, the welfare differences are higher, but the results are robust. This information is important to both economists and policy makers, showing how they can address both efficiency and distributional concerns.

The remainder of this chapter is as follows. Section 4.2 presents the theoretical model used in this study, and then Section 4.3 explains the two policy scenarios and how they are evaluated. Section 4.4 presents the simulation results followed by conclusions in Section 4.6.

## 4.2 Theoretical Model

In this chapter, a similar general equilibrium model to the previous chapter's is employed, but with some changes; in this model, households are different, not only due to having different total wealth endowments, but also because of having different factor endowment shares. It is assumed that there are two production factors, including labor and capital; consumers have different wealth endowments in addition to different capital and labor shares. Low-income groups usually have a relatively higher labor ownership and high-income groups have a relatively higher capital ownership. Therefore, the returns to labor and capital will be another channel of the distributional impacts that are added to this model.

The representative household has non-homothetic preferences over consumption of energy services of durable appliances ($Y$) and all other goods ($X$). The household's utility has a nested Stone-Geary functional form with a unit elasticity of substitution between energy services and other goods. A graphical description of the nesting structure is shown in Figure 4.1. $\bar{Y}$ represents the minimum energy service subsistence level and energy services are a CES function of energy use and energy efficiency capital with the following calibrated share form.

$$U = \phi(Y - \bar{Y})^{\alpha} X^{(1-\alpha)} \tag{4.1}$$

$$Y = Y_0 \left[ \theta \left( \frac{E}{E_0} \right)^{\rho} + (1-\theta) \left( \frac{A}{A_0} \right)^{\rho} \right]^{\frac{1}{\rho}} \tag{4.2}$$

The $\alpha$ parameter is the expenditure share of energy services in discretionary income for the representative household. The benchmark values are shown with a zero subscript. $\theta$ is the calibrated parameter being equal to the value share of energy consumption at the benchmark point.

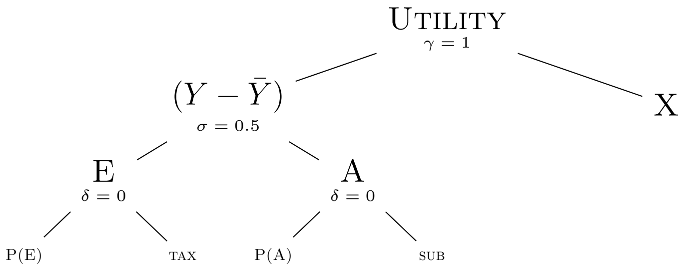

Figure 4.1: Nesting in Household Utility

The demand functions for energy, efficiency capital, and other goods can be derived from maximizing the representative household utility subject to the following budget constraint.

$$Max \;\; U(E, A, X) \tag{4.3}$$

$$s.t. \;\; P_l L + P_k K + trn = P_e E + P_a A + P_x X \tag{4.4}$$

where the left side of the budget constraint represents the income from labor and capital, as well as the cash transfers for each income group.

Depending on the capital and labor endowments of the two household types, the compensated demand functions for each income group are obtained by employing Shephard's lemma. Assuming unit benchmark prices, they have the general following forms:

$$E = Y\theta \left(\frac{P_Y}{P_E}\right)^{\sigma} \tag{4.5}$$

$$A = Y(1-\theta) \left(\frac{P_Y}{P_A}\right)^{\sigma} \tag{4.6}$$

$$X = U(1-\alpha) \left(\frac{P_Y}{P_X}\right)^{\alpha} \tag{4.7}$$

Each good (E, A, and X) is produced using labor and capital factors with Cobb-Douglas production technologies with a unit elasticity of substitution between labor and capital. The producers maximize their profit as shown below.

$$Max \;\; \pi = P_e E + P_a A + P_x X - P_l L - P_k K \tag{4.8}$$

$$s.t. \;\; E = K_e^{\gamma_i} L_e^{(1-\gamma_i)} \tag{4.9}$$

$$A = K_a^{\gamma_i} L_a^{(1-\gamma_i)} \tag{4.10}$$

$$X = K_x^{\gamma_i} L_x^{(1-\gamma_i)} \tag{4.11}$$

The $\gamma_i$ parameter is the output elasticity of capital. The optimal supply functions are derived via the above optimization, employing the Hotelling's lemma.

The consumer's optimization creates the following linear expenditure system that can be used for welfare calculation after each policy.

$$exp = P_Y \bar{Y} + U P_Y^{\alpha} P_X^{1-\alpha} \tag{4.12}$$

Employing the following Equivalent Variation (EV) definition, household welfare after each policy is calculated.

$$EV \equiv \; exp(P_0, U_1) - exp(P_0, U_0) \tag{4.13}$$

## 4.3 Policy Scenarios

After replicating the benchmark values in a general equilibrium modelling, two policy scenarios are evaluated: 1) energy efficiency subsidy (a subsidy on efficiency capital, i.e. $A$). 2) energy tax (a tax on energy use, i.e. $E$) combined with cash transfers. Energy is a polluting good, and it is assumed that energy pollutes at a constant marginal rate so that taxing energy is equivalent to taxing the pollution. Both tax and subsidy rates are endogenous in the model such that energy consumption decreases by the same amount after each policy scenario.

The economy is divided into two income groups: the poor (the lowest income quintile group) and the rich (the rest of the economy). Lump-sum transfers are such that they provide the rich the same amount of welfare gain after each policy scenario. Then the welfare of the poor as well as the whole economy are evaluated.

## 4.4 Numerical Simulation

In order to simulate the welfare impacts of the two policies numerically, I use the appliance market and residential electricity sector in the United States. The 2013 US. national data that was shown in Table 3.1 is employed in this numerical exercise. Employing income data from Table 3.1, the economy is divided into two groups of consumers, the poor (the lowest income quintile) and the rich (the rest of the economy). Electricity consumption and prices are from the U.S. Energy Information Administration (EIA) data. Personal consumption expenditures are from the Bureau of Economic Analysis, and the data for income and production factor ownership by each income quintile are from the Congressional Budget Office. The production factor shares for each income group are shown in Table 4.1. Labor shares in this study are calculated by summing the labor income and other incomes, while the capital shares are calculated by adding the business income and capital income. Then, each income-quintile income value is multiplied by these shares to calculate labor and capital incomes for each income group. The economy is divided into two income groups: the poor (the lowest income group) and the rich (the rest of the economy). Labor and capital incomes for the rich are calculated by summing labor and capital incomes of the top four income groups. The income elasticity of residential demand for electricity ($\eta$) in the United States is set to be 0.3 (the average empirically estimated elasticity), which is used in the calculation of energy services subsistence level. For the base case model, the elasticity of substitution between electricity use and efficiency capital ($\sigma$) is assumed to be 0.5, and then the results are checked by assuming different values for the elasticity.

An energy efficiency subsidy is considered to achieve a 10% increase in energy efficiency. Then, the energy tax policy is such that it provides the same amount of electricity use reduction as the subsidy option.

Table 4.1: Components of Average Market Income, by Market Income Group, US. 2013

| Income quintile group | Lowest | Second | Middle | Fourth | Highest |
|---|---|---|---|---|---|
| Share of Market Income (%) | | | | | |
| Labor income | 66 | 75 | 80 | 82 | 65 |
| Business income | 11 | 5 | 3 | 3 | 12 |
| Capital income and gains | 5 | 4 | 3 | 3 | 16 |
| Other income | 18 | 17 | 14 | 11 | 7 |

Source: US. Congressional Budget Office

### 4.4.1 Results

Employing the base case parameters, Table 4.2 shows the welfare impacts of each policy for the two income groups, as well as for the whole economy. The figure also shows the percentage changes in welfare compared to their benchmark values.

The results show that the energy taxes provide a higher welfare gain for the poor and for the whole economy than the energy efficiency subsidies depending on how the tax revenues are distributed. In addition, they imply that there is a case where the tax policy is progressive with a minimized trade-off between efficiency and equity.

The welfare impacts are evaluated by changing the elasticity of substitution between energy and efficiency capital ($\sigma$) and the results are shown in Figure 4.2. As set by the model's constraint, the high income-group receives the same amount of well-being after the two policy options. The change in this parameter provides robust results. The results also demonstrate that as the elasticity of substitution decreases, the welfare differences between the two policy options increase. The results are not shown for elasticises lower than 0.4 due to the numerical issues. This is because consumers cannot easily substitute more expensive energy with more efficient appliances, so that the cash transfers are not enough to compensate them, and the model cannot be solved with the current constraints. On the other hand, if the elasticity is high, there is not a significant difference between the welfare impacts of the two policies, since the consumers easily substitute energy use with efficiency or visa versa.

Table 4.2: The Base Case Results

| Policy Scenario | Poor | % change | Rich | % change | Total | % change |
|---|---|---|---|---|---|---|
| Subsidy | 461 | -4.42 | 7,946 | 0.05 | 8,407 | -0.21 |
| Tax & transfers | 477 | -0.93 | 7,946 | 0.05 | 8,423 | -0.01 |

Note: The numbers show the welfare changes (in $ billions) and percentage changes compared to the benchmark values after each policy when the cash transfers are such that the high-income group receives the same amount of welfare after each policy.

## 4.5 Imperfect Competition

The general equilibrium framework used in this study assumes a competitive electricity market. According to the first principle of incidence, the economic incidence of taxes in a competitive market is not dependent on whether the tax is physically paid by producers or consumers [56], and this incidence is determined by relative price elasticity of supply

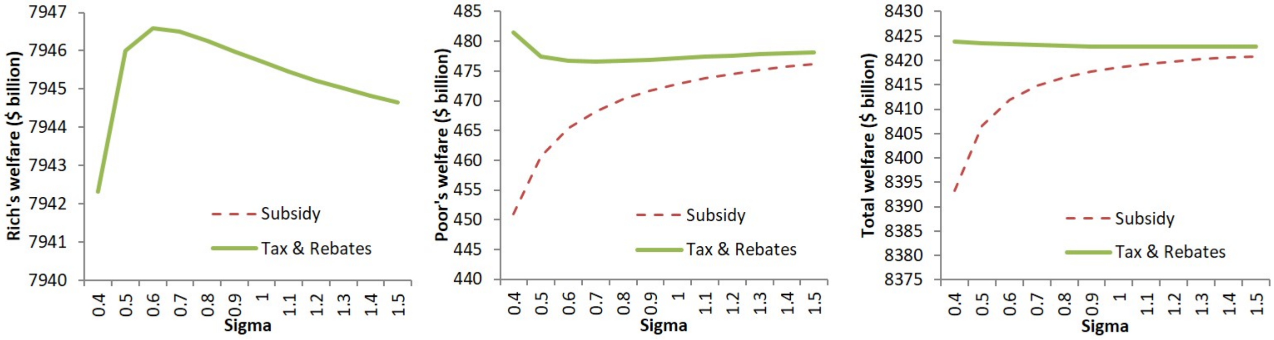

Figure 4.2: Sensitivity Analysis: Elasticity of Substitution Between Energy and Efficiency ($\sigma$)

Note: The graphs show the welfare changes at different levels of elasticity of substitution between energy use and efficiency capital when the cash transfers are such that the high-income group obtains the same welfare after the two policy options.

and demand. However, some authors argue that the electricity market is not perfectly competitive, and they show empirically that generators have been able to increase prices above the competitive levels [14, 59]. In the case of imperfect competition and a tax policy, if a tax is levied on consumers, the incidence will be similar to a competitive case. Nonetheless, if a tax is levied on producers, the total consumers' and producers' burden is greater than tax revenues raised. This is due to the behavioral changes by producers where the quantity sold is distorted downward [83]. In terms of higher prices for consumers, however, the size of pass-through depends on price elasticity of demand [80]. In this case, it is expected that the required tax rate to reduce energy use at the same level as energy efficiency subsidies will be higher, since the marginal revenue curve is steeper than the demand curve. Since energy is a polluting good, imperfect competition in this sector reduces production already, and according to [64], the tax policy in these cases extensively reduces energy use creating deadweight loss which could be high enough that energy taxes are no longer the most efficient policy for low-income groups.

## 4.6 Conclusion

Distributional impacts of energy policies arise due to different factors, such as production factor income, budget share of energy, tax revenue recycling, etc.. Non-homothetic preferences provide the expenditure share of energy services to be a function of income level. The capital endowment share is one of the factors that distinguishes low/high income groups, and a tax on the capital-intensive energy sector reduces returns to capital. This study quantifies the distributional impacts of energy policies by incorporating the mentioned factors.

This study compares the distributional impacts of two energy policies (energy efficiency subsidies versus energy taxes combined with cash transfers) where both policies result in the same amount of energy use reduction. The results show that the energy taxes are preferred for the whole economy and they can also be preferred for the poor depending on the size of cash transfers. Therefore, energy tax policy can be both efficient and progressive depending on the size of cash transfers that are allocated to different income groups of consumers.

# CHAPTER 5

# CONCLUSION

This thesis consists of three individual chapters that deal with distributional impacts of energy policies such as energy taxes, energy efficiency standards and energy efficiency subsidies.

In Chapter 2, I investigate the distribution and the rebound effects of energy efficiency subsidies by using efficient-lighting subsidies in the residential sector. I show that despite having no impact of income level on policy adoption, income level creates heterogeneous impacts on hours of lighting use. The direct rebound effect is mainly created by households that are at the lowest income group and at the lower home-size groups. I also show that these rebound effects are not too large to completely offset the policy's expected electricity use reduction.

In Chapter 3, the distributional impacts of energy efficiency standards versus direct energy taxes are quantified employing non-homothetic preferences in a general equilibrium framework. Taking into account the potential rebound effects emerging from energy efficiency improvements, the distributional impacts of two types of energy policy are compared. The energy tax and efficiency standard are the two instruments that could be employed to reduce energy consumption. Using the 2013 residential electricity data for households in the United States, I compare two policy instruments where both policies result in the same amount of change in electricity consumption. To address the research question, I incorporate non-homothetic preferences by employing a nested Stone-Geary utility function. First, the results for the total welfare resemble other research where the whole economy is better off using an energy tax policy compared to an energy efficiency standard policy. Second, I find that the low-income households would have higher surplus from energy taxes compared to efficiency standards while the tax revenue is allocated such that the two policy options create the same welfare for the high-income group. Under energy taxes policy compared to the alternative policy, distributing the tax revenue evenly across consumers provides the poor with more benefits and the rich with fewer. If the tax revenue allocation is proportional to their initial income share, low-income group is better-off under energy efficiency standards.

Finally in Chapter 4, the distributional impacts of two energy policies (energy efficiency subsidies versus energy taxes combined with cash transfers) are evaluated where both policies result in the same amount of energy use reduction. The cash transfers are such that the high-income group is indifferent between the two policy options. The base case results show that the energy taxes are preferred for the whole economy as well as the poor. Therefore, energy tax policy can be both efficient and progressive conditional on the size of cash transfers that are allocated to different income groups of consumers.

# REFERENCES CITED

[1] **Alberini, Anna and Charles Towe**, “Information v. energy efficiency incentives: Evidence from residential electricity consumption in Maryland,” *Energy Economics*, 2015, *52*, S30 – S40. Frontiers in the Economics of Energy Efficiency.

[2] ___ **, Will Gans, and Daniel Velez-Lopez**, “Residential consumption of gas and electricity in the U.S.: The role of prices and income,” *Energy Economics*, 2011, *33* (5), 870 – 881.

[3] **Allcott, Hunt and Dmitry Taubinsky**, “Evaluating Behaviorally Motivated Policy: Experimental Evidence from the Lightbulb Market,” *American Economic Review*, August 2015, *105* (8), 2501–38.

[4] ___ **and Michael Greenstone**, “Is there an energy efficiency gap?,” *Journal of Economic Perspectives*, 2012, *26* (1), 3–28.

[5] ___ **and Nathan Wozny**, “Gasoline prices, fuel economy, and the energy paradox,” Technical Report 5 2014.

[6] **Amano, Tomomichi and Hiroshi Ohashi**, “Ratcheting, Competition, and the Diffusion of Technological Change: The Case of Televisions under an Energy Efficiency Program,” *Columbia Business School Research Paper*, 2018, (18-71).

[7] **Andrews, Isaiah and James H Stock**, “Weak Instruments and What To Do About Them,” 2018.

[8] **Baum, Christopher F**, “ivreg2: Stata module for extended instrumental variables/2SLS, GMM and AC/HAC, LIML and k-class regression,” *http://ideas. repec. org/c/boc/bocode/s425401. html*, 2007.

[9] **Bento, Antonio M, Lawrence H Goulder, Emeric Henry, Mark R Jacobsen, and Roger H Von Haefen**, “Distributional and efficiency impacts of gasoline taxes: an econometrically based multi-market study,” *American Economic Review*, 2005, *95* (2), 282–287.

[10] **Bento, Antonio M., Lawrence H. Goulder, Mark R. Jacobsen, and Roger H. von Haefen**, “Distributional and Efficiency Impacts of Increased US Gasoline Taxes,” *American Economic Review*, June 2009, *99* (3), 667–99.

[11] **Bento, Antonio M, Lawrence H Goulder, Mark R Jacobsen, and Roger H Von Haefen**, “Distributional and efficiency impacts of increased US gasoline taxes,” *American Economic Review*, 2009, *99* (3), 667–99.

[12] **Bladh, Mats and Helena Krantz**, “Towards a bright future? Household use of electric light: A microlevel study,” *Energy Policy*, 2008, *36* (9), 3521 – 3530.

[13] **Borenstein, Severin**, “The Redistributional Impact of Nonlinear Electricity Pricing,” *American Economic Journal: Economic Policy*, April 2012, *4* (3), 56–90.

[14] ___ **and James Bushnell**, “Electricity restructuring: deregulation or reregulation,” *Regulation*, 2000, *23*, 46.

[15] ___ **and Lucas W Davis**, “The distributional effects of US clean energy tax credits,” *Tax Policy and the Economy*, 2016, *30* (1), 191–234.

[16] **Borger, Bruno De, Ismir Mulalic, and Jan Rouwendal**, “Measuring the rebound effect with micro data: A first difference approach,” *Journal of Environmental Economics and Management*, 2016, *79*, 1 – 17.

[17] **Brännlund, Runar, Tarek Ghalwash, and Jonas Nordström**, “Increased energy efficiency and the rebound effect: Effects on consumption and emissions,” *Energy Economics*, 2007, *29* (1), 1 – 17.

[18] **Bureau, Benjamin**, “Distributional effects of a carbon tax on car fuels in France,” *Energy Economics*, 2011, *33* (1), 121–130.

[19] **Chiroleu-Assouline, Mireille and Mouez Fodha**, “From regressive pollution taxes to progressive environmental tax reforms,” *European Economic Review*, 2014, *69*, 126–142.

[20] **Chun, Natalie and Yi Jiang**, “How households in Pakistan take on energy efficient lighting technology,” *Energy Economics*, 2013, *40*, 277 – 284.

[21] **Consulting, Inc. Navigant**, “Energy Savings Potential of Solid-State Lighting in General Illumination Applications,” *US Department of Energy, Washington, DC*, 2012.

[22] **Davis, Lucas W and Christopher R Knittel**, “Are Fuel Economy Standards Regressive?,” Technical Report, National Bureau of Economic Research 2016.

[23] **Deaton, Angus and John Muellbauer**, “An Almost Ideal Demand System,” *The American Economic Review*, 1980, *70* (3), 312–326.

[24] **Dergiades, Theologos and Lefteris Tsoulfidis**, “Estimating residential demand for electricity in the United States, 1965–2006,” *Energy Economics*, 2008, *30* (5), 2722 – 2730.

[25] **Deryugina, Tatyana, Don Fullerton, and William A Pizer**, “An Introduction to Energy Policy Tradeoffs between Economic Efficiency and Distributional Equity,” 2018.

[26] **EIA**, “Fossil fuels still dominate U.S. energy consumption despite recent market share decline,” 2016. Accessed = 2016-07-01.

[27] **Fowlie, Meredith, Michael Greenstone, and Catherine Wolfram**, “Are the Non-monetary Costs of Energy Efficiency Investments Large? Understanding Low Take-Up of a Free Energy Efficiency Program,” *American Economic Review*, May 2015, *105* (5), 201–04.

[28] **___ , ___ , and ___** , “Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program,” Working Paper 21331, National Bureau of Economic Research July 2015.

[29] **___ , ___ , and ___** , “Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program*,” *The Quarterly Journal of Economics*, 2018, p. qjy005.

[30] **Frondel, Manuel and Steffen Lohmann**, “The European Commission’s light bulb decree: Another costly regulation?,” *Energy Policy*, 2011, *39* (6), 3177 – 3181.

[31] **___ , Jorg Peters, and Colin Vance**, “Identifying the Rebound: Evidence from a German Household Panel,” *The Energy Journal*, 2008, *Volume 29* (Number 4), 145–164.

[32] **___ , Nolan Ritter, and Colin Vance**, “Heterogeneity in the rebound effect: Further evidence for Germany,” *Energy Economics*, 2012, *34* (2), 461 – 467.

[33] **Fullerton, Don**, “A Framework to Compare Environmental Policies,” Working Paper 8420, National Bureau of Economic Research August 2001.

[34] **___** , “Distributional effects of environmental and energy policy: an introduction,” Technical Report, National Bureau of Economic Research 2008.

[35] **___** , “Six distributional effects of environmental policy,” *Risk Analysis: An International Journal*, 2011, *31* (6), 923–929.

[36] **___ and Garth Heutel**, “The General Equilibrium Incidence of Environmental Mandates,” Technical Report 3 2010.

[37] ——— **and Holly Monti**, "Can pollution tax rebates protect low-wage earners?," *Journal of Environmental Economics and Management*, 2013, *66* (3), 539–553.

[38] ——— **, Garth Heutel, and Gilbert E Metcalf**, "Does the indexing of government transfers make carbon pricing progressive?," *American Journal of Agricultural Economics*, 2011, *94* (2), 347–353.

[39] **Gianessi, Leonard P., Henry M. Peskin, and Edward Wolff**, "The Distributional Effects of Uniform Air Pollution Policy in the United States," *The Quarterly Journal of Economics*, 1979, *93* (2), 281–301.

[40] **Gillingham, Kenneth, Alan Jenn, and Inês M.L. Azevedo**, "Heterogeneity in the response to gasoline prices: Evidence from Pennsylvania and implications for the rebound effect," *Energy Economics*, 2015, *52*, S41 – S52. Frontiers in the Economics of Energy Efficiency.

[41] ——— **, David Rapson, and Gernot Wagner**, "The Rebound Effect and Energy Efficiency Policy," *Review of Environmental Economics and Policy*, 2016, *10* (1), 68–88.

[42] ——— **, Matthew J Kotchen, David S Rapson, and Gernot Wagner**, "Energy policy: The rebound effect is overplayed," *Nature*, 01 2013, *493*, 475–6.

[43] **González, Jaume Freire**, "Empirical evidence of direct rebound effect in Catalonia," *Energy Policy*, 2010, *38* (5), 2309 – 2314. Greater China Energy: Special Section with regular papers.

[44] **Gordon, Hal, Dallas Burtraw, and Roberton C Williams**, "A microsimulation model of the distributional impacts of climate policies," 2015.

[45] **Goulder, Lawrence H., Marc A. C. Hafstead, and Roberton C. Williams III**, "General Equilibrium Impacts of a Federal Clean Energy Standard," *American Economic Journal: Economic Policy*, May 2016, *8* (2), 186–218.

[46] **Goulder, Lawrence H, Marc AC Hafstead, GyuRim Kim, and Xianling Long**, "Impacts of a Carbon Tax across US Household Income Groups: What Are the Equity-Efficiency Trade-Offs?," Technical Report, National Bureau of Economic Research 2018.

[47] **Greene, David L., James Kahn, and Robert C. Gibson**, "Fuel Economy Rebound Effect for U.S. Household Vehicles," *The Energy Journal*, 1999, *Volume20* (Number 3), 1–31.

[48] **Guertin, Chantal, Subal C. Kumbhakar, and Anantha K. Duraiappah**, "Determining Demand for Energy Services: Investigating income-driven behaviours," *International Institute for Sustainable Development*, 2003.

[49] **Haas, Reinhard and Peter Biermayr**, "The rebound effect for space heating Empirical evidence from Austria," *Energy Policy*, 2000, *28* (6), 403 – 410.

[50] **Hartman, Raymon S.**, "Self-Selection Bias in the Evolution of Voluntary Energy Conservation Programs," *The Review of Economics and Statistics*, 1988, *70* (3), 448–458.

[51] **Holland, Stephen P, Jonathan E Hughes, and Christopher R Knittel**, "Greenhouse gas reductions under low carbon fuel standards?," *American Economic Journal: Economic Policy*, 2009, *1* (1), 106–46.

[52] **Houde, Sébastien**, "Bunching with the stars: How firms respond to environmental certification," *Manuscript: University of Maryland*, 2014.

[53] **Houde, Sebastien and C. Anna Spurlock**, "Do Energy Efficiency Standards Improve Quality? Evidence from a Revealed Preference Approach," 06/2015 2015.

[54] **Iacus, Stefano M., Gary King, and Giuseppe Porro**, "Causal Inference without Balance Checking: Coarsened Exact Matching," *Political Analysis*, 2012, *20* (1), 1–24.

[55] **III, Roerton C. Williams, Hal Gordon, Dallas Burtraw, Jared C. Carbone, and Richard D. Morgenstern**, "The Initial Incidence of a Carbon Tax across Income Groups," Discussion Papers dp-14-24, Resources For the Future August 2014.

[56] **Jenkin, F**, "On the principles which regulate the incidence of taxes. Reproduced in RA Musgrave and CS Shoup (eds), Readings in the Economics of Taxation, 227-39," 1871.

[57] **Jin, Sang-Hyeon**, "The effectiveness of energy efficiency improvement in a developing country: Rebound effect of residential electricity use in South Korea," *Energy Policy*, 2007, *35* (11), 5622 – 5629.

[58] **Johnstone, Nick, Janaki RR Alavalapati et al.**, *The distributional effects of environmental tax reform*, International Institute for Environment and Development London, 1998.

[59] **Joskow, Paul and Edward Kahn**, "A quantitative analysis of pricing behavior in California's wholesale electricity market during summer 2000," in "2001 Power Engineering Society Summer Meeting. Conference Proceedings (Cat. No. 01CH37262)," Vol. 1 IEEE 2001, pp. 392–394.

[60] **King, Gary, Matthew Blackwell, Stefano Iacus, and Giuseppe Porro**, "cem: Coarsened exact matching in Stata," 2010.

[61] **Kirchner, Mathias, Mark Sommer, Kurt Kratena, Daniela Kletzan-Slamanig, and Claudia Kettner-Marx**, "CO2 taxes, equity and the double dividend – Macroeconomic model simulations for Austria," *Energy Policy*, 2019, *126*, 295 – 314.

[62] **Klenert, David and Linus Mattauch**, "How to make a carbon tax reform progressive: The role of subsistence consumption," *Economics Letters*, 2016, *138*, 100–103.

[63] **Kolmogorov, Andrey**, "Sulla determinazione empirica di una lgge di distribuzione," *Inst. Ital. Attuari, Giorn.*, 1933, *4*, 83–91.

[64] **Kolstad, Charles D.**, *Environmental Economics*, Oxford University Press, 2010.

[65] **Levinson, Arik**, "Energy Efficiency Standards Are More Regressive Than Energy Taxes: Theory and Evidence," Working Paper 22956, Georgetown University and National Bureau of Economic Research 2018.

[66] **Markusen, James R.**, "An Alternative Base Case for Modeling Trade and the Global Environment," *Journal of the Association of Environmental and Resource Economists*, 2017, *4* (3), 895–925.

[67] **Meyer, Breed D.**, "Natural and Quasi-Experiments in Economics," *Journal of Business & Economic Statistics*, 1995, *13* (2), 151–161.

[68] **Mills, Bradford F. and Joachim Schleich**, "Why don't households see the light?: Explaining the diffusion of compact fluorescent lamps," *Resource and Energy Economics*, 2010, *32* (3), 363 – 378.

[69] **Milne, Geoffrey and Brenda Boardman**, "Making cold homes warmer: the effect of energy efficiency improvements in low-income homes A report to the Energy Action Grants Agency Charitable Trust," *Energy Policy*, 2000, *28* (6), 411 – 424.

[70] **Murray, Anthony G. and Bradford F. Mills**, "Read the label! Energy Star appliance label awareness and uptake among U.S. consumers," *Energy Economics*, 2011, *33* (6), 1103 – 1110.

[71] **Olea, José Luis Montiel and Carolin Pflueger**, "A robust test for weak instruments," *Journal of Business & Economic Statistics*, 2013, *31* (3), 358–369.

[72] **Ramos, A., A. Gago, X. Labandeira, and P. Linares**, “The role of information for energy efficiency in the residential sector,” *Energy Economics*, 2015, *52*, S17 – S29. Frontiers in the Economics of Energy Efficiency.

[73] **Sallee, James M**, “Rational inattention and energy efficiency,” *The Journal of Law and Economics*, 2014, *57* (3), 781–820.

[74] **Schleich, Joachim, Bradford Mills, and Elisabeth Dütschke**, “A brighter future? Quantifying the rebound effect in energy efficient lighting,” *Energy Policy*, 2014, *72*, 35 – 42.

[75] **Si, Shuyang, Mingjie Lyu, CYC Lin Lawell, and Song Chen**, “The effects of energy-related policies on energy consumption in China,” in “Cornell University Working Paper” 2017.

[76] **Smirnov, Nikolai V**, “Estimate of deviation between empirical distribution functions in two independent samples,” *Bulletin Moscow University*, 1939, *2* (2), 3–16.

[77] **Su, Qing**, “A quantile regression analysis of the rebound effect: Evidence from the 2009 National Household Transportation Survey in the United States,” *Energy Policy*, 2012, *45*, 368 – 377.

[78] **Thomas, Brinda A. and Inês L. Azevedo**, “Estimating direct and indirect rebound effects for U.S. households with input–output analysis Part 1: Theoretical framework,” *Ecological Economics*, 2013, *86*, 199 – 210. Sustainable Urbanisation: A resilient future.

[79] **Tullock, Gordon**, *Economics of income redistribution*, Springer Science & Business Media, 2013.

[80] **Varian, Hal R**, *Microeconomic analysis*, Norton & Company, 1992.

[81] **Wall, Rob and Tracey Crosbie**, “Potential for reducing electricity demand for lighting in households: An exploratory socio-technical study,” *Energy Policy*, 2009, *37* (3), 1021 – 1031.

[82] **Wang, H., P. Zhou, and D.Q. Zhou**, “An empirical study of direct rebound effect for passenger transport in urban China,” *Energy Economics*, 2012, *34* (2), 452–460.

[83] **Weyl, E Glen and Michal Fabinger**, “Pass-through as an economic tool: Principles of incidence under imperfect competition,” *Journal of Political Economy*, 2013, *121* (3), 528–583.

[84] **Winebrake, James J., Erin H. Green, Bryan Comer, James J. Corbett, and Sarah Froman**, "Estimating the direct rebound effect for on-road freight transportation," *Energy Policy*, 2012, *48*, 252 – 259. Special Section: Frontiers of Sustainability.

[85] **Zivin, Joshua Graff and Kevin Novan**, "Upgrading Efficiency and Behavior: Electricity Savings from Residential Weatherization Programs," *The Energy Journal*, 2016, *Volume 37* (Number 4).