NOT A “WASTE” OF TIME: TEMPORAL RECYCLING POLICIES GIVEN HOUSEHOLD WASTE DISPOSAL ACTIONS

by

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ABSTRACT

Over the past few decades, recycling has gained particular interest due to its beneficial effects on energy consumption, natural resource availability, and ultimately greenhouse gas emissions. However, while recycling generates these benefits, the policies enacted have not captured the potential benefits from materials that yield the highest returns, at least not consistently over time (e.g. aluminum and plastic beverage containers). This dissertation evaluates two mainstream recycling policies at the household-level, specifically deposit-refund systems and curbside recycling programs, to not only theoretically and empirically prove their positive influence on household recycling behavior, but to establish a temporal element to help guide policymakers in maintaining these policies over time in order to realize the full potential of recycling. The analyses provide new evidence on how recycling decisions are made at the household-level, and how regulators can use these decisions to maximize social welfare given various implemented recycling policies.

Chapter 2 empirically tests how deposit-refund systems impact household recycling decisions. While it is expected that cash refunds provided by a regulator will positively alter the household's recycling decision, the range of data used for this analysis is sampled to focus on why beverage container redemption rates have declined over a particular time span. Additionally, it is found that keeping cash refunds constant from their implementation date result in redemption rate reductions due to time influencing factors, such as inflation and opportunity costs of recycling. Next, chapter 3 adds the availability of a curbside recycling program and a fixed amount of landfill space to explain which recycling method is preferred to a household under growing wages. It is theoretically shown that a household's recycling method decision changes over time when wages are expected to increase. Higher wages yield higher opportunity costs of not working, and therefore, a regulator should switch its subsidy focus from one policy to another in order to maximize social welfare and the municipality's

recycling rates. Lastly, chapter 4 builds on the previous chapter to incorporate investment in waste-to-energy technologies, which provide the additional benefits of a "cleaner" energy source and slower landfill space depletion compared to traditional landfilling methods. It is concluded from the theoretical framework that waste-to-energy investments can have negative effects on recycling rates under a fixed regulator budget. This is because a regulator must choose between subsidizing recycling and investing in waste-to-energy technologies, which require large amounts of physical and financial capital. It is also concluded that the optimal investment time period is to occur once consumption reaches a certain level, and the net benefits from the investment outweigh the pecuniary and non-pecuniary benefits received from recycling.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

Cash refund subsidy (for deposit-refund systems) . . . . θ_t

Consumption . . . . c_t

Consumption share of utility . . . . α

Curbside quantity . . . . b_t

Curbside share of utility . . . . ϕ

Deposit-refund quantity . . . . d_t

Labor . . . . n_t

Leisure . . . . ℓ_t

Leisure share of utility . . . . β

Recycling per unit time subsidy (for curbside recycling programs) . . . . γ_t

Regulator income/budget . . . . g_t

Wage . . . . w_t

LIST OF ABBREVIATIONS

Akaike Information Criterion	AIC
Bayesian Information Criterion	BIC
Consumer Price Index	CPI
Curbside	CS
Deposit-Refund	DR
Energy Information Administration	EIA
Environmental Protection Agency	EPA
Fully Modified Ordinary Least Squares	FMOLS
Municipal Solid Waste	MSW
Ordinary Least Squares	OLS
Pay-As-You-Throw	PAYT
Per Capita Personal Income	PCPI
Sierra Club	SC
Waste-to-Energy	WTE

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This dissertation is dedicated to those currently in the Ph.D. process. There is a light at the end of the tunnel, and it is *not* a train.

CHAPTER 1
INTRODUCTION

MSW, commonly referred to as "garbage" or "household waste", has increasingly become of interest to policymakers as population and consumption levels rise. Policymakers have looked to various forms of solid waste management to control these increasing levels by implementing consumer and producer-side instruments. Both forms seek to preserve natural resources by reducing the amount of material in consumer products, promoting recycling, and converting waste into "cleaner" energy via a combustion process.

While producers inherently seek ways to reduce costs by decreasing the amount of material and packaging in their products, they potentially do not account for the downstream effects their products and packaging have on the environment. Therefore, regulators have intervened by establishing source reduction goals, subsidizing product design research and development, and issuing taxes on products to internalize these unaccounted for downstream effects. Similar economic disincentives can also be applied at the consumer-level. Taxes can be placed on single-use products to encourage purchases of more durable, reusable goods (EPA, 1995). Municipalities have also implemented PAYT programs. In contrast to most municipality waste management fees, where the household pays a flat fee, PAYT programs impose a tax on the household that is proportional to the disposed quantity to be landfilled.

Recycling policies have gained much attention over the past few decades with growing public awareness about environmentalism. Policymakers have implemented both local and national recycling policies to preserve scarce resources and conserve energy. In the U.S., DR systems and CS recycling programs have been the main avenues for recycling promotion. DR systems attempt to converge consumption and recycling levels by placing a consumption tax on a product, and subsequently refunding the tax if the product is returned for the purposes of recycling. States with DR systems have been noted to generate recycling rates

2.5 times higher than states without such systems (BEAR, 2002). CS recycling programs do not offer a monetary incentive, but instead offer convenience by picking up recyclables at the household's place of residence. CS recycling programs have grown in popularity since the early 1990s, and have recently been reported to service 71 percent of the U.S. population (EPA, 2014).

The combination of these two methods have contributed to the overall increasing U.S. recycling rates. However, when recycling rates are disaggregated by product, rates can vary widely. Specifically, U.S. beverage container recycling rates have dropped 20 percent compared to their 1990 rates. This declining trend is of particular interest to policymakers, because beverage containers comprise two-thirds of the total aluminum, glass, and plastic material recycled in the MSW stream (EPA, 2014).

In order to implement successful policies and maintain them over time, regulators must consider household behavior. Chapter 2 focuses on DR systems and examines how these programs fare over time. The household decides to recycle via the DR system by weighing the costs associated with cleaning, sorting, storing, and returning beverage containers to a recycling facility against the benefits it receives from cash returns and saving the environment. With the exception of California, states with DR systems have not increased their cash refunds since their date of implementation, all while transportation costs and a household's value of time (using income as a proxy) have increased. This prompts the question of how effective are DR systems over time when taking into account inflation, no to little revision to cash refunds, increasing transportation costs, and increasing value of time? The analysis not only demonstrates that cash refunds encourage household recycling behavior, but that cash refunds over time matter. Simply adjusting the cash refund for inflation can result in an increase of hundreds of millions of beverage containers recycled via the DR system annually.

Chapter 3 expands the notion of updating cash refunds over time in DR municipalities to allow for a substitute recycling policy (i.e. a CS recycling program). As previously suggested, the two recycling methods have been noted to work as complementary programs to maximize a municipality's recycling rate. However at the household-level, these policies are deemed substitutes, albeit not perfect ones. The goal of chapter 3 is to first illustrate the methods of which households choose to recycle when wages are growing, either recycling via the DR system or via the CS recycling program, when there is no consideration for landfill space. With DR systems offering cash refunds to supplement household total income, it is theoretically shown that if a household starts below some wage threshold, the household will recycle more via the DR system. The second goal of chapter 3 is to determine the optimal subsidy levels for each program, provided the actions of the household and a fixed amount of landfill space. Recycling subsidies come in the forms of either increasing the cash refund households receive per unit recycled via the DR system, or by decreasing the per unit time it takes a household to recycle via the CS recycling program. The latter can be a scenario where a regulator takes on the burden of cleaning and/or sorting the household's recyclables.

Lastly, regulators have looked to waste incineration, or WTE, to generate a "cleaner" form of energy and slow down landfill depletion. WTE technologies currently remove 11.7 percent of the waste generated in the U.S., helping reduce waste sent to landfills from 69.8 percent in 1990 to 53.6 percent in 2011 (EPA, 2014). Although this method has environmental benefits, it is the more controversial topic. It is argued that such technology investments promote consumption, working against source reduction plans and a zero-waste goal. In addition, WTE plants are stated to work in opposition to recycling policies, as both achieve the same goal of lowering landfill rates. In chapter 4, this controversial topic is explored to identify optimal investment times of WTE technologies given the actions of the household under growing wages, availability of a recycling program, and a fixed amount of landfill space.

CHAPTER 2

DETERMINANTS OF REDEMPTION RATES OVER TIME: AN EMPIRICAL BEVERAGE CONTAINER RECYCLING STUDY

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This chapter measures the effects of cash refunds and opportunity costs of recycling on redemption rates over time using U.S. state data. Results indicate that cash refunds positively influence recycling via the DR system. However, the opportunity costs of recycling, which is estimated to be equal to household income, significantly reduce the positive influence from cash refunds. The outweighing effect of household income on redemption rates is then linked to the decline in redemption rates in the U.S. from the early-1990s to early-2000s.

2.1 Overview

Beverage container recycling rates in the U.S. have steadily declined from 1990 to 2007 (see Figure 2.1).[1] On average over this time period, beverage containers represent two-thirds of the thousands of tons of aluminum, glass, and plastic recycled. In terms of recycled material composition, aluminum and glass beverage containers comprise as much as 98 percent and 90 percent of their respective material (EPA, 2014). DR systems have been noted to play a significant role in generating high levels of beverage container recycling by targeting specific materials to be recycled (see Lave et al., 1999). It has been documented that states with DR systems recycle 71.6 percent, while states without DR systems recycle only 27.9 percent of their beverage containers (BEAR, 2002). However, how effective are DR systems over time with inflation, no to little revision to cash refunds, increasing transportation costs, and increasing opportunity costs of recycling?

[1]The U.S. EPA reports all materials in thousands of tons. To convert into number of beverage containers, aluminum, glass and plastic values were multiplied by 2000 and then by the number of containers in a pound; 28.7, 1.86, and 15.7, respectively. Materials were summed, and then the recycled values were divided by the generated values to get beverage container recycling rates over time. Sources: U.S. EPA and California's Department of Resources Recycling and Recovery.

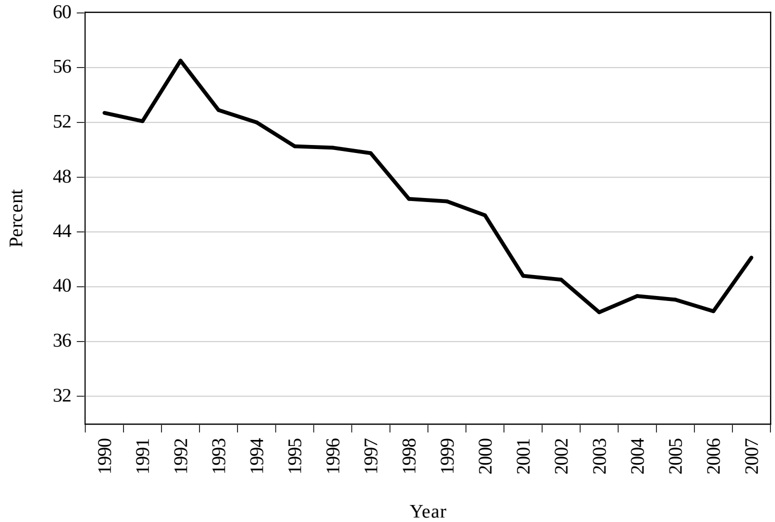

Figure 2.1: U.S. Beverage Container Recycling Rates

The U.S. currently has ten states with mandatory deposits on specific beverage container types.[2] All cash refunds have remained the same since their respective dates of implementation, with the exception of California. California has increased their cash refund three times since the system has been implemented.[3]

DR systems work as follows. Initially, the DR system taxes the consumption of a beverage. The tax will then be refunded to the household if the beverage container is returned to a recycling center.[4] The tax is similar to a Pigouvian tax in that it seeks to tax the household a rate equal to the marginal social damage of waste disposal (Pigou, 1920). The difference is that rather than placing the tax at the point of disposal/landfill, the tax is only placed on households who do not redeem their beverage containers. The benefit of DR systems over

[2]All U.S. deposit states cover all beer, malt, and carbonated soft drinks. In addition to these covered beverage types, California's DR system includes wine, distilled spirits, and all non-alcoholic beverages excluding milk. Connecticut covers bottled water. New York covers both bottled water and wine coolers. Hawaii includes wine coolers, wine, liquor, and mineral water. Massachusetts includes mineral water, and Michigan contains mineral water, wine coolers and canned cocktails. Vermont covers both mixed wine and liquor. Lastly, Oregon's DR system includes all beverages including bottled water, but excluding wine, liquor, milk, and milk substitutes (CRI, 2013).

[3]California's DR system was implemented in 1987 with a deposit amount of 1 cent. The law was then amended in 1990 to 2.5 cents for containers less than 24 ounces, and 5 cents for containers greater than 24 ounces. The deposit was again amended in 2004 to 4 cents for containers less than 24 ounces, and 8 cents for containers greater than 24 ounces. The current law is 5 cents for containers less than 24 ounces and 10 cents for containers greater than 24 ounces, which was established in 2007 (CRI, 2013).

[4]Recycling centers are generally defined as privately owned businesses whose sole purpose is redemption.

a true Pigouvian tax is that DR systems reduce the initiative to illegally dump waste (see Palmer & Walls, 1997; Palmer et al., 1997; Ashenmiller, 2009). The presence of CS recycling programs yield the potential of the deposit acting as a strict consumption tax, because the household may choose to recycle via the CS recycling program or another means that does not refund the deposit (e.g. drop off sites).

Studies have shown DR systems to be more cost effective and efficient compared to other recycling policies, such as advance disposal fees and recycling subsidies (see Dinan, 1993; Fullerton & Kinnaman, 1995; Sigman, 1995; Palmer & Walls, 1997; Acuff & Kaffine, 2013). However, little empirical work has been done with regards to cash refunds and opportunity costs of recycling from DR systems. Most of the empirical research that has been conducted has been survey-based. For example, Bell et al. (2010) found that DR systems influence water bottle recycling more than any other legal regime (e.g. mandatory recycling, opportunities to recycle, recycling plans, and recycling goals).

Several other studies have focused on the opportunity costs associated with recycling (see Halvorsen & Kipperberg, 2003; Halvorsen, 2008; Ashenmiller, 2009). Each of these studies utilized surveys to conclude that higher opportunity costs of recycling yield lower recycling rates. Although opportunity costs of recycling are not exactly equal to the wage rate, it is noted that income and opportunity costs are positively correlated.[5] Viscusi et al. (2013) found that higher income households contribute less to recycling centers (i.e. redeeming for cash), because their time is worth more than lower income households and they simply do not find it worth their time to make a "special" trip to a recycling center. In addition, making a "special" trip to a recycling center can prove to use more energy and resources than it saves (see Lave et al., 1999). However, trips might be deemed "not special" when retailers (e.g. grocery stores) participate in their respective state's DR system and are capable of accepting beverage containers for redemption, because the trip to the grocery store would have been

[5] Shaw (1992) showed that one's wage rate is not exactly equal to one's value of time, because individuals may allocate their time differently at different times of the year. Instead, wage is equal to the ratio of the shadow price of time to the shadow price on the budget constraint.

made regardless.[6] In this case, transportation costs, both explicit gasoline and the time it takes to make the trip, can be rendered insignificant.

This study differs from the previous studies in that it incorporates a time dimension to explain changes in redemption rates, with a focus on the decline period from the early 1990s to early 2000s (as shown in Figure 2.2). It is hypothesized that these rates have declined because cash refunds have declined at the rate of inflation, trip costs, both opportunity and explicit, have increased, and increased access to CS recycling has "can"nibalized from recycling centers.[7]

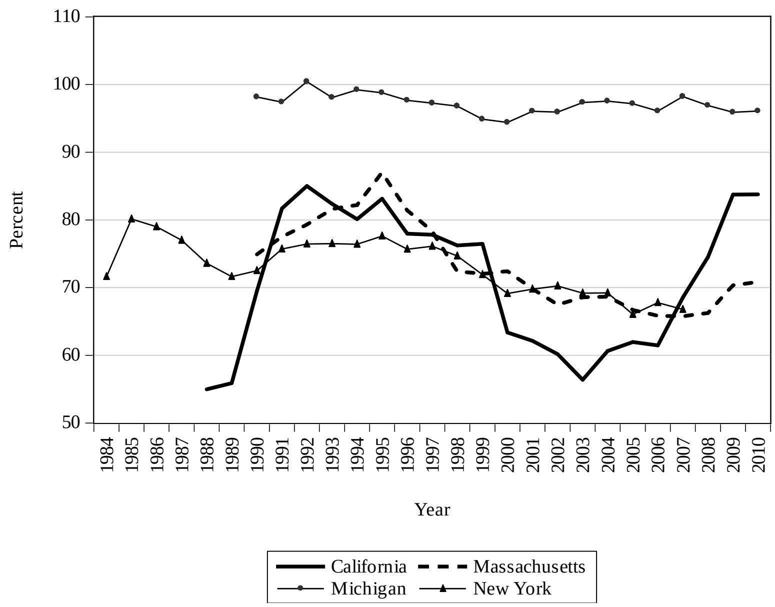

Figure 2.2: Redemption Rates Over Time by State

Sources: California Department of Resources, Recycling and Recovery; Massachusetts Department of Environmental Protection; Michigan Department of Treasury; and New York State Department of Environmental Conservation

[6]Since retailers are do not have the sole purpose of redeeming beverage containers, they generally will have smaller capacities compared to redemption centers. Retailers sometimes limit the quantities or dollars paid to customers in a day. For example in New York, redemption centers (or in general, dealers) are able to limit the number of beverage containers they accept from any one customer in a day (or trip) to 240 or 72, depending on the square footage of the business (NY, 1982). In addition, Oregon law permits dealers to refuse to accept more than 50 individual beverage containers from any one person during one day (Ore, 1983).

[7]Beatty et al. (2007) empirically showed that the benefits of curbside recycling may be over estimated when in the presence of multiple recycling modes such as DR systems, because curbside recycling transfers what would have been recycled via the DR system; hence "can"nibalization from one mode of recycling to another.

Various states employ strategies to manage recycling and redemption rates. For example, California has increased cash refunds three times since the implementation of their DR system. Not surprisingly, the years with upticks in redemption rates, as shown in Figure 2.2, directly correspond to the years that cash refunds were increased (see footnote 3). Also in Figure 2.2, note Michigan's high and relatively stable redemption rates over time. The figure suggests that Michigan's $0.10 cash refund holds its value with inflation more than the $0.05 cash refund of Massachusetts and New York. In 2004 though, Michigan paired its $0.10 cash refund with a command and control approach that prevents containers from entering the MSW stream.[8] Iowa has a similar command and control addition to that of Michigan, but it only applies to dealers, distributors, manufacturers, or a person operating a recycling center, and not to individuals (Iow, 1999). The command and control approach could have some explanatory power in why Michigan's rates have remained relatively stable over the time beginning in 2004. For the purposes of this chapter, the various command and control approaches are not empirically tested.

U.S. data for California, Massachusetts, Michigan, and New York from 1984 to 2010 is used to estimate the effects that real cash refunds, real opportunity costs of recycling, real explicit transportation costs, and warm glow or "green" identity have on redemption rates.[9] All real cash refunds and real costs will henceforth be referred to as cash refunds and costs.

The panel regression analysis finds similar magnitudes across specifications regarding the effect of percent changes in cash refunds on percent changes in redemption rates. Opportunity costs of recycling vary in magnitude across specifications, but the negative effect of opportunity costs of recycling outweigh the positive influence of cash refunds in each specification. This greater magnitude on opportunity costs of recycling provide insight as to why

[8]See Michigan's Public Act 34 of 2004. A person shall not knowingly deliver to a landfill for disposal, or, if the person is an owner or operator of a landfill, knowingly permit disposal in the landfill...subject to subsection (4), more than a de minimis amount of open, empty, or otherwise used beverage containers. As by Sec. 301 from Michigan's Natural Resources and Environmental Protection Act, a person is defined as an individual, partnership, corporation, association, governmental entity, or other legal entity. The subsection (4) just excludes green glass beverage containers before June 1, 2007 (Mic, 2004).

[9]Akerlof & Kranton (2000) showed how one's identity can influence economic outcomes in a game-theoretic framework.

redemption rates have fallen over the time period from 1990 to 2000. If policymakers seek to increase beverage container redemption rates, and thereby increase recycling rates, cash refunds must increase. While CS recycling programs have been shown to increase recycling, it is complementary to DR systems (Ashenmiller, 2009), and one that does not increase recycling rates by as much as DR systems (BEAR, 2002).

The remainder of this chapter proceeds as follows. Section 2.2 develops the conceptual framework that analytically explains how cash refunds, opportunity costs of recycling, gasoline costs, and “green” identity influence the quantity recycled via the DR system. Sections 2.3 and 2.4 then discuss the data and estimation methodology used to empirically test the conceptual framework. Sections 2.5 and 2.6 provide the estimation results and the implications for public policy. Section 2.7 then illustrates alternative estimation methods to account for possible cointegration using panel FMOLS. Finally, section 2.8 concludes the chapter and suggests areas for further exploration.

2.2 Conceptual Framework

This section presents the conceptual framework that will be used to analytically explain the expected empirical results. It builds off of the framework set by Viscusi et al. (2011) to include pecuniary and non-pecuniary benefits, transportation costs and per unit time costs. To begin, consider a representative household who seeks to maximize utility by choosing the quantity of consumption c_t, leisure ℓ_t, and DR recycling d_t.

$$U_t = U\big(c_t,\, \ell_t,\, d_t\big) \tag{2.1}$$

Optimization is subject to both a budget and time constraint. The budget constraint contains the price of consumption, which is set as the numeraire, and embeds the beverage container deposit/tax. The budget constraint also includes the cash refund θ_t, which is received on a per container basis. Therefore, the representative household will receive θ_t for every d_t returned. The last price incorporated in the budget constraint is the explicit transportation costs it takes to make the trip to a recycling center (e.g. the price of gasoline per trip e_t). Since the representative household does not make decisions to return beverage containers on a per container basis, the decision to clean, sort, and store beverage containers is made in advance. To put this into perspective, households generally have a separate receptacle located next to their waste bin to collect the beverage containers they plan to clean, sort, and store. When the receptacle fills up, households make the trip to the recycling center provided the costs are justified. Usually if the decision to separate certain items is made, then the household has already weighed the benefits and costs of redeeming the beverage containers for cash. Households also prefer to take the most they can fit into their vehicle, or as much as the recycling center will allow per trip (see footnote 6 for an example on the maximum containers accepted by a recycling center in a day).

Since transportation costs are not on a per container basis, but rather a per trip basis, costs can be spread over the number of containers the household returns to the recycling center. Again, the household prefers to return the maximum. Trips to recycling centers in a given period N_t are defined as

$$N_t = \frac{d_t}{\overline{d}}, \tag{2.2}$$

where $\overline{d}$ is the maximum quantity of beverage containers a household's vehicle can hold or the maximum quantity per day a recycling center will take from a single household. The budget constraint is then

$$y_t + \theta_t d_t = c_t + e_t \frac{d_t}{\overline{d}}, \tag{2.3}$$

where y_t is income, and a household can add to its income if beverage containers are redeemed at a recycling center for θ_t per container d_t.

The household's time constraint is based on h, the quantity of time in a given period. Given the amount of time, the household can divvy up that time for leisure ℓ_t, time spent performing recycling activities $f(d_t)$, and time spent working, which is set equal to the household's income y_t. Time spent performing recycling activities includes the time spent cleaning, sorting, storing, and returning the beverage containers to a recycling center. It is a function of how many beverage containers the household redeems for cash, where $\partial f/\partial d_t > 0$ and $\partial^2 f/\partial d_t^2 \geq 0$.[10] The household's time constraint is

$$h = \ell_t + y_t + f\big(d_t\big). \tag{2.4}$$

Rearranging (2.3) and (2.4) allow for c_t and ℓ_t to be written in terms of d_t. Specifically, $c_t = y_t + d_t\big(\theta_t - e_t/\overline{\overline{d}}\big)$ and $\ell_t = h - y_t - f\big(d_t\big)$. The household's maximization problem can then be written as an implicit function.

$$\max_{d_t} U_t = U\big(c_t\big(d_t\big),\, \ell_t\big(d_t\big),\, d_t\big) \tag{2.5}$$

Taking the derivative of U_t with respect to d_t yields the following first order condition.

$$\frac{\partial U_t}{\partial d_t} = \frac{\partial U_t}{\partial c_t}\left(\theta_t - \frac{e_t}{\overline{\overline{d}}}\right) - \frac{\partial U_t}{\partial \ell_t}\frac{\partial f}{\partial d_t} + \frac{\partial U_t}{\partial d_t} = 0 \tag{2.6}$$

The household will then redeem beverage containers for cash up to the point where the marginal benefits equal the marginal costs of redeeming beverage containers for cash. Marginal benefits are separated into two categories, pecuniary and non-pecuniary. Pecuniary benefits are $\big(\partial U_t/\partial c_t\big)\theta_t$. Non-pecuniary benefits are the psychological benefits that the household receives from its own "green" identity, $\partial U_t/\partial d_t$. Marginal costs are

$$\frac{\partial U_t}{\partial c_t}\frac{e_t}{\overline{\overline{d}}} + \frac{\partial U_t}{\partial \ell_t}\frac{\partial f}{\partial d_t},$$

where the first term is the explicit marginal cost associated with driving to the recycling center, and the second term is the marginal opportunity cost of time associated with recycling. The implicit function theorem allows for demonstration of how cash refunds, the price of gasoline and the marginal opportunity cost of recycling affect the quantity redeemed for cash.

$$\frac{\partial d_t}{\partial \theta_t} = -\frac{\partial U_t/\partial c_t}{\partial^2 U_t/\partial d_t^2 - \big(\partial U_t/\partial \ell_t\big)\big(\partial^2 f/\partial d_t^2\big)} \qquad > 0$$

[10]Convexity is not required. The cost can also be on a per container basis, where $\partial^2 f/\partial d_t^2 = 0$.

$$\frac{\partial d_t}{\partial e_t} = -\frac{-\left(\partial U_t/\partial c_t\right)/\bar{d}}{\partial^2 U_t/\partial d_t^2 - \left(\partial U_t/\partial \ell_t\right)\left(\partial^2 f/\partial d_t^2\right)} < 0$$

$$\frac{\partial d_t}{\partial\left(\partial f/\partial d_t\right)} = -\frac{-\partial U_t/\partial \ell_t}{\partial^2 U_t/\partial d_t^2 - \left(\partial U_t/\partial \ell_t\right)\left(\partial^2 f/\partial d_t^2\right)} < 0$$

The denominator is negative-definite, because $\partial^2 U_t/\partial d_t^2$ is negative due to the conditions for a maximum, and $\left(\partial U_t/\partial \ell_t\right)\left(\partial^2 f/\partial d_t^2\right)$ being positive or equal to zero. The latter is positive, because $\partial U_t/\partial \ell_t$ and $\partial^2 U_t/\partial d_t^2$ are positive from the conditions for a maximum, and assumed convexity in d_t. Therefore, $\partial d_t/\partial \theta_t > 0$, $\partial d_t/\partial e_t < 0$, and $\partial d_t/\partial\left(\partial f/\partial d_t\right) > 0$.

2.3 Data

The data used for this chapter is an unbalanced panel data set that contains annual data from California, Massachusetts, Michigan, and New York from 1984 to 2010. Redemption rates reported cover all beverage containers in that respective state's DR system. Data for redemption rates was supplied by the California Department of Resources, Recycling, and Recovery, the Massachusetts Department of Environmental Protection, the Michigan Treasury Department, and the New York State Department of Environmental Conservation. Across these four states and over the varying time periods, the average redemption rate is 78.33 percent.

State cash refund data was taken from the Bottle Bill Resource Guide. As noted earlier, cash refunds have only changed for California. PCPI was used as a proxy for the opportunity cost of recycling. This data was taken from the Federal Bank of Saint Louis' FRED database. Average gasoline end user prices (i.e. regular, mid-grade, premium) were used from the U.S. EIA. For the year 1988, average end user prices were not available, therefore retail outlet prices were used for each state. The values for the remaining years were not significantly different from one another. Cash refunds, PCPI, and gasoline prices were then deflated using each respective state's CPI, rebased in 2010 terms.

SC members as a percent of the population will serve as a proxy for the psychological benefit that the household receives from its own "green" identity.[11] SC members include people who pay membership fees, and those who do not pay annual membership fees but have either volunteered with SC or even signed a SC petition. As noted in Mrozek (2000), this "measure is not an ideal measure of preferences, however, for part of the benefit of membership consists of participation in activities sponsored by local chapters."

All variables were then log-transformed to reduce any outliers. Therefore, coefficients in level form can be interpreted as elasticities. Table 2.1 reflects the log-transformed descriptive statistics. In the remainder of this chapter, variables will be referred to in their level form for reading ease (e.g. log of redemption rate will be redemption rate).

Table 2.1: Descriptive Statistics - Log Levels

	Obs.	Mean	Std. Error	Min.	Max.	Jarque-Bera
Redemption Rate	89	4.35	0.16	4.01	4.61	2.23
Cash Refund	105	1.97	0.53	0.57	2.99	1.39
PCPI	108	10.58	0.15	10.20	10.87	1.87
Gasoline Price	108	0.41	0.30	-0.21	1.08	5.85*
SC/Population	108	-1.35	0.54	-2.54	-0.36	3.91

*Note: *, **, and *** represent significance at the 10, 5, and 1 percent levels of the Jarque-Bera test, respectively.*

2.4 Estimation Methodology

This section goes through the estimation methodology. First, the presence of unit roots were tested using the Im et al. (2003) procedure. Based on finding the presence of unit roots, Pedroni (1999) panel cointegration tests were performed with common time dummies to account for cross-sectional dependencies. The test finds high probabilities of failing to reject the null hypothesis of no cointegration. Therefore, a first-differenced model is used to analyze the effects of percent changes in cash refunds, opportunity costs of recycling, gasoline

[11] Mrozek (2000) used the fraction of people in a jurisdiction that are SC members to measure citizen preferences. The number of SC members are "presumed to correlate highly with attitudes toward the environment and, specifically, recycling."

costs, and SC members as a percent of the population on percent changes in redemption rates.

2.4.1 Unit Roots

The Im et al. (2003) panel unit root test was used to test for the presence of unit roots (see Table 2.2). Three tests for each series were performed: one with a constant, one with a constant and a time trend, and one differenced with a constant. The maximum number of lags was chosen via Schwert (1989), $p_{max} = 12\big(T/100\big)^{0.25}$, and the actual lag selection was chosen that minimized the AIC. The test has a null hypothesis of a unit root. It is found that in the case of just a constant, all variables contain a unit root with the exception of the cash refund. In the case with a constant and a time trend, only the redemption rate suggests rejection of the null. The general equation estimated is

$$\Delta y_{i,t} = \alpha_i + \zeta_i t + \beta_i y_{i,t-1} + \sum_{j=1}^{p_i} \theta_{i,j} \Delta y_{i,t-j} + \varepsilon_{i,t};\ i = 1,\ 2,\ 3,\ 4;\ t = 1,\ \ldots,\ T. \qquad (2.7)$$

Table 2.2: Unit Root Test Results - Log Levels

	Level, $\zeta_i = 0$		Level, $\zeta_i \neq 0$		Differenced, $\zeta_i = 0$	
	z_{tbar}	$z_{\tilde{t}bar}$	z_{tbar}	$z_{\tilde{t}bar}$	z_{tbar}	$z_{\tilde{t}bar}$
Redemption Rate	0.10	0.01	-1.79*	-1.20	-7.02***	-4.46***
	[0.54]	[0.50]	[0.04]	[0.11]	[0.00]	[0.00]
Cash Refund	-3.54***	-3.09***	0.91	1.10	-3.53***	-2.78***
	[0.00]	[0.00]	[0.82]	[0.86]	[0.00]	[0.00]
PCPI	0.08	0.05	-0.33	-0.18	-4.93***	-4.01***
	[0.53]	[0.52]	[0.37]	[0.43]	[0.00]	[0.00]
Gasoline Price	0.69	0.59	-1.33*	-1.01	-7.51***	-5.32***
	[0.76]	[0.72]	[0.09]	[0.16]	[0.00]	[0.00]
SC/Population	-0.15	-0.07	1.08	1.12	-4.19***	-3.62***
	[0.44]	[0.47]	[0.86]	[0.87]	[0.00]	[0.00]

*Notes: Numbers reported in brackets, [ ], are p-values. *, **, and *** represent significance at the 10, 5 and 1 percent levels, respectively. $Z_{\tilde{t}bar}$ statistic assumes no serial correlation in the individual errors of the Dickey-Fuller regressions (see Im et al., 2003).*

It is known that in small samples such as this one, the tests do not carry much explanatory power. All variables will be treated as integrated of order 1, denoted I(1). Therefore, before differencing the data, the presence of cointegration will be tested using Pedroni (1999).

2.4.2 Cointegration

Pedroni (1999) cointegration tests with common time dummies were performed for six specifications with and without time trends. Common time dummies were included to account for cross-sectional dependencies by subtracting off sample averages. The regressions performed in Table 2.3 follow the equation

$$y_{i,t} = \alpha_i + \zeta_i t + \beta_{1i} x_{1i,t} + +\beta_{2i} x_{2i,t} + \ldots + \beta_{mi} x_{mi,t} + \varepsilon_{i,t}, \tag{2.8}$$

where t is time [1984, 2010], i is the cross-section [1, 4], and m is the number of regressors varying from 1 to 4. In Table 2.3, seven statistics are reported. The first four statistics (panel) are within-dimesion, and the last 3 statistics (group) are between-dimension. The two types differ in the way the estimators are pooled. Within-dimension "pool the auto-regressive coefficient across different members for the unit root tests on the estimated residuals," while between-dimension "simply average the individually estimated coefficients for each member i" Pedroni (1999).[12] The cointegration tests mostly concludes that the null hypothesis of no cointegration is unable to be rejected. Therefore, the estimation method calls for a first-differenced model.

2.5 Model Specification and Estimation Results

Since all variables have been diagnosed to be I(1) and not to have a cointegrating relationship that makes redemption rates stationary, a first-differenced model needs to be specified. First-differencing eliminates any time or state fixed effects. Time fixed effects could account for national increases in curbside recycling, while state fixed effects could be that particular state's feeling towards "green-ness" or recycling that SC members as a percent of the population does not pick up. The general first-differenced specification is

$$\Delta y_{i,t} = \beta \Delta x_{i,t} + \varepsilon_{i,t}. \tag{2.9}$$

[12]See Table 1 in Pedroni (1999) for specific calculations of within-dimension and between-dimension statistics.

Table 2.3: Pedroni Cointegration Test Results with Common Time Dummies

	(1)		(2)		(3)		(4)		(5)		(6)	
	$\zeta_i = 0$	$\zeta_i \neq 0$	$\zeta_i = 0$	$\zeta_i \neq 0$	$\zeta_i = 0$	$\zeta_i \neq 0$	$\zeta_i = 0$	$\zeta_i \neq 0$	$\zeta_i = 0$	$\zeta_i \neq 0$	$\zeta_i = 0$	$\zeta_i \neq 0$
Panel v	0.87	-0.57	0.32	-0.88	-0.12	-1.24	-0.37	-1.47	0.28	-0.90	0.55	-0.76
Panel ρ	-0.64	0.20	0.12	0.88	0.71	1.51	1.12	1.95	0.14	0.93	-0.10	0.80
Panel pp	-0.78	-0.08	-0.31	0.37	0.19	1.06	0.44	1.46	-0.17	0.61	-0.43	0.25
Panel adf	-1.32*	-0.63	-1.36*	0.20	-1.01	0.87	0.22	1.28	-0.78	0.08	-0.52	0.02
Group ρ	0.43	1.10	1.12	1.71	1.74	2.36	2.12	2.80	1.17	1.80	0.84	1.59
Group pp	-0.13	0.64	0.40	1.01	1.03	1.80	1.23	2.19	0.64	1.38	0.21	0.82
Group adf	-0.88	-0.05	-1.10	0.71	-0.62	1.55	0.85	1.91	-0.35	0.76	0.13	0.76

*Notes: The Pedroni cointegration test is a one-tailed test. All tests are left hand sided tests, with the exception of panel v. Statistics reported are normally distributed; *, **, and *** represent significance at the 10, 5 and 1 percent levels, respectively. Specifications (1) only contain the log of real cash refund as a potential regressor. Specifications (2) include the log of real cash refunds and the log of real per capita personal income (PCPI) as regressors. Specifications (3) are the same as specifications (2), but include the log of real price of gasoline. Specifications (4) include all four potential regressors (i.e. including specifications (3) plus the log of Sierra Club members as a percent of the population). Specification (5) includes the log of real cash refund and the log of real price of gasoline, while specification (6) includes the log of real cash refund and the log of Sierra Club members as a percent of the population.*

Table 2.4 shows the results from the first-differenced estimation with the regressand as the differenced log of redemption rates. Since all variables are in differenced log form, the coefficients are interpreted as percent changes. As expected from the conceptual framework, the cash refund positively affects redemption rates. Increases to the cash refund incentivize households, who were previously indifferent or on the margin about redeeming beverage containers for cash, to now redeem for cash. This is because households on the margin now have marginal benefits that are greater than or equal to the marginal costs associated with redeeming their beverage containers for cash. Note that across all specifications, cash refund is always positive significant and does not change much in magnitude. An increase in the percent change of the cash refund reflects, on average across the specifications shown, a 0.24 percent change increase in redemption rates.

Table 2.4: First-Differenced Estimation: Full Sample - Log Differenced

	(1)	(2)	(3)	(4)	(5)	(6)
Cash Refund	0.24***	0.23***	0.23***	0.24***	0.24***	0.24***
	(27.39)	(15.62)	(13.21)	(10.80)	(16.09)	(14.60)
PCPI		-0.47	-0.41*	-0.32		
		(-1.62)	(-1.69)	(-1.54)		
Gasoline Prices			-0.03	-0.03	-0.05	
			(-0.98)	(-1.19)	(-1.23)	
SC/Population				-0.11**		-0.13*
				(-1.98)		(-1.84)
Degrees of Freedom	84	83	82	81	83	83
Adjusted R^2	0.27	0.32	0.32	0.34	0.28	0.30
AIC	-3.42	-3.48	-3.47	-3.48	-3.43	-3.46
BIC	-3.39	-3.42	-3.38	-3.37	-3.38	-3.40

*Note: Numbers reported in parenthesis, ( ), are t-values. *, **, and *** represent significance at the 10, 5 and 1 percent levels, respectively. All t-values reported are calculated using clustered standard errors.*

Also as expected, PCPI negatively affects redemption rates. If a household's time becomes more valuable, then the opportunity costs of cleaning, sorting, storing, and returning the beverage containers to a recycling center increase, thus making it more costly for a household to redeem for cash. The empirics reflect that a percent change increase in PCPI yields a decrease in the percent change of redemption rates that varies from 0.32 to 0.47. In specification (3), the coefficient on PCPI was significant at the the 10 percent level, while the other two specifications yield borderline significant results.

As for the gasoline price, it is insignificant but with the expected sign. The conceptual framework advocated that rising gasoline costs make redemption for cash more costly, reducing redemption rates. However, an insignificant but correct sign on the coefficient of the real gasoline price suggests that cash recyclers might be returning their beverage containers at retail stores. As mentioned earlier, gasoline prices will be deemed insignificant if households return their beverage containers to retail stores (e.g. grocery stores), because the trip would have been made regardless. Even if this regressor was deemed significant, its magnitude on the percent change in redemption rates would be so small relative to the percent change in PCPI. The results reflect that households are more sensitive to increases in the opportunity costs of recycling, rather than gasoline prices, when deciding to redeem beverage containers for cash. The lower sensitivity of the percent change in real gasoline prices could be from it being more variable than the percent change in PCPI (see Figure 2.3). Recycling behaviors, or even behaviors in general, can be slow to change over time. Therefore, if a decision variable such as the percent change in gasoline prices is not sustained at high levels and fluctuates frequently, then behaviors will not be as quick to change.

The psychological benefit is surprisingly negative significant. While this is an extremely small amount, because the largest ratio of SC members to population is 0.70, it is still negative. It is thought that this negative sign could be explained through CS recycling "can"nibalization from the DR system (see Beatty et al., 2007). As a state's identity becomes more "green", access to CS recycling could increase, reducing the percent redeemed for cash. Mrozek (2000) discusses such a result, where increases to SC members as a percent of a jurisdiction result in increases to the percent of households in that jurisdiction who receive CS service. If increases to SC members as a percent of the population yield higher percentages of the population receiving access to CS, then the negative sign is to be expected for DR

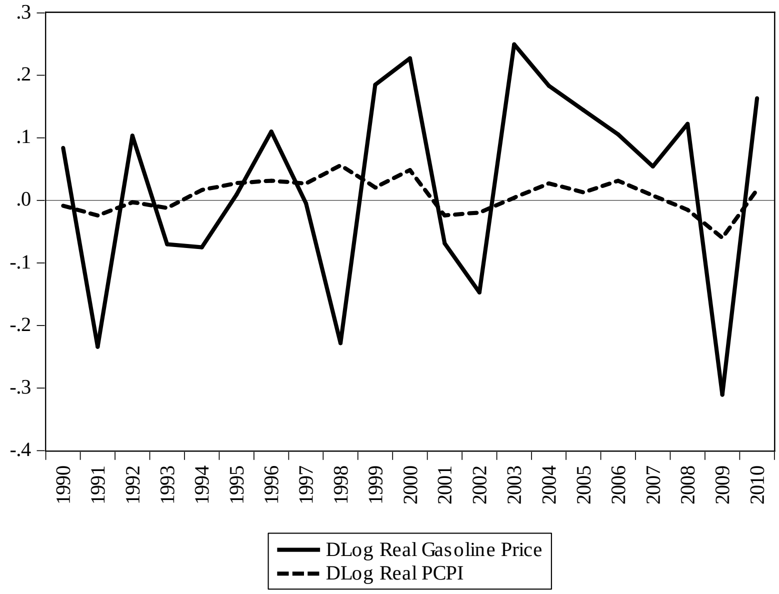

Figure 2.3: California Fluctuations of DLog Real Gasoline Prices and DLog Real PCPI from 1990 to 2010

systems.

Specifically looking at the coefficient magnitudes, the net benefit of redeeming beverage containers for cash over time is negative. The magnitudes of the opportunity cost of recycling (PCPI) and CS recycling access effects via increases in a state's "green" identity clearly outweigh the pecuniary benefits one receives from taking the beverage containers to a recycling center. This reflects the decline in redemption rates from 1990 to 2000. However, since California updated their cash refund over this time period and with percent changes in PCPI falling in 2000 across all four states, it is expected that the net benefit be more negative over the sample period from 1990 to 2000. Table 2.5 shows the same regressions as Table 2.4, but over the sample period from 1990 to 2000.

The significance on cash refunds do not drastically change from the two samples, but the coefficients on PCPI become more negative. Thus, since the magnitude of the coefficients on cash refund does not change significantly, the gap between cash refund, PCPI, and SC members as a percent of the population increases.

Table 2.5: First-Differenced Estimation: Sample 1990 to 2000 - Log Differenced

	(1)	(2)	(3)	(4)	(5)	(6)
Cash Refund	0.24***	0.22***	0.23***	0.24***	0.25***	0.26***
	(27.57)	(19.79)	(13.43)	(15.61)	(16.77)	(16.21)
PCPI		-0.66**	-0.60**	-0.51*		
		(-2.00)	(-2.23)	(-1.78)		
Gasoline Prices			-0.06	-0.06	-0.08	
			(-0.99)	(-0.96)	(-1.11)	
SC/Population				-0.07**		-0.14**
				(-2.48)		(-2.10)
Degrees of Freedom	41	40	39	38	40	40
Adjusted R^2	0.32	0.40	0.41	0.40	0.35	0.35
AIC	-3.17	-3.27	-3.26	-3.23	-3.19	-3.20
BIC	-3.13	-3.18	-3.14	-3.07	-3.10	-3.11

*Note: Numbers reported in parenthesis, ( ), are t-values. *, **, and *** represent significance at the 10, 5 and 1 percent levels, respectively. All t-values reported are calculated using clustered standard errors.*

2.6 Implications for Public Policy

From the previous section, it was found that a one percent change increase in cash refunds correspond to a 0.22 to 0.25 percent change increase in redemption rates. Yet what does this translate to in terms of the quantity of beverage containers that could have been recycled via the DR system if cash refunds had kept pace with inflation?

In order to carry out this calculation, each state's respective implementation year was considered to be the intended cash refund. Real cash refunds decline every year at the rate of inflation until an adjustment to the cash refund is made. For example, Massachusetts implemented their DR system in 1983. The $0.05 in 1983 then declined every year at the rate of inflation, where the $0.05 would be approximately $0.021 in 2010. A state like California however, had an implementation cash refund of $0.01 in 1987. The $0.01 declined at the rate of inflation for 1988 and 1989. Then in 1990, the cash refund was increased to $0.025. The $0.025 declined until 2004, when the cash refund was updated again. Figure 2.4 reflects how California's cash refund changes over time.

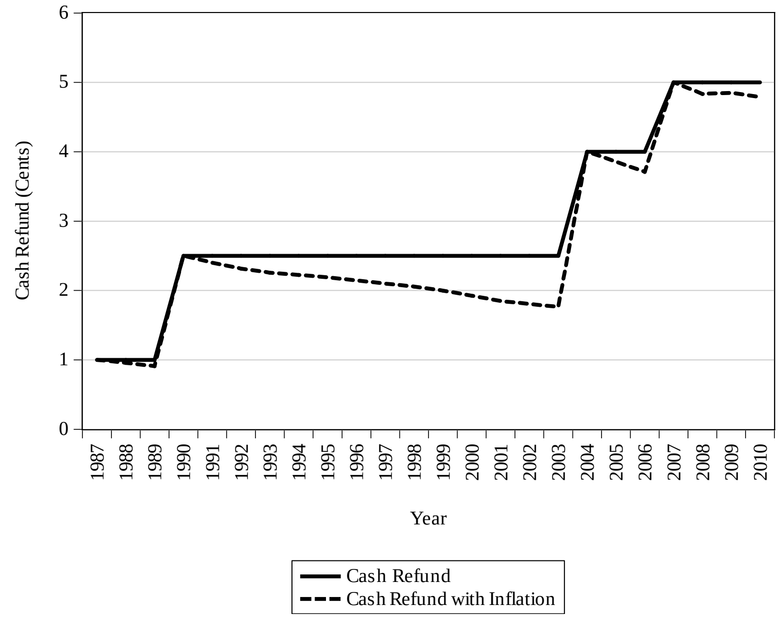

Figure 2.4: California Cash Refund Changes Over Time

Next, the percent increase needed to keep cash refunds at their originally intended value was calculated using the standard growth formula, $g_t = \left(\theta_{t+1}/\theta_t\right) - 1$. This percent increase was multiplied by 0.24 to reflect what the redemption rate would have been if cash refunds had kept pace with inflation. This rate was then multiplied by the quantity of sales to convert the percentage into quantities. Using the proposed returns and subtracting off the original provides the difference in returns or additional beverage containers to be recycled via the DR system.

The actual and proposed redemption rates for California are shown in Figure 2.5. The difference in the redemption rate for California from 1988 to 2010 corresponds to an average of an additional 350 million beverage containers per year that would have been recycled via the DR system if cash refunds had kept up with inflation. Figure 2.5 also reflects how many additional beverage containers per capita would have been recycled via the DR system. Note that in 1990, 2004, and 2007, the difference between the proposed and actual is zero. This reflects implementation dates of an adjustment to the cash refund as the new intended or real values.

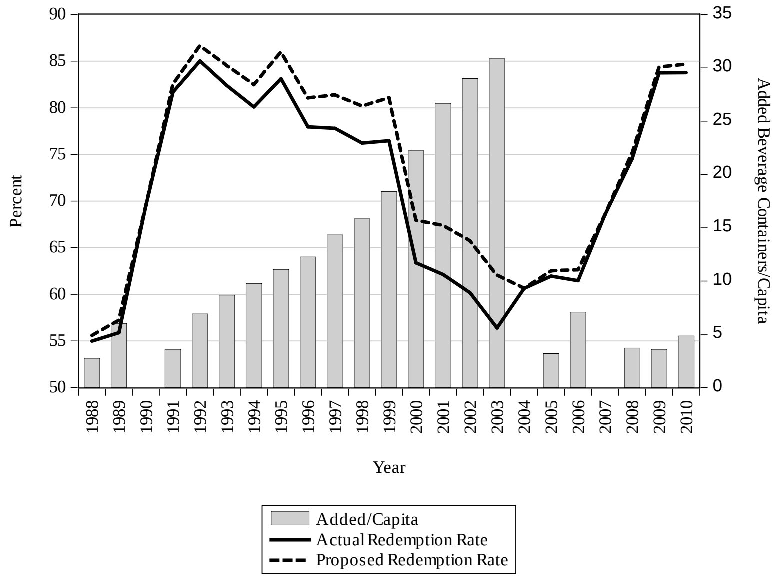

Figure 2.5: California Original Redemption Rates vs. Inflation-Adjusted Redemption Rates with Gained Beverage Containers per Capita

The other states that have not updated their cash refunds since their implementation date simply have diverging actual and proposed redemption rates over time.[13] Table 2.6 shows the average additional returns (or difference in returns) and average beverage containers added per capita per year for each state examined.

Table 2.6: Average Increases in Quantities Recycled via the DR System

	Implementation Date	Time Sample	Avg. Additional Returns	Avg. Additional per Capita
California	1987 : $0.01 1990 : $0.025 2004 : $0.04 2007 : $0.05	1988-2010	350,865,858	10
Massachusetts	1983: $0.05	1990-2010	317,588,849	50
Michigan	1978: $0.10	1990-2010	119,428,571	12
New York	1983: $0.05	1984-2007	634,803,125	34

The average added number of beverage containers recycled via the Massachusetts DR system reaches over 317 million beverage containers per year. Michigan has a relatively

[13]Or until the redemption rate exceeds 100 percent, as in the case of Michigan.

low average added number of beverage containers, because Michigan already has such high redemption rates and the upper limit is bound at 100 percent. However, in one year, Michigan reported a redemption rate greater than 100 percent. Even though \$0.10 holds its value longer than \$0.05, Michigan implemented their DR system in the late 1970s. That \$0.10 in 1978 is only worth \$0.03 by 2010, because of inflation over 32 years. Therefore, to return to the \$0.10, cash refunds must be increased by 226 percent, which results in a 54 percent increase in redemption rates. Again, this value is constrained to 100 percent (with the exception of 1992), so cash refunds need not be increased by 226 percent to achieve a 100 percent redemption rate. Thus every year, Michigan's redemption rate would have reached its maximum limit if the \$0.10 would have kept up with inflation, where the quantity returned via the DR system is equal to the quantity consumed or sold. As for New York, the average quantity improvement is simply sheer volume. For example, New York has a maximum quantity consumed of 6.2 billion beverage containers in a year, while Massachusetts has a maximum of 2.2 billion beverage containers in a year. However, on average per capita, Massachusetts is recorded to have a larger increase in the quantity recycled via the DR system than New York.

2.7 Further Exploration

Pedroni (1999) panel cointegration tests were also performed without common time dummies (see Table 2.7). Excluding common time dummies leaves cross-sectional disturbances as shared (Pedroni, 1999). Note that the presence of cointegration is found across all specifications with the exception of the last specification, which regressed redemption rates on real cash refunds and SC members as a percent of the population. For this specification, exclusion of the time trend made all seven statistics insignificant, yielding no statistical evidence of a cointegrating relationship.

With cointegration present, it is not appropriate to estimate specifications with panel OLS. While panel OLS estimators benefit from properties of super-consistency, they suffer from abnormal distributions which invalidate hypothesis testing. Therefore, specifications

Table 2.7: Pedroni Cointegration Test Results without Common Time Dummies

	(1)		(2)		(3)		(4)		(5)		(6)	
	$\zeta_i = 0$	$\zeta_i \neq 0$	$\zeta_i = 0$	$\zeta_i \neq 0$	$\zeta_i = 0$	$\zeta_i \neq 0$	$\zeta_i = 0$	$\zeta_i \neq 0$	$\zeta_i = 0$	$\zeta_i \neq 0$	$\zeta_i = 0$	$\zeta_i \neq 0$
Panel v	1.44*	0.06	1.55*	0.27	1.20	0.18	0.79	-0.03	1.31*	-0.15	-0.12	0.12
Panel ρ	-1.63*	-0.83	-1.34*	-0.49	-0.42	0.18	-0.22	0.03	-1.01	-0.18	-0.09	-0.81
Panel *pp*	-1.78**	-1.55*	-2.30**	-2.35***	-1.40*	-1.70**	-2.40***	-3.74***	-1.56*	-1.30*	-0.91	-3.13***
Panel *adf*	-1.25	-0.75	-2.79***	-3.01***	-1.46*	-1.27	-3.04***	-2.92***	-0.84	-0.63	-0.62	-1.91**
Group ρ	-0.64	0.11	-0.61	0.25	0.33	0.98	0.64	0.75	-0.07	0.66	0.29	-0.16
Group *pp*	-1.39*	-1.06	-2.21**	-2.04**	-1.14	-1.23	-2.02**	-3.53***	-1.08	-0.80	-1.13	-3.48***
Group *adf*	-0.74	-0.38	-2.50***	-2.49***	-1.01	-0.80	-3.26***	-2.68***	-0.27	-0.46	-1.07	-2.36***

*Notes: The Pedroni cointegration test is a one-tailed test. All tests are left hand sided tests, with the exception of panel v. Statistics reported are normally distributed; *, **, and *** represent significance at the 10, 5 and 1 percent levels, respectively. Specifications (1) only contain the log of real cash refund as a potential regressor. Specifications (2) include the log of real cash refunds and the log of real per capita personal income (PCPI) as regressors. Specifications (3) are the same as specifications (2), but include the log of real price of gasoline. Specifications (4) include all four potential regressors (i.e. including specifications (3) plus the log of Sierra Club members as a percent of the population). Specification (5) includes the log of real cash refund and the log of real price of gasoline, while specification (6) includes the log of real cash refund and the log of Sierra Club members as a percent of the population.*

should then be estimated using panel FMOLS. Panel FMOLS produces asymptotically unbiased estimators, while "produc[ing] nuisance parameter free standard normal distributions." In other words, panel FMOLS provides normal distributions to allow for valid hypothesis testing, which allows for inferences to be made about "common long run relationships." The values reported in Table 2.8 are the group mean or between-dimension estimators, which "provide consistent point estimates of the sample mean of the heterogeneous cointegrating vectors" (Pedroni, 2001).

Table 2.8: Panel FMOLS Estimation - Log Levels

	(1)	(2)	(3)	(4)	(5)	(6)
Cash Refund	0.25***	0.15*	0.17**	0.12**	0.33***	0.15***
	(6.94)	(1.68)	(2.38)	(2.29)	(7.75)	(4.55)
PCPI		-0.64***	-0.48***	-0.45***		
		(-5.71)	(-3.53)	(-5.84)		
Gasoline Price			-0.03	-0.06**	-0.07	
			(-0.23)	(2.00)	(-0.48)	
SC/Population				-0.27***		-0.11***
				(-7.44)		(-3.31)

*Note: Numbers reported in parenthesis, ( ), are t-values. *, **, and *** represent significance at the 10, 5 and 1 percent levels, respectively.*

Since values are reported in logs, the coefficients can now be interpreted as long run elasticities. Notice that in specification (1), the magnitude and significance of the percent change of cash refund is similar to that of what was observed in the first-differenced model specifications. However, cumulatively adding PCPI, gasoline price, and SC members as a percent of the population in specifications (2) through (4) reduces the explanatory power and magnitudes that cash refunds have on redemption rates. Furthermore, the significance and sign of PCPI and SC members as a percent of the population remains the same, where the long run PCPI elasticity of redemption rates ranges from 0.45 to 0.64. In addition, the real gasoline price elasticity is negative and significant at the 5 percent level. It reflects that explicit transportation costs do sometimes matter to households when deciding to redeem beverage containers for cash. In this case, the household would be expected to make a “special” trip to a recycling center instead of a “not special” trip to a grocery store.

In specification (5), the long run cash refund elasticity is more elastic compared to specification (1). Lastly, in specification (4), the long run cash refund elasticity is more inelastic compared to the other specifications containing cash refunds. Also, the coefficient on SC members as a percent of the population is -0.27. From the earlier section, the negative sign on SC members as a percent of the population can be interpreted as a state's increased “greenness”, which induces CS recycling and “can”nibalizes from the DR system (see Mrozek, 2000; Beatty et al., 2007).

2.8 Concluding Remarks

Over the last few decades, landfill space has received growing attention due to an ever increasing population. To mitigate landfill space issues as well as to conserve natural resources (e.g. aluminum in cans and oil in plastic bottles), recycling has gained increased attention. Studies have shown both theoretically and empirically that DR systems are similar to a Pigouvian tax without the drawback of promoting illegal disposal, while generating high levels of recycling (see Palmer & Walls, 1997; Palmer et al., 1997; BEAR, 2002; Ashenmiller, 2009).

This study found that real cash refunds positively influence redemption rates, while real opportunity costs of recycling negatively impact redemption rates. Real PCPI, or equivalently the real opportunity costs of recycling, significantly outweigh the positive pecuniary benefits of real cash refunds. Percent changes in the real cash refund increase percent changes in redemption rates on average by 0.24, while percent changes in real PCPI decrease percent changes in redemption rates between 0.32 and 0.47.

In addition, this chapter showed that adjusting cash refunds for inflation can on average result in an additional hundreds of millions of beverage containers recycled via the DR system annually. Therefore, by using a panel data set, analysis not only demonstrates that cash refunds positively influence recycling behavior, but that temporal cash refunds matter.

Future research for this chapter could extend this model to include population served by CS in order to confirm the findings of Beatty et al. (2007), and the negative impact of SC members as a percent of the population on DR systems. Also, this model does not take into account income distribution effects such as lower income households contributing more to DR systems than higher income households (see Ashenmiller, 2009). Finally, it would be beneficial to explore the various beverage container command and control policies across the U.S. to examine how these approaches impact redemption or recycling rates.

CHAPTER 3

EFFECTS OF GROWING WAGES ON A HOUSEHOLD'S RECYCLING METHOD DECISION

Co-authors: Harrison G. Fell and Daniel T. Kaffine

In the U.S., states with DR systems also provide the option of CS recycling. The two recycling methods have been noted to work as complementary programs to maximize municipal recycling rates. However at the household, they are deemed substitutes, albeit not perfect ones. The goal of this chapter is to first illustrate how households choose to recycle when wages are growing, either recycling via the DR system or via the CS recycling program when there is no consideration for available landfill space. Recycling via the DR system adds to the household's labor income by providing a cash refund per unit recycled. CS recycling programs do not offer such a monetary incentive. Instead, they offer convenience to households by picking up recyclables at the household's place of residence. It is hypothesized that if a household starts below some wage threshold, the household will recycle more via the DR system to supplement its total income.

The second goal of this chapter is to use the private utility maximizing actions of the household as inputs to the regulator's social welfare maximizing problem. The regulator maximizes social welfare by subsidizing each recycling method to account for the fixed stock of available landfill space. Recycling subsidies come in the forms of either increasing the cash refund per unit recycled, or by decreasing the per unit time it takes the household to CS recycle. For the purposes of this chapter, the household receives utility from both methods of recycling, which can result in the regulator allocating the majority of its budget from subsidizing one method of recycling to another.

3.1 Overview

Offering cash refunds to provide an incentive for households to recycle beverage containers, known as DR systems or bottle bills, is a method currently found in 23 countries and 10 U.S. states to preserve scare resources, reduce energy consumption, and reduce the amount of waste going to landfills. While U.S. landfill space may not seem to be an issue, landfill scarcity does arise with the combination of a growing population (EPA, 2013), residents having a "not in my backyard" mentality, and possible soil and groundwater contamination - rendering the process of establishing a landfill site quite difficult (Keeler & Renkow, 1994). To slow depletion of natural resources and landfill sites, DR states have adopted complementary recycling policies such as CS recycling programs to achieve higher recycling rates by targeting different demographics of the population. DR systems are generally thought to target lower income households by offering cash refunds to supplement total household income. CS recycling programs offer a more convenient method of recycling, which is generally more attractive to higher income households, because the opportunity cost of not supplying labor is higher for those with higher wages (see footnote 5).

The purpose of this chapter is two-fold. First, how does household recycling behavior change over time given an exogenous wage growth and no consideration of landfill space? Second, based on the municipality's average household wage, solid waste budget, and amount of landfill space available, should the municipality increase the per unit cash refund the DR system pays out, or make CS recycling more convenient by reducing the per unit time it takes to recycle?

DR systems attempt to internalize the marginal social damage of waste disposal by imposing a per unit consumption tax on beverage containers (Pigou, 1920). However, the tax is only realized by households who do not return the beverage container via the DR system. In other words, there is a net zero gain if a household recycles all of its consumption via the DR system.[14] DR systems have been noted to be better than a Pigouvian tax, because Pigouvian taxes not only have monitoring and enforcement issues, but tax evasion is more of a problem with Pigouvian taxes than with DR systems (Walls, 2011).

Additionally, DR systems have been proven both theoretically and empirically to generate additional benefits, as well as high recycling rates compared to other recycling policies. For example, states with these systems have been noted to have recycling rates in upwards of 2.5 times more than states without such systems (BEAR, 2002). DR systems are also more cost effective than other recycling policies (e.g. advance disposal fees and recycling subsidies), and provide the additional benefit of reducing the incentive for consumers to illegally dump waste (see Palmer & Walls, 1997; Ashenmiller, 2009; Acuff & Kaffine, 2013). Ashenmiller (2010) showed that DR systems also provide the benefit of reducing crime rates, because poor labor market options may increase the incentive for those with such little options to commit property crime.

Ashenmiller (2009) used surveys to empirically show that lower income households contribute the majority of beverage containers to the DR system. Batson & Eggert (2012) (i.e. chapter 2) used a panel of 4 U.S. states to illustrate how higher household income results in higher opportunity costs of recycling, which provides less incentive to make a "special" trip to a recycling center. They also showed that cash refunds are less effective over time due to inflation.

Most states with DR systems have yet to increase their cash refunds since their respective dates of implementation - most being implemented in the 1970s and 1980s.[15] Figure 3.1 contains data from 33 counties in California from 2000 to 2008, and shows how the percentage mix of recycling method changes as household income increases, where household income increases over time. Shares are calculated as $DR\,share = DR/\big(DR + CS\big)$ and $CS\,share = 1 - DR\,share$. Note that as median household income increases, less is recycled via the DR

[14]Net zero is strictly in terms of monetary value paid and refunded. This does not account for travel or opportunity costs.

[15]California is the only state that has increased its cash refund since its date of implementation, increasing it three times since 1987 (CRI, 2013).

system (i.e. more is recycled via the CS program).[16]

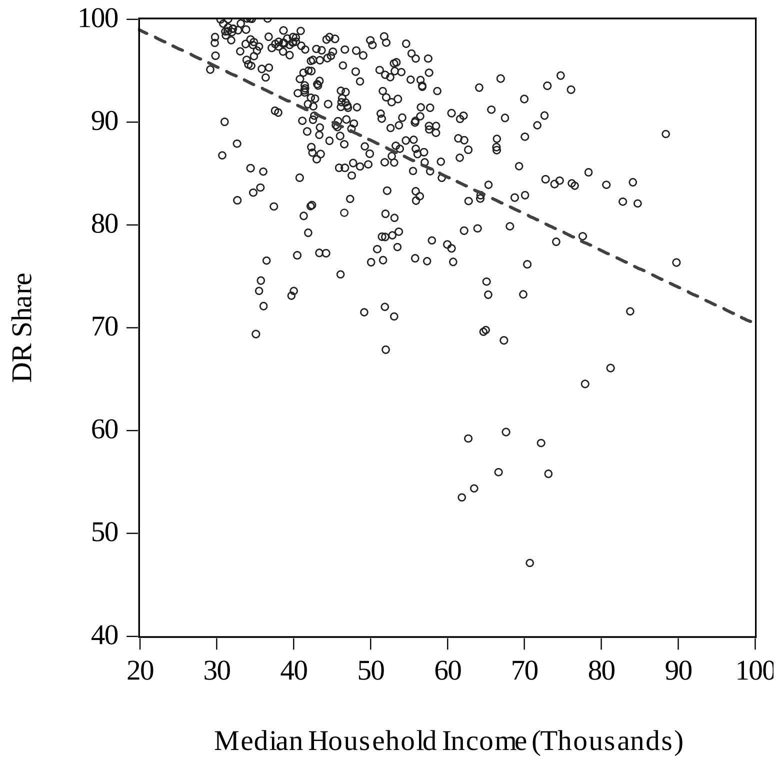

Figure 3.1: Recycling Method Shares Over Median Household Income

With DR systems providing an incentive only for a portion of the population, CS recycling programs have been implemented to complement these programs by offering a more convenient recycling alternative to households in order to achieve high recycling rates. CS recycling programs have gained tremendous popularity over the last two decades, growing from 2,711 programs in 1990 to 9,066 programs in 2012 and serving 71 percent of the population (CRI, 2013; EPA, 2014). Mrozek (2000) showed that "landfill opportunity costs, mandates from higher levels of government, citizen preferences for recycling, and transfers of rents to special interests" increase the probability that a CS recycling program will be adopted. Additionally, CS recycling programs have a higher probability of being adopted in municipalities with regional tipping fees (Kinnaman & Fullerton, 2000). However, it is not to go

[16]This is not an absolute measure of how DR systems interact with household income, as there may be spacial and community attitude variations across counties.

unsaid that while DR systems and CS recycling programs at the aggregate level serve as complementary systems, the two methods do compete for the same goal of increased recycling, as each method has been thought to overstate their respective benefits by "can"nibalizing from the alternative recycling method (i.e. recycling beverage containers that would have been recycled anyway) (see Beatty et al., 2007; Kinnaman & Fullerton, 2000). Furthermore, Kinnaman (2006) noted that CS recycling programs are not beneficial for all municipalities, based on the benefits they provide and their associated operating costs.

States with both types of recycling methods implemented have attempted to increase recycling rates by both increasing cash refunds and access to CS recycling. Increasing cash refunds will increase recycling quantities in the DR system, but may take beverage containers away from CS recycling programs by making the "special" trip now economical for households that were on the margin to recycle for cash. Increasing CS recycling access can in turn do the opposite by offering a more convenient method of recycling to households that receive utility from recycling, but previously only had the option of recycling via the DR system.

Studies have determined optimal levels of recycling and landfill rates over time given a fixed amount of landfill space (see Huhtala, 1997; Highfill & McAsey, 2001), and how recycling technologies impact both the short and long run sustainability of natural resources (see Hoel, 1978; Andre & Cerda, 2006). More specifically, Highfill & McAsey (2001) showed that the municipality will initially landfill most of all of its waste generated, because recycling is considered to be a backstop waste technology. Eventually over time recycling becomes economical because the shadow price on landfill space grows at the discount rate, and the municipality's income increases exogenously over time, allowing it to afford the more expensive waste technology. Andre & Cerda (2004) expanded the fixed amount of landfill space by developing a model to investigate "the optimal capacity and lifetime of landfills [while] taking into account their sequential nature."

Studies have looked more at the dynamics of recycling on resource extraction. Hoel (1978) examined how recycling can in some cases be considered a substitute to resource extraction. He also incorporated the accumulation of harmful residuals (both from extraction and recycling) to explain that physical depletion is not always optimal, because of these negative environmental effects. Andre & Cerda (2006) suggest that recycling is only a short run solution to non-renewable resource depletion due to the possibility of non-decreasing output paths.

This chapter differs from the previous studies mentioned by disaggregating recycling quantities into the two methods discussed earlier, and allowing for the regulator to choose how much of each recycling method to subsidize in order to internalize the scarcity of available landfill space based on a household's private optimal choices. It however, does not account for landfill expansion or recycling's direct effects on non-renewable resources (e.g. bauxite mines). This chapter is organized as follows. In section 3.2, the household and regulator models are introduced using a specific functional form. Next, section 3.3 describes the methodology used to numerically solve the model. In section 3.4, the simulated model results are then presented, including various scenarios. Finally, this chapter concludes with implications for public policy and provides suggestions for future research in section 3.5.

3.2 The Model

The model for this chapter builds on Highfill & McAsey (2001), which showed how municipalities change their method of disposal over time when income grows exogenously, and when faced with a fixed amount of landfill space. In contrast to what Highfill & McAsey (2001) did with their theory of recycling implementation into a municipality, the goal of this paper is again to identify what mix of recycling methods a household chooses under exogenously growing wages, either via the DR system or CS recycling program, and present various scenarios of how the regulator should subsidize each recycling method to account for a fixed amount of landfill space, given the private optimal actions of the household and its own exogenously growing budget.

3.2.1 Household Utility Maximization Problem

Consider a representative household that receives utility from consumption c_t, leisure ℓ_t, CS recycling b_t, and DR recycling d_t. The household is assumed to have a diminishing marginal utility of recycling, and a non-constant marginal rate of substitution to avoid any bang-bang solutions that might arise when b_t and d_t are treated as perfect substitutes. To allow for flexibility and varying subsistence levels of the choice variables, a constant returns to scale Stone-Geary utility function is employed. Therefore, the household utility function is

$$U_t = \alpha ln\big[c_t - \sigma_c\big] + \beta ln\big[\ell_t - \sigma_\ell\big] + \phi ln\big[b_t - \sigma_b\big] + \xi ln\big[d_t - \sigma_d\big], \tag{3.1}$$

where $\xi = \big(1 - \alpha - \beta - \phi\big)$ and σ_c, σ_ℓ, σ_b, and σ_d are the respective subsistence levels of consumption, leisure, CS recycling, and DR recycling.[17]

Suppose the household earns a total income which is solely spent on consumption c_t. Total household income is derived from both labor income and recycling income. Labor income is $w_t n_t$, where $w_t = w_0\big(1+\kappa_w\big)^t$ is the exogenous household wage that grows at some fixed rate κ_w, and n_t is the level of labor supplied by the household. Recycling income is $\theta_t d_t$, where θ_t is the per unit net cash refund received for recycling via the DR system, and d_t is the quantity recycled via the DR system. The per unit net cash refund is the cash refund less the per unit costs of transporting the waste to a recycling center, which will henceforth be referred to as cash refund.[18] It is assumed $\theta_t \geq 0$, as any value less than zero would simply yield the rational household to not recycle via the DR system. The household's budget constraint is

$$c_t = w_t n_t + \theta_t d_t. \tag{3.2}$$

[17]For simplicity, it is assumed that all consumption is waste generating. In Highfill & McAsey (2001) this would be reflected by $\alpha = 1$. It is also assumed that the household does not incur a per unit cost of curbside, because volume-based collections are noted to be extremely rare (Jenkins, 1993).

[18]Batson & Eggert (2012) (i.e. chapter 2) built per unit costs of transportation into the conceptual framework to reflect how increasing transportation costs affect redemption rates (the quantity recycled via the DR system divided by the quantity consumed).

The household is also faced with a time constraint, where time can be spent on recycling, supplying labor, or leisure activities. Recycling both via the DR system and CS recycling programs are both assumed to have a linear per unit time cost of cleaning and sorting. However, recycling via the DR system requires additional time for the household to sort and return the beverage containers to a recycling center. Therefore, the time to recycle via the DR system δ is greater than the time to recycle via the CS recycling program γ_t.[19] The household's time constraint is then

$$h = n_t + \ell_t + \gamma_t b_t + \delta d_t. \tag{3.3}$$

In reality, households do not consider the landfill size when making the decision to recycle, which is why a landfill state equation is not included in the household's utility maximization problem. Without a known and realized state equation by the household, the representative household's utility maximization problem can be solved using a static framework. The household's utility maximization problem is

$$\max_{c_t, \ell_t, b_t, d_t} U_t = \alpha ln\big[c_t - \sigma_c\big] + \beta ln\big[\ell_t - \sigma_\ell\big] + \phi ln\big[b_t - \sigma_b\big] + \xi ln\big[d_t - \sigma_d\big] \tag{3.4}$$

subject to (3.2) and (3.3). With (3.2) holding with equality, one can reduce the household's maximization problem to three choice variables by solving for n_t from (3.3) and plugging it into (3.2), yielding $c_t = w_t\big(h - \ell_t - \gamma_t b_t - \delta d_t\big) + \theta_t d_t$. This reduces the maximization to solve for ℓ_t, b_t, and d_t. The first order conditions are as follows.

$$\frac{\partial U_t}{\partial \ell_t} = \frac{\beta}{\ell_t - \sigma_\ell} + \frac{\alpha w_t}{\sigma_c - d\theta_t + \big(\delta d_t + b_t\gamma_t + \ell_t - h\big)w_t} \leq 0 \qquad \ell_t \geq 0 \qquad \frac{\partial U_t}{\partial \ell_t}\ell_t = 0$$

$$\frac{\partial U_t}{\partial b_t} = \frac{\phi}{b_t - \sigma_b} + \frac{\alpha \gamma_t w_t}{\sigma_c - d\theta_t + \big(\delta d_t + b_t\gamma_t + \ell_t - h\big)w_t} \leq 0 \qquad b_t \geq 0 \qquad \frac{\partial U_t}{\partial b_t}b_t = 0$$

$$\frac{\partial U_t}{\partial d_t} = \frac{-\xi}{d_t - \sigma_d} + \frac{\alpha\big(\theta_t - \delta w_t\big)}{\sigma_c - d\theta_t + \big(\delta d_t + b_t\gamma_t + \ell_t - h\big)w_t} \leq 0 \qquad d_t \geq 0 \qquad \frac{\partial U_t}{\partial d_t}d_t = 0$$

[19] If the regulator subsidized grocery stores, or other convenient DR recycling centers where the household would make the trip regardless, then it is possible for $\delta = \gamma_t$

Solving the choice variables through the first order conditions result in the following optimal household choice variables.

$$c_t^* = \sigma_c - \alpha\sigma_c + \alpha\sigma_d\theta_t - \alpha\big(\sigma_\ell + \sigma_d\delta + \sigma_b\gamma_t - h\big)w_t \tag{3.5}$$

$$\ell_t^* = \frac{\sigma_\ell w_t - \beta\big(\sigma_c - \sigma_d\theta_t + \big(\sigma_\ell + \sigma_d\delta + \sigma_b\gamma_t - h\big)w_t\big)}{w_t} \tag{3.6}$$

$$b_t^* = \frac{\sigma_b\gamma_t w_t - \phi\big(\sigma_c - \sigma_d\theta_t + \big(\sigma_\ell + \sigma_d\delta + \sigma_b\gamma_t - h\big)w_t\big)}{\gamma_t w_t} \tag{3.7}$$

$$\begin{aligned} d_t^* = &\frac{1}{\theta_t - \delta w_t}\Bigg(\sigma_c\xi + \sigma_d\big(\alpha + \beta + \phi\big)\theta_t + \sigma_\ell w_t - \big(-\sigma_b\gamma_t + h + \dots \\ &\big(\sigma_\ell + \sigma_d\delta + \sigma_b\gamma_t - h\big)\big(\alpha + \beta + \phi\big)\big)w_t\Bigg) \end{aligned} \tag{3.8}$$

$$n_t^* = h - \ell_t^* - \gamma_t b_t^* - \delta d_t^* \tag{3.9}$$

Under the Stone-Geary utility function, the comparative "statics" with respect to wages can be quite ambiguous.

$$\frac{\partial c_t^*}{\partial w_t} = -\alpha\big(\sigma_\ell + \sigma_d\theta_t + \sigma_b\gamma_t - h\big)$$

$$\frac{\partial \ell_t^*}{\partial w_t} = \frac{\beta\big(\sigma_c - \sigma_d\theta_t\big)}{w_t^2}$$

$$\frac{\partial b_t^*}{\partial w_t} = \frac{\phi\big(\sigma_c - \sigma_d\theta_t\big)}{\gamma_t w_t^2}$$

$$\frac{\partial d_t^*}{\partial w_t} = \frac{\xi\big(\sigma_c\delta + \big(\sigma_\ell + \sigma_b\gamma_t - h\big)\theta_t\big)}{\big(\theta_t - \delta w_t\big)^2}$$

All choice variable movements can either be increasing or decreasing in w_t, depending on the size of the subsistence parameters. Consumption will increase with wages as long as the time spent in a given period h exceeds $\sigma_\ell + \sigma_d\theta_t + \sigma_b\gamma_t$. A similar formulation holds true for DR quantities. It is different in the sense that as wages increase, DR quantities are not dependent on their own subsistence level. These quantities will decrease as long as the time spent in a given period h exceeds $\sigma_\ell + \sigma_b\gamma_t$. It seems to be more likely that $h < \sigma_\ell + \sigma_b\gamma_t$, because $0 \leq \ell_t \leq h \Rightarrow 0 \leq \sigma_\ell \leq h$ and $0 \leq \gamma_t \leq h$, where γ_t is expected to be closer to its lower bound. CS recycling and leisure changes with respect to wages depend on $\sigma_c \lesseqgtr \sigma_d\theta_t$. If the subsistence level on consumption exceeds the product of the subsistence level on DR quantities and the cash refund, then both CS recycling quantities and leisure increase in wages.

This ambiguity goes away when subsistence levels go to zero and the utility function reduces to a Cobb-Douglas utility function. Note that under this scenario, consumption is ever increasing with exogenously growing wages and no consideration of landfill space. Increasing wages result in the opportunity cost of not working to increase, causing the time spent supplying labor to increase, which directly and positively affects consumption. Since θ_t and γ_t are set by the regulator and exogenous to the household, CS recycling quantities and leisure are unaffected by wages under this scenario. Provided a constant returns to scale utility function and h normalized to 1, leisure is solely dependent on its share of utility, while CS recycling quantities are dependent on the ratio of its share of utility to the per unit time it takes to CS recycle. Increases to this ratio increase the amount recycled via the CS recycling program. In other words, there will be more recycling via the CS recycling program as the household receives more utility from CS recycling relative to the per unit time it takes to CS recycle.

Furthermore, under the Cobb-Douglas scenario, where CS recycling quantities and leisure are constant, the household faces a DR recycling-labor tradeoff over time, where $\partial d_t^*/\partial w_t < 0$ and $\partial n_t^*/\partial w_t > 0$. This essentially states that households incur an opportunity cost of not working as time progresses and wages rise. It is also important to note that increasing the cash refund will yield more to be recycled via the DR system. The next section uses the private optimal values from the household as inputs to the regulator's problem.

3.2.2 Regulator's Social Welfare Maximization Problem

Now consider a regulator who wishes to maximize social welfare derived from the representative household over an infinite-horizon, given a fixed amount of landfill space. Using (3.5) to (3.9), the utility U_t enjoyed by the household in period t becomes

$$\begin{aligned} U_t = &\alpha ln\big[c_t^* - \sigma_c\big] + \beta ln\big[\ell_t^* - \sigma_\ell\big] + \phi ln\big[b_t^* - \sigma_b\big] + \xi ln\big[d_t^* - \sigma_d\big] + \dots \\ &\psi\Big(g_t - \theta_t d_t^* - \frac{\upsilon}{\gamma_t}\Big). \end{aligned} \tag{3.10}$$

Similar to what the household experiences with wages, the regulator has its own exogenously growing income $g_t = g_0\big(1+\kappa_g\big)^t$, where κ_g is the fixed rate at which regulator income grows. It is assumed that regulator income can only be spent on increasing the cash refund a household receives for recycling via the DR system and/or reducing the time it takes the household to CS recycle. The cost of subsidizing the DR system is a strict payout to the households a value of the cash refund θ_t times the quantity the household recycles via the DR system d_t^*. The cost of subsidizing the CS recycling program is a function where the regulator incurs more cost by decreasing the per unit time it takes the household to CS recycle. For example, the CS recycling subsidy could come in the form of the regulator taking on the burden of cleaning and/or sorting the households recyclables.[20] More specifically,

$$g_t \geq \theta_t d_t^* + \frac{\upsilon}{\gamma_t}. \tag{3.11}$$

Even though there is no saving built into this model, the regulator's budget is allowed to be greater than or equal to the amount it spends on subsidizing recycling programs to allow for flexibility in the numerical solution. The regulator also gains utility from not spending all of its income at some rate ψ, which can be thought of as a bonus to the solid waste group

[20]The CS recycling subsidy assumption is similar to what Berglund (2006) examined, where higher income households, who generally have higher opportunity costs, have a higher willingness to pay to let someone else sort their waste.

of the government for promoting recycling and coming under budget at the end of a period.

The regulator provides subsidies based on the household's optimal private actions, its own budget, and the initial size of available landfill space. Available landfill space declines at the rate of consumption less what is recycled.

$$s_{t+1} = s_t - \left(c_t^* - b_t^* - d_t^*\right) \tag{3.12}$$

The state equation, (3.12), is used to solve for γ_t in terms of θ_t, all known model parameters and state transitions. The amount recycled is not to exceed consumption, and the amount dumped in the landfill cannot exceed the available landfill space.

$$0 \leq c_t^* - b_t^* - d_t^* \leq s_t \tag{3.13}$$

Also, a maximum cash refund subsidy $\overline{\theta}_t$ is imposed to prevent any negative values of labor or leisure from arising in the numerical solution. For simplicity, assume $\sigma_b = \sigma_d = 0$, such that their Engel curves pass through the origin. This will reduce (3.8) and (3.9) to the following two equations.

$$d_t^* = \frac{\xi\left(\sigma_c + \left(-h + \sigma_\ell\right)w_t\right)}{-\theta_t + \delta w_t}$$

$$n_t^* = \frac{1}{w_t\left(-\theta_t + \delta w_t\right)}\Big(-(\beta+\phi)\sigma_c\theta_t + \left(\delta\left(\sigma_c - \alpha\sigma_c\right) + \ldots \right.$$
$$\left.\left(-1+\beta+\phi\right)\left(h-\sigma_\ell\right)\theta_t\right)w_t + \alpha\delta\left(h-\sigma_\ell\right)w_t^2\Big)$$

Now only DR recycling and labor are functions of θ_t. The maximum cash refund subsidy is then solved for by setting $n_t^* = 0$ and solving for θ_t in terms of all known model parameters.

$$\overline{\theta}_t = \frac{-\left(\delta w_t\left(\sigma_c - \alpha\sigma_c + \alpha\left(h - \sigma_\ell\right)w_t\right)\right)}{\left(-h + \sigma_\ell\right)w_t - \phi\left(\sigma_c - hw_t + \sigma_\ell w_t\right) - \beta\left(\sigma_c + \left(-h + \sigma_\ell\right)w_t\right)} \tag{3.14}$$

There is also a minimum level on the per unit time CS recycling $\underline{\gamma_t}$. It is derived from (3.11) and equal to υ/g_t. The same approach can be done for scenarios where the subsistence levels on CS recycling and DR recycling are non-zero. The assumption made here simply makes for an easier calculation, and essentially states that households do not have to recycle a minimum amount to receive utility. The regulator's maximization problem is given as

$$\max_{\gamma_t,\,\theta_t} \sum_{t=0}^{T} \alpha ln\big[c_t^* - \sigma_c\big] + \beta ln\big[\ell_t^* - \sigma_\ell\big] + \phi ln\big[b_t^* - \sigma_b\big] + \xi ln\big[d_t^* - \sigma_d\big] + \dots$$

$$\psi\Big(g_t - \theta_t d_t^* - \frac{\upsilon}{\gamma_t}\Big) + \sum_{t=T+1}^{\infty} \Phi_t \tag{3.15}$$

subject to

$$\underline{\gamma_t} \leq \gamma_t \tag{3.16}$$

$$0 \leq \theta_t \leq \overline{\theta}_t \tag{3.17}$$

$$\theta_t d_t^* + \frac{\upsilon}{\gamma_t} \leq g_t \tag{3.18}$$

$$0 \leq s_t \leq \bar{s}. \tag{3.19}$$

Post-depletion T, the household receives the terminal discounted utility of $\sum_{t=T+1}^{\infty} \Phi_t$, where $c_{T+1} = b_{T+1} + d_{T+1}$. In other words, post-depletion, all consumption must be recycled, either via the CS recycling program, the DR system, or some combination of the two.

The regulator's problem can thus be characterized by an infinite-horizon recursive Bellman equation whose value function $V_t(s_t)$ specifies the maximum present value of household utility from time period t forward, discounted at the per period factor ρ, and given the amount of available landfill space at the beginning of the period $s_0 = \bar{s}$. Specifically,

$$V_t(s_t) = \max_{\gamma_t,\,\theta_t} \Bigg\{ \alpha ln\big[c_t^* - \sigma_c\big] + \beta ln\big[\ell_t^* - \sigma_\ell\big] + \phi ln\big[b_t^* - \sigma_b\big] + \xi ln\big[d_t^* - \sigma_d\big] + \dots$$

$$\psi\Big(g_t - \theta_t d_t^* - \frac{\upsilon}{\gamma_t}\Big) + \rho V_{t+1}(s_{t+1}) + \lambda_{1t}(\overline{\theta}_t - \theta_t) + \lambda_{2t}(\gamma_t - \underline{\gamma_t}) + \Phi_{T+1} \Bigg\} \tag{3.20}$$

subject to (3.5) through (3.9), and the terminal condition $c_{T+1} = b_{T+1} + d_{T+1}$. The function Φ_{T+1} is interpreted as the terminal discounted utility that households receive post-depletion and is equivalent to the continuous time expression $\Phi_{T+1} = (1/r)e^{-r(T+1)}U_{T+1}(\gamma_{T+1},\, \theta_{T+1})$, where r is the discount rate.[21] See Appendix A.1 for the maximization setup and first order conditions of the post-depletion portion of the model. The first order conditions for the pre-depletion maximization portion are

$$\begin{aligned}\frac{\partial V_t}{\partial \gamma_t} =& \frac{\alpha \partial c_t^*/\partial \gamma_t}{-\sigma_c + c_t^*} + \frac{\beta \partial \ell_t^*/\partial \gamma_t}{-\sigma_\ell + \ell_t^*} + \frac{\phi \partial b_t^*/\partial \gamma_t}{-\sigma_b + b_t^*} + \frac{\xi \partial d_t^*/\partial \gamma_t}{-\sigma_d + d_t^*} + \dots \\ & \psi\left(\frac{\upsilon}{\gamma_t^2} - \theta_t \frac{\partial d_t^*}{\partial \gamma_t}\right) + \rho \frac{\partial V_{t+1}}{\partial s_{t+1}}\left(-\frac{\partial c_t^*}{\partial \gamma_t} + \frac{\partial b_t^*}{\partial \gamma_t} + \frac{\partial d_t^*}{\partial \gamma_t}\right) + \lambda_{2t} = 0\,,\end{aligned} \tag{3.21}$$

and

$$\begin{aligned}\frac{\partial V_t}{\partial \theta_t} =& \frac{\alpha \partial c_t^*/\partial \theta_t}{-\sigma_c + c_t^*} + \frac{\beta \partial \ell_t^*/\partial \theta_t}{-\sigma_\ell + \ell_t^*} + \frac{\phi \partial b_t^*/\partial \theta_t}{-\sigma_b + b_t^*} + \frac{\xi \partial d_t^*/\partial \theta_t}{-\sigma_d + d_t^*} + \dots \\ & \psi\left(d_t^* + \theta_t \frac{\partial d_t^*}{\partial \theta_t}\right) + \rho \frac{\partial V_{t+1}}{\partial s_{t+1}}\left(-\frac{\partial c_t^*}{\partial \theta_t} + \frac{\partial b_t^*}{\partial \theta_t} + \frac{\partial d_t^*}{\partial \theta_t}\right) - \lambda_{1t} = 0\,,\end{aligned} \tag{3.22}$$

with the envelope condition

$$\frac{\partial V_t}{\partial s_t} = \rho \frac{\partial V_{t+1}}{\partial s_{t+1}}. \tag{3.23}$$

With ρ being the discount factor, it is shown that from (3.23) the shadow price on the landfill rises at the rate of interest. The conditions $\gamma_t = \Gamma(\theta_t)$ and $\theta_t = \Theta(\gamma_t)$ are derived from (3.21) and (3.22). However, this problem cannot be solved analytically unless it is assumed that $\sigma_b = \sigma_d = 0$. Under this assumption, the following conditions are derived.

$$\gamma_t = \frac{-\xi \phi w_t \pm \sqrt{\varrho(\theta_t,\, \lambda_{1t},\, \lambda_{2t},\, w_t)}}{-\xi 2 \lambda_{2t} w_t} \tag{3.24}$$

$$\theta_t = \frac{-\xi}{2\lambda_{1t}} + \delta w_t \pm \frac{\varphi(\gamma_t,\, \lambda_{1t},\, \lambda_{2t},\, w_t)}{2\lambda_{1t}\sqrt{\phi}} \tag{3.25}$$

Using these conditions with (3.23) yields the Euler equations $\gamma_t = \Gamma(\gamma_{t+1})$ and $\theta_t = \Theta(\theta_{t+1})$.

[21] Oren & Powell (1985) use this expression to add the discounted utility received when production switches from a depletable non-renewable resource to a renewable backstop.

$$\theta_t = \delta w_t + \frac{1}{2\lambda_{1t}}\left(-\xi \pm \frac{\sqrt{\nu\big(\theta_{t+1},\, w_{t+1},\, \lambda_{1,t+1},\, w_t,\, \lambda_{1t}\big)}}{\big(\sigma_c + \big(-h+\sigma_\ell\big)w_{t+1}\big)} \right) \tag{3.26}$$

$$\gamma_t = \frac{\phi \pm \sqrt{\iota\big(\gamma_{t+1},\, w_{t+1},\, \lambda_{1,t+1},\, \lambda_{2,t+1},\, w_t,\, \lambda_{1t},\, \lambda_{2t}\big)}}{2\lambda_{2t}\big(-\lambda_{1,t+1}^2\xi w_t\big(\sigma_c + \big(-h+\sigma_\ell\big)w_{t+1}\big)\big)} \tag{3.27}$$

Full equations can be viewed in Appendix B.1. As one can see, it is difficult to gain insights from these Euler equations. Therefore, the model is solved numerically to illustrate how the share of a regulator's budget is spent on subsidizing alternative recycling policies over time.

3.3 Numerical Solution Methodology

Due to the constraints and exogenously growing parameters w_t and g_t, the analytic solution, where control variables are functions of the state variables and other model parameters, is difficult to interpret. Therefore, γ_t and θ_t are solved numerically using a backward recursion process over a discretized state space, similar to what Fell et al. (2010) employed. The steps used to arrive at the numerical solution are as follows.

First, a discretized state space is generated where the time paths of w_t and g_t are known and grow at their fixed rates of κ_w and κ_g, respectively. Next, the backward recursion begins by solving for the terminal values of θ_T provided the landfill state terminal condition $s_{T+1} = 0$. Then, (3.21) and (3.22) are used to get $\gamma_t = \Gamma\big(\theta_t\big)$, which in turn calculate all other choice variables.

This creates a terminal value matrix V_T that provides utility values from any possible state in period T to state values of zero in period $T+1$. With the final period's value function known, the model is stepped back one period to $T-1$ and determine the optimal γ_{T-1} and θ_{T-1} for each state s_{T-1}. These optimal decisions are then used and added to the discounted V_T to provide values for V_{T-1}. This process is continued until $t = 1$.

Through this backward recursion process, the optimal recycling subsidies for each state in each time period are collected to simulate how the landfill state depletes over time. To begin the simulation process, it is specified that $\overline{s} = s_1$. Then using the optimal recycling subsidies matrix, an optimal landfill state depletion path is formed. The results are presented in the following section.

3.4 Numerical Solution Results

In this section, the model is simulated using the parameters shown in Table 3.1. The parameters are then varied to reflect how changes to the model parameters can alter the landfill depletion path, and the time at which the share of regulator budget switches from one method of recycling to another.

Table 3.1: Numerical Model Parameters

Parameter	Parameter Value	Parameter Definitions
α	0.6	*Consumption's share of utility*
β	0.39	*Leisure's share of utility*
ϕ	0.005	*Curbside recycling's share of utility*
σ_c	2	*Subsistence level on consumption*
σ_ℓ	0.1	*Subsistence level on leisure*
σ_b	0	*Subsistence level on curbside quantities*
σ_d	0	*Subsistence level on deposit-refund quantities*
h	1	*Time available in a given period*
δ	0.0095	*Per unit time to recycle via deposit-refund system*
ν	0.03	*Cost parameter on curbside recycling*
ψ	0.0002	*Rate at which excess regulator budget is received*
$\overline{s}$	50	*Initial amount of available landfill space*
w_0	115	*Initial household wage*
g_0	1000	*Initial regulator budget*
κ_w	0.02	*Household wage growth rate*
κ_g	0.02	*Regulator budget growth rate*
ρ	0.91	*Discount factor (discount rate $r = 0.1$)*

Figure 3.2, the base case, illustrates both the time paths of available landfill space and consumption. Landfill depletion occurs as expected given the evolution of marginal utility, marginal costs, and shadow price of available landfill space under exogenously growing wages.

In the period just before physical exhaustion, there is a small uptick in the depletion path which is due to the discretized nature of the state variable. Additionally, consumption follows the presumed path explained in the comparative "statics" portion of section 3.2.1.[22]

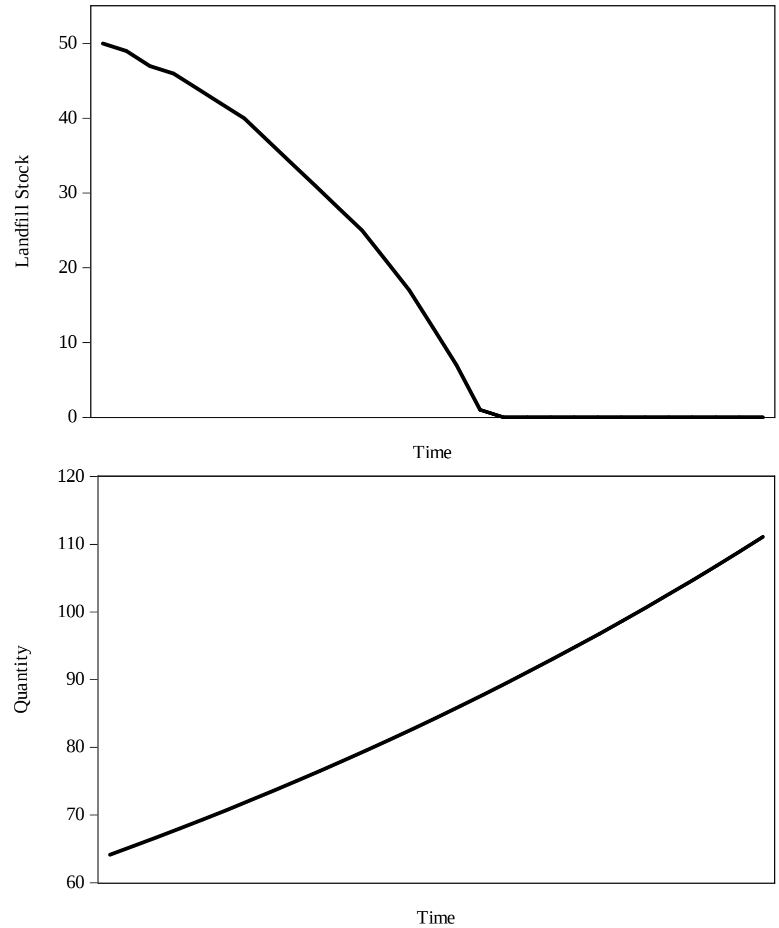

Figure 3.2: Landfill Depletion and Consumption Time Paths

With regards to the shares of regulator spending on DR and CS recycling, it is found that it can be optimal for a regulator to switch its subsidy focus from DR to CS recycling as household wages rise and available landfill space falls (see Figure 3.3). It is not always the case that both regulator spending shares and household recycling shares cross, because of the expense incurred by the regulator. For example, to keep DR quantities at a constant rate or the maximum allotted given the time constraint on the household, the regulator

[22]Consumption rises at rate α of wage when the household utility function collapses to a Cobb-Douglas form.

must increase the cash refund that households receive at the rate wages grow κ_w. Otherwise, the relative value diminishes and households will select the less time consuming recycling method (i.e. CS recycling) or not to recycle at all, depending on the available landfill space left in that time period. If the maximum DR quantity is to occur, then the income derived from recycling will grow at rate κ_w.

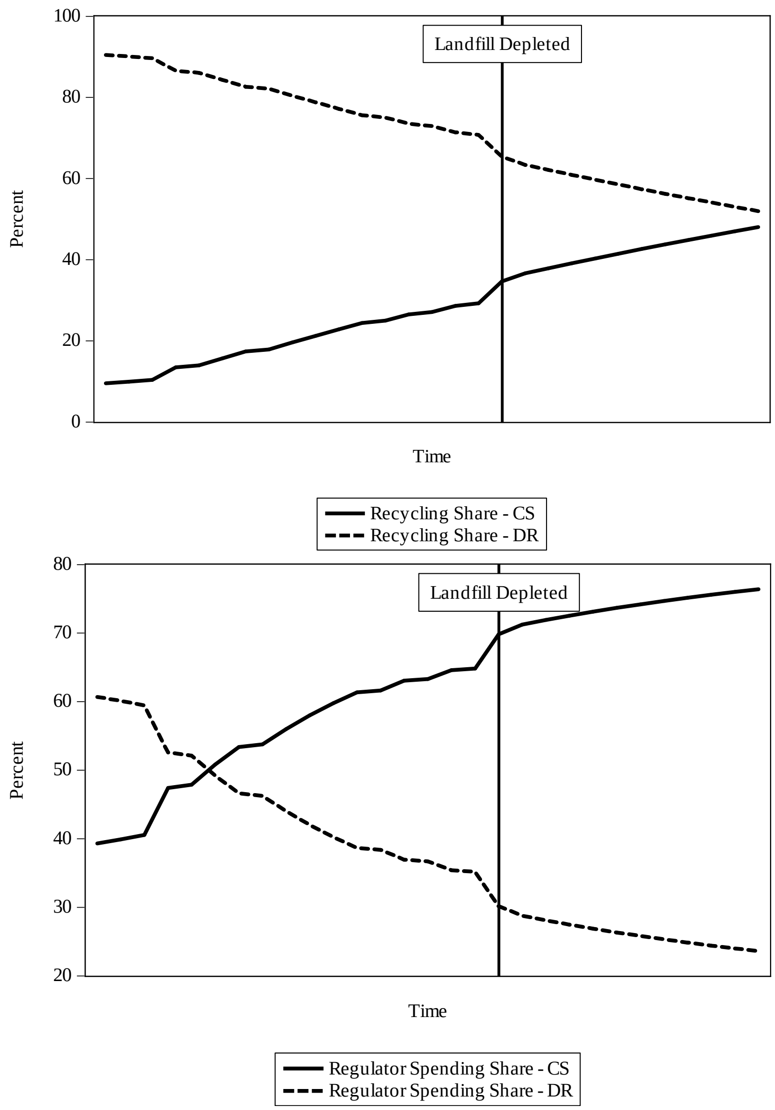

Figure 3.3: Recycling and Regulator Spending Shares

Additionally, there is a drop in excess regulator budget post-depletion. This is to be expected as all that is consumed is to be recycled after landfill space is exhausted. Even though consumption has to equal recycling from $T+1$ to ∞, it does not have to be the case that $g_t = \theta_t d_t + \upsilon/\gamma_t$ over this time interval. In other words, it can still be that $g_t > \theta_t d_t + \upsilon/\gamma_t$ over this time interval if the regulator can satisfy the terminal condition without using all of its budget, such that it continues to receive the additional utility $\psi\big(g_t - \theta_t d_t - \upsilon/\gamma_t\big)$. If the regulator receives this additional utility, then there will be a constant rise in excess budget beyond $T+1$ due to the exogenous growth rate κ_g. In the upcoming subsections, it is explained how parameter changes can affect the landfill depletion times, regulator spending switching points, and labor-leisure-recycling tradeoffs.

3.4.1 Changes in Initial Regulator Budget

In the scenario where the initial regulator budget is low, but still able to fully subsidize recycling programs, it is possible to not have physical exhaustion of available landfill space. This is because the regulator is forced to spend all of its budget on recycling and not receive additional utility from excess regulator budget. In addition, households end up trading off time spent working for recycling, where most recycling comes from CS recycling programs, because the regulator cannot make the cash refund attractive enough to the household to keep them recycling via the DR system.

With still a low budget but more than just explained, the landfill is depleted quicker and the regulator will not be able to keep the cash refund as a designated percentage of the household's wage (see Figure 3.4). Rather than the cash refund rising at the wage growth κ_w until the terminal time, it only does so until the landfill is depleted. The regulator simply subsidizes as much as it can until it can no longer afford to maintain this policy, resulting in DR quantities going from their maximum $d_t = D\big(\bar{\theta}_t\big)$ to some new level less than the maximum.

With this drastic change in DR quantities, CS recycling quantities can take over as the dominant form of recycling once the landfill is depleted, giving way to a switch in how the regulator spends its budget. In a moderate regulator income environment relative to household wages, the regulator can have zero excess budget post-depletion, because it will

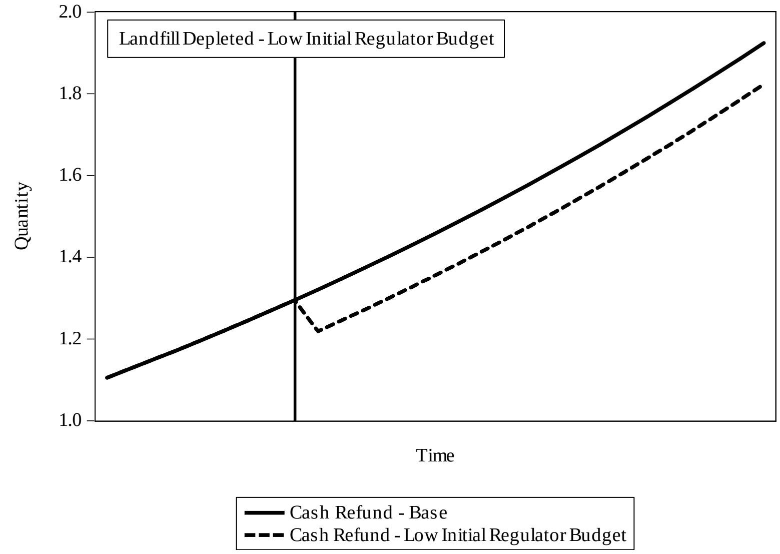

Figure 3.4: Cash Refund Changes Under Low Initial Regulator Budget

have to use all of its financial means to subsidize recycling. Also, it is possible that in this situation for the regulator to subsidize as much recycling as it can in the beginning periods, such that household income is only derived from recycling via the DR system. The opportunity costs of not working eventually rise enough for the household to switch from recycling for cash to supplying labor. For this scenario, this will occur once the landfill is depleted because of the regulator's low initial budget.

If however, the regulator's budget is high (relative to the base case), then there will be minimal changes in the optimal time paths provided the regulator's budget was already efficiently allocated to the appropriate methods of recycling. What changes is the discounted utility. With more budget and no real changes in the time paths, the regulator gets more of a bonus, yielding higher utility.

3.4.2 Changes in Initial Household Wages

Similar to the scenario where the regulator's budget is low/moderate relative to household wages, increases to initial household wages yield an earlier depletion time. The idea is that as the gap between household wages and regulator budget diminishes, the regulator will not have as much income to subsidize the DR system in a manner that is attractive to the household. Once the landfill is depleted, there can be direct shifts in both the DR and CS recycling quantities, where DR quantities fall and CS recycling quantities jump and continue along a specified optimal time path. These shifts may or may not result in changes in switching points of the regulator's recycling budget share.

Also with high wages, it may be the case that the regulator subsidizes the CS recycling program more throughout time, such that initial CS recycling quantities are greater than DR recycling quantities and continue like this throughout time. In this case, the regulator's budget mix may always favor the CS recycling program. In other words, while the DR system is subsidized, it is just not enough of the budget in the initial periods to enforce a switching point in the allocation of the regulator's budget. This is intuitive in that if you have a municipality with a high mean income, their time is worth more than a poor municipality, and those that have a high mean income prefer the more convenient method of recycling (i.e. CS recycling).

Post-depletion, the case is identical to the other scenarios, where more of the recycling mixture from households comes from the CS recycling program. It is possible to observe constant levels of DR recycling. This is stemmed from cash refunds keeping pace with the growth rates of household wages and the regulator's budget. If θ_t grew at a rate different from κ_w, then changes in DR quantities would occur.[23] At this point, where wages are so high, the regulator can no longer make it worthwhile for households to recycle via the DR system. If the regulator has such a large budget that it can afford to keep cash refunds on par with wages, then it is possible for households to not even work after depletion, since they can make it so monetarily beneficial for households to recycle via the DR system.

Additionally, given the household's utility from leisure, it can in fact receive less money from working if only a certain amount of time can be devoted to labor. Stated otherwise,

[23]The notion of cash refunds keeping pace with wages or inflation comes from Batson & Eggert (2012) (i.e. chapter 2). It is specified that in order to keep recycling policies afloat, the regulator must tie the cash refund to household wages or inflation to keep the relative value at least constant over time.

if each container is worth a significant amount, then households can make more money recycling than working. Households therefore prefer to not work, but to recycle in order to maintain increasing consumption. This may result in switching points between recycling quantities post-depletion, with the same jumps in quantities at the time of depletion. Regulator spending, however, can then mostly be allocated to subsidizing CS recycling rather than DR recycling, where no switching point occurs.

3.4.3 Changes in Household Wage Growth

Changes to household wage growth κ_w can result in exponential or horizontal consumption time paths, depending on the size of the growth rate. As expected, low wage growth yields a landfill depletion time that is equal to or greater than the base case, while high wage growth depletes the landfill quicker or the same as the base case. The interesting part is that there can be a solution where all consumption is recycled in the beginning time periods before the landfill is depleted. If the regulator's budget is high enough, then recycling can be subsidized enough, such that households spend less time recycling while receiving more money from DR recycling.

With high growth, consumption positively diverges from its base case, whereas low growth yields a more linear path. This higher growth rate results in a landfill depletion time less than or equal to the base case. There can be a knife-edge solution, where all is recycled for some time before the landfill begins to deplete. While households do spend less time recycling, if the regulator's budget is high enough, it is able to provide enough cash per container recycled via the DR system that all can be recycled. Additionally, if the regulator can put off depleting the resource for the initial few time periods, then it is worthwhile to conserve the resource since consumption will be higher and landfill space will be depleted quicker. This yields earlier regulator spending switching points from DR recycling to CS recycling, which relates back to the high wages. With high wages or high wage growth and equivalent regulator budget growth, it is optimal to switch from subsidizing DR recycling to CS recycling earlier, because these households prefer convenience over cash.

3.4.4 Changes in Curbside Recycling Cost Scalar

Similar to when the regulator's budget is low/moderate, the landfill is depleted quicker with all excess regulator budget going to zero when it becomes too costly to subsidize CS recycling. It is found that switching points do occur in both recycling and regulator budget shares. The switching point is earlier than in the base case, because now it costs the regulator more money to subsidize CS recycling (provided the same utility shares).

3.4.5 Changes in Per Unit of Time to Deposit-Refund Recycle

With it being more time consuming to recycle via the DR system, it simply decreases the level of DR quantities from the base case. Like in the high wage scenario, there can be scenarios that do not have any switching point in the regulator's budget share. Now with it being more difficult to DR recycle and households receiving an equal share of utility from CS recycling, it may be the case that most regulator spending is allocated to reducing the time it takes a household to CS recycle. This conclusion becomes even more apparent after the landfill is depleted. The levels of recycling, however, can have a switching point, because of the cost structure we have assumed in the model.[24]

3.4.6 Changes in Utility Shares of Recycling

With equal amounts of utility on DR and CS quantities, but overall higher utility on recycling than the base case, it is not always the case that the regulator's spending percentages switch. In the instances that they do switch, they switch at a later date, as does depletion when compared to the base case. In this scenario, DR and CS recycling spending may increase over time, with CS recycling starting off at a lower level but increasing faster than DR quantities. Stated differently, the percent of the regulator's budget spent on CS recycling increases at a decreasing rate, while the percent spent on DR recycling decreases at a decreasing rate.

[24] A way to get around this perplexity is to choose δ, and allow for an unlimited amount of cans to be returned to a recycling center that would have been made regardless (see footnote 6).

If CS recycling has more utility share than DR recycling, regulator spending shares switch at an earlier date, because of the relative cost of CS recycling (i.e. it is more expensive, because the regulator seeks to decrease γ_t more than the base case). This results in θ_t having to be a little higher to keep DR recycling at its maximum in order to make it worthwhile for households to continue to recycle via the DR system. Since households get more utility from CS recycling, the regulator must make it monetarily better to get households to go to a DR recycling center. As with higher but equal recycling utility shares, landfill space is not depleted as quickly as compared to the base case.

3.4.7 Changes in Benefit Received from Excess Regulator Budget

With a greater benefit payout from not spending all regulator budget, the landfill is depleted quicker. This would be the scenario where the regulator would like to have the added utility post-depletion now for not spending all of its budget. However, this hurts the regulator in the future, because it gets less additional utility later as it is forced to do all recycling at an earlier time. Post-depletion, recycling quantities are the same in this case as the base case. See Figure 3.5.

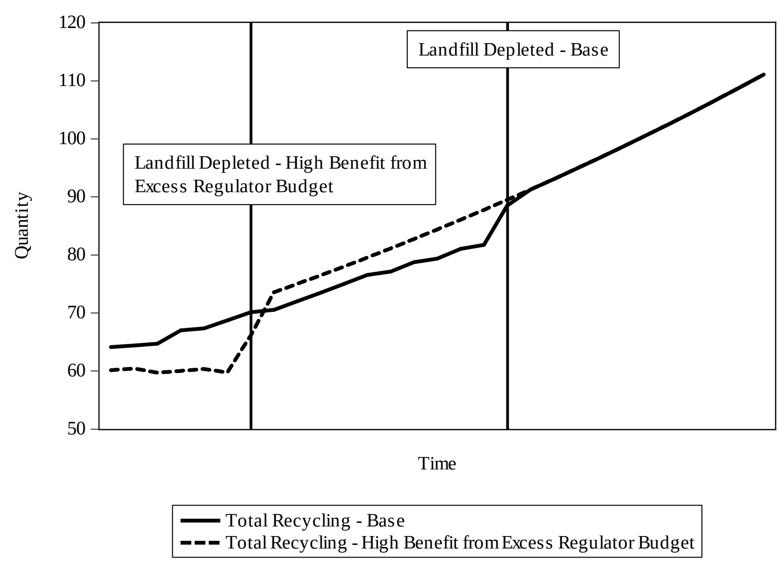

Figure 3.5: Total Recycling Changes Under High Benefit from Excess Regulator Budget

3.4.8 Changes in Discount Rate

As theory states, the discount rate has a negative impact on the time of which the resource is depleted. With higher discount rates (lower discount factors), this model confirms the theory by depleting the landfill in an earlier period. The lower the discount rate, future time periods hold more value and thus landfill depletion occurs at a later time. Due to the nature of the model, changes to the discount rate do not have any impact on the consumption time path. The long run path is the same for CS recycling quantities regardless of the discount rate. It simply depends on when the jump in CS recycling quantities occur (earlier for high discount rates). Additionally, there is no impact on DR recycling quantities. The interesting fact is that for higher discount rates, the switching point of the regulator's budget share happens later than in the base case. This is because with high discount rates, the landfill is depleted quicker, yielding an earlier jump/drop in CS/DR recycling shares.

3.4.9 Changes in Subsistence Levels

With high subsistence levels for consumption, it is apparent that consumption levels will shift up to meet the new subsistence level. This higher subsistence level results in an earlier depletion and an earlier jump in CS recycling quantities. DR recycling quantities have more of a bow in the levels, with the overall quantities declining over time.

With higher subsistence levels on leisure, a tradeoff between consumption and leisure really becomes prominent. Like the higher subsistence level on consumption, a higher subsistence level on leisure results in an earlier depletion time than the base case. The share of regulator spending on CS recycling is initially lower, because households prefer leisure to working or recycling. In the long run, there is not effect on θ_t or γ_t.

3.5 Concluding Remarks

This chapter examined how a regulator of a municipality or state should subsidize its recycling programs based on the actions of the private utility maximizing household. While previous studies either assumed one type of recycling program or no recycling-labor tradeoff, this chapter accounted for how households act in reality - no consideration of landfill space. Under this assumption and the assumption that household wage grows exogenously, similar results to Ashenmiller (2009) are found, where lower income households use the DR system as a substantial source of income. It is then showed that based on the regulator's budget, DR recycling can only be subsidized for a period of time due to it becoming too costly for the regulator to continue making DR cash refunds attractive enough to a now more wealthier household. In the long run, it was shown that subsidizing CS recycling programs is the solution to a depleted landfill.

Future research is to calibrate this model to an actual municipality. It would also be beneficial to policymakers if this model were expanded to allow for multiple landfill sites with varying marginal costs, similar to the optimal order extraction model Holland (2003) developed.

CHAPTER 4

OPTIMAL WASTE-TO-ENERGY INVESTMENTS IN THE PRESENCE OF RECYCLING PROGRAMS AND GROWING HOUSEHOLD WAGES

Co-author: Harrison G. Fell

This chapter constructs a theoretical model that combines elements of Batson et al. (2013) (i.e. chapter 3) with investments in WTE technologies. Simulation results indicate that optimal investments in such technologies should occur at a point when the net benefits of investment exceed the pecuniary and non-pecuniary benefits received from recycling. This concept is then related to the current debates surrounding this topic, such as the promotion of consumption and the demotion of recycling policies.

4.1 Overview

Energy recovery from waste, or WTE, is a process that includes incinerating non-recyclable waste material from landfills to generate an alternative form of energy. WTE plants either take the initiative of removing recyclables at a receiving area, or rely on municipal recycling programs to perform a "first-pass" of solid waste sorting before proceeding to the shredders and furnaces. In either case, WTE plants remove recyclable material from the system to ensure that no "can"nibalization of waste is occurring. In other words, WTE plants are not to benefit from the incineration of materials that should have not been in their system initially. Investment in such plants offer benefits of reducing the use of landfills and generating "cleaner" emitting energy.[25]

The purpose of this chapter is to provide a theoretical framework that will assist policymakers in determining whether or not to convert waste into energy through an optimal

[25] This is noted to be "cleaner", because incineration does generate greenhouse gas and acid rain emissions, as well as residuals and dioxins (Vollebergh, 1997).

investment strategy, given the actions of a representative household that experiences exogenously growing wages and an available recycling method. It probes the question, at what times is it appropriate to invest in WTE technologies and how do these investments impact a municipality's recycling rates and social welfare over time, provided their added associated net benefits and a fixed amount of landfill space?

While WTE plants have the benefit of slowing down landfill depletion and generating "cleaner" energy, not all are in favor of such an investment. Those who oppose promoting these plants argue that they have negative effects on municipal recycling programs, promote additional consumption, and that selecting an incinerator site is a difficult process (Rosenthal, 2010). However, studies have shown that states with WTE plants do not demote recycling programs or reduce recycling rates. In fact, "communities using WTE have recycling rates that are five percentage points or more above the national average" (Berenyi, 2009). Those who have argued the point of promoting consumption make a valid observation. For a WTE investment to make economic sense, there has to be enough waste material supplied to justify building a plant that reduces carbon emissions and slows down landfill depletion. To counter this point, population growth and economic growth are thought to be growing faster than society is moving towards a zero-waste world (Cheng et al., 2007). Lastly, and not unlike the landfill story, selecting a site for an incinerator or landfill is difficult, because households have a "not in my backyard" mentality.

Studies carried out have yet to capture the investment decision in such technologies. Keeler & Renkow (1994) however, developed a static model to show the effects WTE technologies have on a municipality's waste disposal efficiency. The regulator seeks to minimize costs by determining the capacity of a WTE plant, and by determining recycling, landfill, and incineration quantities. They find that higher fixed costs of WTE plants and higher recycled quantities render a WTE plant less attractive, while higher levels of waste and higher landfill costs make the plant more attractive.

Other studies have confirmed such claims. For example, Dijkgraaf & Vollebergh (2004) explained that yes, WTE plants have high gross private costs and are “a very expensive way to save on climate change emissions”, but they can be preferred over landfilling when only environmental costs are considered.[26] Vollebergh (1997) stated that these private costs may be offset or at least the net private costs may be lowered with electricity sales. As for higher landfill costs, investments in such technologies have been noted to be more successful where land is scarce (Kinnaman & Fullerton, 1999). With land being scarce, landfill costs increase, resulting in the adoption of WTE plants becoming more economical. This is in part why Japan, parts of Europe, and the northeast region of the U.S. have adopted such mechanisms since the 1970s (Kinnaman & Fullerton, 1999).

As mentioned in Batson et al. (2013) (i.e. chapter 3), theoretical studies have used dynamic models to incorporate a fixed amount of landfill space. Specifically, Highfill & McAsey (2001) used a dynamic model to show that municipalities with higher income will have high levels of recycling, because recycling is considered to be a backstop waste technology. This is similar to what Viscusi et al. (2013) uncovered in their survey. They found that municipalities with higher income households, which generally have higher property taxes, allow for those municipalities to have “more access to recycling options that minimize opportunity costs.”

Additionally, Highfill & McAsey (2001) established that lower income municipalities should rely less on recycling, exhausting landfill space if it is small. As shown in Batson et al. (2013) (i.e. chapter 3), exhaustion is an outcome, but it is possible to have recycling in earlier periods given a DR system. Furthermore, Huhtala (1997) used a dynamic model with fixed landfill space to “account for the physical costs of recycling, the social costs of landfilling, and consumers’ environmental preferences.” She then used the model to simulate

[26] Villanueva & Wenzel (2007) conducted a life cycle assessment that showed it is better to recycle paper than landfill or incinerate it based on the environmental impact categories: energy use/generation, abiotic and biotic resource consumption, energy related impacts (e.g. global warming potential, acidification potential, nutrient enrichment potential, and photochemical ozone formation potential), toxicity of emissions, waste generation, and wastewater generation.

an optimal waste management plan with the assumption that recycling technology and costs are relatively constant over time.

The model presented in this chapter is at the forefront of economic research pertaining to the combination of recycling policies and WTE investments. In contrast to Huhtala (1997), this study allows for changes in waste management technologies via a WTE investment opportunity. It reflects how recycling policies and WTE investments can work in conjunction to offset consumption and consequently landfill space depletion. The results indicate that policymakers can use the theory illustrated in this paper to justify an investment in WTE technologies under various scenarios. The justification of an investment is highly dependent on the response of household behavior to recycling policy changes, and the net benefits received from the investment. The latter is not too surprising in that an investment should occur if the marginal net benefits are positive. The intriguing aspect of this chapter is that the investment is to occur not only if the net benefits are positive, but if these net benefits outweigh the pecuniary and non-pecuniary benefits received by the household from recycling, and some bonus benefit that is received by the regulator for being below budget.

This chapter is organized as follows. First, section 4.2 formulates household and regulator models using a specific functional form. Next, section 4.3 explains the methodology used to solve the model. The model results are then presented, including various scenarios in section 4.4. Section 4.5 provides insight to how policy makers can use these findings to determine if a WTE investment is economical, and what effects such an investment will have on recycling rates. Finally, section 4.6 concludes this chapter and provides suggestions for future research.

4.2 The Model

The model for this chapter builds on the fundamental framework formulated in Batson et al. (2013) (i.e. chapter 3). This model simplifies that model to consider the recycling decisions of a representative private utility maximizing household based on an available DR system (i.e. no CS recycling program will be considered in this chapter). Under a DR system, household decisions are based on a cash refund supplied by the regulator. In addition to subsidizing recycling, the regulator has the binary decision to invest or not to invest in WTE technologies in order to alter the landfill space depletion path. This decision takes into account net benefits received from selling the "cleaner" energy, the fixed cost of the investment, and the variable costs of operating and maintaining the investment.

Again, the goal of this paper is to reflect when it is economically justifiable to invest in WTE technologies, and how this investment will impact recycling rates and social welfare. The remainder of this section is broken into two subsections. The first subsection will present the household's utility maximization problem given a DR system available. The second subsection will then use the outputs from the household's utility maximization problem as inputs to the regulator's social welfare maximization problem.

4.2.1 Household Utility Maximization Problem

Consider a representative household that receives utility from consumption c_t, leisure ℓ_t, and DR recycling d_t. The household is assumed to have a diminishing marginal utility of recycling, and a non-constant marginal rate of substitution to avoid any bang-bang solutions. Like in Batson et al. (2013) (i.e. chapter 3), a constant returns to scale Stone-Geary utility function is employed to allow for flexibility and varying subsistence levels in the choice variables. The household utility function is

$$U_t = \alpha ln\big[c_t - \sigma_c\big] + \beta ln\big[\ell_t - \sigma_\ell\big] + \big(1 - \alpha - \beta\big) ln\big[d_t - \sigma_d\big], \tag{4.1}$$

where σ_c, σ_ℓ, and σ_d are the respective subsistence levels of consumption, leisure, and DR recycling. The household's budget constraint is

$$c_t = w_t n_t + \theta_t d_t. \tag{4.2}$$

The household earns income from labor n_t and recycling d_t, which is solely spent on consumption c_t. Earned labor income is derived from exogenously growing wages, which rise at some fixed rate κ_w, and follow the compounded growth function $w_t = w_0 \left(1 + \kappa_w\right)^t$. Earned recycling income is derived from the per unit net cash refund θ_t households receive for recycling via the DR system.[27] It is assumed $\theta_t \geq 0$, as any value less than zero would simply indicate that the household would be willing to take a monetary loss in order to recycle.

The household is also faced with a time constraint, where time can be spent on recycling d_t, supplying labor n_t, or leisure activities ℓ_t. Like in the previous chapter, the time associated with recycling via the DR system is assumed to be a linear per unit time cost, which encompasses the time it takes to clean, sort, store, and return a beverage container to a recycling center. Therefore, the household's time constraint is

$$h = n_t + \ell_t + \delta d_t, \tag{4.3}$$

where h is the time available in a period and δ is the per unit time cost associated with recycling via the DR recycling system.

As assumed in Batson et al. (2013) (i.e. chapter 3), households in reality do not consider landfill space when making the decision to recycle. Therefore, no landfill state equation is formulated in the household's utility maximization problem. Without a known and realized state equation by the household, the representative household's utility maximization can be solved using a static framework. The household's utility maximization problem is

$$\max_{c_t,\, \ell_t,\, d_t} U_t = \alpha ln\big[c_t - \sigma_c\big] + \beta ln\big[\ell_t - \sigma_\ell\big] + \big(1 - \alpha - \beta\big) ln\big[d_t - \sigma_d\big], \tag{4.4}$$

subject to (4.2) and (4.3). Provided both constraints hold with equality, the household's maximization problem can be reduced to two choice variables by solving for labor n_t from (4.3) and plugging it into (4.2). This results in $c_t = \big(h - \ell_t\big)w_t + d_t\big(\theta_t - \delta w_t\big)$, and reduces the maximization problem to the following two first order conditions.

$$\frac{\partial U_t}{\partial \ell_t} = \frac{\beta}{\ell_t - \sigma_\ell} + \frac{\alpha w_t}{\sigma_c - d_t\theta_t + d_t\delta w_t - h w_t + \ell_t w_t} \leq 0, \quad \ell_t \geq 0, \quad \frac{\partial U_t}{\partial \ell_t}\ell_t = 0$$

[27]Recall from chapter 3 that the per unit net cash refund is the cash refund received less the per unit costs of transporting the waste to the recycling center, which will henceforth be referred to as cash refund.

$$\frac{\partial U_t}{\partial d_t} = -\frac{-1+\alpha+\beta}{d_t-\sigma_d} + \frac{\alpha\big(\theta_t-\delta w_t\big)}{-\sigma_c+\big(h-\ell_t\big)w_t+d\big(\theta_t-\delta w_t\big)} \quad \leq 0, \quad d_t \geq 0, \quad \frac{\partial U_t}{\partial d_t}d_t = 0$$

Solving the choice variables through the first order conditions and plugging the optimal solutions into the constraints yield the following optimal household choice variables.

$$c_t^* = \sigma_c - \alpha\sigma_c + \alpha\Big(\big(h-\sigma_\ell\big)w_t + \sigma_d\big(\theta_t-\delta w_t\big)\Big) \tag{4.5}$$

$$\ell_t^* = \frac{\sigma_\ell w_t + \beta\big(\sigma_c - \sigma_d\theta_t - hw_t + \delta\sigma_d w_t + \sigma_\ell w_t\big)}{w_t} \tag{4.6}$$

$$\begin{aligned} d_t^* =& \frac{1}{-\theta_t+\delta w_t}\Big(\big(-1+\alpha+\beta\big)\sigma_c - \beta\sigma_d\theta_t + hw_t - \beta hw_t + \beta\delta\sigma_d w_t - \ldots \\ & \sigma_\ell w_t + \beta\sigma_\ell w_t + \alpha\big(-\sigma_d\theta_t - hw_t + \delta\sigma_d w_t + \sigma_\ell w_t\big)\Big) \end{aligned} \tag{4.7}$$

$$\begin{aligned} n_t^* =& \frac{1}{w_t\big(-\theta_t+\delta w_t\big)}\Big(-\beta\theta_t\big(\sigma_c - \sigma_d\theta_t - hw_t + \delta\sigma_d w_t + \sigma_\ell w_t\big) + w_t\big(\big(-h+\ldots \\ & \sigma_\ell\big)\theta_t - \alpha\delta^2\sigma_d w_t + \delta\big(\sigma_c - \alpha\sigma_c + \alpha\sigma_d\theta_t + \alpha hw_t - \alpha\sigma_\ell w_t\big)\big)\Big) \end{aligned} \tag{4.8}$$

Under the Stone-Geary function, the comparative "statics" with respect to wages can be quite ambiguous.

$$\frac{\partial c_t^*}{\partial w_t} = \alpha\big(h - \delta\sigma_d - \sigma_\ell\big)$$

$$\frac{\partial \ell_t^*}{\partial w_t} = \frac{\beta\big(\sigma_c - \sigma_d\theta_t\big)}{w_t^2}$$

$$\frac{\partial d_t^*}{\partial w_t} = -\frac{\big(-1+\alpha+\beta\big)\big(\delta\sigma_c + \big(-h+\sigma_\ell\big)\theta_t\big)}{\big(\theta_t-\delta w_t\big)^2}$$

$$\frac{\partial n_t^*}{\partial w_t} = \frac{1}{w_t^2\big(\theta_t-\delta w_t\big)^2}\Bigg(\big(-1+\alpha\big)\delta\big(\delta\sigma_c + \big(-h+\sigma_\ell\big)\theta_t\big)w_t^2 + \ldots$$

$$\beta\theta_t\big(\delta\big(-h+\sigma_\ell\big)w_t^2-\sigma_c\big(\theta_t-2\delta w_t\big)+\sigma_d\big(\theta_t-\delta w_t\big)^2\big)\Bigg)$$

Most choice variable movements can either be increasing or decreasing in w_t, depending on the size of the subsistence parameters. Consumption is most likely increasing in wages, because both σ_ℓ and $\delta\sigma_d$ are bound between 0 and h from (4.3). Leisure on the other hand, can be increasing or decreasing in wages, depending if $\sigma_c \gtrless \sigma_d\theta_t$. It is known that $\sigma_c > \sigma_d$, therefore the way leisure changes as wages increase depends on how much the regulator subsidizes DR recycling. If the regulator subsidizes DR recycling by more than σ_c/σ_d, then the representative household will decrease the amount of time in a period it dedicates to leisure activities.

For DR quantities, the change per period with increasing wages depends on the inequality $\delta\sigma_c \gtrless (-h+\sigma_\ell)\,\theta_t$. DR quantities will increase with wages provided $\delta\sigma_c>(-h+\sigma_\ell)\,\theta_t$. As for labor amounts, it is very ambiguous on whether or not labor is increasing or decreasing in wages. Therefore, to take away the ambiguity of these comparative "statics", it is assumed that all subsistence levels are zero and the utility function reduces to a Cobb-Douglas utility function.

Under this simplicity assumption it is clear that consumption increases definitively. It also simplifies the problem such that leisure is independent of wages. DR quantities are decreasing in wages, which is similar to what Ashenmiller (2009) alluded to with her empirical research on recycling centers. Labor increases in wages due to the increasing opportunity costs of not working (i.e. it becomes more costly not to work as wages grow over time).

4.2.2 Regulator's Social Welfare Maximization Problem

Now consider a regulator who wishes to maximize the welfare derived by the representative household over an infinite-time horizon, given a fixed stock of available landfill space, and under an available DR system. Using (4.5) to (4.8), the utility U_t enjoyed by the household in period t becomes

$$U_t = \alpha ln\big[c_t^* - \sigma_c\big] + \beta ln\big[\ell_t^* - \sigma_\ell\big] + \big(1-\alpha-\beta\big) ln\big[d_t^* - \sigma_d\big] + \dots$$
$$\psi\Big(g_t - \theta_t d_t^* + D_{1t}\Big(P_p\big(1-\pi\big)z_t - \omega\frac{\big(1-\pi\big)z_t^2}{2}\Big) - D_{2t}\eta\Big). \tag{4.9}$$

Similar to what the household experiences with wages, the regulator has its own exogenously growing income $g_t = g_0\big(1+\kappa_g\big)^t$, where κ_g is the fixed rate at which regulator income grows. The regulator may supplement its income if it invests in WTE technologies with the per unit price P_p for selling the "cleaner" power. The term z_t simply refers to material not consumed or recycled. Of this available material π, bound between 0 and 1, goes to the landfill. The portion $\big(1-\pi\big)$ thus goes to an incinerator for "cleaner" power generation since this additional income is only captured by the regulator if an investment has occurred.[28] Mathematically, $D_{1t} = 0$ if no investment was made in period t or any prior period. Otherwise, $D_{1t} = 1$, rendering the investment irreversible.

Total regulator income can be spent on increasing the cash refund θ_t a household receives for recycling via the DR system and/or paying the power generation cost $\omega\big(1-\pi\big)z_t^2/2$ to operate and maintain the WTE investment, where ω is the coefficient on the power generation costs. Additionally, η is the fixed investment cost that is only made in the period the investment is initiated. Therefore, $D_{2t} = 1$ if and only if the investment was made in period t. Otherwise, $D_{2t} = 0$. Any excess regulator budget is received at rate ψ, which contributes to utility and is thought of as a bonus to the solid waste management group for promoting recycling and "cleaner" power generation while not spending all of its budget. The regulator provides the recycling subsidy to households and invests in WTE technologies based on the household's optimal private actions, its own budget (both the exogenously growing portion and what is received from "cleaner" power generation), the cost incurred for investing in WTE technologies, and the initial size of available landfill space. Landfill space declines as

[28]This assumption accounts for the fact that WTE plants are not to benefit from the incineration of materials that should not have been in their system initially (e.g. beverage containers).

follows.

$$s_{t+1} = s_t - \big(c_t^* - d_t^* - D_{1t}\big(1-\pi\big)z_t\big) \tag{4.10}$$

Under no investment (i.e. $D_{1t} = D_{2t} = 0$), available landfill space declines at the rate of consumption less what is recycled. Under investment, however, landfill space declines at the rate consumption less recycled material, and less any discarded material that is burned for "cleaner" power generation.

A maximum cash refund subsidy $\overline{\theta}_t$ is imposed to prevent the regulator's budget constraint from being violated in the numerical solution. For simplicity, assume $\sigma_d = 0$. The maximum cash refund subsidy is then solved from $g_t = \theta_t d_t^*$.

$$\overline{\theta}_t = \frac{\delta g_t w_t}{g_t + \big(-1+\alpha+\beta\big)\big(\sigma_c + \big(-h+\sigma_\ell\big)w_t\big)} \tag{4.11}$$

The regulator's maximization problem is given as

$$\begin{aligned} \max_{\theta_t,\, z_t} \sum_{t=0}^{T} \alpha ln\big[c_t^* - \sigma_c\big] + \beta ln\big[\ell_t^* - \sigma_\ell\big] + \big(1-\alpha-\beta\big) ln\big[d_t^* - \sigma_d\big] + \ldots \\ \psi\Big(g_t - \theta_t d_t^* + D_{1t}\Big(P_p\big(1-\pi\big)z_t - \omega\frac{\big(1-\pi\big)z_t^2}{2}\Big) - D_{2t}\eta\Big) + \sum_{t=T+1}^{\infty}\Phi_t \end{aligned} \tag{4.12}$$

subject to

$$0 \le \theta_t \le \overline{\theta}_t \tag{4.13}$$

$$\theta_t d_t^* + D_{1t}\big(\omega\big(1-\pi\big)z_t^2/2\big) + D_{2t}\eta \le g_t + D_{1t}P_p\big(1-\pi\big)z_t \tag{4.14}$$

$$0 \le s_t \le \bar{s}. \tag{4.15}$$

Post-depletion T, the household receives the terminal discounted utility of $\sum_{t=T+1}^{\infty}\Phi_t$, where $c_{T+1} = d_{T+1} + D_{1(T+1)}\big(1-\pi\big)z_{T+1}$. In other words, all consumption must be either recycled, burned for power generation, or some combination of the two once the landfill is depleted.

The regulator's problem can thus characterized by an infinite-horizon recursive Bellman equation whose value function $V_t\big(s_t\big)$ specifies the maximum net present value of household utility from period t forward, discounted at the per period factor ρ, and given the amount of available landfill space at the beginning of the period $s_0 = \overline{s}$. Specifically,

$$V_t\big(s_t\big) = \max_{\theta_t,\, z_t} \Bigg\{ \alpha ln\big[c_t^* - \sigma_c\big] + \beta ln\big[\ell_t^* - \sigma_\ell\big] + \big(1-\alpha-\beta\big) ln\big[d_t^* - \sigma_d\big] + \ldots$$

$$\psi\Big(g_t - \theta_t d_t^* + D_{1t}\Big(P_p\big(1-\pi\big)z_t - \omega\frac{\big(1-\pi\big)z_t^2}{2}\Big) - D_{2t}\eta\Big) + \rho V_{t+1}\big(s_{t+1}\big) + \ldots \tag{4.16}$$

$$\lambda_{1t}\big(\overline{\theta}_t - \theta_t\big) + \Phi_{T+1}\Bigg\}$$

subject to (4.5) to (4.8), and the terminal condition $c_{T+1} = d_{T+1} + D_{1(T+1)}\big(1-\pi\big)z_{T+1}$.

The terminal discounted utility is equivalent to the continuous time expression $\Phi_{T+1} = \big(1/r\big)e^{-r(T+1)}U_{T+1}\big(\theta_{T+1},\, z_{T+1}\big)$, where r is the discount rate (see footnote 21). Appendix A.2 formulates the maximization setup and first order conditions of the post-depletion portion of the model. The first order conditions for the pre-depletion maximization portion are

$$\frac{\partial V_t}{\partial \theta_t} = \frac{\alpha \partial c_t^*/\partial \theta_t}{-\sigma_c + c_t^*} + \frac{\beta \partial \ell_t^*/\partial \theta_t}{-\sigma_\ell + \ell_t^*} + \frac{\big(-1+\alpha+\beta\big)\partial d_t^*/\partial \theta_t}{\sigma_d - d_t^*} - \ldots$$

$$\psi\left(d_t^* + \theta_t \frac{\partial d_t^*}{\partial \theta_t}\right) + \rho\left(-\frac{\partial c_t^*}{\partial \theta_t} + \frac{\partial d_t^*}{\partial \theta_t}\right)\frac{\partial V_{t+1}}{\partial s_{t+1}} - \lambda_{1t} \tag{4.17}$$

and

$$\frac{\partial V_t}{\partial z_t} = -\,D_{1t}\big(-1+\pi\big)\Big(\psi\big(P_p - \omega z_t\big)\rho\frac{\partial V_{t+1}}{\partial s_{t+1}}\Big) \tag{4.18}$$

with the envelope condition

$$\frac{\partial V_t}{\partial s_t} = \rho \frac{\partial V_{t+1}}{\partial s_{t+1}}. \tag{4.19}$$

With the discount factor ρ, (4.19) reflects that the shadow price on the landfill state rises at the rate of interest. The conditions $\theta_t = \Theta\big(z_t\big)$ and $z_t = Z\big(\theta_t\big)$ are derived from (4.17) and (4.18). However, this problem cannot be solved analytically unless it is assumed that $\sigma_d = 0$. Under this assumption, the following conditions are derived.

$$\theta_t = \frac{1}{2\lambda_{1t}}\Big(-1 + \alpha + \beta + 2\delta\lambda_{1t}w_t \pm \chi\big(z_t,\, w_t\,, \lambda_{1t}\big)\Big) \tag{4.20}$$

$$\begin{aligned} z_t = & \frac{1}{\omega\psi}\Big(P_p\psi + \frac{1}{\big(-1+\alpha+\beta\big)\big(\sigma_c + \big(-h+\sigma_\ell\big)w_t\big)}\Big(\lambda_{1t}\theta_t^2 - \theta_t\big(-1+\alpha+\ldots \\ & \beta + 2\delta\lambda_{1t}w_t\big) + \delta w_t\big(\big(-1+\alpha+\beta\big)\big(1+\psi\sigma_c\big) + \big(\delta\lambda_{1t} + \big(-1+\alpha+\ldots \\ & \beta\big)\psi\big(-h+\sigma_\ell\big)\big)w_t\big)\Big) \end{aligned} \tag{4.21}$$

Using these conditions with envelope condition (4.19) yield the Euler equations $\theta_t = \Theta\big(\theta_{t+1}\big)$ and $z_t = Z\big(z_{t+1}\big)$.

$$\begin{aligned} \theta_t = & \frac{1}{2\lambda_{1t}\big(\sigma_c + \big(-h+\sigma_\ell\big)w_{t+1}\big)}\Big(-\sigma_c + \alpha\sigma_c + \beta\sigma_c + 2\delta\lambda_{1t}\sigma_c w_t + hw_{t+1} - \ldots \\ & \alpha hw_{t+1} - \beta hw_{t+1} - \sigma_\ell w_{t+1} + \alpha\sigma_\ell w_{t+1} + \beta\sigma_\ell w_{t+1} - 2\delta h\lambda_{1t}w_t w_{t+1}\ldots \\ & + 2\delta\lambda_{1t}\sigma_\ell w_t w_{t+1} \pm \sqrt{\tau\big(\theta_{t+1},\, w_{t+1},\, \lambda_{1,t+1},\, w_t,\, \lambda_{1t}\big)}\Big) \end{aligned} \tag{4.22}$$

$$z_t = \frac{P_p - P_p\rho + \omega\rho z_{t+1}}{\omega} \tag{4.23}$$

Full equations can be viewed in Appendix B.2. As one can see, it is difficult to gain insights from the first Euler equation. As for z_t, its evolution along the optimal path is solely dependent on the per unit price the regulator receives from selling WTE power P_p, and the power generation cost coefficient ω. However from (4.21), z_t is dependent on how much recycling occurs d_t, which is determined by the size of the cash refund θ_t. Therefore, the model is solved numerically to illustrate how the investment in WTE technologies and landfill depletion occurs over time.

4.3 Numerical Solution Methodology

Due to the constraints and exogenously growing parameters w_t and g_t, the analytic solution, where control variables are functions of continuous state variables and other model parameters, is difficult to interpret. Therefore, θ_t and z_t are solved numerically using a backward recursion process over a discretized state space, a similar method to what Fell et al. (2010) and Batson et al. (2013) (i.e. chapter 3) employed.

In both cases, a discretized state space of dimensions $\overline{s}$ by $\overline{s}$ is first generated where the time paths of w_t and g_t are known and grow at the fixed rates κ_w and κ_g, respectively. Next, two investment matrices of D_{1t} and D_{2t} are generated, expanding the feasible matrix dimensions to $2\overline{s}$ by $2\overline{s}$. These state and investment matrices are then used to generate a landfill depletion rate matrix by solving for the terminal values of θ_T provided the landfill state terminal condition $c_{T+1} = d_{T+1} + D_{1(T+1)}\big(1 - \pi\big)z_{T+1}$. These values are in turn used to calculate all other choice variables.

All choice variables then feed into our generated terminal value matrix V_T, which provides utility values from any possible state in period T to state values of zero in period $T + 1$. With the final period's value function known, the model is stepped back one period to $T - 1$ and determine the optimal θ_{T-1} for each state s_{T-1}. These optimal decisions are added to the discounted V_T to provide values for V_{T-1}. The process in continued until $t = 1$.

Through this backward recursion process, optimal recycling subsidies for each state, recycling case, and investment case in each time period to simulate landfill state depletion over time are collected. The simulation process begins with $\bar{s} = s_1$. Then using the optimal recycling subsidy matrix, an optimal state depletion path is formed. It uses the thought that investment is irreversible. Once the investment is made, then there is no going back to the non-investment strategy depletion path. The results for each recycling case are presented in the following section.

4.4 Numerical Solution Results

In this section, the model is simulated with non-calibrated parameters. The parameters are then varied to reflect how changes to the model parameters can alter the time of investment in WTE technologies. The model was simulated using the parameters shown in Table 4.1.

Table 4.1: Numerical Model Parameters - Investment Model

Parameter	Parameter Value	Parameter Definitions
α	0.7	*Consumption's share of utility*
β	0.25	*Leisure's share of utility*
σ_c	50	*Subsistence level on consumption*
σ_ℓ	0.1	*Subsistence level on leisure*
σ_d	0	*Subsistence level on deposit-refund quantities*
h	1	*Time available in a given period*
δ	0.001	*Per unit time to recycle via deposit-refund system*
ψ	0.001	*Rate at which excess regulator budget is received*
$\overline{s}$	50	*Initial amount of available landfill space*
w_0	70	*Initial household wage*
g_0	1000	*Initial regulator budget*
κ_w	0.021	*Household wage growth rate*
κ_g	0.021	*Regulator budget growth rate*
π	0.15	*Landfill space decline rate under investment*
P_p	5	*Per unit benefit from WTE power generation*
η	1.5	*Fixed cost of investment*
ω	.25	*Variable cost coefficient on WTE power generation*
ρ	0.91	*Discount factor (discount rate $r = 0.1$)*

Figure 4.1, the base case, illustrates the time paths of available landfill space, investment in WTE technologies, and consumption. Consumption follows the presumed time path under exogenously growing wages, as shown in subsection 4.2.1. Landfill depletion occurs as expected post-investment, reflecting a similar curve to that illustrated in the previous chapter. It depletes in a concave manner based on the evolution of marginal utility, marginal costs, and the shadow price on landfill space.

Figure 4.1 reflects a drop in available landfill space from the initial period to the time of investment. This is attributed to the fixed cost of investment, as well as the variable costs associated with operating and maintaining the investment. The more the costly the investment, the less excess regulator budget is available, thus reducing the amount of available budget to subsidize recycling. With this lack of funding for recycling, less recycling is performed by the household. In terms of shares of regulator spending, before investment, regulator spending is solely devoted to recycling, as there is no power generation to consider

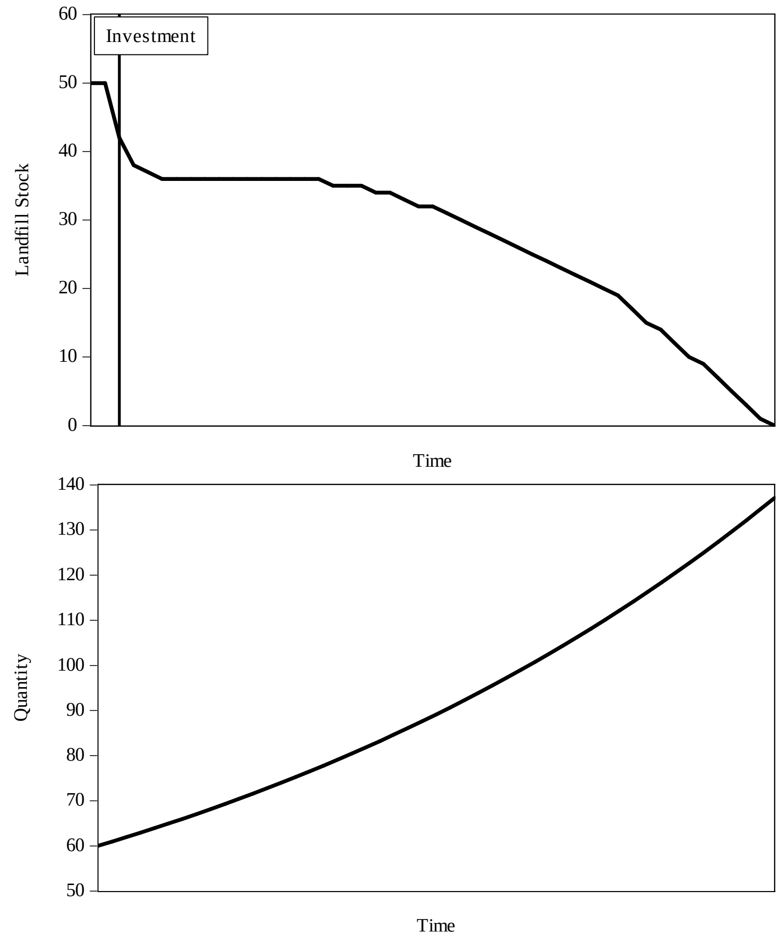

Figure 4.1: Landfill Depletion and Consumption Time Paths Under Investment

(see Figure 4.2). In the period of investment, there is a sharp change in regulator spending, where the percent of spending on recycling goes from 100 percent (i.e. no funds spent on WTE technologies) to near negligible amounts once an investment in WTE technologies is made.[29]

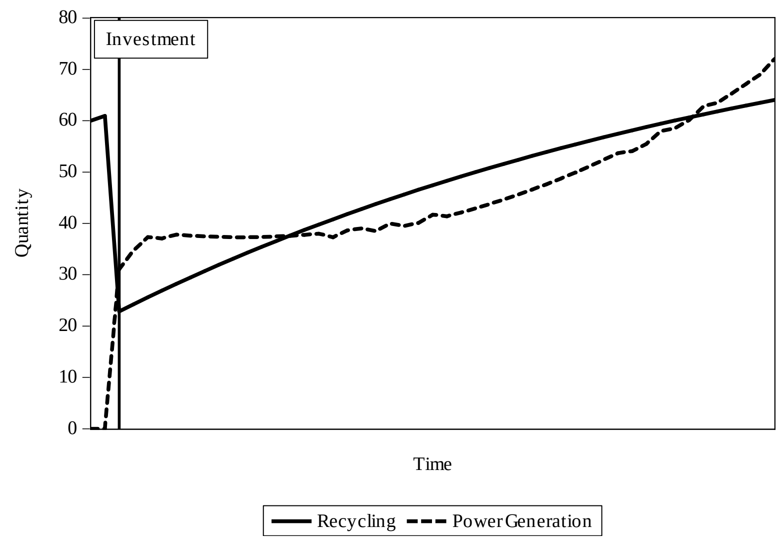

Figure 4.2: Power Generation and Recycling Quantities

Less time spent recycling allows the household to supply more labor and devote more time to leisure activities. While Figure 4.3 shows a decline over time in the household's time allocated to supplying labor, it is higher than if no investment were to occur. It declines due to increasing wages, which require less labor to maintain the presumed consumption time path. Declining labor thus allows more time for the household to dedicate towards leisure and recycle activities, but at decreasing rates.

In scenarios where initial wages w_0 are lower relative to the base case, investment generally occurs in a later period. This is because the regulator's budget is sufficient enough to fully subsidize recycling based on the low household wages. With the recycling subsidy able to offset landfill space depletion, it is possible that no investment in WTE is required to supplement the recycling policy. If however, the regulator has a large budget initially g_0,

[29]The percent goes to near zero because of the assumed convexity in the cost function.

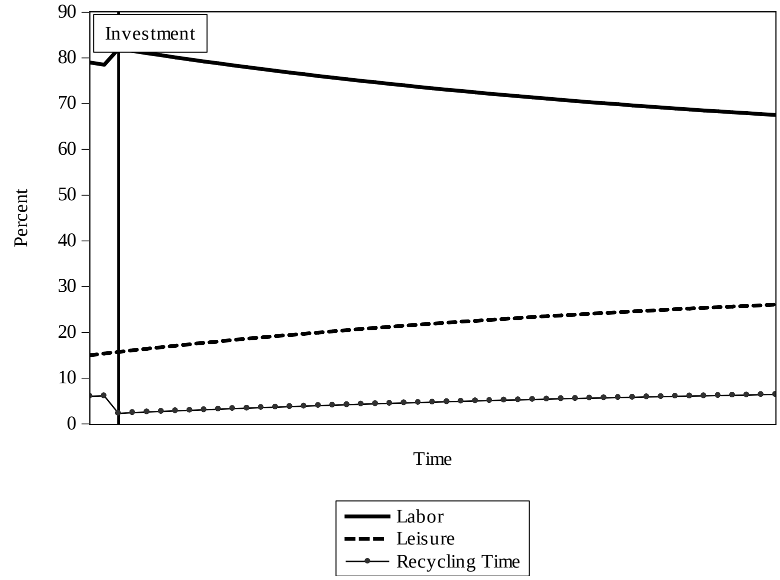

Figure 4.3: Labor, Leisure, and Recycling Shares

then it is possible that there will not be any change in the time of investment. If the regulator's budget is at an efficient allocation based on the given fixed cost η, the variable costs of generation $\omega\big(1-\pi\big)z_t^2/2$, and the price received for "cleaner" power generation P_p, then investment cannot occur any earlier or later than the base case. In other words, there is a threshold where it does not matter how much regulator budget is available, because there will be an optimal time of investment due to the shadow price on landfill space and an efficient allocation of regulator spending. The difference is in discounted utility, which will be higher in these cases compared to the base case. Contrastingly, in extremely low regulator budget scenarios, it is possible for the investment to never take place, as there simply is not enough funding to justify the investment.

Results may vary in scenarios where growth rates of wages κ_w and regulator budget κ_g are altered and unequal. When $\kappa_w > \kappa_g$, results can either be unchanged or yield a later time of investment relative to the base case. This depends on how much exogenous regulator budget is initially available. If the regulator has enough exogenous budget to subsidize recycling for some time, invariant to the rate at which wages rise, then it is possible for the regulator to fully subsidize recycling for a longer period of time. Similarly when $\kappa_w < \kappa_g$, it is possible for an earlier investment time where the regulator can capture the added benefits from the WTE investment earlier since its budget rises faster than wages. This excess budget can be chosen to accumulate at rate ψ, or be invested in WTE technologies to receive rate P_p from "cleaner" energy generation while paying out the fixed cost and the variable costs of operating and maintaining the investment.

The results pertaining to the financial aspects of WTE investments are not surprising. Higher per unit prices received from generating WTE power P_p yield an earlier investment time. Additionally, a higher fixed cost η and a higher coefficient on the variable costs of generation ω push out the time of investment. In certain parameter combinations, it may be optimal for the regulator to not invest in WTE technologies, depending on the costs of opening, operating, and maintaining the investment.

4.5 Implications for Public Policy

From the previous section, it was shown that a recycling policy, such as a DR system, combined with an investment opportunity in WTE technologies can work together to achieve the same goal of slowing landfill space depletion. One of the major concerns with the WTE technology concept is that it is said to promote consumption to make the investment economically justifiable. This model showed that even under exogenously growing wages and consequently growing consumption, recycling policies and WTE investments can be used as complements to offset consumption and ultimately landfill space deletion. Yet what does this mean for policymakers in terms of recycling rates and social welfare under communities faced with restricted landfill space?

It means that policymakers should look to incorporate WTE technologies with recycling policies, provided the goal is to slow landfill depletion and maximize social welfare by supplementing municipality income. The investment should be made if the net monetary benefits received from "cleaner" power generation are sufficient enough to outweigh the monetary benefits households receive when the regulator subsidizes recycling, and the "warm glow" effects that households receive from knowing they are recycling. Investing in such technologies

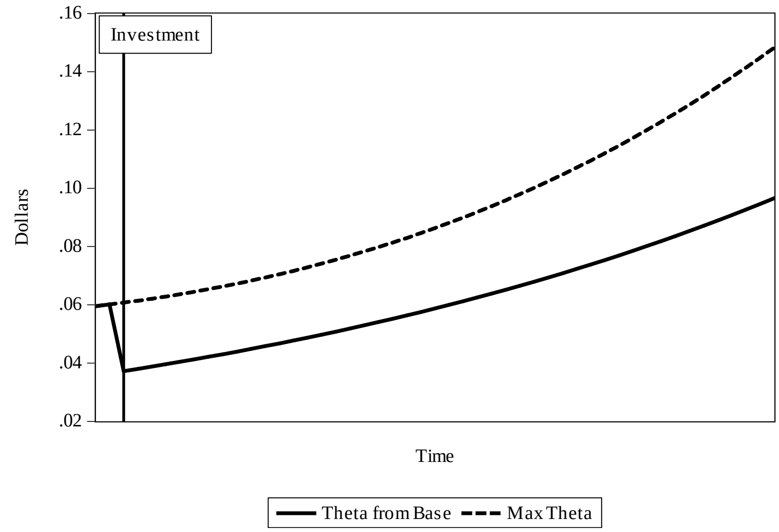

Figure 4.4: Cash Refunds - Base Case and Maximum Case

allow for a policymaker to not have to maintain the cash refund as much (see Figure 4.4). A policymaker can instead utilize its funds to invest in WTE technologies, which provide the added benefit of "cleaner" power generation as well as a pecuniary benefit. This of course has a negative impact on recycling rates (see Figure 4.5). Using the excess budget to invest in WTE technologies yields lower recycling rates than otherwise would have been if all regulator budget was used to subsidize recycling. Therefore, there is a tradeoff between the two landfill space saving methods.

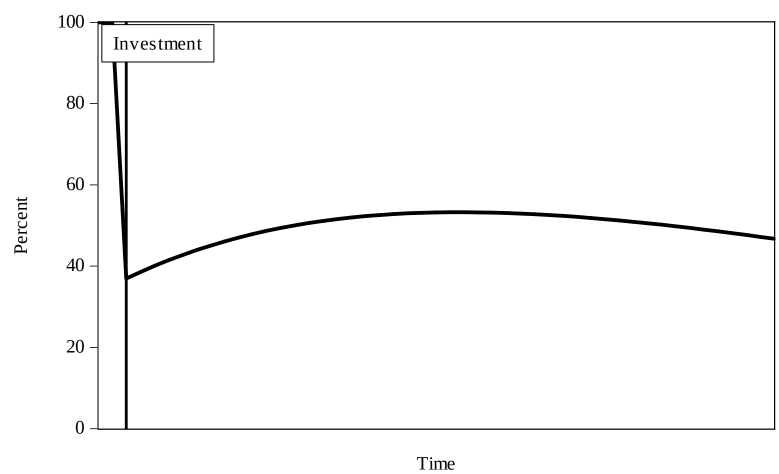

Figure 4.5: Recycling Rates from Base Case

The pecuniary benefit received from selling the power generated by the WTE investment can be used by a policymaker to supplement its income. In theory, the more income a municipality has, the less it requires income from sources such as city/state taxes paid by households. The model in this chapter assumes that the cost of power to the household is embedded in consumption. Therefore, it would be appropriate to look into alternative power generation means to observe when investment in this backstop power technology should occur. The added income from selling WTE power as a percentage of the regulator's exogenously growing budget is illustrated in Figure 4.6.

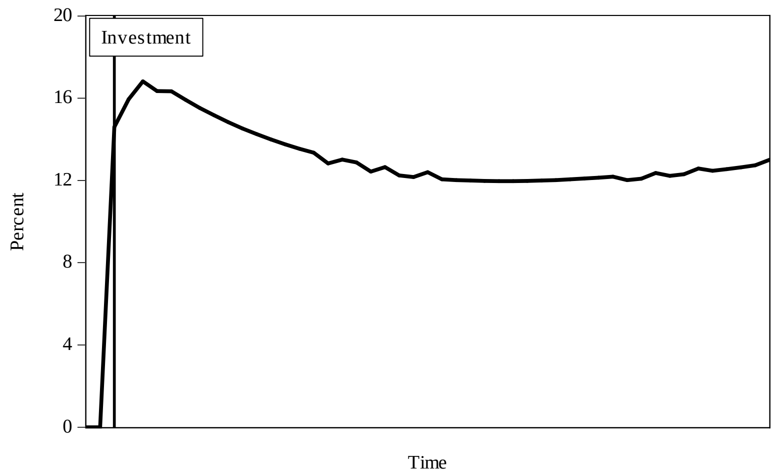

Figure 4.6: Percent Additions of Power Generation to Regulator Budget from Base Case

As regulator budget g_0 increases, the supplemental income from power generation will yield somewhat of a convex function based on the allowable amount of incineration of waste. Again, this model does not account for fuel switching, but it does provide insight to potential power available. It reflects how much can be burned given the fixed percentage $\left(1 - \pi\right)$. Using this percentage, the model can provide policymakers with the fundamentals that will help determine whether or not the investment is economically feasible given its associated prices and costs. If the current costs of maintaining such a plant are high relative to the potential revenues generated, where the cost is more than a substitutable power source, then no investment might be socially optimal. This is a concept that all policymakers are familiar with. However, policymakers are to ensure that these net benefits outweigh the "warm glow" households receive from recycling plus the pecuniary benefit they receive from recycling via the DR system. In a low income municipality, the pecuniary benefits from recycling might be a large portion of the household's total income. Therefore, an optimal investment strategy could in fact be not to invest in WTE technologies.

The decision to invest is also dependent on how much landfill space is available. With small landfill sizes, the initial shadow price on landfill space is higher than in scenarios with large landfill sizes. In order to make the more constrained landfill spaces economical, due to the shadow price, either the price at which "cleaner" energy is sold must increase or the operating and maintenance costs must decrease. Again, this model does not account for substitution of power generation. Therefore, price changes have no effect on the type of power generated and sold.

Lastly, and as more of a side-note, suppose costs of operating and maintaining the investment decrease over time, similar to what a learning curve would yield.[30] Knowing that costs will decrease and prices will remain constant (i.e. more net benefit over time) yields an earlier time of investment such that these increasing net benefits are captured in subsequent periods (see Figure 4.7). In other words, this could be thought of as an initial subsidy to an infant industry, where the subsidy helps WTE technologies become cost competitive with other power sources such as coal, oil, and natural gas.

4.6 Concluding Remarks

This chapter examined how a regulator of a municipality or state should subsidize recycling and/or invest in WTE technologies based on the actions of a private utility maximizing household. Previous arguments have stated that investment in WTE technologies and recycling can have counterproductive efforts, while other say they can work together. Under the

[30]This simulation does not fully account for any of the complexities that infant industry arguments or learning curves truly have on WTE investments. It simply shows that given the expectation that costs decrease over time, it is in a policymaker's best interest to capitalize on the increasing net benefits to maximize social welfare.

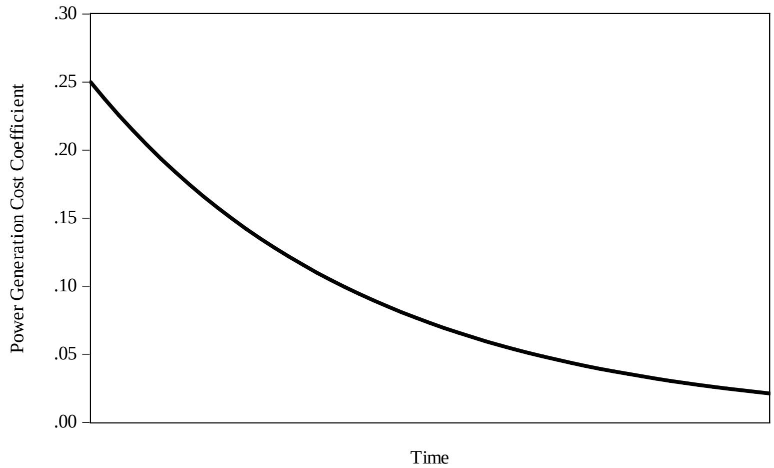

Figure 4.7: Decreasing Cost of Operating and Maintaining the Investment

assumptions of this model, an investment in WTE technologies may have a negative impact on municipal recycling programs. The two, however, work together to achieve an optimal depletion path that maximizes social welfare. Like all investments, early investment and no investment scenarios depend on the incurred costs and received benefits of the investment. This chapter also confirmed that WTE investments do require a certain level of consumption to be performed to make the technology investment economical relative to their fixed capital costs and variable costs of operating and maintaining the investment.

Future research would be to expand this foundational study to incorporate sorting at WTE plants, such that investments in technologies can promote recycling. Other possible areas for future research would be to allow for an alternative power generation source (e.g. non-renewables). With WTE technologies being both a backstop waste technology and backstop means of power generation, it would be advantageous to include the infant industry argument with a learning curve to get WTE technologies cost competitive with alternative sources. Lastly, it might be worthwhile to use this model as a foundation for a double-dividend study. A society could receive benefits from the "cleaner" energy source, while the regulator receives monetary benefits from selling the power or taxing the non-renewable energy source, resulting in reductions of city/state taxes that households pay.

CHAPTER 5
CONCLUSION

Recycling policies have traditionally been analyzed using either survey-based or theoretic methodologies. While the research presented in this dissertation does contain theoretic methods, it provides a new perspective on how policies and investments in waste reduction affect a household's decision to recycle and by which method over time. By impacting the behavioral element, a municipality can fully realize the total social benefits provided by recycling and waste-to-energy technologies (e.g. reducing the waste going to landfills and emitting "cleaner" emissions through alternative power generation methods). The recommendations emphasized in this dissertation can provide policymakers with a general framework of how to think about waste management over time.

Chapter 2 provided empirical backing to previous literature that cash refunds positively influence recycling and redemption rates. It also estimated the opportunity cost of recycling to be equivalent to per capita personal income in order to hone in on the declining beverage container recycling and redemption rate time periods. Furthermore, this chapter explained how simply adjusting the cash refund for inflation, or for income changes, can alter a household's decision to recycle via the deposit-refund system; allowing a municipality to better internalize the potential benefits to be gained from recycling.

Next, chapter 3 simultaneously evaluated two mainstream recycling policies to suggest how a regulator should allocate its budget over time as wages rise (similar to the inflation explanation of chapter 2) and given a fixed amount of landfill space. It theoretically proved that optimal recycling policies should consider a municipality's economic demographics and available landfill space. Under various conditions, it was shown that a municipality should subsidize the deposit-refund system provided wages are less than some threshold, and change its mix of subsidy over time as wages rise. The change in mix occurred for two reasons, the regulator was unable to keep pace with inflation or rising wages to make the cash refund worthwhile to the household, and the household prefers convenience over cash as wages rise due to the increasing opportunity costs of not working.

Finally, chapter 4 provided suggestions for when an investment in waste-to-energy technologies should be carried out given increases to household wages, a fixed amount of landfill space, and an available recycling policy. Under a designated regulator budget, this chapter theoretically favored the argument that recycling and investment in waste-to-energy technologies have opposing forces in terms of recycling rates. It however, did not account for the potential of these technologies to sort out recyclable material. This resulted in investments beyond a point where the net benefits from the waste-to-energy investment exceed the pecuniary and non-pecuniary benefits received from recycling. During the time of investment, financial resources are taken away from subsidy capital that could be allocated to maintaining recycling policies. Furthermore, it is shown that for these investments to be economical, there must be a certain amount of non-recycled consumption material to justify the costs associated with building, operating, and maintaining a WTE plant.

This thesis not only contributes to waste management policy design, but offers computational and empirical methods that have yet to be fully developed in the environmental economics literature. Simply implementing a recycling policy will essentially not allow for realization of the full potential these policies have to offer given the externalities of landfill scarcity and greenhouse gas emissions. To capture the full benefits, the regulator of a municipality must adjust the policies over time to account for inflation and rising wages. Lastly, this thesis provides the framework and model for calibration to a specific municipality, and allows for further exploration on the waste-to-energy investment front.

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APPENDIX A - ADDITIONAL FORMULATIONS

A.1 Additional Formulations for Chapter 3

The post-depletion problem and first order conditions are proved below with the additional assumption $\sigma_c = \sigma_\ell = 0$. Recall that this problem is the sum of all utility when $s_t = 0$ and all that is consumed must be recycled $c_t = b_t + d_t$.

$$\begin{aligned}\Phi_{T+1} =& \max_{\gamma_t,\,\theta_t} \Bigg\{ \alpha ln\big[b_t^* + d_t^* - \sigma_c\big] + \beta ln\big[\ell_t^* - \sigma_\ell\big] + \phi ln\big[b_t^*\big] + \xi ln\big[d_t^*\big] + \dots \\ & \psi\Big(g_t - \theta_t d_t^* - \frac{\upsilon}{\gamma_t}\Big) + \mu_{1t}\big(\overline{\theta}_t - \theta_t\big) + \mu_{2t}\big(\gamma_t - \underline{\gamma_t}\big)\Bigg\}\end{aligned} \tag{A.1}$$

$$\begin{aligned}\frac{\partial \Phi_{T+1}}{\partial \gamma_t} =& \frac{\alpha\phi\big(\theta_t - \delta w_t\big)\big(-\sigma_c + \big(h - \sigma_\ell\big)w_t\big)}{\gamma_t\big(\phi\big(\theta_t + \big(-\delta + \gamma_t\big)w_t\big)\big(\sigma_c + \big(-h + \sigma_\ell\big)w_t\big) - \varsigma\big(\gamma_t,\, \theta_t,\, w_t\big)\big)} + \dots \\ & \mu_{2t} - \frac{\phi}{\gamma_t} + \frac{\psi\upsilon}{\gamma_t^2}\end{aligned} \tag{A.2}$$

$$\begin{aligned}\frac{\partial \Phi_{T+1}}{\partial \theta_t} =& \frac{-\alpha\gamma_t\xi w_t\big(\sigma_c + \big(-h + \sigma_\ell\big)w_t\big)}{\big(\theta_t - \delta w_t\big)\big(-\phi\big(\theta_t + \big(-\delta + \gamma_t\big)w_t\big)\big(\sigma_c + \big(-h + \sigma_\ell\big)w_t\big) + \varsigma\big(\gamma_t,\, \theta_t,\, w_t\big)\big)} - \dots \\ & \mu_{1t} + \frac{\xi}{\theta_t - \delta w_t} + \frac{\delta\xi\psi w_t\big(\sigma_c + \big(-h + \sigma_\ell\big)w_t\big)}{\big(\theta_t - \delta w_t\big)^2}\end{aligned} \tag{A.3}$$

where $\varsigma = \gamma_t w_t\big(\big(-1 + \alpha + \beta\big)\big(h - \sigma_\ell\big)w_t - \sigma_c\big(-1 + \alpha + \beta + \theta_t - \delta w_t\big)\big)$.

A.2 Additional Formulations for Chapter 4

The post-depletion problem and first order conditions are proved below with the additional assumption $\sigma_c = \sigma_\ell = 0$. Recall that this problem is the sum of all utility when $s_t = 0$ and all that is consumed must be recycled, burned for power generation, or some combination of the two $c_t = d_t + D_{1t}\big(1 - \pi\big)z_t$.

$$\Phi_{T+1} = \max_{\theta_t,\, z_t} \Big\{ \alpha ln\big[d_t^* + \big(1-\pi\big)z_t - \sigma_c\big] + \beta ln\big[\ell_t^* - \sigma_\ell\big] + \big(1-\alpha-\beta\big) ln\big[d_t^*\big] + \ldots$$

$$\psi\Big(g_t - \theta_t d_t^* + D_{1t}\Big(P_p\big(1-\pi\big)z_t - \omega\frac{\big(1-\pi\big)z_t^2}{2}\Big) - D_{2t}\eta\Big) + \mu_{1t}\big(\overline{\theta}_t - \theta_t\big)\Big\} \tag{A.4}$$

$$\frac{\partial \Phi_{T+1}}{\partial \theta_t} = \frac{\alpha\big(-1+\alpha+\beta\big)\big(\sigma_c + \big(-h+\sigma_\ell\big)w_t\big)}{\big(\theta_t - \delta w_t\big)\big(\big(-1+\alpha+\beta\big)\big(\sigma_c + \big(-h+\sigma_\ell\big)w_t\big) + \big(-1+\pi\big)\big(\theta_t - \delta w_t\big)z_t\big)} - \ldots$$

$$\mu_{1t} + \frac{-1+\alpha+\beta}{\theta_t - \delta w_t} - \frac{\big(-1+\alpha+\beta\big)\delta\psi w_t\big(\sigma_c + \big(-h+\sigma_\ell\big)w_t\big)}{\big(\theta_t - \delta w_t\big)^2} \tag{A.5}$$

$$\frac{\partial \Phi_{T+1}}{\partial z_t} = -D_{1t}\big(-1+\pi\big)\psi\big(P_p - \omega z_t\big) + \ldots$$

$$\frac{\alpha\big(1-\pi\big)\big(-\theta_t + \delta w_t\big)}{\big(-1+\alpha+\beta\big)\big(\sigma_c + \big(-h+\sigma_\ell\big)w_t\big) + \big(-\theta_t + \delta w_t\big)\big(z_t - \pi z_t\big)} \tag{A.6}$$

APPENDIX B - ADDITIONAL EQUATIONS

B.1 Additional Equations for Chapter 3

$$\varrho = -\xi w_t\big(4\lambda_{2t}\phi\theta_t\big(-\xi-\lambda_{1t}\theta_t\big)+\big(-\xi\phi\big(\phi-4\delta\big(\lambda_{2t}+\lambda_{2t}\psi\sigma_c\big)\big)+\ldots \\ 8\delta\lambda_{1t}\lambda_{2t}\phi\theta_t+4\lambda_{2t}\xi\psi\upsilon\big)w_t-4\delta\lambda_{2t}\phi\big(\delta\lambda_{1t}+\xi\psi\big(h-\sigma_\ell\big)\big)w_t^2\big) \tag{B.1}$$

$$\varphi = \sqrt{-\xi}\sqrt{\phi^2-4\lambda_{1t}\big(\gamma_t^2\lambda_{2t}+\psi\upsilon\big)w_t+\phi\big(-1+\alpha+\beta+4\lambda_{1t}w_t\big(\gamma_t-\ldots} \\ \overline{\delta\psi\big(\sigma_c-hw_t+\sigma_\ell w_t\big)\big)\big)} \tag{B.2}$$

$$\nu = \big(\sigma_c+\big(-h+\sigma_\ell\big)w_{t+1}\big)\big(4\delta\lambda_{1t}\xi\psi\sigma_c^2\big(w_t-\rho w_{t+1}\big)+\sigma_c\big(1-2\alpha+\ldots \\ \alpha^2-2\beta+2\alpha\beta+\beta^2-2\phi+2\alpha\phi+2\beta\phi+\phi^2+4\lambda_{1t}\rho\theta_{t+1}-\ldots \\ 4\alpha\lambda_{1t}\rho\theta_{t+1}-4\beta\lambda_{1t}\rho\theta_{t+1}-4\lambda_{1t}\phi\rho\theta_{t+1}-4\lambda_{1t}\lambda_{1,t+1}\rho\theta_{t+1}^2-\ldots \\ 4\delta h\lambda_{1t}\psi w_t^2+4\alpha\delta h\lambda_{1t}\psi w_t^2+4\beta\delta h\lambda_{1t}\psi w_t^2+4\phi\delta h\lambda_{1t}\psi w_t^2+\ldots \\ 4\delta\lambda_{1t}\psi\sigma_\ell w_t^2-4\alpha\delta\lambda_{1t}\psi\sigma_\ell w_t^2-4\beta\delta\lambda_{1t}\psi\sigma_\ell w_t^2-4\delta\lambda_{1t}\phi\psi\sigma_\ell w_t^2-\ldots \\ 4\delta\lambda_{1t}\big(-\rho\big(-\xi-2\lambda_{1,t+1}\theta_{t+1}\big)+\big(-\xi\big)\psi\big(-1+\rho\big)\big(h-\sigma_\ell\big)w_t\big)w_{t+1}+\ldots \\ 4\delta\lambda_{1t}\rho\big(\delta\lambda_{1,t+1}+\big(-\xi\big)\psi\big(-h+\sigma_\ell\big)\big)w_{t+1}^2\big)+\big(h-\sigma_\ell\big)\big(-\big(-\xi\big)^2w_{t+1}+\ldots \\ 4\lambda_{1t}w_t\big(\delta\xi\psi\big(h-\sigma_\ell\big)w_tw_{t+1}+\rho\big(-\lambda_{1,t+1}\theta_{t+1}^2+\theta_{t+1}\big(-\xi+\ldots \\ 2\delta\lambda_{1,t+1}w_{t+1}\big)-\delta w_{t+1}\big(-\xi+\big(\delta\lambda_{1,t+1}+\big(-\xi\big)\psi\big(-h+\sigma_\ell\big)\big)w_{t+1}\big)\big)\big)\big)\big) \tag{B.3}$$

$$
\begin{aligned}
\iota =& \lambda_{1,t+1}^2\big(-\xi\big)w_t\big(\sigma_c+\big(-h+\sigma_\ell\big)w_{t+1}\big)\big(2\lambda_{1t}\lambda_{2t}\rho\big(\sigma_c+\big(-h+\sigma_\ell\big)w_t\big)\big(-\phi^3+\ldots\\
& 2\big(-1+\alpha+\beta\big)\lambda_{1,t+1}\big(\gamma_{t+1}\lambda_{2,t+1}+\psi\upsilon\big)w_{t+1}+\phi\big(-\big(-1+\alpha+\beta\big)^2+\ldots\\
& 2\lambda_{1,t+1}\big(\gamma_{t+1}-\gamma_{t+1}\big(\alpha+\beta-\gamma_{t+1}\lambda_{2,t+1}\big)+\big(-1+\alpha+\beta\big)\delta\big(-1+\ldots\\
& \psi\sigma_c\big)+\psi\upsilon\big)w_{t+1}-2\delta\lambda_{1,t+1}\big(\delta\lambda_{1,t+1}+\big(-1+\alpha+\beta\big)\psi\big(h-\sigma_\ell\big)\big)w_{t+1}^2\big)-\ldots\\
& 2\phi^2\big(-1+\alpha+\beta+\lambda_{1,t+1}w_{t+1}\big(\delta+\gamma_{t+1}-\delta\psi\sigma_c+\delta\psi\big(h-\sigma_\ell\big)w_{t+1}\big)\big)+\ldots\\
& \frac{\phi^{1.5}\sqrt{-\xi}\sqrt{\phi^2-4\lambda_{1,t+1}\big(\gamma_{t+1}^2\lambda_{2,t+1}+\psi\upsilon\big)w_{t+1}+\phi\big(-1+\alpha+\beta+\ldots}}{4\lambda_{1,t+1}w_t\big(\gamma_{t+1}-\delta\psi\big(\sigma_c-hw_{t+1}+\sigma_\ell w_{t+1}\big)\big)\big)}+\sqrt{\phi}\sqrt{-\xi}\big(-1+\alpha+\beta+\ldots\\
& \frac{2\delta\lambda_{1,t+1}w_{t+1}\big)\sqrt{\phi^2-4\lambda_{1,t+1}\big(\gamma_{t+1}^2\lambda_{2,t+1}+\psi\upsilon\big)w_{t+1}+\phi\big(-1+\alpha+\beta+\ldots}}{4\lambda_{1,t+1}w_t\big(\gamma_{t+1}-\delta\psi\big(\sigma_c-hw_{t+1}+\sigma_\ell w_{t+1}\big)\big)\big)\big)}+\lambda_{1,t+1}\big(\lambda_{1,t+1}\phi^2\big(-\xi\big)w_t\big(\sigma_c+\ldots\\
& \big(-1+\sigma_\ell\big)w_{t+1}\big)-2\lambda_{2t}\big(-\phi^3\rho\big(\sigma_c+\big(-h+\sigma_\ell\big)w_t+2\big(-1+\alpha+\ldots\\
& \beta\big)\lambda_{1,t+1}\psi\upsilon w_t\big(\sigma_c+\big(-h+\sigma_\ell\big)w_{t+1}\big)+\phi\big(2\lambda_{1,t+1}\psi\upsilon w_t\big(\sigma_c-hw_{t+1}+\ldots\\
& \sigma_\ell w_{t+1}\big)+\rho\big(\sigma_c-hw_t+\sigma_\ell w_t\big)\big(-\big(-1+\alpha+\beta\big)^2+2\big(-1+\alpha+\ldots\\
& \beta\big)\delta\lambda_{1,t+1}\big(-1+\psi\sigma_c\big)w_{t+1}-2\delta\lambda_{1,t+1}\big(\delta\lambda_{1,t+1}+\big(-1+\alpha+\ldots\\
& \beta\big)\psi\big(h-\sigma_\ell\big)\big)w_{t+1}^2\big)\big)+2\phi^2\rho\big(\sigma_c+\big(-h+\sigma_\ell\big)w_t\big)\big(1-\alpha-\beta+\ldots\\
& \delta\lambda_{1,t+1}w_{t+1}\big(-1+\psi\big(\sigma_c-hw_{t+1}+\sigma_\ell w_{t+1}\big)\big)\big)+\phi^{1.5}\sqrt{-\xi}\rho\big(\sigma_c+\ldots\\
& \frac{\big(-h+\sigma_\ell\big)w_t\sqrt{\phi^2-4\lambda_{1,t+1}\big(\gamma_{t+1}^2\lambda_{2,t+1}+\psi\upsilon\big)w_{t+1}+\phi\big(-1+\alpha+\beta+\ldots}}{4\lambda_{1,t+1}w_{t+1}\big(\gamma_{t+1}-\delta\psi\big(\sigma_c-hw_{t+1}+\sigma_\ell w_{t+1}\big)\big)\big)\big)}+\sqrt{\phi}\sqrt{-\xi}\rho\\
& \frac{\big(\sigma_c+\big(-h+\sigma_\ell\big)w_t\big(-1+\alpha+\beta+2\delta\lambda_{1,t+1}w_{t+1}\big)\sqrt{\phi^2-4\lambda_{1,t+1}\big(\gamma_{t+1}^2\lambda_{2,t+1}+\ldots}}{\psi\upsilon\big)w_{t+1}+\phi\big(-1+\alpha+\beta+4\lambda_{1,t+1}w_{t+1}\big(\gamma_{t+1}-\delta\psi\big(\sigma_c-hw_{t+1}+\sigma_\ell w_{t+1}\big)\big)\big)\big)\big)\big)\big)}
\end{aligned} \tag{B.4}
$$

B.2 Additional Equations for Chapter 4

$$\chi = \sqrt{-1+\alpha+\beta}\sqrt{-1+\alpha+\beta-4\lambda_{1t}\psi\big(\sigma_c - hw_t + \sigma_\ell w_t\big)\big(P_p + \delta w_t - \omega z_t\big)} \tag{B.5}$$

$$\begin{aligned}
\tau =& \big(\sigma_c + \big(-h+\sigma_\ell\big)w_{t+1}\big)\big(-4\big(-1+\alpha+\beta\big)\delta\lambda_{1t}\psi\sigma_c^2\big(w_t - \rho w_{t+1}\big) + \big(h - \ldots \\
&\sigma_\ell\big)\big(-\big(-1+\alpha+\beta\big)^2 w_{t+1} - 4\lambda_{1t}w_t\big(\big(-1+\alpha+\beta\big)\delta\psi\big(h-\sigma_\ell\big)w_t w_{t+1} + \ldots \\
&\rho\big(\lambda_{1,t+1}\theta_{t+1}^2 - \theta_{t+1}\big(-1+\alpha+\beta+2\delta\lambda_{1,t+1}w_{t+1}\big) + \delta w_{t+1}\big(-1+\alpha+\ldots \\
&\beta + \delta\lambda_{1,t+1}w_{t+1} + h\psi w_{t+1} - \alpha h\psi w_{t+1} - \beta h\psi w_{t+1} - \psi\sigma_\ell w_{t+1} + \ldots \\
&\alpha\psi\sigma_\ell w_{t+1} + \beta\psi\sigma_\ell w_{t+1}\big)\big)\big)\big) + \sigma_c\big(1+\alpha^2+\beta^2+4\lambda_{1t}\rho\theta_{t+1} + \ldots \\
&4\lambda_{1t}\lambda_{1,t+1}\rho\theta_{t+1}^2 - 4\delta h\lambda_{1t}\psi w_t^2 + 4\delta\lambda_{1t}\psi\sigma_\ell w_t^2 - 4\delta\lambda_{1t}\rho w_{t+1} - \ldots \\
&8\delta\lambda_{1t}\lambda_{1,t+1}\rho\theta_{t+1}w_{t+1} - 4\delta h\lambda_{1t}\psi w_t w_{t+1} + 4\delta h\lambda_{1t}\psi\rho w_t w_{t+1} + \ldots \\
&4\delta\lambda_{1t}\psi\sigma_\ell w_t w_{t+1} - 4\delta\lambda_{1t}\psi\rho\sigma_\ell w_t w_{t+1} + 4\delta^2\lambda_{1t}\lambda_{1,t+1}\rho w_{t+1}^2 + \ldots \\
&4\delta h\lambda_{1t}\psi\rho w_{t+1}^2 - 4\delta\lambda_{1t}\psi\rho\sigma_\ell w_{t+1}^2 + \beta\big(-1-4\lambda_{1t}\big(-\delta\psi\big(h - \ldots \\
&\sigma_\ell\big)w_t\big(w_t + w_{t+1}\big) + \rho\big(\theta_{t+1} + \delta w_{t+1}\big(-1+h\psi\big(w_t+w_{t+1}\big) - \ldots \\
&\psi\sigma_\ell\big(w_t+w_{t+1}\big)\big)\big)\big)\big)\big) + 2\alpha\big(-1+\beta-2\lambda_{1t}\big(-\delta\psi\big(h-\sigma_\ell\big)w_t\big(w_t + \ldots \\
&w_{t+1}\big) + \rho\big(\theta_{t+1} + \delta w_{t+1}\big(-1+h\psi\big(w_t+w_{t+1}\big) - \psi\sigma_\ell\big(w_t+w_{t+1}\big)\big)\big)\big)\big)\big)\big)
\end{aligned} \tag{B.6}$$

APPENDIX C - CODE

C.1 Code for Chapter 2 Using Regression Analysis of Time Series (RATS)

```
*Checking to make sure all was imported correctly
print / red_rate cash_refund sc_members pcpi gas_price
*Calculate Sierra Club Members as percent of the population
set sc_pop = sc_members/population*100
*Rebasing dollar terms into 2010 USD
set real_cash_refund = cash_refund/cpi2010
set real_pcpi = pcpi/cpi2010
set real_gas_price = gas_price/cpi2010
*Logging the data
set lred_rate = log(red_rate)
set lreal_cash_refund = log(real_cash_refund)
set lsc_pop = log(sc_pop)
set lreal_pcpi = log(real_pcpi)
set lreal_gas_price = log(real_gas_price)
*Differencing the data
set dlred_rate = lred_rate - lred_rate{1}
set dlreal_cash_refund = lreal_cash_refund - lreal_cash_refund{1}
set dlsc_pop = lsc_pop - lsc_pop{1}
set dlreal_pcpi = lreal_pcpi - lreal_pcpi{1}
set dlreal_gas_price = lreal_gas_price - lreal_gas_price{1}
*Descriptive statistics in levels
statistics red_rate
statistics real_cash_refund
statistics real_pcpi
statistics real_gas_price
statistics sc_pop
table / red_rate real_cash_refund real_pcpi real_gas_price sc_pop
*Descriptive statistics in logs
statistics lred_rate
statistics lreal_cash_refund
statistics lreal_pcpi
statistics lreal_gas_price
statistics lsc_pop
table / lred_rate lreal_cash_refund lreal_pcpi lreal_gas_price lsc_pop
*Im, Pesaran and Shin Unit root tests on log-levels
@ipshin(crit=aic,title="IPS Unit Root Test: Log Red Rate w/ Constant")
   lred_rate
@ipshin(crit=aic,title="IPS Unit Root Test: Log Real Cash Refund w/
   Constant") lreal_cash_refund
@ipshin(crit=aic,title="IPS Unit Root Test: Log Real PCPI w/ Constant")
    lreal_pcpi
```

```
@ipshin(crit=aic,title="IPS Unit Root Test: Log Real Gas Price w/
   Constant") lreal_gas_price
@ipshin(crit=aic,title="IPS Unit Root Test: Log SC Pop w/ Constant")
   lsc_pop
@ipshin(crit=aic,det=trend,title="IPS Unit Root Test: Log Red Rate w/
   Constant and Trend") lred_rate
@ipshin(crit=aic,det=trend,title="IPS Unit Root Test: Log Real Cash
   Refund w/ Constant and Trend") lreal_cash_refund
@ipshin(crit=aic,det=trend,title="IPS Unit Root Test: Log Real PCPI w/
   Constant and Trend") lreal_pcpi
@ipshin(crit=aic,det=trend,title="IPS Unit Root Test: Log Real Gas
   Price w/ Constant and Trend") lreal_gas_price
@ipshin(crit=aic,det=trend,title="IPS Unit Root Test: Log SC Pop w/
   Constant and Trend") lsc_pop
*Im, Pesaran and Shin Unit root tests on differenced log-levels
@ipshin(crit=aic,title="IPS Unit Root Test: DLog Red Rate") dlred_rate
@ipshin(crit=aic,title="IPS Unit Root Test: DLog Real Cash Refund")
   dlreal_cash_refund
@ipshin(crit=aic,title="IPS Unit Root Test: DLog Real PCPI")
   dlreal_pcpi
@ipshin(crit=aic,title="IPS Unit Root Test: DLog Real Gas Price")
   dlreal_gas_price
@ipshin(crit=aic,title="IPS Unit Root Test: DLog SC Pop") dlsc_pop
*Panel cointegration test - Pedroni w/ common time dummies, no trend
@pancoint(tdum)
# lred_rate lreal_cash_refund
@pancoint(tdum)
# lred_rate lreal_cash_refund lreal_pcpi
@pancoint(tdum)
# lred_rate lreal_cash_refund lreal_pcpi lreal_gas_price
@pancoint(tdum)
# lred_rate lreal_cash_refund lreal_pcpi lreal_gas_price lsc_pop
@pancoint(tdum)
# lred_rate lreal_cash_refund lreal_gas_price
@pancoint(tdum)
# lred_rate lreal_cash_refund lsc_pop
*Panel cointegration test - Pedroni w/ common time dummies and trend
@pancoint(tdum,trend)
# lred_rate lreal_cash_refund
@pancoint(tdum,trend)
# lred_rate lreal_cash_refund lreal_pcpi
@pancoint(tdum,trend)
# lred_rate lreal_cash_refund lreal_pcpi lreal_gas_price
@pancoint(tdum,trend)
# lred_rate lreal_cash_refund lreal_pcpi lreal_gas_price lsc_pop
@pancoint(tdum,trend)
# lred_rate lreal_cash_refund lreal_gas_price
```

```
@pancoint(tdum,trend)
# lred_rate lreal_cash_refund lsc_pop
*First differenced estimation
pregress(method=fd,cluster=%indiv(t)) lred_rate
# lreal_cash_refund
pregress(method=fd,cluster=%indiv(t)) lred_rate
# lreal_cash_refund lreal_pcpi
pregress(method=fd,cluster=%indiv(t)) lred_rate
# lreal_cash_refund lreal_pcpi lreal_gas_price
pregress(method=fd,cluster=%indiv(t)) lred_rate
# lreal_cash_refund lreal_pcpi lreal_gas_price lsc_pop
pregress(method=fd,cluster=%indiv(t)) lred_rate
# lreal_cash_refund lreal_gas_price
pregress(method=fd,cluster=%indiv(t)) lred_rate
# lreal_cash_refund lsc_pop
*First differenced estimation - sample period 1990 to 2000
set panelsmpl = %period(t)>=1990:1.and.%period(t)<=2000:1
pregress(method=fd,cluster=%indiv(t),smpl=panelsmpl) lred_rate
# lreal_cash_refund
pregress(method=fd,cluster=%indiv(t),smpl=panelsmpl) lred_rate
# lreal_cash_refund lreal_pcpi
pregress(method=fd,cluster=%indiv(t),smpl=panelsmpl) lred_rate
# lreal_cash_refund lreal_pcpi lreal_gas_price
pregress(method=fd,cluster=%indiv(t),smpl=panelsmpl) lred_rate
# lreal_cash_refund lreal_pcpi lreal_gas_price lsc_pop
pregress(method=fd,cluster=%indiv(t),smpl=panelsmpl) lred_rate
# lreal_cash_refund lreal_gas_price
pregress(method=fd,cluster=%indiv(t),smpl=panelsmpl) lred_rate
# lreal_cash_refund lsc_pop
*Further exploration: Panel cointegration test - Pedroni w/out common
   time dummies and trend
@pancoint
# lred_rate lreal_cash_refund
@pancoint
# lred_rate lreal_cash_refund lreal_pcpi
@pancoint
# lred_rate lreal_cash_refund lreal_pcpi lreal_gas_price
@pancoint
# lred_rate lreal_cash_refund lreal_pcpi lreal_gas_price lsc_pop
@pancoint
# lred_rate lreal_cash_refund lreal_gas_price
@pancoint
# lred_rate lreal_cash_refund lsc_pop
*Further exploration: Panel cointegration test - Pedroni w/out common
   time dummies but w/ trend
@pancoint(trend)
# lred_rate lreal_cash_refund
```

```
@pancoint(trend)
# lred_rate lreal_cash_refund lreal_pcpi
@pancoint(trend)
# lred_rate lreal_cash_refund lreal_pcpi lreal_gas_price
@pancoint(trend)
# lred_rate lreal_cash_refund lreal_pcpi lreal_gas_price lsc_pop
@pancoint(trend)
# lred_rate lreal_cash_refund lreal_gas_price
@pancoint(trend)
# lred_rate lreal_cash_refund lsc_pop
*Further exploration: Panel FMOLS estimation
@panelfm
# lred_rate lreal_cash_refund
@panelfm
# lred_rate lreal_cash_refund lreal_pcpi
@panelfm
# lred_rate lreal_cash_refund lreal_pcpi lreal_gas_price
@panelfm
# lred_rate lreal_cash_refund lreal_pcpi lreal_gas_price lsc_pop
@panelfm
# lred_rate lreal_cash_refund lreal_gas_price
@panelfm
# lred_rate lreal_cash_refund lsc_pop
```

C.2 Code for Chapter 3 Using Matlab

The code supplied in this section includes the master, optimization, and constraint codes for chapter 3.

C.2.1 Master Code

```
%Model Parameters
T = 30;
T = floor(T);
delta = .0095;
alpha = .6;
beta = .39;
phi = .005;
upsilon = .03;
sigmaCONS = 2;
sigmaLEISURE = 0.1;
psi = .0002;
sbar = 50;
wage0 = 115;
g0 = 1000;
h = 1;
```

```
kappa_wage = .02;
kappa_g = .02;
discountrate = .1;
rho = 1/(1+discountrate);
wage = wage0*(1+kappa_wage).^[1:T]';
g = g0*(1+kappa_g).^[1:T]';

%State Space
S = (0:sbar)';
n = length(S);
St = repmat(S',n,1);
Stminusone = repmat(S,1,n);
Sdiff = St-Stminusone;

options = optimset('Algorithm','active-set','MaxIter',5000);
options.Algorithm = 'active-set';
options.MaxIter = 5000;
options.MaxFunEvals = 5000;

wageterm = wage(T,1);
gterm = g(T,1);
lbterm = 0;

ubterm = -(delta*wageterm*(sigmaCONS-alpha*sigmaCONS+alpha*(h-
    sigmaLEISURE).*wageterm))./((-h+sigmaLEISURE).*wageterm-phi*(
    sigmaCONS-h*wageterm+sigmaLEISURE*wageterm)-beta*(sigmaCONS+(-h+
    sigmaLEISURE).*wageterm));

for i=1:sbar+1
    for j=1:sbar+1
        Stterm = St(i,j);
        Stminusoneterm = Stminusone(i,j);
        thetatermGUESS = (wageterm.*(-(-1+alpha+beta+phi)*upsilon*(
            sigmaCONS+(-h+sigmaLEISURE).*wageterm)+delta*(upsilon*
            wageterm.*(sigmaCONS-alpha*sigmaCONS+Stterm-Stminusoneterm+
            alpha*(h-sigmaLEISURE).*wageterm)+gterm*phi.*(sigmaCONS-h*
            wageterm+sigmaLEISURE*wageterm)))))./(upsilon*wageterm.*(
            sigmaCONS-alpha*sigmaCONS+Stterm-Stminusoneterm+alpha*(h-
            sigmaLEISURE).*wageterm)+(-1+alpha+beta)*phi*(sigmaCONS-h*
            wageterm+sigmaLEISURE*wageterm).^2+phi^2.*(sigmaCONS-h*
            wageterm+sigmaLEISURE*wageterm).^2+gterm*phi*(sigmaCONS+(-h+
            sigmaLEISURE).*wageterm));
        thetaterm(i,j) = fmincon('MaxUtility_SGLinearEngel',
            thetatermGUESS,[],[],[],[],lbterm,ubterm,'
            GovernmentBudgetConstraint_SGLinearEngel',options,alpha,beta
            ,phi,h,delta,wageterm,gterm,Stterm,Stminusoneterm,upsilon,
            sigmaCONS,sigmaLEISURE,psi);
```

```
        end
    end

gamterm = (phi*(thetaterm-delta*wageterm).*(sigmaCONS+(-h+sigmaLEISURE)
    .*wageterm))./(wageterm.*((-1+alpha+beta+phi).*(h-sigmaLEISURE).*
    wageterm-sigmaCONS*(-1+alpha+beta+phi+thetaterm-alpha*thetaterm+(-1+
    alpha)*delta.*wageterm)-(thetaterm-delta*wageterm).*(St-Stminusone+
    alpha*(h-sigmaLEISURE).*wageterm)));

csterm = -(phi*(sigmaCONS+(-h+sigmaLEISURE).*wageterm))./(gamterm.*
    wageterm);
drterm = ((-1+alpha+beta+phi)*(sigmaCONS+(-h+sigmaLEISURE).*wageterm))
    ./(-thetaterm+delta*wageterm);
leisureterm = repmat(sigmaLEISURE+beta*(h-(sigmaCONS+sigmaLEISURE*
    wageterm)./wageterm),sbar+1,sbar+1);
laborterm = (-(beta+phi)*sigmaCONS*thetaterm+(delta*(sigmaCONS-alpha*
    sigmaCONS)+(-1+beta+phi)*(h-sigmaLEISURE).*thetaterm).*wageterm+
    alpha*delta*(h-sigmaLEISURE).*wageterm.^2)./(wageterm.*(-thetaterm+
    delta*wageterm));
consterm = repmat(sigmaCONS-alpha*sigmaCONS+alpha*(h-sigmaLEISURE)*
    wageterm,sbar+1,sbar+1);
zterm = consterm-csterm-drterm;

testgspendterm = gterm-thetaterm.*drterm-upsilon./gamterm;
testconsterm = consterm-wageterm.*laborterm-thetaterm.*drterm;
testtimeterm = h-leisureterm-laborterm-gamterm.*csterm-delta*drterm;

vterm = alpha*log(consterm-sigmaCONS)+beta*log(leisureterm-sigmaLEISURE
    )+phi*log(csterm)+(1-alpha-beta-phi)*log(drterm)+psi*(gterm-upsilon
    ./gamterm-thetaterm.*drterm);
vterm = vterm(:,1);
vterm(imag(vterm)>0) = -inf;
vmatrix = ones(length(S),1)*vterm';

for t=T-1:-1:1
    wage1 = wage(t,1);
    g1 = g(t,1);
    lb = 0;
    ub = -(delta*wage1*(sigmaCONS-alpha*sigmaCONS+alpha*(h-sigmaLEISURE
        ).*wage1))./((-h+sigmaLEISURE).*wage1-phi*(sigmaCONS-h*wage1+
        sigmaLEISURE*wage1)-beta*(sigmaCONS+(-h+sigmaLEISURE).*wage1));
    for i=1:sbar+1
        for j=1:sbar+1
            St1 = St(i,j);
            Stminusone1 = Stminusone(i,j);
            thetaGUESS = (wage1.*(-(-1+alpha+beta+phi)*upsilon*(
                sigmaCONS+(-h+sigmaLEISURE).*wage1)+delta*(upsilon*wage1
```

```
                .*(sigmaCONS-alpha*sigmaCONS+St1-Stminusone1+alpha*(h-
                sigmaLEISURE).*wage1)+g1*phi.*(sigmaCONS-h*wage1+
                sigmaLEISURE*wage1))))./(upsilon*wage1.*(sigmaCONS-alpha
                *sigmaCONS+St1-Stminusone1+alpha*(h-sigmaLEISURE).*wage1
                )+(-1+alpha+beta)*phi*(sigmaCONS-h*wage1+sigmaLEISURE*
                wage1).^2+phi^2.*(sigmaCONS-h*wage1+sigmaLEISURE*wage1)
                .^2+g1*phi.*(sigmaCONS+(-h+sigmaLEISURE).*wage1));
            theta(i,j) = fmincon('MaxUtility_SGLinearEngel',thetaGUESS
                ,[],[],[],[],lb,ub,'
                GovernmentBudgetConstraint_SGLinearEngel',options,alpha,
                beta,phi,h,delta,wage1,g1,St1,Stminusone1,upsilon,
                sigmaCONS,sigmaLEISURE,psi);
        end
    end

gam = (phi.*(theta-delta*wage1).*(sigmaCONS+(-h+sigmaLEISURE).*wage1))
    ./(wage1.*((-1+alpha+beta+phi).*(h-sigmaLEISURE).*wage1-sigmaCONS
    *(-1+alpha+beta+phi+theta-alpha*theta+(-1+alpha)*delta.*wage1)-(
    theta-delta*wage1).*(St-Stminusone+alpha*(h-sigmaLEISURE).*wage1)));

cs = -(phi*(sigmaCONS+(-h+sigmaLEISURE).*wage1))./(gam.*wage1);
dr = ((-1+alpha+beta+phi)*(sigmaCONS+(-h+sigmaLEISURE).*wage1))./(-
    theta+delta*wage1);
leisure = repmat(sigmaLEISURE+beta*(h-(sigmaCONS+sigmaLEISURE*wage1)./
    wage1),sbar+1,sbar+1);
labor = (-(beta+phi)*sigmaCONS*theta+(delta*(sigmaCONS-alpha*sigmaCONS)
    +(-1+beta+phi)*(h-sigmaLEISURE).*theta).*wage1+alpha*delta*(h-
    sigmaLEISURE).*wage1.^2)./(wage1.*(-theta+delta*wage1));
cons = repmat(sigmaCONS-alpha*sigmaCONS+alpha*(h-sigmaLEISURE)*wage1,
    sbar+1,sbar+1);
z = cons-cs-dr;
z = cons-cs-dr;

testgspend = g1-theta.*dr-upsilon./gam;
testcons = cons-wage1.*labor-theta.*dr;
testtime = h-leisure-labor-gam.*cs-delta*dr;

payoff = alpha*log(cons-sigmaCONS)+beta*log(leisure-sigmaLEISURE)+phi*
    log(cs)+(1-alpha-beta-phi)*log(dr)+psi*(g1-upsilon./gam-theta.*dr);
payoff = tril(payoff);
payoff(payoff==0) = -inf;
addedbenefit = rho*vmatrix;
value = payoff+addedbenefit;
value = tril(value);
value(value==0) = -inf;
value(imag(value)>0) = -inf;
[val row] = max(value,[],2);
```

```
        for i=1:length(S)
          gammarecords(i,t) = gam(i,row(i,1));
          thetarecords(i,t) = theta(i,row(i,1));
          zrecords(i,t) = z(i,row(i,1));
          consrecords(i,t) = cons(i,row(i,1));
          drrecords(i,t) = dr(i,row(i,1));
          leisurerecords(i,t) = leisure(i,row(i,1));
          csrecords(i,t) = cs(i,row(i,1));
          laborrecords(i,t) = labor(i,row(i,1));
        end
          rows(:,t) = row;
          vals(:,t) = val;
end

%Simulation
for t=1:1:T-1
    if t==1
          sindex = length(S);
          steeminusone = S(sindex);
          stee = S(sindex);
          gamma_sim = gammarecords(sindex,t);
          theta_sim = thetarecords(sindex,t);
          cs_sim = csrecords(sindex,t);
          dr_sim = drrecords(sindex,t);
          leisure_sim = leisurerecords(sindex,t);
          labor_sim = laborrecords(sindex,t);
          cons_sim = consrecords(sindex,t);
          z_sim = zrecords(sindex,t);
          steecheck = steeminusone - cons_sim + cs_sim + dr_sim;
          stee = round(steecheck);
          sindex = find(S==stee);
          steeminusone = stee;
    else
          gamma_sim = gammarecords(sindex,t);
          theta_sim = thetarecords(sindex,t);
          cs_sim = csrecords(sindex,t);
          dr_sim = drrecords(sindex,t);
          leisure_sim = leisurerecords(sindex,t);
          labor_sim = laborrecords(sindex,t);
          cons_sim = consrecords(sindex,t);
          z_sim = zrecords(sindex,t);
          steecheck = steeminusone - cons_sim + cs_sim + dr_sim;
          stee = round(steecheck);
          sindex = find(S==stee);
          steeminusone = stee;
    end
```

```
    gamma_sims(t,1) = gamma_sim;
    theta_sims(t,1) = theta_sim;
    cs_sims(t,1) = cs_sim;
    dr_sims(t,1) = dr_sim;
    leisure_sims(t,1) = leisure_sim;
    labor_sims(t,1) = labor_sim;
    cons_sims(t,1) = cons_sim;
    S_sims(t,1) = stee;
    z_sims(t,1) = z_sim;
end

test_time = h - gamma_sims.*cs_sims - labor_sims - dr_sims*delta -
   leisure_sims;
test_gspend = g(1:T-1,1) - upsilon./gamma_sims - dr_sims.*theta_sims;
test_cons = cons_sims - theta_sims.*dr_sims - wage(1:T-1,1).*labor_sims
   ;

govtspendcs = upsilon./gamma_sims;
govtspenddr = theta_sims.*dr_sims;
govtspendcs_share = govtspendcs./(govtspendcs+govtspenddr);
govtspenddr_share = govtspenddr./(govtspendcs+govtspenddr);

discfactor = rho.^(1:1:T-1)';
depletiontime = find(S_sims==0);
endoftime = isempty(depletiontime);
depletiontime(endoftime==1)=T;
depletiontime=depletiontime(1,1);

if depletiontime<T
simulated_util = alpha*log(cons_sims(1:depletiontime)-sigmaCONS)+beta*
   log(leisure_sims(1:depletiontime)-sigmaLEISURE)+phi*log(cs_sims(1:
   depletiontime))+(1-alpha-beta-phi)*log(dr_sims(1:depletiontime))+psi
   *(g(1:depletiontime)-upsilon./gamma_sims(1:depletiontime)-dr_sims(1:
   depletiontime).*theta_sims(1:depletiontime));
added_util = (1./discountrate).*exp(-discountrate*depletiontime).*((
   alpha*log((cs_sims(depletiontime,1)+dr_sims(depletiontime,1))-
   sigmaCONS)+beta*log(leisure_sims(depletiontime,1)-sigmaLEISURE)+phi*
   log(cs_sims(depletiontime,1))+(1-alpha-beta-phi)*log(dr_sims(
   depletiontime,1)))+psi*(g(1:depletiontime)-upsilon./gamma_sims(1:
   depletiontime)-dr_sims(1:depletiontime).*theta_sims(1:depletiontime)
   ));
npv_util = -(sum(simulated_util.*discfactor(1:depletiontime))+
   added_util);
else
    simulated_util = alpha*log(cons_sims(1:depletiontime-1)-sigmaCONS)+
        beta*log(leisure_sims(1:depletiontime-1)-sigmaLEISURE)+phi*log(
        cs_sims(1:depletiontime-1))+(1-alpha-beta-phi)*log(dr_sims(1:
```

```
        depletiontime -1))+psi*(g(1:depletiontime -1)-upsilon./gamma_sims
        (1:depletiontime -1)-dr_sims(1:depletiontime -1).*theta_sims(1:
        depletiontime -1));
    added_util = (1./discountrate).*exp(-discountrate*depletiontime)
        .*((alpha*log((csterm+drterm)-sigmaCONS)+beta*log(leisureterm-
        sigmaLEISURE)+phi*log(csterm)+(1-alpha-beta-phi)*log(drterm))+
        psi*(gterm-upsilon./gamterm-drterm.*theta));
    added_util = added_util(1,1);
    npv_util = -(sum(simulated_util.*discfactor(1:depletiontime -1))+
        added_util);
end

results.npv = npv_util(:,1);
results.cons = cons_sims(:,1);
results.cs = cs_sims(:,1);
results.dr = dr_sims(:,1);
results.leisure = leisure_sims(:,1);
results.labor = labor_sims(:,1);
results.S = S_sims(:,1);
results.theta = theta_sims(:,1);
results.gamma = gamma_sims(:,1);
results.test_time = test_time(:,1);
results.test_gspend = test_gspend(:,1);
results.test_cons = test_cons(:,1);

recyshare_cs = cs_sims./(cs_sims+dr_sims);
recyshare_dr = dr_sims./(cs_sims+dr_sims);

recyclingtime = gamma_sims.*cs_sims+delta*dr_sims;

%Plot Figures
figure
plot(govtspendcs_share,'red');
hold on
plot(govtspenddr_share);
hold off;
title('Shares of Govt Spending');

figure
plot(govtspendcs,'red');
hold on
plot(govtspenddr);
hold off;
title('Levels of Govt Spending');

figure
plot(S_sims);
```

```
title('Landfill Depletion');

figure
plot(cs_sims,'red');
hold on;
plot(dr_sims);
hold off;
title('Levels DR vs CS');

figure
plot(recyshare_cs,'red');
hold on;
plot(recyshare_dr);
hold off;
title('DR Share vs CS Share');

figure
plot(recyclingtime,'green');
hold on;
plot(labor_sims,'blue');
hold on;
plot(leisure_sims,'black');
hold off;
title('Labor-Leisure-Recycling Share');

figure
plot(cons_sims);
title('Consumption');

figure
plot(test_gspend,'green');
hold on;
plot(test_cons,'blue');
hold on;
plot(test_time,'black');
hold off;
title('Government Spending Check (=0)');
```

C.2.2 Optimization Code

```
function [MaximizeUtilitySG] = MaxUtility_SGLinearEngel(theta,alpha,
    beta,phi,h,delta,wage,g,St,Stminusone,upsilon,sigmaCONS,sigmaLEISURE
    ,psi)

gam_max = (phi*(theta-delta*wage).*(sigmaCONS+(-h+sigmaLEISURE).*wage))
    ./(wage.*((-1+alpha+beta+phi).*(h-sigmaLEISURE).*wage-sigmaCONS*(-1+
    alpha+beta+phi+theta-alpha*theta+(-1+alpha)*delta.*wage)-(theta-
    delta*wage).*(St-Stminusone+alpha*(h-sigmaLEISURE).*wage)));
```

```
cs_max = -(phi*(sigmaCONS+(-h+sigmaLEISURE).*wage))./(gam_max.*wage);
dr_max = ((-1+alpha+beta+phi)*(sigmaCONS+(-h+sigmaLEISURE).*wage))./(-
    theta+delta*wage);
leisure_max = sigmaLEISURE+beta*(h-(sigmaCONS+sigmaLEISURE*wage)./wage)
    ;
labor_max = (-(beta+phi)*sigmaCONS*theta+(delta*(sigmaCONS-alpha*
    sigmaCONS)+(-1+beta+phi)*(h-sigmaLEISURE).*theta).*wage+alpha*delta
    *(h-sigmaLEISURE).*wage.^2)./(wage.*(-theta+delta*wage));
cons_max = sigmaCONS-alpha*sigmaCONS+alpha*(h-sigmaLEISURE)*wage;
z_max = cons_max-cs_max-dr_max;

MaximizeUtilitySG = -(alpha*log(cons_max-sigmaCONS)+beta*log(
    leisure_max-sigmaLEISURE)+phi*log(cs_max)+(1-alpha-beta-phi)*log(
    dr_max)+psi*(g-theta.*dr_max-upsilon./gam_max));
```

C.2.3 Constraint Code

```
function [c,ceq] = GovernmentBudgetConstraint_SGLinearEngel(theta,alpha
    ,beta,phi,h,delta,wage,g,St,Stminusone,upsilon,sigmaCONS,
    sigmaLEISURE,psi)

gam_constraint = (phi*(theta-delta*wage).*(sigmaCONS+(-h+sigmaLEISURE)
    .*wage))./(wage.*((-1+alpha+beta+phi).*(h-sigmaLEISURE).*wage-
    sigmaCONS*(-1+alpha+beta+phi+theta-alpha*theta+(-1+alpha)*delta.*
    wage)-(theta-delta*wage).*(St-Stminusone+alpha*(h-sigmaLEISURE).*
    wage)));

cs_constraint = -(phi*(sigmaCONS+(-h+sigmaLEISURE).*wage))./(
    gam_constraint.*wage);
dr_constraint = ((-1+alpha+beta+phi)*(sigmaCONS+(-h+sigmaLEISURE).*wage
    ))./(-theta+delta*wage);
leisure_constraint = sigmaLEISURE+beta*(h-(sigmaCONS+sigmaLEISURE*wage)
    ./wage);
labor_constraint = (-(beta+phi)*sigmaCONS*theta+(delta*(sigmaCONS-alpha
    *sigmaCONS)+(-1+beta+phi)*(h-sigmaLEISURE).*theta).*wage+alpha*delta
    *(h-sigmaLEISURE).*wage.^2)./(wage.*(-theta+delta*wage));
cons_constraint = sigmaCONS-alpha*sigmaCONS+alpha*(h-sigmaLEISURE)*wage
    ;
z_constraint = cons_constraint-cs_constraint-dr_constraint;

c(1) = -g+theta.*dr_constraint+upsilon./gam_constraint;
c(2) = -cons_constraint;
c(3) = -cs_constraint;
c(4) = -dr_constraint;
c(5) = -h+labor_constraint;
c(6) = -h+leisure_constraint;
ceq(1) = wage*labor_constraint+theta*dr_constraint-cons_constraint;
```

```
ceq(2) = -h+leisure_constraint+labor_constraint+gam_constraint.*
    cs_constraint+delta*dr_constraint;
```

C.3 Code for Chapter 4 Using Matlab

The code supplied in this section includes the master, optimization, and constraint codes for chapter 4.

C.3.1 Master Code

```
%Model Parameters
T = 50;
delta = .001;
alpha = .7;
beta = .25;
sigmaCONS = 50;
sigmaLEISURE = .1;
psi = .001;
pi = .15;
Pp = 5*(1-.0).^[1:T]';
sbar = 50;
wage0 = 70;
g0 = 1000;
h = 1;
omega = 0.25*(1-.0).^[1:T]';
eta = 1.5;
kappa_wage = .021;
kappa_g = .021;
discountrate = .1;
rho = 1/(1+discountrate);
wage = wage0*(1+kappa_wage).^[1:T]';
g = g0*(1+kappa_g).^[1:T]';

%State Space
S = (0:sbar)';
n = length(S);
Stee = repmat(S',n*2,2);
Steeminusone = repmat(S,2,n*2);
St = repmat(S',n,1);
Stminusone = repmat(S,1,n);
Sdiff = Stee-Steeminusone;

options = optimset('Algorithm','active-set','MaxIter',5000);
options.Algorithm = 'active-set';
options.MaxIter = 5000;
options.MaxFunEvals = 5000;
```

```
wageterm = wage(T,1);
gterm = g(T,1);

thetaterm = (h*wageterm+sigmaCONS*(-1+alpha+beta+(-1+alpha)*delta*
    wageterm)-wageterm*(sigmaLEISURE+delta*(St-Stminusone)+(h-
    sigmaLEISURE)*(alpha+beta+alpha*delta*wageterm)))./((-1+alpha)*
    sigmaCONS-St+Stminusone+alpha*(-h+sigmaLEISURE).*wageterm);
dterm = ((-1+alpha+beta).*(sigmaCONS+(-h+sigmaLEISURE).*wageterm))./(-
    thetaterm+delta*wageterm);
consterm = repmat(sigmaCONS-alpha*sigmaCONS+alpha*(h-sigmaLEISURE)*
    wageterm,(sbar+1),(sbar+1));
landfillterm = consterm-dterm;
leisureterm = repmat(sigmaLEISURE+beta*(h-(sigmaCONS+sigmaLEISURE.*
    wageterm)./wageterm),sbar+1,sbar+1);
laborterm = h-leisureterm-delta*dterm;

lbterm = 0;
ubterm = (delta*gterm*wageterm)./(gterm+(-1+alpha+beta)*(sigmaCONS+(-h+
    sigmaLEISURE)*wageterm));

%With Investment to Investment
for i=1:sbar+1
     Stterm = sbar;
     Stminusoneterm = Stminusone(i);
     thetatermGUESS = ubterm./2;
     thetainvterm1(i) = fmincon('chapter4_utilitymaximization',
         thetatermGUESS,[],[],[],[],lbterm,ubterm,'
         chapter4_utilityconstraint',options,alpha,beta,h,delta,wageterm,
         gterm,Stterm,Stminusoneterm,sigmaCONS,sigmaLEISURE,psi,pi,Pp(T),
         omega(T));
end

thetainvtermMAT = zeros(length(thetainvterm1),length(thetainvterm1));

for i=sbar+1:-1:1
     thetainvterm = circshift(thetainvterm1,[1,i]);
     thetainvtermMAT(i,:) = thetainvterm;
end

dinvterm = ((-1+alpha+beta).*(sigmaCONS+(-h+sigmaLEISURE).*wageterm))
    ./(-thetainvtermMAT+delta*wageterm);
consinvterm = repmat(sigmaCONS-alpha*sigmaCONS+alpha*(h-sigmaLEISURE)*
    wageterm,(sbar+1),(sbar+1));
zinvterm = (St-Stminusone+(consinvterm-dinvterm))./(1-pi);
zinvterm(zinvterm<0) = 0;
zPOWERinvterm = (1-pi)*zinvterm;
```

```
zLANDinvterm = pi*zinvterm;
LANDinvterm1 = consinvterm-dinvterm-zinvterm;
landfillinvtermcheck = LANDinvterm1+zLANDinvterm;
leisureinvterm = repmat(sigmaLEISURE+beta*(h-(sigmaCONS+sigmaLEISURE.*
    wageterm)./wageterm),sbar+1,sbar+1);
laborinvterm = h-leisureinvterm-delta*dinvterm;
landfillinvterm = (consinvterm-dinvterm-(1-pi)*zinvterm);

%Compilation
Dterm = [dterm,dinvterm;ones(sbar+1,sbar+1).*NaN,dinvterm];
THETAterm = [thetaterm,thetainvtermMAT;ones(sbar+1,sbar+1).*NaN,
    thetainvtermMAT];
CONSterm = [consterm,consterm;ones(sbar+1,sbar+1).*NaN,consterm];
LANDFILLterm = [landfillterm,landfillinvterm;ones(sbar+1,sbar+1).*NaN,
    landfillinvterm];
POWERterm = [zeros(sbar+1,sbar+1),zPOWERinvterm;ones(sbar+1,sbar+1).*
    NaN,zPOWERinvterm];
LEISUREterm = [leisureterm,leisureinvterm;ones(sbar+1,sbar+1).*NaN,
    leisureinvterm];
LABORterm = [laborterm,laborinvterm;ones(sbar+1,sbar+1).*NaN,
    laborinvterm];
LABORterm(LABORterm<0) = NaN;
LABORterm(LABORterm>h) = NaN;
InvCost = [zeros(sbar+1,sbar+1),ones(sbar+1,sbar+1);zeros(sbar+1,sbar
    +1),zeros(sbar+1,sbar+1)];

Investmentcostterm = eta.*InvCost;
Powernetbenefitsterm = Pp(T)*POWERterm-omega(T).*((POWERterm.^2)./2)-
    Investmentcostterm;
Util_Excessbudgetterm = psi*(gterm-Dterm.*THETAterm+
    Powernetbenefitsterm);
Util_term = alpha*log(CONSterm-sigmaCONS)+beta*log(LEISUREterm-
    sigmaLEISURE)+(1-alpha-beta)*log(Dterm);
vterm = Util_term+Util_Excessbudgetterm;
vterm(isnan(vterm)) = -inf;
vterm(imag(vterm)>0) = -inf;
vmatrix = [ones(length(S),1)*vterm(1:sbar+1,1)',ones(length(S),1)*vterm
    (1:sbar+1,sbar+2)';ones(length(S),1)*vterm(sbar+2:end,1)',ones(
    length(S),1)*vterm(sbar+2:end,sbar+2)'];
vmatrix(vmatrix==0) = -inf;

for t=T:-1:1
    wage1 = wage(t,1);
    g1 = g(t,1);

    %No Investment
```

```
theta = (h*wage1+sigmaCONS*(-1+alpha+beta+(-1+alpha)*delta*wage1)-
    wage1*(sigmaLEISURE+delta*(St-Stminusone)+(h-sigmaLEISURE)*(
    alpha+beta+alpha*delta*wage1)))./((-1+alpha)*sigmaCONS-St+
    Stminusone+alpha*(-h+sigmaLEISURE).*wage1);
d = ((-1+alpha+beta).*(sigmaCONS+(-h+sigmaLEISURE).*wage1))./(-
    theta+delta*wage1);
cons = repmat(sigmaCONS-alpha*sigmaCONS+alpha*(h-sigmaLEISURE)*
    wage1,(sbar+1),(sbar+1));
landfill = cons-d;
leisure = repmat(sigmaLEISURE+beta*(h-(sigmaCONS+sigmaLEISURE.*
    wage1)./wage1),sbar+1,sbar+1);
labor = h-leisure-delta*d;

lb = 0;
ub = (delta*g1*wage1)./(g1+(-1+alpha+beta)*(sigmaCONS+(-h+
    sigmaLEISURE)*wage1));

%With Investment to Investment
for i=1:sbar+1
     St1 = sbar;
     Stminusone1 = Stminusone(i);
     thetaGUESS = ub./2;
     thetainv1(i) = fmincon('chapter4_utilitymaximization',
         thetaGUESS,[],[],[],[],lb,ub,'chapter4_utilityconstraint',
         options,alpha,beta,h,delta,wage1,g1,St1,Stminusone1,
         sigmaCONS,sigmaLEISURE,psi,pi,Pp(t),omega(t));
end

thetainvMAT = zeros(length(thetainv1),length(thetainv1));

for i=sbar+1:-1:1
     thetainv = circshift(thetainv1,[1,i]);
     thetainvMAT(i,:) = thetainv;
end

dinv = ((-1+alpha+beta).*(sigmaCONS+(-h+sigmaLEISURE).*wage1))./(-
    thetainvMAT+delta*wage1);
consinv = repmat(sigmaCONS-alpha*sigmaCONS+alpha*(h-sigmaLEISURE)*
    wage1,(sbar+1),(sbar+1));
zinv = (St-Stminusone+(consinv-dinv))./(1-pi);
zinv(zinv<0) = 0;
zPOWERinv = (1-pi)*zinv;
zLANDinv = pi*zinv;
LANDinv1 = consinv-dinv-zinv;
landfillinvcheck = LANDinv1+zLANDinv;
leisureinv = repmat(sigmaLEISURE+beta*(h-(sigmaCONS+sigmaLEISURE.*
    wage1)./wage1),sbar+1,sbar+1);
```

```
laborinv = h-leisureinv-delta*dinv;
landfillinv = (consinv-dinv-(1-pi)*zinv);

%Compilation
D = [d,dinv;ones(sbar+1,sbar+1).*NaN,dinv];
THETA = [theta,thetainvMAT;ones(sbar+1,sbar+1).*NaN,thetainvMAT];
CONS = [cons,cons;ones(sbar+1,sbar+1).*NaN,cons];
LANDFILL = [landfill,landfillinv;ones(sbar+1,sbar+1).*NaN,
    landfillinv];
POWER = [zeros(sbar+1,sbar+1),zPOWERinv;ones(sbar+1,sbar+1).*NaN,
    zPOWERinv];
LEISURE = [leisure,leisureinv;ones(sbar+1,sbar+1).*NaN,leisureinv];
LABOR = [labor,laborinv;ones(sbar+1,sbar+1).*NaN,laborinv];
LABOR(LABOR<0) = NaN;
LABOR(LABOR>h) = NaN;
InvCost = [zeros(sbar+1,sbar+1),ones(sbar+1,sbar+1);zeros(sbar+1,
    sbar+1),zeros(sbar+1,sbar+1)];

Investmentcost = eta.*InvCost;
Powernetbenefits = Pp(t)*POWER-omega(t).*((POWER.^2)./2)-
    Investmentcost;
Util_Excessbudget = psi*(g1-D.*THETA+Powernetbenefits);
Util_ = alpha*log(CONS-sigmaCONS)+beta*log(LEISURE-sigmaLEISURE)
    +(1-alpha-beta)*log(D);
payoff = Util_+Util_Excessbudget;

payoffD0D0 = tril(payoff(1:sbar+1,1:sbar+1));
payoffD0D1 = tril(payoff(1:sbar+1,sbar+2:end));
payoffD1D0 = zeros(sbar+1,sbar+1);
payoffD1D1 = tril(payoff(sbar+2:end,sbar+2:end));

testgspend = g1+Powernetbenefits;
testcons = CONS-wage1.*LABOR-THETA.*D;
testtime = h-LEISURE-LABOR-delta.*D;

payoffMat = [payoffD0D0,payoffD0D1;payoffD1D0,payoffD1D1];
payoffMat(payoffMat==0) = -inf;
payoffMat(imag(payoffMat)>0)=-inf;
payoffMat(labor<0)=-inf;
payoffMat(isnan(payoffMat)) = -inf;
addedbenefit = rho*vmatrix;
value = payoffMat+addedbenefit;
value(imag(value)>0)=-inf;
value(isnan(value)) = -inf;
value = real(value);
[val row] = max(value,[],2);
```

```
    for i=1:length(value)
        thetarecords(i,t) = THETA(i,row(i,1));
        landfillrecords(i,t) = LANDFILL(i,row(i,1));
        consrecords(i,t) = CONS(i,row(i,1));
        drecords(i,t) = D(i,row(i,1));
        leisurerecords(i,t) = LEISURE(i,row(i,1));
        laborrecords(i,t) = LABOR(i,row(i,1));
        Powerrecords(i,t) = POWER(i,row(i,1));
        testgspendrecords(i,t) = testgspend(i,row(i,1));
        testconsrecords(i,t) = testcons(i,row(i,1));
        testtimerecords(i,t) = testtime(i,row(i,1));
        valuerecords(i,t) = value(i,row(i,1));
    end
    rows(:,t) = row;
    vals(:,t) = val;
end

landfillrecordsNI = landfillrecords(1:sbar+1,:);
thetarecordsNI = thetarecords(1:sbar+1,:);
consrecordsNI = consrecords(1:sbar+1,:);
drecordsNI = drecords(1:sbar+1,:);
leisurerecordsNI = leisurerecords(1:sbar+1,:);
laborrecordsNI = laborrecords(1:sbar+1,:);
PowerrecordsNI = Powerrecords(1:sbar+1,:);
testgspendrecordsNI = testgspendrecords(1:sbar+1,:);
testbudgetrecordsNI = testconsrecords(1:sbar+1,:);
testtimerecordsNI = testtimerecords(1:sbar+1,:);
valuerecordsNI = valuerecords(1:sbar+1,:);
landfillrecordsYI = landfillrecords(sbar+2:end,:);
thetarecordsYI = thetarecords(sbar+2:end,:);
consrecordsYI = consrecords(sbar+2:end,:);
drecordsYI = drecords(sbar+2:end,:);
leisurerecordsYI = leisurerecords(sbar+2:end,:);
laborrecordsYI = laborrecords(sbar+2:end,:);
PowerrecordsYI = Powerrecords(sbar+2:end,:);
testgspendrecordsYI = testgspendrecords(sbar+2:end,:);
testbudgetrecordsYI = testconsrecords(sbar+2:end,:);
testtimerecordsYI = testtimerecords(sbar+2:end,:);
valuerecordsYI = valuerecords(sbar+2:end,:);

%Simulation
for t=1:1:T-1
    if t==1
        sindex = length(S);
        if rows(sindex,t)<=sbar+1
            steeminusone = S(sindex);
                stee = S(sindex);
```

```
            investment = 0;
            theta_sim = thetarecordsNI(sindex,t);
            d_sim = drecordsNI(sindex,t);
            leisure_sim = leisurerecordsNI(sindex,t);
            labor_sim = laborrecordsNI(sindex,t);
            cons_sim = consrecordsNI(sindex,t);
            landfill_sim = landfillrecordsNI(sindex,t);
            testgspend_sim = testgspendrecordsNI(sindex,t);
            testbudget_sim = testbudgetrecordsNI(sindex,t);
            testtime_sim = testtimerecordsNI(sindex,t);
            Powerrecords_sim = PowerrecordsNI(sindex,t);
            valuerecords_sim = valuerecordsNI(sindex,t);
            steecheck = steeminusone - landfill_sim;
            stee = round(steecheck);
            sindex = find(S==stee);
            steeminusone = stee;
        else
            steeminusone = S(sindex);
            stee = S(sindex);
            investment = 1;
            theta_sim = thetarecordsYI(sindex,t);
            d_sim = drecordsYI(sindex,t);
            leisure_sim = leisurerecordsYI(sindex,t);
            labor_sim = laborrecordsYI(sindex,t);
            cons_sim = consrecordsYI(sindex,t);
            landfill_sim = landfillrecordsYI(sindex,t);
            testgspend_sim = testgspendrecordsYI(sindex,t);
            testbudget_sim = testbudgetrecordsYI(sindex,t);
            testtime_sim = testtimerecordsYI(sindex,t);
            Powerrecords_sim = PowerrecordsYI(sindex,t);
            valuerecords_sim = valuerecordsYI(sindex,t);
            steecheck = steeminusone - landfill_sim;
            stee = round(steecheck);
            sindex = find(S==stee);
            steeminusone = stee;
        end
    else
        if investment_sims(t-1,1)==0
          investment = 0;
          theta_sim = thetarecordsNI(sindex,t);
          d_sim = drecordsNI(sindex,t);
          leisure_sim = leisurerecordsNI(sindex,t);
          labor_sim = laborrecordsNI(sindex,t);
          cons_sim = consrecordsNI(sindex,t);
          landfill_sim = landfillrecordsNI(sindex,t);
          testgspend_sim = testgspendrecordsNI(sindex,t);
          testbudget_sim = testbudgetrecordsNI(sindex,t);
```

```
            testtime_sim = testtimerecordsNI(sindex,t);
            Powerrecords_sim = PowerrecordsNI(sindex,t);
            valuerecords_sim = valuerecordsNI(sindex,t);
            steecheck = steeminusone - landfill_sim;
        if Powerrecords_sim>0
            investment = 1;
            theta_sim = thetarecordsYI(sindex,t);
            d_sim = drecordsYI(sindex,t);
            leisure_sim = leisurerecordsYI(sindex,t);
            labor_sim = laborrecordsYI(sindex,t);
            cons_sim = consrecordsYI(sindex,t);
            landfill_sim = landfillrecordsYI(sindex,t);
            testgspend_sim = testgspendrecordsYI(sindex,t);
            testbudget_sim = testbudgetrecordsYI(sindex,t);
            testtime_sim = testtimerecordsYI(sindex,t);
            Powerrecords_sim = PowerrecordsYI(sindex,t);
            valuerecords_sim = valuerecordsYI(sindex,t);
            steecheck = steeminusone - landfill_sim;
        end
            stee = round(steecheck);
            sindex = find(S==stee);
            steeminusone = stee;
        else
            investment = 1;
            theta_sim = thetarecordsYI(sindex,t);
            d_sim = drecordsYI(sindex,t);
            leisure_sim = leisurerecordsYI(sindex,t);
            labor_sim = laborrecordsYI(sindex,t);
            cons_sim = consrecordsYI(sindex,t);
            landfill_sim = landfillrecordsYI(sindex,t);
            testgspend_sim = testgspendrecordsYI(sindex,t);
            testbudget_sim = testbudgetrecordsYI(sindex,t);
            testtime_sim = testtimerecordsYI(sindex,t);
            Powerrecords_sim = PowerrecordsYI(sindex,t);
            valuerecords_sim = valuerecordsYI(sindex,t);
            steecheck = steeminusone - landfill_sim;
            stee = round(steecheck);
            sindex = find(S==stee);
            steeminusone = stee;
        end
    end

    investment_sims(t,1) = investment;
    theta_sims(t,1) = theta_sim;
    d_sims(t,1) = d_sim;
    leisure_sims(t,1) = leisure_sim;
    labor_sims(t,1) = labor_sim;
```

```
    cons_sims(t,1) = cons_sim;
    landfill_sims(t,1) = landfill_sim;
    S_sims(t,1) = stee;
    test_timeconstraint(t,1) = testtime_sim;
    test_consconstraint(t,1) = testbudget_sim;
    test_gspend(t,1) = testgspend_sim;
    Power_sims(t,1) = Powerrecords_sim;
    value_sims(t,1) = valuerecords_sim;
    begofperiod = S_sims + cons_sims - d_sims;
end

recyclingtime = delta*d_sims;

%Plot Figures
figure
plot(cons_sims,'black');
hold on;
plot(d_sims,'green');
hold on;
plot(Power_sims,'red');
hold off;
title('Consumption v Recycling v Power');

figure
plotyy(1:T-1,S_sims,1:T-1,investment_sims);
title('Investment v Depletion');

figure
plot(recyclingtime,'green');
hold on;
plot(labor_sims,'blue');
hold on;
plot(leisure_sims,'black');
hold off;
title('Labor-Leisure-Recycling Share');

figure
plot(test_timeconstraint,'green');
hold on;
plot(test_gspend,'blue');
hold on;
plot(test_consconstraint,'black');
hold off;
title('Testing Equalities');

figure
plotyy(1:T-1,Power_sims,1:T-1,d_sims);
```

```
title('Power v Recycling');
```

C.3.2 Optimization Code

```
function [ch4_maxutility] = chapter4_utilitymaximization(theta,alpha,
    beta,h,delta,wage,g,St,Stminusone,sigmaCONS,sigmaLEISURE,psi,pi,Pp,
    omega)

d_max = ((-1+alpha+beta)*(sigmaCONS+(-h+sigmaLEISURE)*wage))./(-theta+
    delta*wage);
cons_max = sigmaCONS-alpha*sigmaCONS+alpha*(h-sigmaLEISURE)*wage;
z_max = (St-Stminusone+(cons_max-d_max))./(1-pi);
labor_max = h-sigmaLEISURE+(beta*(sigmaCONS+(-h+sigmaLEISURE)*wage))./
    wage-((-1+alpha+beta)*delta*(sigmaCONS+(-h+sigmaLEISURE)*wage))./(-
    theta+delta*wage);
leisure_max = sigmaLEISURE+beta*(h-(sigmaCONS+sigmaLEISURE*wage)./wage)
    ;

zPOWER_max = (1-pi)*z_max;
Powernetbenefits_max = Pp*zPOWER_max-omega.*(zPOWER_max.^2)./2;
UtilExcessBudget_max = psi*(g-d_max.*theta+Powernetbenefits_max);

ch4_maxutility = -(alpha*log(cons_max-sigmaCONS)+beta*log(leisure_max-
    sigmaLEISURE)+(1-alpha-beta)*log(d_max)+UtilExcessBudget_max);
ch4_maxutility(ch4_maxutility>0) = 0;
```

C.3.3 Constraint Code

```
function [c,ceq] = chapter4_utilityconstraint(theta,alpha,beta,h,delta,
    wage,g,St,Stminusone,sigmaCONS,sigmaLEISURE,psi,pi,Pp,omega)

d_constraint = ((-1+alpha+beta)*(sigmaCONS+(-h+sigmaLEISURE)*wage))./(-
    theta+delta*wage);
cons_constraint = sigmaCONS-alpha*sigmaCONS+alpha*(h-sigmaLEISURE)*wage
    ;
z_constraint = (St-Stminusone+(cons_constraint-d_constraint))./(1-pi);
labor_constraint = h-sigmaLEISURE+(beta*(sigmaCONS+(-h+sigmaLEISURE)*
    wage))./wage-((-1+alpha+beta)*delta*(sigmaCONS+(-h+sigmaLEISURE)*
    wage))./(-theta+delta*wage);
leisure_constraint = sigmaLEISURE+beta*(h-(sigmaCONS+sigmaLEISURE*wage)
    ./wage);

zPOWER_constraint = (1-pi)*z_constraint;
Powernetbenefits_constraint = Pp*zPOWER_constraint-omega.*(
    zPOWER_constraint.^2)./2;
UtilExcessBudget_constraint = psi*(g-d_constraint.*theta+
    Powernetbenefits_constraint);
```

```
ch4_constraintutility = -(alpha*log(cons_constraint-sigmaCONS)+beta*log
    (leisure_constraint-sigmaLEISURE)+(1-alpha-beta)*log(d_constraint)+
    UtilExcessBudget_constraint);

c(1) = -g-UtilExcessBudget_constraint+theta.*d_constraint;
c(2) = -cons_constraint;
c(3) = -d_constraint;
c(4) = -h+labor_constraint;
c(5) = -h+leisure_constraint;
c(6) = -z_constraint;
c(7) = -cons_constraint+d_constraint-St+Stminusone;
ceq(1) = wage*labor_constraint+theta*d_constraint-cons_constraint;
ceq(2) = -h+leisure_constraint+labor_constraint+delta*d_constraint;
```