# THE EFFECTS OF RENEWABLE ENERGY POLICIES ON LANDFILL GAS-TO-ENERGY PROJECT DEVELOPMENT

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**by**

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# ABSTRACT

As the call for greenhouse gas mitigation becomes more and more urgent, both in the United States and in many other countries, landfill owners are encouraged to contribute to emission reduction by developing Landfill Gas-to-Energy (LFGE) projects. Since the first LFGE electricity generation project in 1982 and with the increased support for renewable sources of energy, LFGE projects have increased in number.

This study examines the influence of state policies, including state grants, production tax credits, investment tax credits, and Renewable Portfolio Standards, on landfill owners' and developers' decisions to build LFGE projects. This question is addressed using econometric models such as linear probability models and various logit models.

The four policy variables are shown to have no significant effect on LFGE project adoption according to the logit estimations. Variables such as the gas price, public ownership, landfill age, and amount of waste are shown to have a significant effect on increasing project adoption. The linear probability model, despite its flaws in addressing the issue, produces positive and significant results for the effects of the RPS and state grant policies on project adoption.

# BIOGRAPHICAL SKETCH

Han Kyul Yoo earned her Bachelor of Arts degree in Economics from Yonsei University in 2011. In 2011 she joined the Master's program in Applied Economics at Cornell University.

While pursuing her degree, she worked as a research assistant for the department of Applied Economics. She interned at Resource for the Future in 2012.

*To William, Sheila, Joan, and Oscar*

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TABLE OF CONTENTS

# Chapter 1: Introduction

As the call for greenhouse gas mitigation becomes more and more urgent, both in the United States and in many other countries, landfill owners are encouraged to contribute to emission reduction by developing Landfill Gas-to-Energy (LFGE) projects. Compared to other renewable energy sources, LFGE projects are relatively small in generation capacity, but their potential as a renewable energy has induced various forms of government support and the idea of converting waste into energy has won public attention. Since the first LFGE electricity generation project in 1982 and with the increased support for renewable sources of energy, LFGE projects have increased in number.

According to reports by the International Panel for Climate Change (IPCC), methane is currently the second most important greenhouse gas and was responsible for 15% of the change in radiative forcing from 1980 to 1990.[1] In the United States, Municipal Solid Waste (MSW) landfills are the third-largest source of human-made methane emissions, and were responsible for 17% of the methane emissions in 2009.[2]

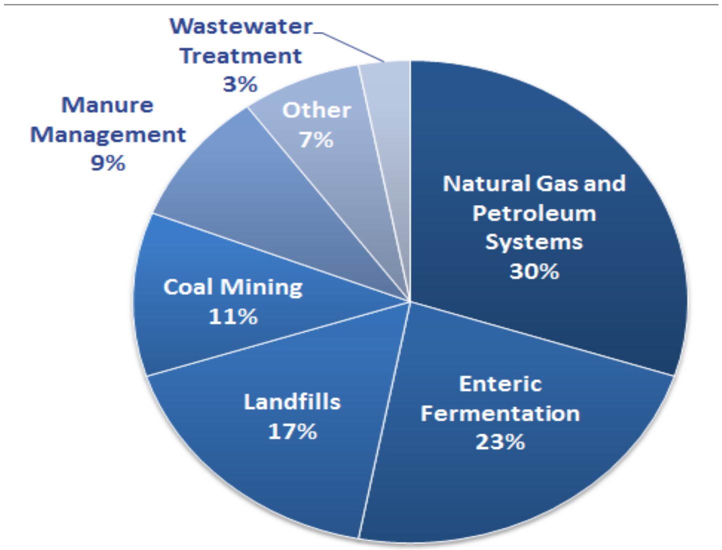


Figure 1.1. U.S. Methane Emissions by Source

Source: U.S. Environmental Protection Agency

The gas generated and emitted from a landfill contains a large amount of methane - a very powerful greenhouse gas. An LFGE project collects the Landfill Gas (LFG) that would otherwise have been released to the atmosphere, and uses it to generate heat or power. When landfill gas is burned, the methane is converted to carbon dioxide, which has a significantly smaller warming effect.[3] Additionally, the generated heat or power defers the need to burn other types of fuels such as coal or oil. Because of its environmental effects and because landfilling is an inevitable consequence of human activity, LFG is considered a renewable energy. Further, the sale of LFG creates revenue for LFGE developers, but the costs and benefits of a project differ widely for each landfill. Nonetheless, the sale of LFG may be a potential source of additional net revenue for some landfill owners. The environmental and economic benefits of LFGE projects have made them a viable option for local governments and businesses to take responsibility as well as secure a source of energy and revenue.

This study investigated the effects of the state Renewable Portfolio Standards and other financial incentives on the decision of landfill owners to adopt landfill gas-to-energy projects. These effects are estimated from carefully specified econometric models. Several model specifications and estimating methods are used, and the performances of the models are compared.

## 1.1 Background

There are about 2,400 currently operating or recently closed landfills in the United States. Among these landfills, there were 560 operating LFGE projects in 2010, 410 of which were electricity generation and 150 of which were direct-use applications (Table 1). The total electric generation capacity was over 1,700 mW and collectively these landfills produced about 300 million standard cubic feet of LFG per day (mmscfd) in direct-use applications.[4]

**Table 1. Breakdown of Landfill Gas Energy Projects in 2010**

| Landfill Gas Energy Use | Number of Projects |
|---|---|
| **Electric** | |
| Reciprocating Engines | 313 |
| Gas Turbines | 31 |
| Other | 66 |
| All Electric | 410 |
| **Direct** | |
| Boilers | 59 |
| Direct Thermal & Leachate Evaporation | 57 |
| Other | 34 |
| All Direct | 150 |

| | |
|---|---|
| **Total** | 560 |
| **All Landfills** | 2399 |

Source: US EPA Landfill Methane Outreach Program

LFGE projects have become increasingly popular in recent years due to a host of contributing factors such as increasing energy costs, policies and regulations to promote renewable energy, and technology improvement. The number of operating projects increased from 113 to 560 during 1991-2010 (Figure 1.1). The largest increase, 46 new projects was observed during 1997-1998 period, possibly due to the expiration at the end of 1998 of Section 29 tax credit for non-conventional gas production.[5]

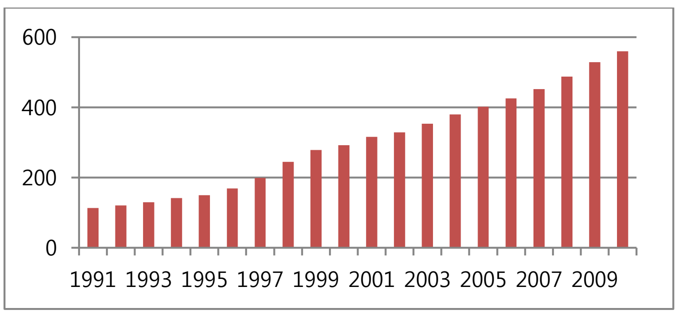


**Figure 1.2.** Total Number of Operating LFGE Projects 1991- 2010

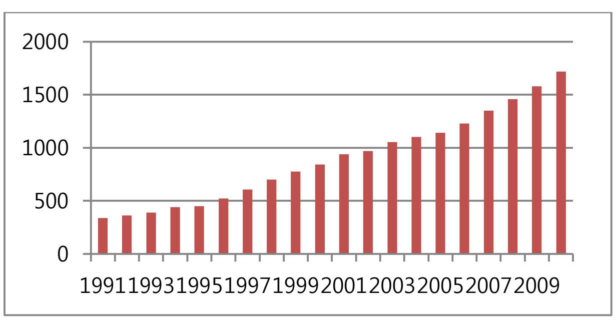


**Figure 1.3.** Time Trend of Cumulative LFGE Electricity Generating Capacity (mW)

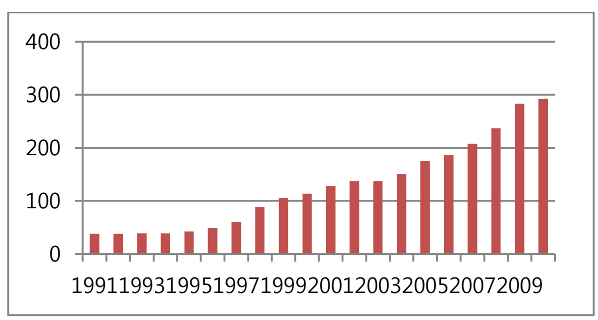


**Figure 1.4.** Time Trend of Cumulative Direct Use Applications (mmscfd)

Source: US EPA Landfill Methane Outreach Program

There are three kinds of LFGE projects depending on how the LFG is used. An electricity generation project uses various technologies such as engines, turbines, micro turbines, and fuel cells, to generate electricity from LFG. This power is used on-site or is transmitted through the power grid and sold to consumers. A direct use project uses the LFG to heat boilers, kilns, greenhouses or other thermal applications. Finally, a cogeneration plant uses LFG for its thermal energy and electricity generations. The cogeneration plant is especially attractive because of its efficiency. Out of the 560 LFGE projects presently operating, two thirds are electricity generation projects, one third is direct use, and a small proportion is cogeneration plants.[6]

## 1.2 Basic Concepts

### 1.2.1 The Science of Landfill Gas to Energy Projects

Landfill gas is composed of methane, carbon dioxide, and non-methanogenic organic compounds. Methane is considered the second most important anthropogenic greenhouse gas and the waste in landfills is the single largest human-made source of methane in the United States. (Chen and Greene, 2003) Other than its methane content, LFG is hazardous because it can cause explosion when accumulated in enclosed spaces. In addition, LFG may contain small amounts of ozone-forming volatile organic compounds (VOC's) and toxic or carcinogenic hazardous air pollutants (HAP's).

Landfill gas is generated from a chain of physical, chemical, and microbial (bacterial activities) processes that occur in the waste – the most important of the processes being the anaerobic decomposition of organic waste. The process happens for a total of 10 to 80+ years. Appreciable amounts of LFG are produced within 1-3 years of waste placement, peaking at 5-7 years after.[7] For the purpose of this study, it is important to examine the conditions at which the anaerobic decomposition of organic matters is most active. Because the gas is generated from the decomposition of organic matter, the amount of organic matter is most important. Also, the anaerobic state must be achieved, which can be affected by the cover of the landfill. Compact waste and large waste particles can inhibit moisture and nutrient transport, decreasing microbial activity. Warmer temperatures and sufficient moisture content assists microbial activity. Further, waste with a lower pH (acidic waste) and waste with low nutrient content tend to generate gas slowly.[8] [9]

### 1.2.2 Landfill gas recovery and utilization technology

In order to use LFG to generate energy, the gas must first be collected from the waste. The gas is extracted by gas extraction wells distributed throughout the landfill waste. The gas extraction wells are connected to a gas collection pipe, which directs the collected gas to a central point where the gas will be processed and treated according to the ultimate use of the gas. Figure 1.4 below shows a simple diagram of an LFG extraction and collection system.

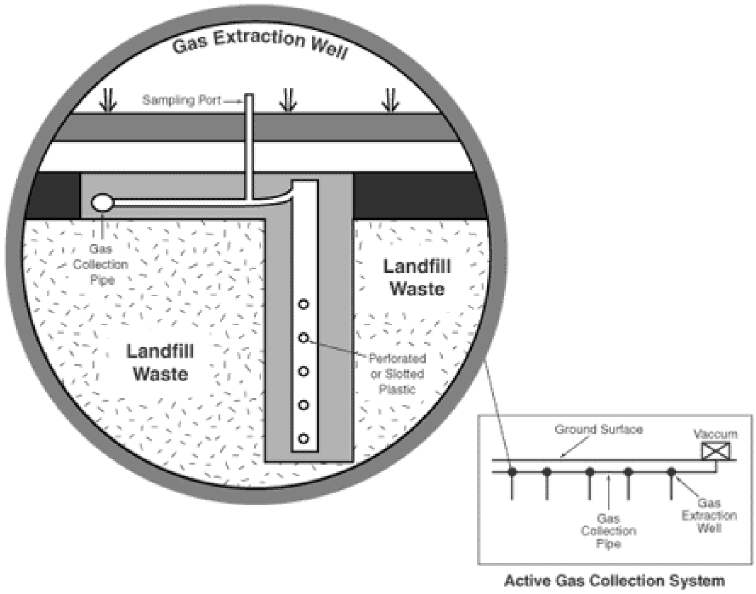


**Figure 1.5.** Diagram of Landfill Gas Extraction Well

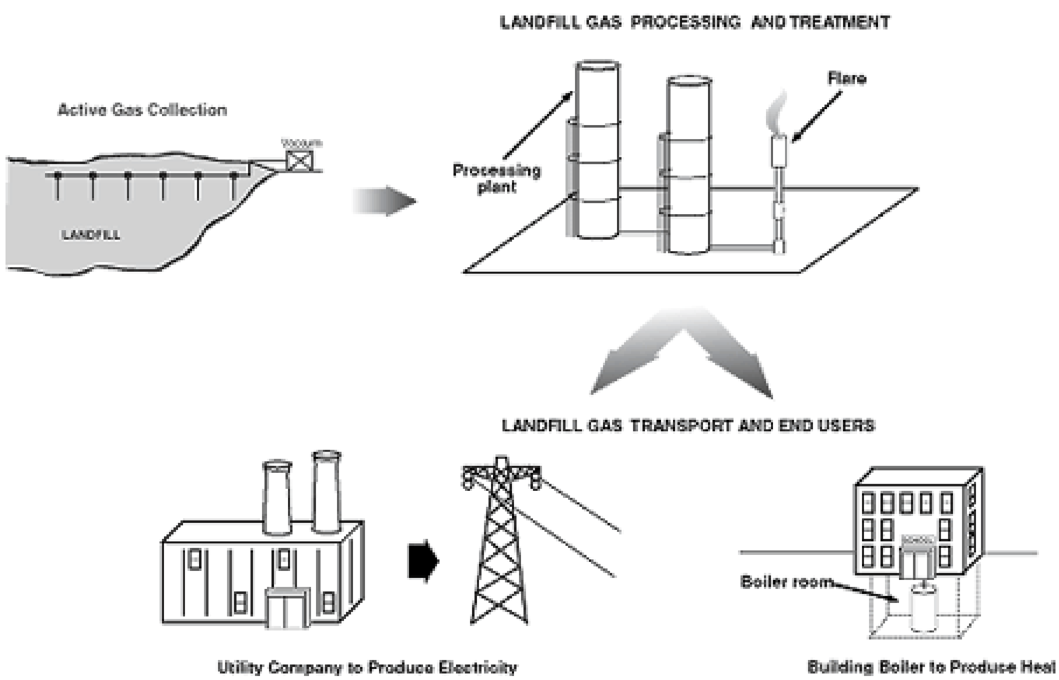


**Figure 1.6.** Diagram of an LFG collection system
Source: Agency for Toxic Substances and Disease Registry

LFG can be used directly as gas or can be used indirectly as fuel to generate electricity.

*Electricity Generation*

Two-thirds of the LFGE projects in the United States are electricity generation plants. The electricity is generated by fueling internal combustion engines, turbines, micro turbines, and fuel cells. Most of the electricity generation projects use internal combustion engines, but microturbines are often chosen at smaller landfills. Internal combustion engine capacity ranges from 100kW to 3mW, turbines have capacities from 800kW to 10.3mW, and micro turbines range from 30kW to 250kW.[10]

*Direct Use*

LFG can also be used directly in place of other fuel, such as natural gas, coal, and fuel oil. The gas can be used in thermal applications, including boilers, greenhouses, etc. Examples of industries that directly use LFG range as wide as manufacturing, wastewater treatment, chemical production, consumer electronics, prisons and hospitals.[11]

*Cogeneration*

Cogeneration, also called combined heat and power, projects use LFG to generate both electricity and thermal energy. These projects capture the heat in addition to generating electricity, making them especially efficient.[12]

### 1.2.3 Economics of LFGE project

The economic feasibility of an LFGE project can be determined by examining the cost and revenues of a project. An LFGE project involves construction and installation costs (i.e. capital costs), and operation and maintenance costs. Some of these costs can be mitigated by grants, low-interest loans, investment tax credits, and sales tax exemptions. The main revenues of an LFGE project would be derived from the sales of electricity and gas, and thus would depend on the electricity and gas prices. These electricity or gas price might include a premium in the case that demand exceeds supply that may result from renewable portfolio standards or green power purchase initiatives. In addition to the energy sales revenue, the project owner may be able to sell Renewable Energy Credits (RECs) or receive production incentives or production tax credits for every unit of energy sold.

*Costs of LFGE projects*

The capital cost of constructing an LFGE project depend on a myriad of factors including methane production, size of landfill, type of engine, total generation capacity, distance to power grid, etc. The landfill owner or developer will determine the project capacity considering all these factors.

According to a study done in 2005 by Jaramillo and Matthews, the costs of a collection and flare system range from $628,000 to $3,599,000 for landfills that have daily gas flows of 642,000 cf/day and 5,266,000 cf/day. The capital cost of installing an internal combustion engine ranges from $151,500 for a 100 kW engine to $4,595,000 for a 5 mW engine. A paper by Morgan and Yang (2001) conducted economic feasibility studies on three St. Louis landfills. The paper provided the estimated total capital and operation costs of these landfills, assuming that the most profitable capacity is chosen. The West County landfill had 6,000,000 tons of waste in 1999, and West Lake landfill had 10,615,857 tons of waste. The capital cost of building a 7.8 mW project at West County landfill was estimated to be $8.4 million for a facility and a 13.4 mW project was estimated to cost $14.6 million at West Lake landfill. The annual operation and maintenance costs were estimated at $1.9 million for West County and $3.2 million for West Lake. It should be noted, however, that the capacities selected for these case studies are at the higher end; typically, LFGE projects have smaller capacities and thus require smaller capital costs.

According to a report by the Natural Resource Defense Council (2003), a typical landfill costs $ 1.5 million. Also, the report provides a comparison of cost and benefits, as shown in figure 1.7. For smaller landfills or landfills with less methane production, the cost per kWh of electricity is about 7.5 cents. Even the larger landfills have a cost of 5.5 cents per kWh. However, with the New Source Performance standard, the gas-collection system is mandatory for some landfills, making the cost for installing gas-collection facility a sunk cost. Excluding the gas-collection system cost, the cost of generating a kWh of electricity ranges from 4 to 5 cents. The wholesale electricity price at the time the report was written was around 2.5 to 3 cents, making an LFGE project unfeasible. For the landfills that benefited from the section 29 tax credit, the project is more likely to breakeven. Considering these cost and benefit figures it is clear that financial incentives are essential to many landfill gas-to-energy projects.

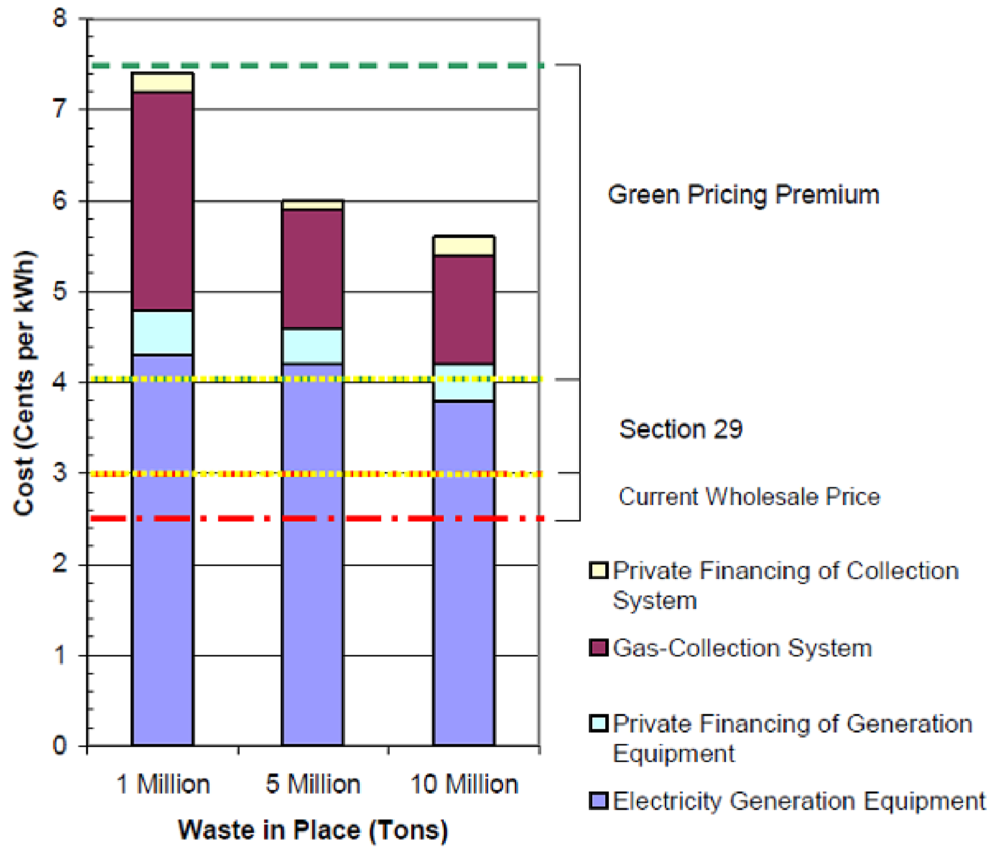


**Figure 1.7.** Landfill-Gas Energy Production Costs Vs. Electricity Sales Revenue

Source: Natural Resources Defense Council

*Revenue of LFGE Projects*

The major source of revenue for a project owner is the revenue from the sales of electricity or gas. Electricity can be sold to a utility or transferred directly to an end-user. The revenue in the first case would be the wholesale electricity price. In the second case, if the power is used on-site, the revenue is the retail electricity price, but if the power is used by a second party, the revenue would be the pre-set energy price. The same applies to direct use project – the price is determined by to whom the gas is sold.

The major complication with power and gas prices is that a decision to build the project must be based on the expected prices of electricity or gas, in the future period when the commodity would be sold. Since an LFGE project is typically operated for about 15 years, the decision turns in part on an accurate forecast of revenue that would be discounted appropriately over the 15 years after a project is open. However, it is difficult to attain the data on expected energy price. As an alternative, lagged price can be used, because price expectation is often based on the current price at the time the decision is made. Because the decision to embark on a project would be made approximately 1-2 years before the project is open, the electricity price a year prior to the project open date would be influence the decision to build a project. Also, assuming that price expectations are rational, and thus accurate (Fair, 1989), an average of the lagged, present, and future prices can be used as a proxy. In the present study, the average energy price of 3 years (the previous, present, and next year) was used to represent the expected price.

There are two factors about energy sales that would be important to the project owner. The first is the price premium that could result from a scarcity in renewable energy. For instance, if a state requires utilities to generate or purchase a certain portion of their electricity from renewable sources, and thus, the demand becomes larger than the supply, utilities will offer prices higher than the wholesale energy market price to renewable energy generators. The Renewable Portfolio Standard is a regulation that requires utilities to acquire a certain amount of their energy supply from renewable sources. Green power purchase programs are another policy measure that requires certain, mostly public, organizations to purchase a portion of their electricity from renewable sources.

*Government Regulations and Incentives*

Another factor that contributes to cost recovery is the availability of contracts to sell the energy for a given period of time. If a project owner is able to enter into a contract with a utility or other buyer, he/she is guaranteed a stable source of revenue for a period of time, which decreases risk. A good example of such a contract is the Tennessee Valley Authority's Generation Partners Program. TVA bases the standard offer on a seasonal time-of-day averages chart, which sets base prices for the term of the contract. These prices increase at a rate of 3% per year and may be changed with 90 days' notice by TVA (but the change can be no more than 1% per year). The contract periods are 10, 15, or 20 years.[13] Policies such as renewables portfolio standards are the main reason that utilities offer such contracts. Utilities secure sources of renewable energy in expectation of future regulations.

Renewable Energy Credits (REC's) are another form of price premium that renewable energy generators can receive. When a firm generates renewable energy, they can receive RECs, and these RECs are certified by a certifying authority. The REC's can be bundled with the energy and sold as a package, or they can be sold separately. Utilities, non-profits, and other environmental organizations buy RECs.[14] REC's can be purchased by utilities in lieu of purchasing renewable electricity, to meet RPS requirements. However, only a handful of states have a significant compliance REC (REC's traded as a means to comply to RPS requirements) prices, and the voluntary REC prices have dropped to low levels.[15] The higher REC prices, Massachusetts, New Hampshire, Rhode Island, Connecticut, and Maine, range around $40-$60 per mWh ( ¢ 0.6 per kWh), which is a significant amount. But, many other states have REC prices close to zero.

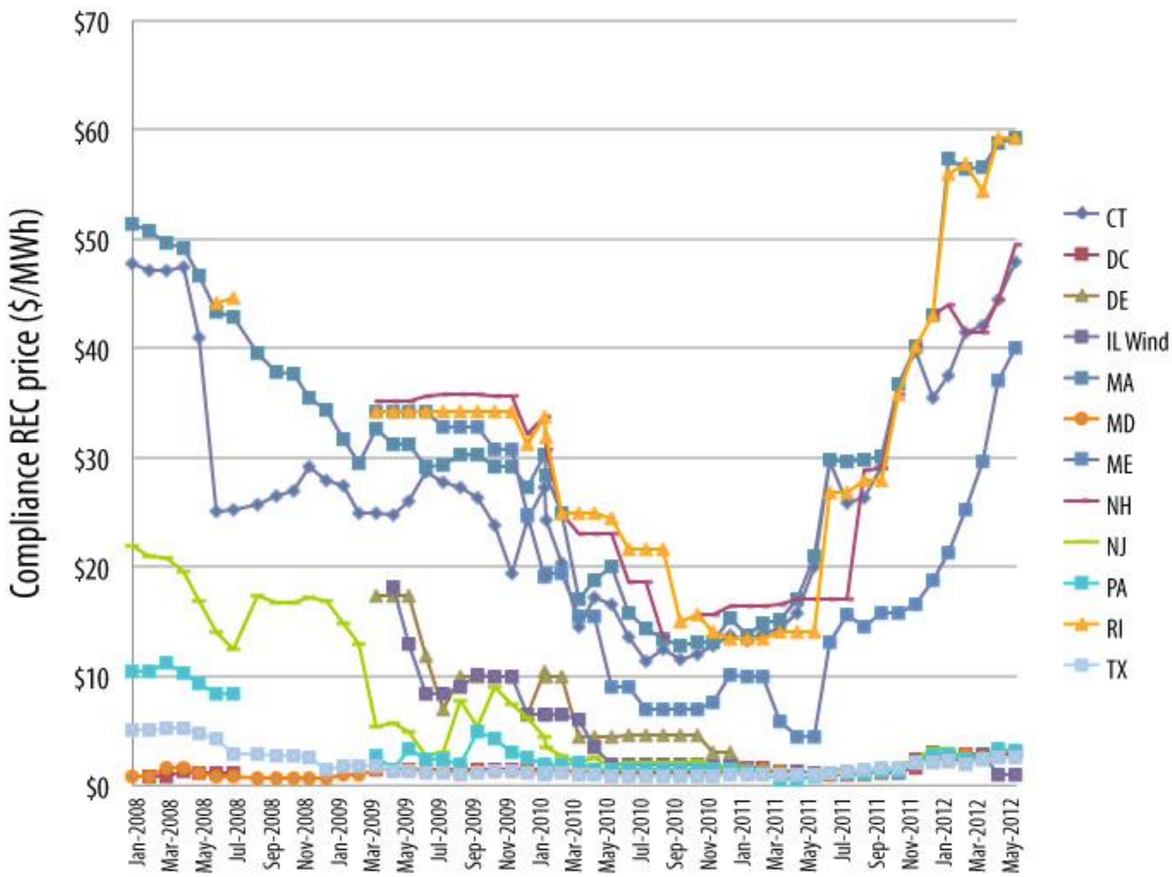


**Figure 1.8.** Compliance REC prices, January 2008 to June 2012

Sources: Spectron Group<http://www.spectrongroup.com/> (2012)

Source: U.S. Department of Energy, Energy Efficiency and Renewable Energy

Production incentives and production tax credits can be an additional source of revenue. These two policies add to the energy price received by the LFGE project owner, because the incentives are given for every unit of energy produced. The Section 29 tax credit was an important Federal production tax incentive given to LFGE project owners. According to this policy, projects placed in service after Dec 31, 1992 and prior to June 30, 1998, can claim tax credit of $0.01/kWh through year 2007.[16] This policy is known to have encouraged many landfills to adopt LFGE projects. (Chen and Greene, 2003) Some states also offer a similar type of production tax credit policy. Production incentives are similar to production tax credits, except that the incentive is given as money rather than tax credits.

Because many renewable energy projects are capital intensive, policies that mitigate the cost burden are also important. Investment tax credits and grants partially alleviate the financial burden of building a renewable energy facility. Investment tax credits (ITC) are given to eligible facilities as a pre-determined percentage of the construction and installation costs. Grants work in a similar way, and the percentage of the cost that is covered is different for each policy. ITC's are often offered at the state level, and grants are offered by state and city governments, as well as by private utilities.

An important regulation concerning landfill gas emissions is the New Source Performance Standard, which requires newer landfill facilities with large design capacities to install a gas collection and control system. The owners of these large landfills had a choice between flaring the collected gas and using it in a gas-to-energy facility. This regulation further lowers the cost of building an LFGE project for larger landfill owners, because they would no longer consider the cost for a collection system as part of the LFGE project cost. This would mean that the amount of waste is doubly important, first because it approximates the amount of organic matter, and second because larger landfills are obligated to install a collection system regardless of whether the owner wants to pursue a gas-to-energy project, bringing down the cost of project installation.

In the next chapter, I will present a review of studies and reports that lend insight into the factors that affect LFGE projects as well as investigate the effectiveness of RPS policy. Chapter 3 introduces variables – landfill characteristics, energy prices, financial incentives – that were included in the study as contributing factors to LFGE project development along with data explanation. Chapter 4 provides the econometric models used to estimate the effects of each policy on project adoption. In chapter 5, I present and discuss the results of the econometric estimations. Based on these results, the simulated effects of each policy are also presented. Chapter 6 concludes the findings of the study and discusses the limits and possible improvements of the study.

## Chapter 2: Literature Review

The empirical literature on the effect of RPS on Landfill Gas-to-Energy projects is not extensive. Accordingly, after a review of an empirical study similar to the present paper, I expanded the literature review to include a general report on LFGE projects, feasibility studies of LFGE projects, reports on the effect of RPS on the overall renewable energy industry, and papers that examine the driving force behind other renewables, namely, wind energy.

An empirical study similar to that of the present present paper was done by Katherine Delhotal (2007). In her study, she assesses the effect of renewable portfolio standards on the diffusion of Landfill gas-to-energy technology in the United States. The paper uses landfill data and renewables policy data from the LMOP database and DSIRE, respectively. However, Delhotal chooses a survival analysis model to assess the rate of diffusion of the LFGE technology. This particular model was chosen because the author believes that cost recovery and profitability are not the only factors of technology adoption. Instead, technology adoption has much to do with the information available to the adopter; not all adopters have the same information. As the technology is adopted by more firms, the information is spread and adoption rate will increase. Such a focus on adoption rate makes survival analysis appropriate, because the survival model assumes that adopters will adopt at different paces due to the difference in information. However, in order for a survival model to work, all adopters must have the same preference for the technology and face the same costs at all time periods. For this reason, the paper limited its estimation to 'candidate' landfills from the LMOP database. Candidate landfills are those that could build a profitable LFGE project, considering the cost and benefits associated with building the project.

The results of the analysis show that RPS, net metering, methane potential, private ownership and electricity prices are significant in increasing the probability of LFGE technology adoption. This result is consistent with the theory. Interconnection standards and oil price, however, do not turn out to be significant factors in technology diffusion. The financial incentives, including PTC, ITC, grants, and tax exemptions were estimated to be effective at the 90% significance level. Because of the similarity in data form and model specification, the results of this study lend particularly important insights into the model specifications for the work in this thesis.

A report by Natural Resources Defense Council (NRDC) (Chen and Greene, 2003) gives an overview of the types of federal and state level incentives that might influence the opening of a landfill gas to energy project. One federal incentive is the renewable energy production incentive which gives approximately 1.5 cents per kWh of renewable energy produced. However, this policy designates LFGE as a tier2 source of energy and thus the incentive allotted to landfill projects fluctuates annually. Another federal incentive is the section 29 tax credit, which subsidizes LFG collection facilities about 1 cent per kWh. This tax incentive proved to be quite effective considering the spike in LFGE projects after its implementation. At the state and local level, California gives an incentive of 1.13 cents per kwh and Illinois has a generous grant for LFGE projects. At the retail level, green power programs sell renewable energy to consumers who are willing to pay a premium. Also, most states have adopted the Renewable Portfolio Standard to encourage renewable energy generation. The report states that the RPS does not provide as large an incentive as the green power programs. It is helpful to note that the report was written in 2003 when RPS was relatively new.

A feasibility study (Morgan and Yang 2001) was conducted on four St. Louis, Missouri landfills, to determine the breakeven price that would make a Landfill Gas-to-Energy profitable. The result of the study was that the four landfills would profit from an LFGE project if the electricity is sold at around 4 cents per kilowatt-hour. This estimate is higher than the avoided cost provided by utilities at the time of the study, implying that additional revenue, such as government subsidy, is necessary to make the projects feasible. The paper used E-PLUS (Energy Project Landfill Gas Utilization Software), a program provided by the USEPA to estimate the cost of building and operating an LFGE project. The factors that determine the costs include landfill age, landfill depth, total waste in place, and annual rate at which waste is accepted. Financial factors such as loan rate and project type is also important in determining the financial performance of a project. It is should also be noted that the landfills used in the study are on the larger side in landfill size, ranging from 6 to 13 million tons of waste, thus the results might not be as favorable for smaller-size landfills.

Jaramillo and Matthews (2005) conducted a feasibility analysis on the same St. Louis landfills. This study did not use the EPLUS program, but conducted its own cost analysis. The results of this study yield a lower breakeven point, even though the methane production was estimated to be lower. It is somewhere between 3 cents to 4 cents per kWh, compared to 4 cents in Morgan and Yang's paper. This is suggested to be because the analysis assumed larger generation capacities compared to those assigned by the EPLUS software used in Morgan and Yang. The three main parts of the cost analysis is the collection system, engine system, and flaring costs. The collection system and engine both show economies of scale, meaning the larger the collection system and larger the engine capacity, the more economically efficient is the cost of installing and operating the facility. A further analysis of the paper is the net social benefit of a LFGE project calculated by avoided methane emissions and emission offsets. If benefits from emission offsets are included, the break-even price of electricity decreases to less than 2 cents per kWh. The emission benefits are the largest benefits. This suggests that government subsidies on LFGE projects may be a justifiable considering the social benefit of reduced emissions. Another point made in the paper is that IC engines lead to the highest private net present value (NPV) but gas turbines lead to the highest social NPV because they create less emission.

Some ex-ante studies have been conducted on the effect of RPS on renewable energy generation. There is a report by the Energy Information Administration (EIA) on the effect of a 10 percent RPS scenario. The study assumes a scenario where the RPS starts at the rate of 2.5% of retail electricity sales in 2005 and gradually reaches 10% by 2020. Using the Electricity Market Model which consists of modules for the demand, supply and conversion of energy, the study predicts that the 10% RPS case will increase electricity generation by landfill gas by 25% in 2005 compared to a reference scenario in the absence of RPS. In 2010 this figure is predicted to be 25% and in 2020 16%. The main factors that drive the amount of renewable energy generation are the cost of the renewable technology, the cost to continue generation in existing plants, and the consumers' willingness to pay.

Both Lyon and Yin (2009) and National Renewable Energy Laboratory (Cory and Swezey, 2007) suggest that the market structure for electricity buyers and sellers can influence renewable energy generation under RPS. The market could consist of a single electricity provider or it could be restructured to allow competition. The NREL report predicts that the former case would provide a more stable environment to make investment in renewable energy generation, but suggests that this effect is ambiguous when specific cases are studied. Lyon and Yin (2009) find that a state with a restructured market has a higher probability of RPS adoption. According to the NREL, the two kinds of risk involved in financing a renewable energy project are investment risk and revenue risk. The tax incentives that reduce overall costs reduce the investment risk and long-term purchasing contracts decreases the revenue risk. It was shown that states that require utilities to sign long-term purchasing contracts with renewable energy generators have better results in renewable development.

A report by the Lawrence Berkeley National Laboratory (Wiser and Barbose 2008) predicts that RPS will induce sizable renewable energy development. As an indicator, more than 50% of the newly added renewable energy capacity from 1998 through 2007 occurred in states with active, mandatory RPS policies. The figure rises to 60% in 2002 and reached 76% in 2007. However, it is also mentioned that the RPS policy is likely to be enacted in states that have higher renewable energy potential. In 2007, wind power was the sector most supported by the RPS requirement, but many states plan to support specific renewables that at the time had higher costs but were nonetheless promising, especially solar power. This specific support is given through credit multipliers and some states, including Massachusetts and Washington DC, apply credit multipliers to methane.

Lyon and Yin (2009) investigate the factors that determine whether or not a state adopts the RPS. The paper uses a logit model to test whether factors such as existing renewable energy potential, the share of natural gas in the electricity fuel mix, and democratic presence in state legislature affect the decision to adopt RPS among various other factors. The findings are that strong existing renewable energy potential, a small share of natural gas in the electricity market, and organized renewable energy interest contribute to the adoption of RPS. These factors are important to consider when using RPS as an independent variable of a model, because the study suggests that existing landfill to energy projects could affect RPS resulting in potential simultaneity.

Because of the scarcity of literature on the impacts of landfill gas-to-energy projects, several papers on wind energy were also examined to acquire insight into on the impacts of government policy on building renewable energy projects. The first paper is a report by the National Renewable Energy Laboratory (NREL) (Bird and Parsons 2003) that examines the factors at play in the states that have substantial wind energy investment. The main drivers of wind energy development include renewable portfolio standards, favorable market conditions, system benefits funds, settlement agreements with large power plants, property tax exemption, sales tax exemption, and green power markets. The California restructuring debacle in 2000 and 2001 drove up energy prices, making market conditions favorable for wind energy developers in its neighboring states, namely Oregon and Washington. System benefits funds are collected by charging utilities a designated amount for every unit of electricity sold. In many cases, this fund is given to renewable energy projects in the form of production incentives. An example of a settlement agreement that benefited wind energy is the one in Minnesota where Xcel energy was required to develop or purchase 825 mW of wind power in exchange for the right to store nuclear waste. A renewable energy project may be exempt from property taxes. Renewable energy generating equipment may also be is exempt from sales taxes as another way to support their development. In some states utilities are obliged to supply a green power option to its customers, and in some cases, the market is formed voluntarily.

For the purpose of the present study, factors such as settlement agreements and system benefits funds are difficult to quantify, because they are a one-time occurrence and the dispersion of benefits is not systematic. Market conditions are mainly represented by electricity prices, which can be easily quantified. Also, renewable portfolio standards, property and sales tax exemptions, and green power markets can all be predicted to affect landfill gas energy in a manner to how they affect wind energy projects.

Another report published by NREL (Short, Blair, and Heimiller 2004) uses a projection model – WinDS – to estimate the impact of policy initiatives on the expansion of wind energy capacity. The paper examines the impact of three types of policies – R&D investment, production tax credits, and RPSs - on the expansion of wind energy capacity. The R&D has a significant effect – it is estimated that only 30% of wind energy capacity would occur if R&D in wind is discontinued. The production tax credit (PTC) does not have an effect in the long run, but it will speed up wind energy development. This is because a PTC would eventually end and will only encourage faster development in regions favorable to wind farms, but would not improve prospects for regions that have poor wind resources. The RPS is also projected to have a significant effect on the expansion of wind capacity, especially if there is a significant penalty for non-compliance. In 2025, an RPS with an $ 18/mWh penalty it is estimated that there will be an increase in the total wind energy capacity by more than 60%.

## Chapter 3: Independent Variables and Data Explanation

This study uses three separate econometric models to estimate the effects of the RPS and other financial incentives on LFGE project decision. The three models are the linear probability model, logit model, and a mixed logit model that incorporates random effects. Before discussing these models in greater detail, we describe the data used in the estimation. Much of this discussion focuses on the construction of a number of explanatory variables to explain the probability of LFGE project adoption.

The study uses a panel of individual landfills over a period of 20 years. The data includes landfill characteristics variables, weather variables, and economic variables. The landfill characteristics data, which include landfill age, waste in place, landfill owner, distance to power grid, and LFGE project variable, are individual-level data. The temperature and precipitation data are averaged county-level data. The economic and policy variables – electricity and gas price, state RPS, state grant, production tax credit, investment tax credit, power purchase agreement – are state-level data.

The US Environmental Protection Agency's Landfill Methane Outreach Program (LMOP) provides a database for about 2400 landfills in the United States. These data includes the date at which the landfill was open, waste in place, landfill owner, and landfill location (state, city, county), whether there is an operational LFGE project, and if there is - project type, project capacity, and project developer. The EPA also provided longitude and latitude data for each landfill.

We proceed with a discussion of how each of the variables is defined and how they relate to a theory for the adoption of an LFGE project.

### 3.1.1 Landfill Characteristics

***Factors related to methane potential***

The methane production potential of a landfill is an important determinant of the economic feasibility of an LFGE project because, as with many other production firms, an LFGE system has economies of scale. (see Jaramillo and Matthews 2005) This means that a larger amount of methane production would make an LFGE project more economically efficient. LFG is produced by the anaerobic decomposition of organic waste. Consequently, LFG production can be simplified into a function of the size and age of the waste volume, waste type, moisture content, and temperature (Rajaram, Siddiqui, and Kahn 2011). In this study, I was able to incorporate four of these factors: size of the waste volume (waste in place), age of the waste, moisture content, and temperature.

*Waste in Place*

Because the methane in LFG is produced by the anaerobic decomposition of organic waste, it is important to know the amount of organic matter in the waste. This would involve knowledge of the exact proportions of various waste products in the waste, or at least the proportions of waste type – such as industrial/commercial/institutional waste and residential waste. If the waste content is known, one can use this information to derive the organic content of the waste. However, because waste content information is impossible to attain, we will use the total waste in place as a proxy for organic content.

The data are provided in the USEPA LMOP database. The waste in place ranges from 700 to 120,000,000 tons with an average of 4,997,673 tons. Because of the large values, this variable is scaled by its mean.

*Landfill Age*

The LFG gene ration at a landfill happens in several phases, each of which takes different periods of time. Methane generation typically starts 1 to 3 years after the waste is dumped in the landfill and peaks at 5 – 7 years. Almost all gas is produced within 20 years after the waste is dumped, although small amounts of methane can be produced after this period.[17] Figure 3.1 represents an example of how to characterize the methane production of a landfill. It is useful to note that a landfill often accepts waste for 20 – to 30 – years; which means significant amounts of methane would be produced for 30 – to 40 – years.

The data are also provided in the USEPA LMOP database. The landfill age covered by the data panel used in this study ranges from 1 to 99 years, with an average of 24 years.

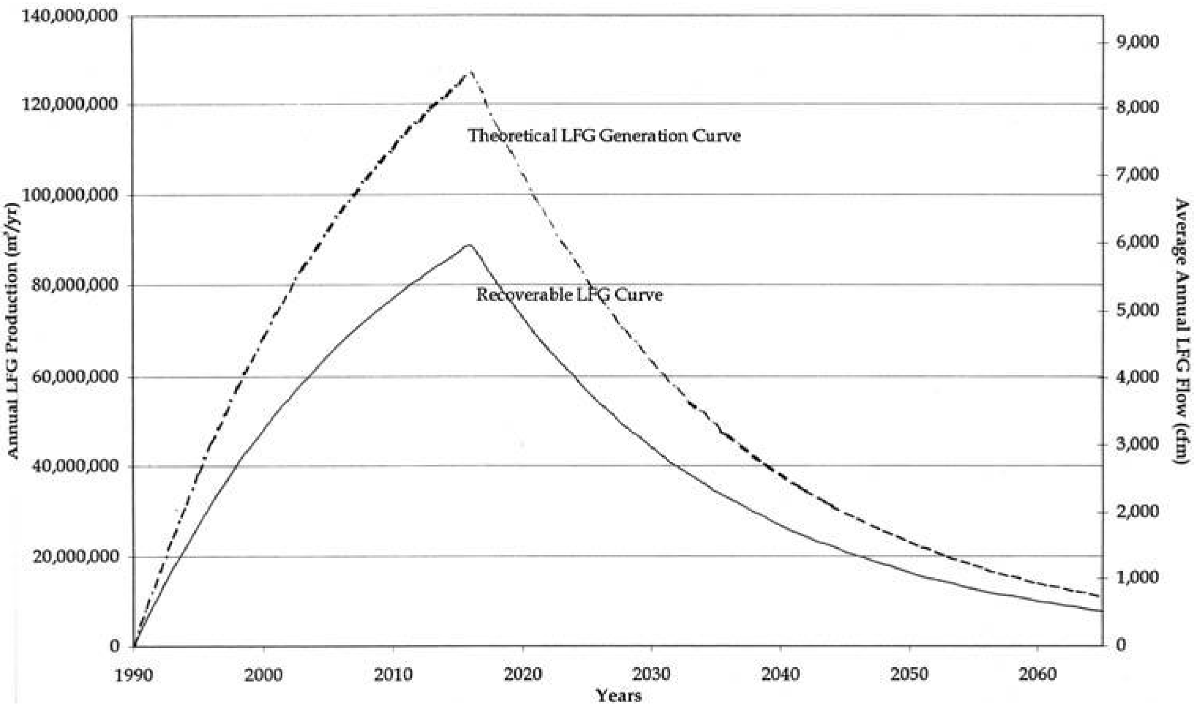


**Figure 3.1** LFG generation curves

Source: *From landfill gas to energy technologies and challenges*. 2012.

*Moisture Content*

Moisture in the waste increases the production of gas because the water encourages bacteria growth and spreads nutrients and bacteria to wide areas of the landfill. Although the moisture content of a landfill is determined by various factors, including type of landfill cover, condition of cover, temperature and precipitation, type of leachate collection system, etc[18], we use precipitation as an estimate for moisture content.

The precipitation data are the average precipitation at the county level from year 1999 to 2005. Precipitation ranges from 8,275 to 262,653 with an average of 104,954. These data are obtained from the authors of the paper - *Creating County-Level Estimates from National Weather Service*

*Data*.

*Temperature*

Warmer temperatures also cause more bacterial activity, which increases the rate of landfill gas production. There is a sharp decrease in bacterial activity below 50° Fahrenheit. The temperature data was also incorporated into the model.

The data are also the average temperature at the county level from year 1999 to 2005. Temperature data ranges from 49.7 to 88.3, with an average of 69 degrees Fahrenheit. It was provided by the authors of the paper- *Creating County-Level Estimates from National Weather Service Data*.

### *Other Landfill Characteristics*

*Public Ownership*

In order to gain insight into other real factors that affect LFGE project decisions, interviews were conducted with several landfill owners and developers, and there was a distinct difference between private landfill developers and public landfill owners. The major motivation for private LFGE developers was the profitability of the project, including tax credits and electricity prices. On the other hand, managers of public landfills adopt waste-to-energy projects as a public service. Publicly owned and operated LFGE projects are often built to provide energy to a public facility such as a local prison or a waste water management facility. Although profitability is important to public landfill managers, their decision to start a project seems to be affected by the public's environmental concerns and feel-good factors as well as profitability. For this reason, the private or public ownership of a landfill may affect the probability that a project is built at the site, although it is ambiguous as to what direction the effect would be. That is, a private landfill owner might be more enthusiastic to create extra profit by building a project. On the contrary, public landfill managers might have better access to funds and would feel less of the risk in developing a project.

Out of the 2,854 landfills included in the LMOP database, there are 1,618 public landfills. The variable is either 0 or 1 with a mean of 0.5878.

*Distance to Nearest Power Grid*

Although the cost of installing a transmission line does not comprise a large portion of the project capital cost (approximately 5%), the costs vary a great deal depending on the distance to the nearest power grid, making it an important factor in project decisions.[19] According to the NRDC report (Chen and Greene, 2003), the cost of interconnection can vary from $20,000 to $500,000.

The data on distance to nearest power grid data were obtained from NREL. These data indicate the straight line distance from a landfill to the nearest transmission line. The transmission line recorded in the NREL database goes down to 13kV, but some transmission lines with a capacity below 100kV can possibly be missing in the database. The distance ranges from 0.00075 km to 89.6 km, with an average of 2.6 km.

### 3.1.2 Energy Prices

The electricity and gas price data were obtained from the US Energy Information Administration (EIA). The electricity price data is the average retail electricity price to ultimate customers, averaged by state and year. The values are converted to real prices using 1991 as the base year. The values are in cents per Kilowatt-hour. The variable ranges from 3.4 ¢/kWh to 12.1 ¢/kWh, with an average of 6.21 ¢/kWh. The natural gas price data are the annual average city-gate natural gas price by state and year, provided by the EIA. The citygate is a point or measuring station at which a distributing gas utility receives gas from a natural gas pipeline company or transmission system. These data are real prices with the base year 1991 and are in dollars per Thousand Cubic Feet. The variable ranges from $1.67 to $7.81, with an average of $4.07.

### 3.1.3 Financial Incentives

*Renewable Portfolio Standards (RPS)*

The renewable portfolio standard (RPS) is a regulation that requires utility companies to supply a designated portion of their electricity from renewable energy generation such as wind, solar, biomass, or other alternatives to fossil and nuclear electric generation. Each state has an RPS policy that specifies the eligible types of renewable energy sources as well as the utilities that must abide by the standard.[20] The first RPS was enacted in 1983 by Iowa and an increasing number of states have adopted their own variation of this type of policy. As in figure 3.2, the number of states that mandate an RPS that includes landfill gas as an eligible energy source, increased dramatically in the late 2000's, peaking in 2012-2015 at 28 states. The target RPS level ranges from 2% in Iowa to 40% in Maine.

For RPS information specific to landfill gas energy, Figure 3.3 is a graph that presents each state's target RPS fraction that includes landfill gas as an eligible energy source in year 2012. The most common target RPS that includes landfill gas is around 20 percent.

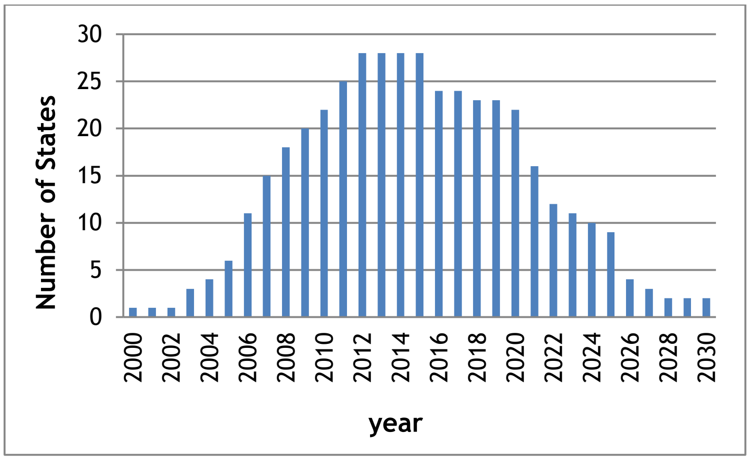


**Figure 3.2** Time trend of the number of states that enforce an RPS

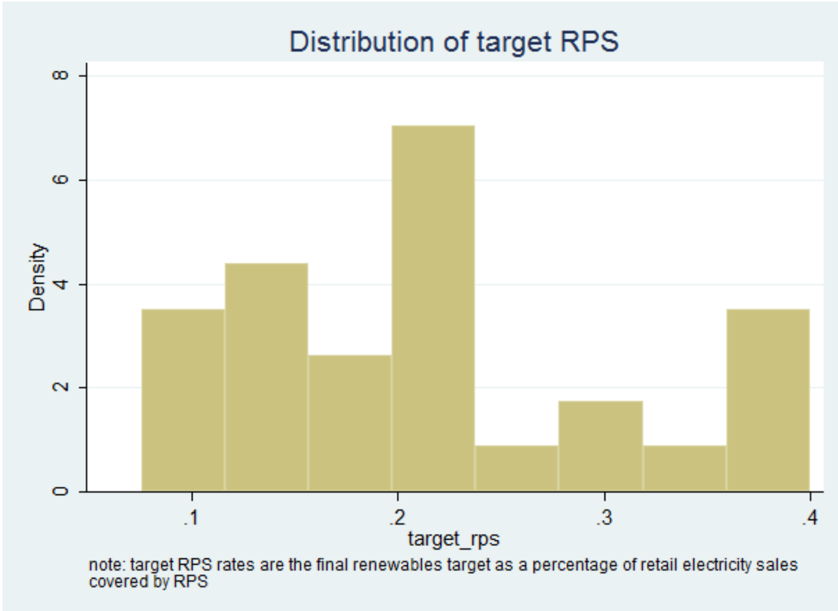


**Figure 3.3** Distribution of target RPS levels

DSIRE is a website that provides comprehensive information on federal, state, and local incentive and policies that aid renewable energy project development. The RPS data were obtained from this website, which gives the percentage of each state's RPS, the implementation schedule, and the information on alternative compliance payment rates.

Each state has different supplementary devices to the RPS policy. Some states have different types of renewable portfolio standards that are divided into Primary, Secondary, and Tertiary RPS's. For example, Oregon requires a 25% RPS to larger utilities, 10% to smaller utilities, and 5% to the smallest utilities, all targeted to be reached by 2025. Other states, such as North Carolina and Colorado, have different RPS standards for investor-owned utilities and municipal utilities.

Most states have various tiers within their RPS. The tiers "refer to requirements that a specified portion of the renewable energy obligation be met with certain resources or class of resources." [21] This is similar to the common solar set-aside, which mandates that a small portion of the overall RPS requirement be met specifically by solar energy sources. This ensures the states' ability to promote specific energy projects that are deemed to have greater potential.

For the purpose of this study, the RPS policy variable only considers the primary RPS and tiers that include landfill gas as an eligible energy source. In the example below (Table 3.1) of Colorado, landfill gas is included in all RPS types and all tiers. Since the study only considers primary RPS, the RPS policy variable for 2014 would be 0.12 (0.1075+0.0125).

| State (Notes and comments) | RPS Type (Primary, etc.) | Tier | Target for 2014 |
|---|---|---|---|
| **Colorado** | 1 | 1 | 0.1075 |
| | 1 | 2 | 0.0125 |
| | 2 | 1 | 0.03 |

**Table 3.1** Composition of RPS in the state of Colorado

Source: Database of State Incentives for Renewables and Efficiency (DSIRE)

The price premium for renewable energy is explicitly represented through Renewable Energy Certificates, also known as REC's. A graph of REC prices in the market from 2002 to 2007 is presented in Figure 3.4. If a REC is priced $10/mWh, it would mean that a renewable electricity generator will earn 1 cent per KWh of electricity.

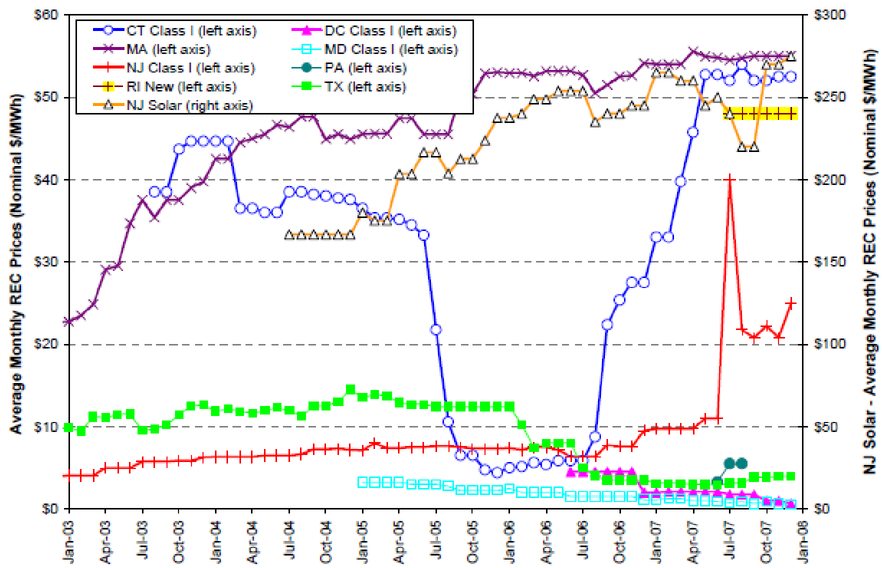


**Figure 3.4** REC Prices in RPS Compliance Markets (Main Tier and Class I)

Source: National Renewable Energy Laboratory (NREL)

*Production Tax Credit (PTC)*

State production tax credits (PTC) are also included as an incentive that benefits LFGE project developers. The state PTC is tax credit given to a renewable energy generator for every kWh of electricity generated. Among the six states that provide PTC's to LFGE project owners, the PTC rates range from 0.075¢/kWh (Nebraska) to 1.5¢/kWh (Iowa), with an average of 0.80¢/kWh.

The earliest production tax credit policy was enacted in 2000 in Maryland, and by 2010 five other states had adopted the subsidy. Figure 3.5 shows the number of states that offer production tax credits each year. Because landfills owned by local government do not have to pay tax, this policy would not benefit municipal LFGE developers.

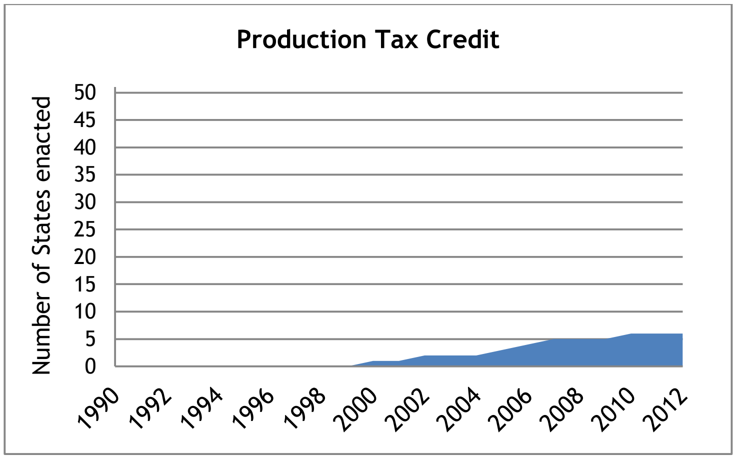


**Figure 3.5** Time Trend of Number of States with Production Tax Credit

In the panel, this variable has a non-zero value if in that time period, the state in which the landfill is located, has a production tax credit. The values for this variable are in cents per kilowatt-hour, and they are stated in each state's PTC policy. The data was created in reference to policy data provided by DSIRE.

*Investment Tax Credit (ITC)*

Investment tax credits (ITC) are granted to a taxpayer that installs a renewable energy facility, primarily as a percentage of the cost to construct the system. An LFGE project that generates electricity would benefit from this incentive. For the seven states that have an ITC policy, the ITC rate ranges from 10% (Kansas) to 100% (Kentucky) of the cost, with an average of 35%. The policy information was provided by DSIRE. In figure 3.7, the amount of ITC is presented according to the cost of the project and the stipulated ITC rate. According to the report by NRDC, the cost of building an LFGE project varies from $850,000 to $4,500,000, while a typical project costs $1,500,000 to build. This would mean that a typical landfill project that accepts an average amount of ITC would still need to procure 1 million dollars of funds. Figure 3.7 presents the number of states that offer and ITC for each year.

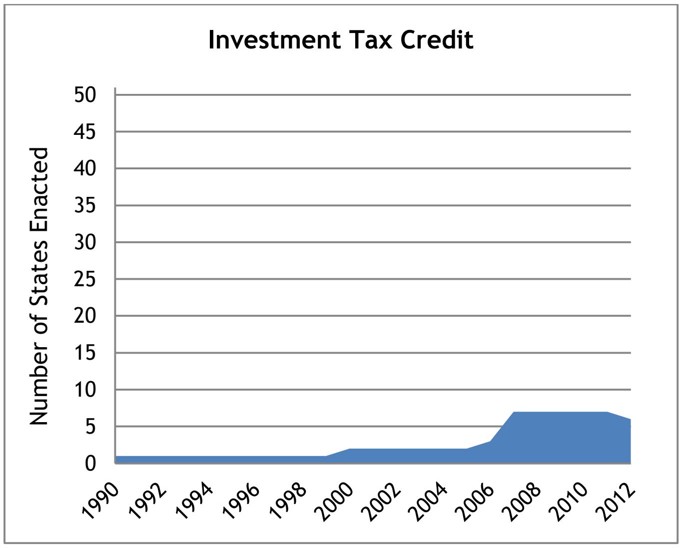


**Figure 3.6** Time Trend of States with Investment Tax Credits

In the panel, this variable has a non-zero value, if in that time period, the state, in which the landfill is located, has an investment tax credit. The values in this variable are the percentages of cost defined by each state policy.

**Table 3.2** Total Amount of ITC Depending on the Rate of ITC and Cost of LFGE Project

| | Rate of ITC | | | |
|---|---|---|---|---|
| Cost of LFGE Project | | 10% | 35% | 100% |
| | $850,000 | $85,000 | $297,500 | $850,000 |
| | $1,500,000 | $150,000 | $525,000 | $1,500,000 |
| | $4,500,000 | $450,000 | $1,575,000 | $4,500,000 |

Note: The figures for cost of LFGE project were taken from the NRDC report "Is landfill Gas Green Energy?"

*State Grants*

Many states grant funds to applicants that submit proposals to develop renewable energy. The amounts of the grant and eligibility requirements differ for each grant program. For example, some of the state grants included in the DSIRE database are only for innovative technologies i.e. technology that has not been commercialized. (e.g. New Jersey's REED program). Some of the grants that are included have size requirements, cost requirements, and are targeted to fund research by municipalities and public schools. Some grant programs require that the facility is located in the service territory of the state's major utilities. Other programs require that a certain amount of power be used on site, in order for the project to qualify for state funding. Many programs require that the project generate electricity.

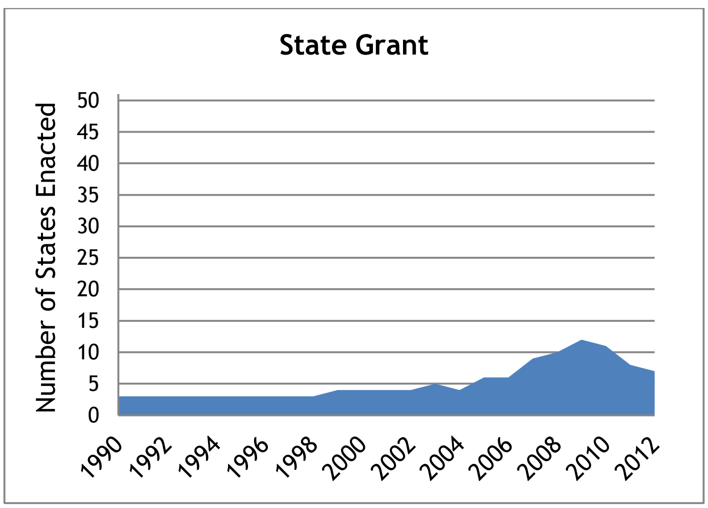


**Figure 3.7.** Time Trend of Number of States with State Grant Program

In the model for the present study, the state grant is included as a dummy variable, ignoring various requirements and grant amounts. State grants that were excluded are those that mandate innovative, non-commercialized technology and grants that are given to support research of renewable projects instead of facility construction. Figure 3.8 presents the number of states that offer a state grant in each year.

*Power Purchase Agreements*

Power purchase agreements provide a stable stream of revenue that could boost the probability and or reduce the revenue uncertainty associated with an LFGE project. The retail electricity suppliers would offer purchasing contracts to renewable generators as a means to fulfill their RPS requirements. The contracts promise to purchase electricity at a specified rate for some specified period of time. Figure 3.9 presents the number of states in which a power purchase agreement program is available.

The data are included in the model as a dummy variable that indicates whether there is a retail electricity supplier in the state that offers such a purchase program.

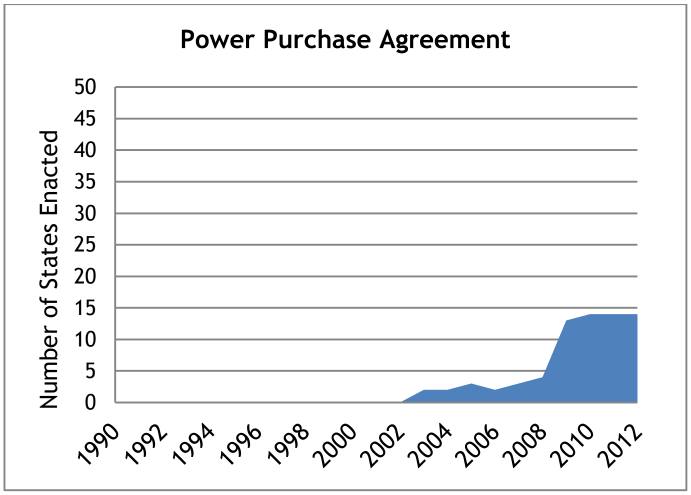


**Figure 3.8.** Time Trend of Number of States in which a Power Purchase Agreement is Available

Note: Power purchase agreements are offered by utilities. The graph represents the total number of states that have at least one utility company that offers power purchase agreements

*Year fixed effects*

The inclusion of year fixed effects is designed to control for the factors that change by time, but are common to all landfills. For example, federal policies such as the Section 29 tax credit were uniformly available to all landfills that started their service between 1992 and 1998. Also, factors such as the availability of landfill recovery and use technology are largely similar to all landfills, and thus only vary by time. The inclusion of yearly dummy variables controls for these effects that are common to all landfills in each year.

*State fixed effects*

The inclusion of state fixed effects is designed to control for time-invariant factors that are common to all landfills within each state. Examples of state fixed effects could be any state policy that stays constant during the time period at which the data are available. To illustrate, property tax on energy projects that are not modified during the time frame could be a state fixed effect that affects project decisions.

*Individual Landfill Effects*

There are various individual landfill characteristics that affect the decision to open a project. While landfill characteristics such as waste in place, temperature, and type of ownership can be observed, many other characteristics that affect the probability of project development are not observable or readily available in a data format. For example, the degree of risk aversion differs by landfill owner, yet these are unobservable. The same is true for the preference to adopt a technology. Further, data for factors such as organic content and moisture content of the waste are not readily available. Assuming that these factors are constant in time for each landfill, the inclusion of individual fixed effect will control for such factors.

The study estimates the effects of the RPS, state grant, production tax credit, and investment tax credit on the adoption of LFGE projects. The variable for the RPS policy is the yearly fractional RPS rate, represented for each state. Production tax credit is a variable of the cents given per kilowatt of electricity generation and investment tax credit is represented as a percentage of cost of installment. The state grant variable is a dummy that indicates whether there is an opening for grant proposal for each state and year. The dummy variable for whether a state has an entity offering power purchase agreements and a dummy variable for the existence of an alternative compliance payment are other policy variables tested in the study.

The control variables include electricity price and gas price – averaged for 3 years. Landfill characteristics such as waste in place, age of landfill, temperature, precipitation, distance to nearest power grid, and public ownership are also considered as control variables.

**Model Specification**

Table 3.3 presents the variables included in the final model specification that was used in econometric estimation along with a brief description of the each variable. The estimation results from different specifications are presented in Appendix 1.

**Table 3.3 Model Specification table**

| *Variable* | *Description* | *Source* |
|---|---|---|
| **State policies** | | |
| **Renewable Portfolio Standards (RPS)** | Variable is equal to the RPS level (percentage) for the corresponding year and state. | DSIRE database |
| **State grants** | Variable is equal to 1 if the state accepts project proposals in that year. | DSIRE database |
| **State Production Tax Credits (PTC)** | Variable equal to the cent-per-kilowatt value if the state has a PTC policy in that year. Zero otherwise. | DSIRE database |
| **State Investment Tax Credits (ITC)** | Variable is equal to the percentage of cost covered by the state ITC, if the state has an ITC policy in that year. Zero otherwise. | DSIRE database |
| **Energy Prices** | | |
| **Electricity prices** | The 3 year average of the state average retail electricity price. | EIA |
| **Gas prices** | The 3 year average of the state citygate natural gas price. | EIA |

| **Control Variables** | | |
|---|---|---|
| **Methane Potential** | Measured by waste, precipitation and temperature | |
| **Waste-in-place(WIP)** | The amount of waste placed in each landfill in tons. Scaled by dividing all values by the mean | USEPA |
| **Precipitation** | The amount of rainfall averaged for years 1999 to 2005 on the county level. Scaled by dividing with mean. | Authors of *Creating County-Level Estimates from National Weather Service Data* |
| **Temperature** | The temperature averaged for year 1999 to 2005 on the county level. Scaled by dividing with mean | Authors of *Creating County-Level Estimates from National Weather Service Data* |
| **Interaction of Waste and precipitation** | Multiplication of WIP and precipitation variables | |
| **Interaction of Waste and Temperature** | Multiplication of WIP and temperature variables | |
| **Distance to the nearest power grid** | The distance from each landfill to the nearest power grid with capacity larger than 40kv. Distance in kilometers. | NREL |
| **Public ownership** | Variable equal to 1 if the owner of the landfill is a public entity. | USEPA |
| **Year fixed effect** | Year fixed effects are included as year dummy variables. The values for each year dummies are equal to one if the data corresponds to that year | |
| **State fixed effect** | State fixed effects are included as state dummy variables. The state dummy is equal to one if the landfill is located in that state | |
| **Individual landfill fixed effect** | Individual fixed effect is included in the linear probability model by demeaning. In the random effect logit model, it is included as the random effect term. | |

# Chapter 4: Methodology

In order to determine the influence of renewable policies on whether or not a landfill develops an LFGE project, the study employs two kinds of econometric models – the linear probability model and the logit model. As discussed in detail in Chapter 3, the data includes characteristics and policy data for 2853 landfills in the United States over 20 years. The dependent variable should represent a landfill owner/developer's decision to build or not to build a LFGE project at the landfill site in a given year. If a landfill does not have a project in a specific year, it means that the landfill owner decided not to build a project that year, thus the decision variable would be zero. In the first year that a landfill has a project – the project open year, the landfill owner has decided to build a LFGE project and the decision variable would be one. However, once the project is built the landfill owner no longer makes a choice. Thus, the data mimics the form of a survival model, in which the subject (mostly a patient) survives for a period of time and dies, after which the data ceases to exist.[22]

## 4.1 Linear Probability, Logit, and Mixed Logit Models: Basic Concepts

This study uses three econometric models to estimate the effect of the RPS and other financial incentives on LFGE project decision. The three models used are the linear probability model, the logit model, and a mixed logit model that incorporates random effects.

The most straight forward method to estimate a project adoption choice such as in the present case, is to use a logit model. The logit model allows one to estimate how different factors affect the probability that an event will occur (i.e. adoption of an LFGE project). The model is estimated through maximum likelihood methods. The discrete nature of the dependent variable makes the logit model more appropriate than an Ordinary Least Squares (OLS) model.[1]

However, it is complicated to account for fixed effects in a logit model, especially when there are a large number of individuals. The simple method of “demeaning” used in OLS models cannot be used in a logit model, because “demeaning” the data would alter the form of the dependent variable so that it is no longer appropriate. The solution to the issue of including individual effects is to use a linear probability model, conditional logit model, or random effect logit model. The conditional logit model is excluded, because it would only use landfill data that eventually does adopt a project, dropping more than half of the data. Consequently, estimation is done using the linear probability, logit, and random effect logit models.

*Logit model*

As mentioned before, the logit model is a straight-forward way to estimate the effects of independent variables on the probability that an event would occur. The dependent variable is in

[1] An ordinary least squares (OLS) model assumes that the dependent variable is an unbounded and continuous value. Thus, predictions from an OLS model can result in real numbers from negative infinity to positive infinity. However, the dependent variable of the present study is whether a landfill owner/developer opens a project, which is a represented by the numbers 0 and 1. Predictions from an OLS model would not make sense, since they can be any real number that is not 0 or 1.

a discrete form – 0 or 1. The logit method assumes an implied utility curve that is determined by the independent variables. If the utility is above a threshold, the dependent variable would be 1, meaning that the project is adopted, and if the utility is below the threshold, the dependent variable would be zero.[23] In a logit model the state and year fixed effect can be included as dummy variables, but individual landfill fixed effects cannot be included as dummies, because this would create more than 2000 variables.

*Random Effect Logit Model*

The random effect logit model is the same as a logit model in that the model estimates the effect of independent variables on the probability that a discrete choice event will occur. However, this model is able to account for individual random effects for each landfill, which means important unobserved variables, such as organic content of waste and landfill owner risk preference, are controlled. In order to control for unobserved individual landfill effects, the individual landfill effects are simulated and included in the model. Including unobserved individual landfill random effects greatly improves the model in that it prevents bias from omitted variables. (Greene 2012)

*Linear Probability Model*

A linear probability model is an Ordinary Least Squares model, same as a linear regression model, except that the dependent variable is interpreted as a probability.[24] The dependent variable in the present case would be the dummy variable that indicates whether a landfill has started an

LFGE project in a particular year. The independent variable would be the factors that account for the project decisions: individual landfill characteristics, financial incentives, and state, year, and individual fixed effects. The regression would be run the same way an OLS regression would be run. However, a crucial shortcoming of the model is that the predicted values for the dependent variable would not necessarily be between 0 and 1.[25] Since we want to interpret the dependent variable as the probability of opening a project, it would be difficult to make any meaningful interpretation of the estimation coefficient in terms of how much they affect this probability. Nevertheless, because of the simplicity that an OLS model lends when incorporating individual fixed effects, the study used the linear probability model as an estimation method.

## 4.2 The Models

*Logit Model*

In order to estimate a logit model we assume an implied utility curve, which in the present case would be the net present discounted benefit of an LFGE project to the landfill owner, with the following variables:

$$\pi_{it} = f(X_{it}, Z_{it}, \tau_t, \lambda_s;\ \theta) + e_{it},$$

where *i* is a landfill index, *t* is a year index, and *s* is a state index. $X_{it}$ is a vector including non-policy variables that may affect the net benefit such as landfill age and electricity prices. $Z_{it}$ is a vector including policy variables such as RPS design parameters (e.g., target level, eligible generation technologies, clauses on RECs) and state incentives. $\tau_t$ is year fixed effect to capture common factors that affect all landfills such as progress in generation technology and federal policy variables. $\lambda_s$ is a state fixed effect that includes the common factors that affect landfills in the same state in the same way – time invariant state characteristics such as state size would be included in this variable. $\tau_t$, and $\lambda_s$ control for factors that are unobservable to researchers but affect the decision-making of landfill owners. $\theta$ is a vector of parameters to be estimated based on data (e.g., revealed decisions that landfill owners have made). $e_{it}$ is the error term. If a landfill owner has not decided to build a landfill prior to time *t – 1*, the probability that landfill owner *i* will make the decision to adopt a LFGE project in year *t* is:

$$P(d_{it} = 1 \mid X_{it}, Z_{it}, \tau_t, \lambda_s;\ \theta) = P(\pi_{it} > 0 \mid X_{it}, Z_{it}, \tau_t, \lambda_s;\ \theta)$$
$$= P[e_{it} > -f(X_{it}, Z_{it}, \tau_t, \lambda_s;\ \theta)]$$

Assuming $e_{it}$ has a logistic distribution, hence the logit model, the probability has the following closed form:

$$P(d_{it} = 1 \mid X_{it}, Z_{it}, \tau_t, \lambda_s;\ \theta) = \frac{\exp[f(X_{it}, Z_{it}, \tau_t, \lambda_s;\ \theta)]}{1 + \exp[f(X_{it}, Z_{it}, \tau_t, \lambda_s;\ \theta)]}.$$

The logit model is a Maximum Likelihood Estimator, which produces estimated parameters that maximize the likelihood that the observed data would emerge given the parameters. The joint probability function for a landfill *i* to not adopt a LFGE project until year *T* would be:

$$P_i = P(d_{i1} = 0, d_{i2} = 0, \dots, d_{iT} = 0 \mid X_{it}, Z_{it}, \tau_t, \lambda_s;\ \theta)$$

$$= \prod_{t=1}^{T} P(d_{it} = 0 \mid X_{it}, Z_{it}, \tau_t, \lambda_s;\ \theta).$$

For a landfill that has adopted LFGE project at year *k*, the joint probability function of the k decisions before year *k+1* is:

$$P_i = P(d_{i1} = 0, d_{i2} = 0, \dots, d_{ik} = 1 \mid X_{it}, Z_{it}, \tau_t, \lambda_s;\ \theta)$$

$$= \int \prod_{t=1}^{k-1} P(d_{it} = 0 \mid X_{it}, Z_{it}, \lambda_s, \tau_t;\ \theta)\ P\ (d_{ik} = 1 \mid X_{ik}, Z_{ik}, \lambda_s, \tau_k;\ \theta)\ . \qquad (5)$$

The coefficients that maximize function (5) would be the estimation results.

$$\max_{\theta} Log\ L(\theta) = \sum_{i=1}^{I} log\hat{P}_i \qquad (6)$$

*Random Effect Logit Model*

The mixed logit model with random effects is a well established method of incorporating individual effects to a discrete choice situation, by simulating the random effects and applying them to the logit model framework. (McFadden and Train, 2000)

The random effect logit model would have an implied utility curve as shown below:

$$\pi_{it} = f(X_{it}, Z_{it}, \tau_t, \lambda_s, \eta_i;\ \theta) + e_{it},$$

The utility function looks the same as that of the logit model, except for the inclusion of the individual random effect term - $\eta_i$. This term controls for unobserved time-invariant individual landfill characteristics, such as landfill owner risk preference and organic waste content.

The closed form probability that a project would be adopted is similar to that of the logit model, except for the inclusion of $\eta_i$:

$$P(d_{it} = 1 \mid X_{it}, Z_{it}, \eta_i, \tau_t, \lambda_s;\ \theta) = \frac{\exp[f(X_{it}, Z_{it}, \eta_i, \tau_t, \lambda_s;\ \theta)]}{1 + \exp[f(X_{it}, Z_{it}, \eta_i, \tau_t, \lambda_s;\ \theta)]}$$

However, since $\eta_i$ is a result of simulation, the joint probability function for a landfill *i* to not adopt a LFGE project until year *T* would be:

$$P_i = P(d_{i1} = 0, d_{i2} = 0, \dots, d_{iT} = 0 \mid X_{it}, Z_{it}, \tau_t, \eta_i;\ \theta)$$

$$= \int \prod_{t=1}^{T} P(d_{it} = 0 \mid X_{it}, Z_{it}, \eta_i, \tau_t;\ \theta)\, dF(\eta_i;\ \gamma).$$

$F(\eta_i, \gamma)$ is the cumulative density function of $\eta_i$ and $\gamma$ is a vector of parameters to characterize the distribution. In the estimation, the researcher can specify the distribution and estimate $\gamma$ together with $\theta$. It is common to assume that $\eta_i$ has a normal distribution with mean zero and $\gamma$ to be a scalar for the standard deviation. The integral in the above equation can be approximated using simulations or the quadrature method.

For a landfill that has adopted LFGE project at year *k*, the joint probability function of the k decisions before year *k+1* is:

$$P_i = P(d_{i1} = 0, d_{i2} = 0, \dots, d_{ik} = 1 | X_{it}, Z_{it}, \eta_i, \tau_t;\ \theta)$$

$$= \int \prod_{t=1}^{k-1} P(d_{it} = 0\ |X_{it}, Z_{it}, \eta_i, \tau_t;\ \theta)\ P\ (d_{ik} = 1\ |X_{ik}, Z_{ik}, \eta_i, \tau_k;\ \theta)\ dF(\eta_i;\ \gamma).$$

With these joint probability functions, we can write down the log-likelihood function over all landfills in the data. The parameters $\theta$ and $\gamma$ can be estimated using the simulated maximum likelihood method (SMLE). (Train, 1999)

$$\max_{\theta,\gamma} Log\ L(\theta,\gamma) = \sum_{i=1}^{I} log\hat{P}_i, \qquad (7)$$

where $\hat{P}_i$ is simulated choice probabilities – the individual joint probabilities that include a simulated random error term. In the case of a landfill that has not adopted a LFGE project by time *T*, it is used to simulate the choice probability defined in equation (8).

One way of approximating $P_i$ is:

$$\hat{P}_i = \sum_{s=1}^{S} w^s \prod_{t=1}^{T} P(d_{it} = 0 \,| X_{it}, Z_{it}, \eta_i{}^s, \tau_t;\ \theta).$$

$\eta_i{}^s$ is the *s*th random draw from the standard normal distribution (when assuming unobserved landfill characteristics $\eta_i$ has a normal distribution). $w_i^s$ is the weight and equal to 1/*S* with *S* being the total number of random draws. The choice probability $P_i$ can also be simulated using other techniques such as randomized Halton sequences or Gauss-Hermite quadrature to improve efficiency.

*Partial Effects of Logit Estimation*

Because the coefficients of a discrete choice model are odds ratios, one must calculate the marginal effect of each variable in order the estimate the effectiveness of each renewable policy on the probability that a landfill owner will adopt a project. In general the marginal effect of a variable in a discrete choice model with the probability function $E[y \mid x] = F(x'\theta)$ would look like the following:

$$\frac{\partial E[y \,| x]}{\partial \mathrm{x}} = \left[\frac{d\, F(x'\theta)}{d(x'\theta)}\right] \times\ \theta$$

In a logit model, the probability of project adoption can be expressed as follows:

$$P(d_{it} = 1 \,| X_{it}, Z_{it}, \tau_t, \lambda_s; \theta) = \frac{\exp[f(X_{it}, Z_{it}, \tau_t, \lambda_s; \theta)]}{1 + \exp[f(X_{it}, Z_{it}, \tau_t, \lambda_s; \theta)]}.$$

Then the marginal effects the variables would be:

$$\frac{dP(d_{it} = 1 \,| X_{it}, Z_{it}, \tau_t, \lambda_s; \theta)}{d(X_{it}, Z_{it}, \tau_t, \lambda_s)} \times \theta = \frac{\exp[f(X_{it}, Z_{it}, \tau_t, \lambda_s;\ \theta)]}{[1 + \exp[f(X_{it}, Z_{it}, \tau_t, \lambda_s;\ \theta)]]^2} \times \theta$$

The average partial effect of each variable can be estimated in two ways. The marginal effect function shown above can be calculated at the means of the data. Another method would be to calculate the marginal effects at every observation and take the sample average of the individual marginal effects as the average partial effect. In large samples the two methods produce approximately the same answer.[26]

*Linear Probability Model*

Because the unobserved characteristics of a landfill (i.e. risk-averseness of the landfill owner, etc.)  may critically affect the decision to build a LFGE project, a model that controls for individual fixed effects is the ideal model that can represent the true relationship between the policies and project decision. For this reason, a data was also analyzed using a Linear Probability Model. In general, the LFGE project decisions have the probability function as follows:

$$\text{Prob}(\text{Y} = 1|x) = f(x, \beta)$$

$$\text{Prob}(\text{Y} = 0|x) = 1 - f(x, \beta)$$

In the above probability functions, $x$ is a matrix of the independent variables that affect $Y$. One may simply assume that the function $f$ retains a linear form:

$$f(x, \beta) = x'\beta$$

Because $E[y|x] = 0[1 - f(x,\beta)] + 1[f(x,\beta)] = f(x,\beta)$,

$$y = E[y|x] + [y - E[y|x]]$$

$$= x'\beta + \varepsilon$$

It is simple to estimate individual fixed effects with a linear probability model, but it has a crucial flaw. The left hand side of the regression equation represents the probability that y = 1, but the model is not constrained such that y is in the 0-1 interval. For this reason, the linear probability model is not used often. In this paper, it was used nevertheless as a simple method to control for fixed effects before the somewhat complicated mixed logit model was applied.

## Chapter 5: Results

Econometric estimation was conducted using the variables specified in section 3.2, using the linear probability model, logit model, and mixed-logit model with individual random effects, as presented in section 4.2. The results of the estimation are shown in Table 5 with partial effects for the logit models. The two logit models show that none of the policy variables are significant although they are all positive. The linear probability model produces positive and significant results for the RPS and state grant variables, but yields different results for the gas price and production tax credit variables.

**Table 5.** Linear Probability and Logit Model Estimation Results

| | **Linear Probability** | **Logit** | | **Mixed Logit with Random Effects** | |
|---|---|---|---|---|---|
| | Est. | Est. | P.E. | Est. | P.E. |
| VARIABLES | (1) | (2) | (3) | (4) | (5) |
| RPS | 0.000519* | 0.00976 | 0.000131 | 0.0148 | 0.000073 |
| | (0.000309) | (0.0134) | (0.00018) | (0.0157) | (0.00008) |
| Electricity price | 0.00219 | 0.146 | 0.00196 | 0.141 | 0.000695 |
| | (0.00206) | (0.101) | (0.00135) | (0.115) | (0.00064) |
| Gas price | -0.00311** | 0.452*** | 0.00607*** | 0.558*** | 0.00275* |
| | (0.00150) | (0.148) | (0.002) | (0.172) | (0.0015) |
| Lagged state grant | 0.0246*** | 0.246 | 0.00363 | 0.363 | 0.00206 |
| | (0.00661) | (0.221) | (0.00359) | (0.257) | (0.00184) |
| Investment tax credit | 0.0117 | 0.543 | 0.0073 | 0.556 | 0.00275 |
| | (0.0169) | (0.665) | (0.00893) | (0.757) | (0.00388) |
| Production tax credit | -0.00922 | 0.731 | 0.00983 | 0.599 | 0.00296 |
| | (0.00867) | (0.532) | (0.00712) | (0.577) | (0.00322) |
| Waste in place | | 0.322* | 0.00433* | 0.601* | 0.00297 |
| | | (0.175) | (0.00236) | (0.353) | (0.00197) |
| Temperature | | -0.155 | -0.00208 | -0.428 | -0.00211 |
| | | (0.605) | (0.00813) | (0.998) | (0.00489) |
| Precipitation | | 0.103 | 0.00139 | 0.0617 | 0.000305 |
| | | (0.203) | (0.00273) | (0.335) | (0.00167) |
| Interaction- waste & temperature | | -0.193 | -0.00259 | -0.359 | -0.00177 |
| | | (0.161) | (0.00217) | (0.318) | (0.00167) |
| Interaction – waste & precipitation | | 0.0238 | 0.00032 | 0.0778 | 0.000384 |
| | | (0.0411) | (0.00055) | (0.0871) | (0.00042) |
| Landfill age | 0.00657*** | 0.0452*** | 0.000607*** | 0.0779*** | 0.000384*** |
| | (0.000557) | (0.0120) | (0.00016) | (0.0232) | (0.00014) |
| Landfill age squared | -1.39e-05* | -0.000737*** | 0.00001*** | -0.00116*** | -0.00001** |

| | | | | | |
|---|---|---|---|---|---|
| | (7.92e-06) | (0.000189) | (0) | (0.000331) | (0) |
| Distance to power grid | | -0.0440*** | -0.00059*** | -0.0756*** | -0.000373** |
| | | (0.0165) | (0.00022) | (0.0292) | (0.00017) |
| Public ownership | | -0.532*** | -0.00757*** | -0.777*** | -0.0042*** |
| | | (0.0964) | (0.00146) | (0.199) | (0.0016) |
| Year fixed effect | Yes | Yes | | Yes | |
| State fixed effect | Yes | Yes | | Yes | |
| Individual fixed effect | Yes | no | | Yes | |
| Constant | -0.131*** | -7.530*** | | -8.711*** | |
| | | (1.269) | | | |
| Observations | 27,318 | 27,318 | | 27,318 | |
| R-squared | 0.034 | | | | |
| Number of lfid | 1,774 | | | 1,774 | |

Note: Standard errors in parentheses. Columns (2) and (4) contain the estimated coefficients for equations (6) and (7), respectively. The partial effects in columns (3) and (5) are the marginal effects calculated at the mean of each variable. The partial effects in column (5) are derived when random effects are equal to zero. The asterisks indicate the significance levels of each coefficient estimation: *** p<0.01, ** p<0.05, * p<0.1.

### 5.1.1 Estimation Results for Linear Probability Model

The results from the linear probability model are presented in column (1) of Table 5. As noted before, there is no sensible way to interpret the coefficient of the linear probability model because it fits a discrete choice into a continuous model. However, the significant positive coefficient for the RPS variable indicates that a higher RPS has a positive effect on LFGE project decision. Unlike the RPS variable, the gas price variable behaves in the opposite direction that would be predicted by theory. Since the gas price is revenue for an LFGE owner, it should encourage project development, but the estimation predicts differently. Lagged state grant is positive and significant, which is consistent to theory, because to build and open a project takes about a year after the funding decision is made.

The estimated coefficients of landfill age and landfill age squared behave in the expected direction, that is, the probability of an LFGE project draws an inverted U shape with respect to landfill age, which can be related to the fact that the methane production curve shows a hill-shaped progression with respect to the age of waste. However, calculation yields the peak of this hill to be at approximately 240 years, whereas, research show the peak methane production would be somewhere between 7 to 20 years after waste placement. The delayed peak may have occurred because a typical landfill continues to accept waste for about 30-40 years, making the methane production curve flatter. However, even such a delay should not be as great as 240 years. Nevertheless, the data includes landfills that are from a year old to 99 years old with a mean age of 24. Thus, the estimated coefficients of the landfill age variables indicate that, within the dataset, landfill age has a positive effect that is increasing at a decreasing rate.

The electricity price is expected to have a positive effect on the decision to start an LFGE project, but the estimation result indicates a positive effect that is not significant. The same is true for state production tax credit. The coefficient for the investment tax credit is estimated to be positive but insignificant.

### 5.1.2 Estimation Results for Logit and Random Effects Logit Model

The values in column (2) are the coefficients resulting from the logit model, and the values in column (3) are the partial effects at the mean of each variable. The RPS variable has a positive coefficient, but is not significant. The same is true for the electricity price variable. However, the result indicates that gas price has a positive and significant effect on LFGE project decision. Again this is consistent to what would be expected. The partial effect - estimated at the mean of each independent variable – is 0.006. The figure represents the increase in probability when the gas price is increased by $1 per thousand cubic feet. Although, is it only 0.6% probability increase, considering the fluctuation in natural gas price, it can be an important factor. The state grant, state PTC, and state ITC variables all are positive but insignificant.

The waste in place is significant at the 10% significance level, and the partial effect is .00433. This means that when the waste is increased by approximately 5 million tons (the wasteinplace2 variable is the wasteinplace variable divided by its mean – 5 million tons), the probability of opening a project increases 0.4%. Although the coefficient is not significant, the temperature variable is not estimated to affect project decision in the intuitive direction, because a higher temperature is likely to increase methane production. The same is true for the interaction variable for temperature and waste in place. For every additional amount of waste, the effect of an increase in temperature is negative. The precipitation variable is not significant but behaves in accordance to theory. More moisture content increases the possibility of an LFGE project.

The coefficients landfill age and its squared term suggest that the probability of opening a project draws an inverted U shape with a peak around 30 years. This is somewhat consistent with the theory that methane production occurs around 8 years after the landfill is open and that landfills accept waste for about 30-40 years.

The distance from power grid has a significant negative effect on project decision. The partial effect value indicates that if the nearest power grid becomes 1 km closer, the probability of opening a project will increase by 0.06%. Public ownership of the landfill is estimated to decrease the probability of an LFGE project by 0.4%.

The results of the random effect logit model are similar to those of the logit model, in terms of the coefficients' significance and the direction of effect. However, the partial effects of each significant variable are estimated to be smaller than those of the logit model. A dollar increase in thousand cubic feet of gas has a 0.3% increase in LFGE adoption probability. And the effect of 5 million tons of more waste is 0.3% instead of 0.4%. The partial effects of both the distance to grid variable and the public ownership variable are also smaller than those shown in the logit model. The coefficients of the landfill age and its squared term indicate a similar inverted U-shaped curve with a slightly steeper slope, but a very similar peak – around 33 years after the landfill is open.

### 5.1.3 Comparison of Results for the Logit Models and the Linear Probability Model

The results for the logit and mixed-logit models are overall similar in the direction of the coefficients, although the partial effects appear dampened in the mixed-logit model. The two logit models and the linear probability model have the same signs (negative/positive) for all policy and economic variables except for gas price and production tax credit. Also, RPS and state grant is shown to have a positive and significant effect in the linear probability model, whereas, it is positive but not significant in the logit models. The linear probability model yields a negative and significant coefficient for gas price, whereas the two logit models yield a positive and significant result for gas price. Although not significant in any of the models, the production tax credit has a negative sign in the linear probability model, while it shows positive effect in the two logit models.

Another difference of the estimations is that the logit models predict that the peak for project adoption occurs at 30 and 33 years, while the linear probability model estimates the peak at 240 years after a landfill is open.

### 5.2.1 Observed outcomes vs. simulated outcomes

The effects of each financial incentive can be shown in graphs that compare the actual number of LFGE projects with the simulated number of projects adopted in the absence of a financial incentive.

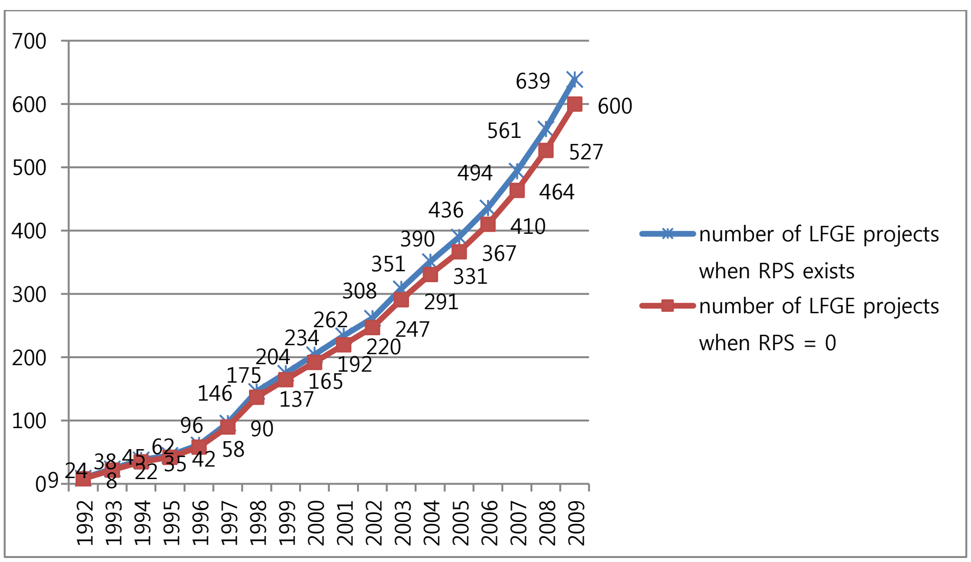


**Figure 5.1** Predicted LFGE project adoption rate in the absence of an RPS

(The prediction was made using the logit model estimations, setting RPS = 0 for all states in all years)

Figure 5.1 plots the number of projects that would be adopted, if there were no RPS but all other conditions were the same. It is presented in comparison to the actual number of projects adopted. The simulation is based on the logit estimation. As shown by the insignificant but positive coefficient of the RPS, in the absence of an RPS policy there would be marginally smaller number of LFGE projects. The total number of projects in 1999 is 639, compared to the simulated number of 600 in the absence of an RPS policy. The gap between the two plots widen near the late 1990's, which is the time that the first states started to enforce the RPS policy.

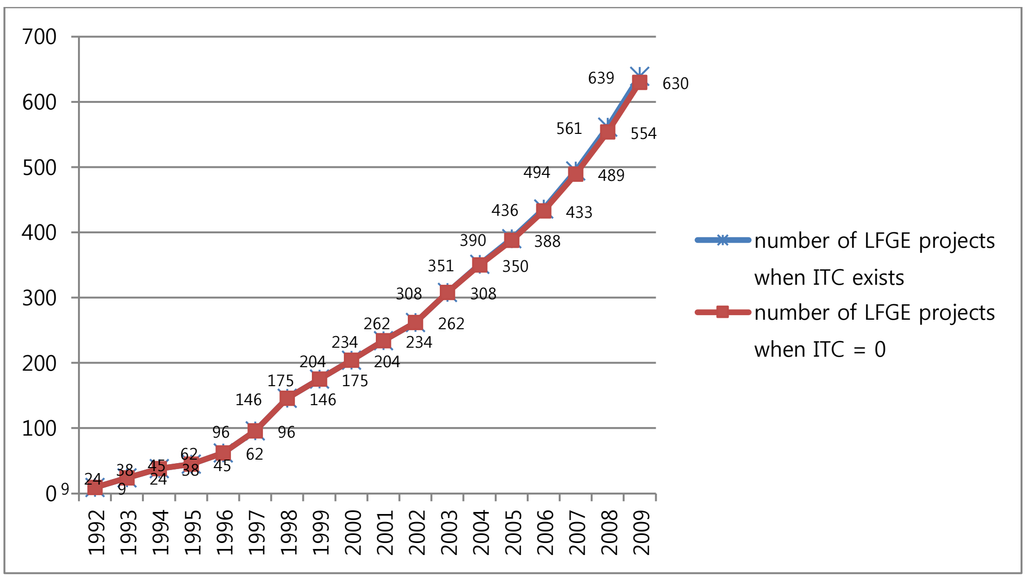


**Figure 5.2** Predicted LFGE project adoption rate in the absence of ITC

(The prediction was made using the logit model estimations, setting ITC = 0 for all states in all years)

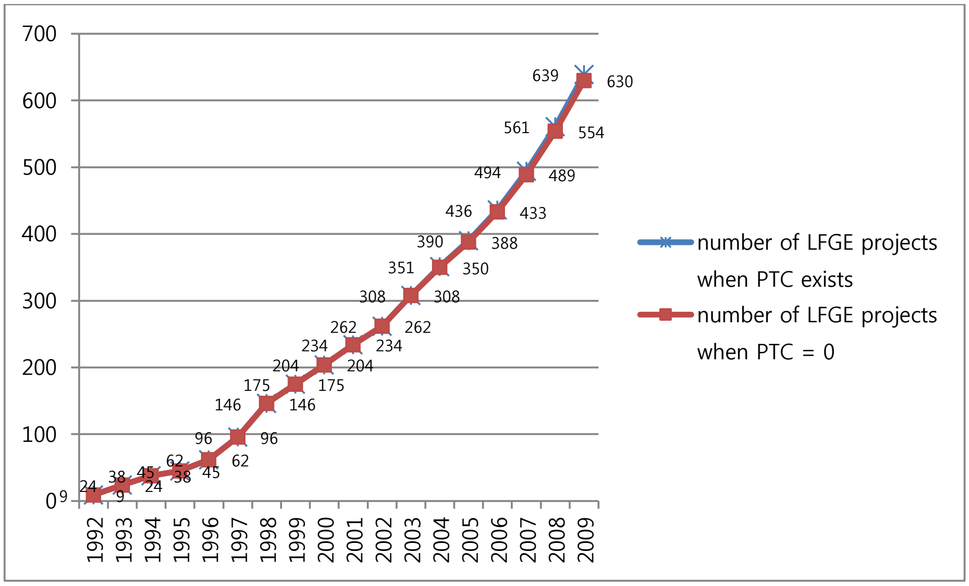


**Figure 5.3** Predicted LFGE project adoption rate in the absence of PTC

(The prediction was made using the logit model estimations, setting PTC = 0 for all states in all years)

Figure 5.2 and 5.3 present similar plots for the state ITC and PTC, the absences of which are estimated to have an even smaller effect. For the ITC and PTC policies, the difference in number of landfills in 1999 is only 9.

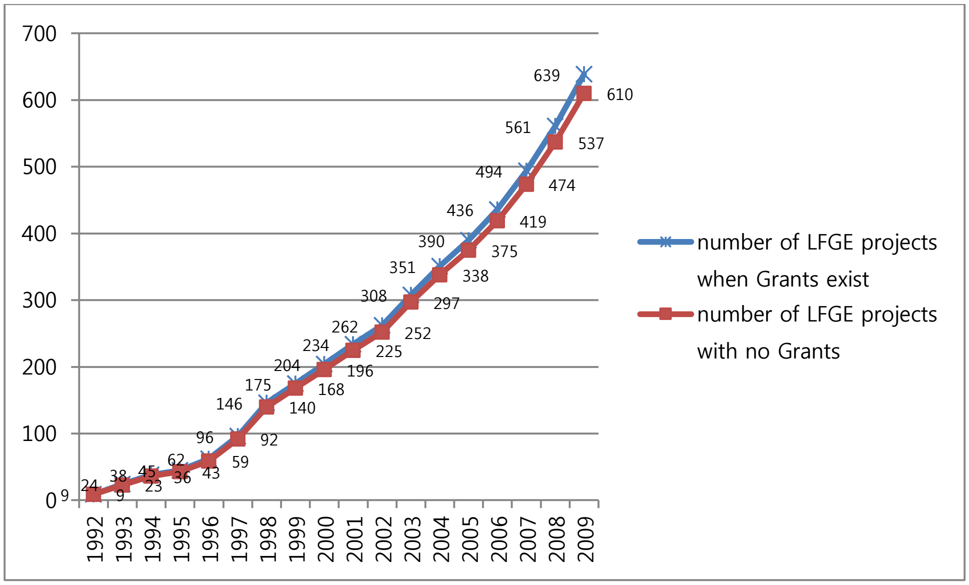


**Figure 5.4** Predicted LFGE Project Adoption Rate in the Absence of State Grant

(The prediction was made using the logit model estimations, setting State Grant = 0 for all states in all years)

The simulated effect of the absence of a state grant is shown in figure 5.4. The number of adopted projects is estimated to be slightly smaller when there is no state grant. In the late 1990's, state grant appears to pick up the number of projects, although slightly. This is the time that the number of available state grants started to pick up.

### 5.2.2 Predictions from Linear Probability Model

As mentioned in the end of section 4.2, the linear probability model suffers a critical flaw in that the model does not confine the predictions to the 0 to 1 interval. Thus, it is impossible to interpret the results of this model.

To check whether the predictions from the linear probability model make sense, I examined the distribution of the predicted values. A histogram of the predicted probabilities is shown in Figure 5.5. More than a quarter of the predicted probabilities are negative. This result shows that it is unlikely that the probability function is linear.

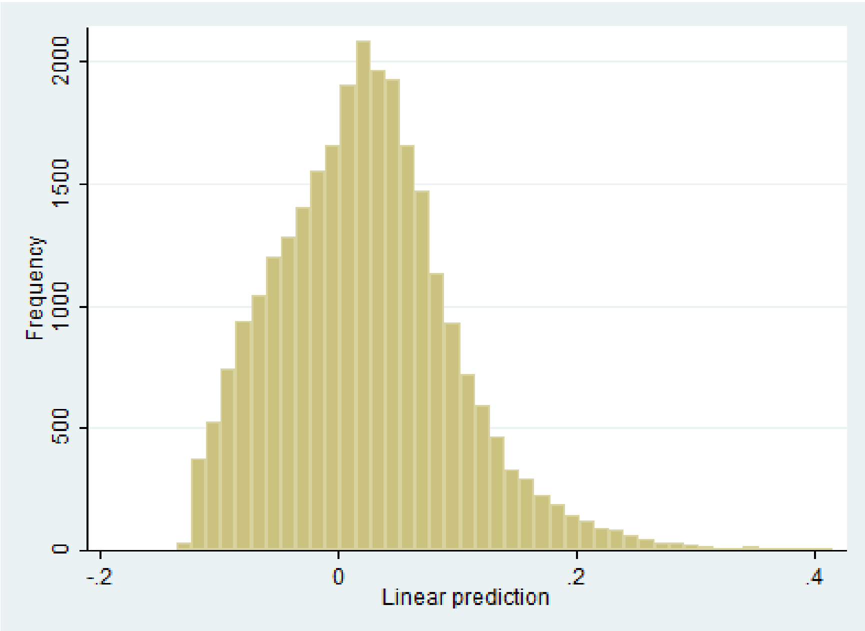


**Figure 5.5.** Histogram of Predicted Probabilities from the Linear Probability Model

### 5.3 Discussion of Results and Issues

The results from the linear probability model are quite different from those from the logit models. In this model, RPS and the availability of a state grant in the previous year appears to have a significant positive effect on LFGE project decision, whereas, the gas price has a negative effect. The different results of the logit and linear probability model are likely to have originated from the limitations of the linear model to estimate discrete choice models. Because the linear model estimates a curve that fits the given data, the estimates can be largely affected by a small range of particular values, making predictions outside the data range largely inaccurate. Consequently, I give more weight to the results of the logit model estimation.

*Gas Price, Waste, Distance to Power Grid, Public Ownership, and Landfill Age*

The results of the logit model estimation indicate that gas price, waste, distance to power grid, public ownership, and landfill age significantly affect the decision to start an LFGE project. Because gas price is directly linked to the major source of revenue in a project, it must have a positive effect on project decision. The amount of waste is directly related to the amount of methane that can be collected from a landfill, which is one of the first factors that landfill owners and developers consider in making a decision to build a project. The distance to a power grid is can widely vary for each landfill, and is a source of significant variation in cost. Another important characteristic is the ownership of the landfill. Although I had expected that public landfill owners would more eager to open a gas-to-energy facility as a public service, estimations show that private owners are keener to build and operated LFGE project. The landfill age affects project decision as can be predicted by the shape of the methane production curve across time after waste placement.

*Tax Credits*

RPS, state grant, production tax credit, and investment tax credit are estimated to be insignificant in the landfill owner or developer's decision to build a project, although the positive directions of the coefficient are consistent with expectation. Tax credits can be expected not to benefit public landfills because they are not subject to tax. However, a model with an interaction variable of tax credits and public ownership does not show that the effects of tax credit are not significant. The insignificant estimation results may be due to the small variation in the PTC and ITC variables. Only a total of six states had a PTC and seven ITC in the period covered by the dataset.

*State Grants*

The availability of a state grant in the previous year is also estimated to be insignificant in landfill gas-to-energy project adoption. The complicated with the lagged state grant variable is that the time that a project is open might take longer than a year, although many state grant policies require that the project be built within a year of the funding decision.

*RPS*

The RPS is also estimated to be insignificant in project adoption. The RPS data itself may be a problem. In our model, the RPS percent is a state's specific fractional target for a particular year, but it does not take account of the final RPS goal and its achievement date. When landfill owners make decisions on whether to open the project or not, they may not only consider this year's RPS rate but also what the final RPS target is going to be and when the goal will be realized. Some landfill owners may hold opening until the year when the RPS target rate is fully realized, and some others may just choose to open this year since the target year is approaching. The current value of the benefits of future years should be included into the RPS variable by employing a scientific way to discount the future RPS rates into present rates. Further, eight states such as Indiana have established voluntary RPS goals. Although they are not compulsory and have no penalty on the utilities who do not meet the objectives, there could be some influence on the utilities' electricity-generating resource portfolio and the decisions of landfill owners, compared with states that do not have even a voluntary RPS. In our model, the RPS percent values for these eight states are entered as zero and therefore some effects are omitted. The voluntary RPS goal needs to be incorporated into the model in a way that is different from compulsory RPS.

Furthermore, RPS ratio may not be directly related to the benefits of operating a landfill project. The landfill owners receive revenue from getting renewable energy certificates (RECs) by generating electricity. But the prices of RECs and embedded price premiums are determined by both supply and demand conditions. In a competitive market, the revenue that landfill owners can get actually depends on the competition with many other forms of renewable energy. In this case, the data of the supply of other forms of renewable energy in each state for 20 years is needed. And even after such data is achieved, the inclusion of this factor would cause endogeneity problems because many states have set their RPS goals with consideration of the already existing amount of renewable energy. An ideal variable would be one that represents the amount of additional renewable energy that a state wants to achieve for each year.

*Electricity Price*

The electricity price data is problematic because it is the retail electricity price, which can be considerably different from wholesale electricity prices. Many of the LFGE facilities would sell the generated power to a utility company, receiving the wholesale price. The EIA does not have the wholesale electricity price for all of the states, but rather prices for several regions of the United States, centered in the wholesale markets formed after the restructuring of the power market. This data is only available for several years. The difference between retail and wholesale electricity price is likely to have affected the estimation, because electricity price should be an important consideration in starting a power generating facility.

*Year Fixed Effects*

All three of the models include year fixed effects that are mostly significant. The year fixed effects control for federal policies such as the Section 29 tax credit, and the NSPS regulation. These federal policies are suggested to have driven many landfill owners and developers to start LFGE projects. Consequently, it may be true that LFGE projects decisions benefited more from federal policies rather than state policies.

*Weather Variables*

The logit estimations indicate that precipitation has a positive coefficient, but that the effect is not significant. On the other hand, the temperature variable has a negative coefficient that is not significant. This is unexpected because a warmer climate should help anaerobic decomposition of the waste and improve methane production. The estimation results might be due to state fixed effect, some of which are estimated to have significant effect on project decision. Assuming that a state has an overall similar climate, controlling for each state's time-invariant characteristics might have absorbed some of the effect of precipitation and temperature.

## Chapter 6: Conclusion

As an effort to reduce greenhouse gas emissions, Landfill Gas-to-Energy projects have been encouraged by a variety of policy measures. This study has examined the effectiveness of each policy measure in increasing the probability that the landfill owner or developer would install an LFGE project.

The factors that affect the adoption of the LFGE project include physical characteristics of the landfill, including the organic content of the waste, the moisture content, temperature, and age of the landfill. These characteristics determine the amount of methane that is produced at the landfill site. The distance from the landfill to the nearest power grid makes the building cost different. Further, private and public landfill owners are expected to behave differently.

The policies aimed to support project adoption include the state Renewable Portfolio Standards, federal and state tax credits, the New Source Performance Standards, state and local grants, green power purchase programs, among many others. The price of electricity and natural gas is the revenue of many of the LFGE projects, and thus are influential factors. In addition to this, the availability of end-users, the diffusion of information are other factors that determine project adoption.

In this study, I estimated the effects of three four major state policies – RPS, production tax credit, investment tax credit, and state grants – on the decision of landfill owners or developers to build an LFGE project, using a linear probability model, logit model, and a random effect logit model. Aside for the four policy variables, electricity and gas prices, waste in place, precipitation, temperature, landfill age, distance to grid and public ownership were controlled for in the model.

The importance of the linear probability model and random effect logit model is that they can control for the individual landfill characteristics. For example, the individual landfill owner's risk preference and preference for technology can be an important variable. In order to include such factors in the estimation, the linear probability model with individual fixed effects and the mixed logit model with random effects were used.

The results of the estimation indicate that the state policies are insignificant in an LFGE project decision, although the directions of the effects are estimated to be positive. The gas price is estimated to have a significant positive effect on the probability of LFGE project adoption. Also, the model correctly estimates the effect of the landfill's age and distance to a power grid. An interesting result is that public ownership of a landfill is negatively related to the probability of project adoption.

The reason that the RPS is insignificant may be because landfill gas-to-energy projects are less competitive in the renewables market. In an interview with an LFGE project developer, he mentioned that many utilities might prefer to fulfill their RPS requirements by purchasing from wind farms, largely because LFGE facilities have significantly smaller generation capacities than wind power. The problem with the state tax credit variables is that they are not very prevalent.

The lack of variance in the independent variable could have lent weak results. Another problem with these state policy variables are that they last for a while, and the expectation of future policy could affect landfill project decisions, but it is difficult to correctly model these future expectations.

# Endnotes


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**Appendix 1 : Model Specification Tests**

The three policy variables of interest – RPS, production tax credit, investment tax credit and lagged state grant – are included in all specifications. The state grant, power purchasing agreement, and alternative compliance payments were included and left out as seen fit. The natural gas price is shown to have a significant effect on the probability that a landfill developer would decide to build a LFGE project. The positive sign of the coefficient is consistent with the theory, because natural gas price would be a source of revenue for the LFGE owner. Landfill age and its squared term turn out to be significant, with a positive sign for landfill age and negative for landfill age squared. This should be the case because methane production would draw a bell-shaped curve across the age of a landfill. The variable that measures the distance to a power grid also behaves consistent to theory, indicating a greater distance to a power grid would make a landfill less favorable for an LFGE project. The public ownership dummy variable is negative and significant, which means that if a landfill is owned by a public entity, such as a city government, then it is less likely that there would be a LFGE project on the landfill. This could be because private enterprises are generally more sensitive to profitability than are government officials. However, the opposite might be true because public landfill managers might take on a project to win political support or as a public service. Nevertheless, results show that public landfills are less likely to have a project.

In the benchmark model – column (1) of Table A1, none of the four policy variables appear to be a significant influence on LFGE project development. The addition of the PPA, ACP, and ACP rate variables – column (2) - does not change the results except that the ACP dummy and ACP rate appear to be significant factors in project decision. However, the signs of both variables are the opposite of what is expected. That is, the existence of an Alternative Compliance Payment, represented by the ACP dummy, would possibly discourage LFGE adoption because the electric utilities might choose to pay the fee instead of buying from renewable generators. However, the estimation results show that having an alternative payment policy encourages landfill energy development. Further, a higher ACP rate should encourage more renewable energy development, but the estimation results show the opposite effect. There does not seem to be a good explanation for the behavior of these two variables.

When all policy variables are controlled – column (4), the state grant dummy and its lagged term are significant and the signs are consistent with intuition. When a state government accepts grant application, it would take several months to make the funding decision and generally the grant stipulates that the project be built within a year after the funding decisions. In a year when grant applications are accepted, most developers would wait for the grant decisions and hold off on project construction, explaining the negative coefficient. The year after the grant application is due, the landfill project that were waiting for the grant decisions would go into construction, which explains the positive effect of the lagged state grant variable. The state grant dummy and its lagged term behave similarly in the model that includes the state grant dummy in addition to the variables in the benchmark model – column (3). The behavior of the two state grant variables in the aforementioned two models - column (3) and (4) – might be due to cancelation between the two variables. This is because if there was a state grant program in the previous year, it is with almost with 100% certainty that this year, there would not be a state grant program. Thus, the two variables are close to multi-collinear. Therefore, an accurate model should include just one of the two variables.

Table A1. Results of Logit Model estimation

| | Benchmark model | Model with PPA and ACP | Model with state grant | Model with PPA, ACP and state grant | Present and lagged energy prices |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) |
| **Economic Variables** | | | | | |
| RPS | 0.00979 | 0.0120 | 0.00900 | 0.0109 | 0.0132 |
| | (0.0134) | (0.0147) | (0.0135) | (0.0147) | (0.0151) |
| Electricity Price | 0.146 | 0.109 | 0.164 | 0.126 | |
| | (0.101) | (0.103) | (0.101) | (0.104) | |
| Gas Price | 0.452*** | 0.373** | 0.470*** | 0.396*** | |
| | (0.148) | (0.153) | (0.148) | (0.153) | |

| | | | | | |
|---|---|---|---|---|---|
| Electricity price (non average) | | | | | 0.148 |
| | | | | | (0.132) |
| Gas price (non average) | | | | | 0.179 |
| | | | | | (0.114) |
| Lagged electricity price | | | | | -0.0456 |
| | | | | | (0.134) |
| Lagged gas price | | | | | 0.202* |
| | | | | | (0.121) |
| State grant | | | -0.508* | -0.560** | -0.549** |
| | | | (0.268) | (0.270) | (0.270) |
| Lagged state grant | 0.246 | 0.301 | 0.553** | 0.647** | 0.621** |
| | (0.221) | (0.226) | (0.275) | (0.281) | (0.280) |
| Investment tax credit | 0.543 | 0.493 | 0.557 | 0.487 | 0.482 |
| | (0.665) | (0.669) | (0.665) | (0.670) | (0.670) |
| Production tax credit | 0.731 | 0.677 | 0.718 | 0.662 | 0.651 |
| | (0.532) | (0.534) | (0.533) | (0.534) | (0.534) |
| Power purchase agreement | | 0.0900 | | 0.182 | 0.131 |
| | | (0.233) | | (0.238) | (0.236) |
| Lagged purchase agreement | | -0.416 | | -0.507* | -0.493* |
| | | (0.284) | | (0.287) | (0.288) |
| Alternative compliance payment | | 1.114* | | 1.087* | 1.061* |
| | | (0.586) | | (0.586) | (0.586) |
| Alternative compliance payment rate | | -0.0226** | | -0.0224** | -0.0220* |
| | | (0.0114) | | (0.0114) | (0.0114) |
| **Control Variables** | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Waste in place | 6.64e-08* | 6.38e-08* | 6.65e-08* | 6.40e-08* | 6.38e-08* |
| | (3.65e-08) | (3.67e-08) | (3.65e-08) | (3.66e-08) | (3.66e-08) |
| Temperature | -0.00237 | -0.00233 | -0.00237 | -0.00231 | -0.00230 |
| | (0.00876) | (0.00877) | (0.00876) | (0.00877) | (0.00877) |
| Precipitation | 9.93e-07 | 9.11e-07 | 9.76e-07 | 8.94e-07 | 8.80e-07 |
| | (1.93e-06) | (1.94e-06) | (1.93e-06) | (1.94e-06) | (1.94e-06) |
| Interaction- waste & temperature | -5.68e-10 | -5.45e-10 | -5.70e-10 | -5.47e-10 | -5.45e-10 |
| | (4.87e-10) | (4.88e-10) | (4.87e-10) | (4.88e-10) | (4.88e-10) |
| Interaction – waste & precipitation | 0 | 0 | 0 | 0 | 0 |
| | (0) | (0) | (0) | (0) | (0) |
| Landfill age | 0.0452*** | 0.0457*** | 0.0448*** | 0.0453*** | 0.0454*** |
| | (0.0120) | (0.0121) | (0.0120) | (0.0121) | (0.0121) |
| Landfill age squared | -0.000737*** | -0.000748*** | -0.000731*** | -0.000740*** | -0.000742*** |
| | (0.000189) | (0.000190) | (0.000189) | (0.000190) | (0.000190) |
| Distance to power grid | -0.0440*** | -0.0437*** | -0.0439*** | -0.0436*** | -0.0436*** |
| | (0.0165) | (0.0165) | (0.0165) | (0.0165) | (0.0165) |
| Public ownership | -0.533*** | -0.535*** | -0.532*** | -0.534*** | -0.533*** |
| | (0.0964) | (0.0964) | (0.0964) | (0.0965) | (0.0965) |
| Year fixed effect | yes | yes | yes | yes | yes |
| State fixed effect | yes | yes | yes | yes | yes |
| Individual fixed effect | no | no | no | no | no |
| Constant | -7.520*** | -6.968*** | -7.512*** | -6.995*** | -6.948*** |
| | (1.269) | (1.310) | (1.270) | (1.312) | (1.301) |
| Observations | 27,318 | 27,318 | 27,318 | 27,318 | 27,318 |

Note: Standard errors in parentheses. The asterisks indicate the significance levels of each coefficient estimation: *** p<0.01, ** p<0.05, * p<0.1. The waste, precipitation, and temperature data are not scaled in these models, unlike in the main model presented in chapter 5. The electricity price and gas price variables are the 3 year average prices. The electricity price (non average) and gas price (non average) are the respective energy prices for individual year without averaging. The same is true for lagged electricity/gas price (non average).

In Table A2, are the results of the linear probability models with year and landfill fixed effects. The models specifications are similar to that in Table A1., except that time-invariant individual landfill characteristics were dropped because they are included in the landfill fixed effects.

The most significant difference in the linear probability model is that the RPS variable has a positive and significant effect on landfill energy project decisions – columns (1), (3), (4), and (5), especially when the ACP and PPA variables are included – columns (3), (4) and (5). Further, the lagged state grant variable was significant in all model specifications, even without the inclusion of the state grant dummy.

However, natural gas price appears to have a negative effect on project development in all the specification. And the lagged PPA has a negative effect, which means if there was a power purchasing agreement available the year before, it is less likely that a LFGE project will be built. This is counterintuitive because the existence of a PPA in previous years should encourage project development. The ACP dummy and ACP rate variables are behaving counter-intuitively as in the logit models. Nevertheless, controlling for ACP and PPA variables seem to affect the coefficient of the RPS variable.

Table A2. Linear probability models with different specifications

| | Bench mark model specification | Model with state grant | Model with PPA & ACP | Model with PPA, ACP & state grant | Model with present & lagged energy prices |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) |
| **Economic Variables** | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| RPS | 0.000519* | 0.000500 | 0.000787** | 0.000762** | 0.000775** |
| | (0.000309) | (0.000309) | (0.000332) | (0.000333) | (0.000337) |
| Electricity Price | 0.00219 | 0.00236 | 0.000901 | 0.00108 | |
| | (0.00206) | (0.00207) | (0.00213) | (0.00213) | |
| Gas Price | -0.00311** | -0.00304** | -0.00282* | -0.00270* | |
| | (0.00150) | (0.00150) | (0.00150) | (0.00151) | |
| Electricity price (non average) | | | | | 0.00219 |
| | | | | | (0.00318) |
| Gas price (non average) | | | | | -0.00191 |
| | | | | | (0.00117) |
| Lagged electricity price | | | | | -0.00174 |
| | | | | | (0.00330) |
| Lagged gas price | | | | | 0.00124 |
| | | | | | (0.00135) |
| State grant | | -0.00922 | | -0.0109 | -0.0108 |
| | | (0.00805) | | (0.00812) | (0.00814) |
| Lagged state grant | 0.0246*** | 0.0309*** | 0.0270*** | 0.0346*** | 0.0347*** |
| | (0.00661) | (0.00862) | (0.00667) | (0.00874) | (0.00875) |
| Investment tax credit | 0.0117 | 0.0119 | 0.00904 | 0.00898 | 0.00798 |
| | (0.0169) | (0.0169) | (0.0170) | (0.0170) | (0.0171) |
| Production tax credit | -0.00922 | -0.00944 | -0.00944 | -0.00971 | -0.0101 |
| | (0.00867) | (0.00867) | (0.00870) | (0.00871) | (0.00872) |
| Power purchase agreement | | | 0.00158 | 0.00267 | 0.00341 |
| | | | (0.00657) | (0.00661) | (0.00660) |
| Lagged purchase agreement | | | -0.0199** | -0.0211*** | -0.0227*** |
| | | | (0.00775) | (0.00781) | (0.00783) |
| Alternative compliance payment | | | -0.00138*** | -0.00139*** | -0.00139*** |
| | | | (0.000361) | (0.000361) | (0.000361) |
| Alternative compliance payment rate | | | 0.0798*** | 0.0799*** | 0.0796*** |
| | | | (0.0193) | (0.0193) | (0.0194) |

| **Control Variables** | | | | | |
|---|---|---|---|---|---|
| Landfill age squared | -1.39e-05* | -1.34e-05* | -1.29e-05 | -1.23e-05 | -1.23e-05 |
| | (7.92e-06) | (7.93e-06) | (7.97e-06) | (7.98e-06) | (7.98e-06) |
| Landfill age | 0.00657*** | 0.00656*** | 0.00644*** | 0.00641*** | 0.00593*** |
| | (0.000557) | (0.000557) | (0.000570) | (0.000571) | (0.000569) |
| Year fixed effect | Yes | Yes | Yes | Yes | Yes |
| State fixed effect | Yes | Yes | Yes | Yes | Yes |
| Individual landfill fixed effect | yes | yes | yes | yes | Yes |
| Constant | -0.131*** | -0.132*** | -0.121*** | -0.122*** | -0.115*** |
| | (0.0156) | (0.0156) | (0.0164) | (0.0164) | (0.0174) |
| Observations | 27,318 | 27,318 | 27,318 | 27,318 | 27,318 |
| R-squared | 0.034 | 0.034 | 0.035 | 0.035 | 0.035 |
| Number of projects | 1,774 | 1,774 | 1,774 | 1,774 | 1,774 |

Note: Standard errors in parentheses. The asterisks indicate the significance levels of each coefficient estimation: *** p<0.01, ** p<0.05, * p<0.1. The electricity price and gas price variables are the 3 year average prices. The electricity price (non average) and gas price (non average) are the respective energy prices for individual year without averaging. The same is true for lagged electricity/gas price (non average).

In the fixed effect linear probability model, the results for RPS, state grant, and landfill age were consistent with the theory. However, the effects of gas price, PPA, and ACP are counterintuitive. Comparing this with the logit model, there is a consensus that the gas price, landfill age, distance to grid, and public ownership has an effect on project decision. The other variables show mixed results depending on the model type and specification.

The results of the random effect logit models are presented in Table A3. The landfill age, distance to power grid, public ownership variables are significant and the signs are as expected. The amount of waste is also significant in a 10% significance level. As in the logit model, the natural gas price is significant in all model specifications. Among the policy variables the lagged state grant is the only significant factor, especially when the state grant variable is included in the model. However, as mentioned earlier, this may be due to multi-collinearity. Further, the signs of the ACP dummy, ACP rate and lagged PPA behave counterintuitively as they did in the fixed effect linear probability model.

Table A3. Random Effect Logit models with different specifications.

| | Benchmark model | Model with state grant | Model with PPA & ACP | Model with PPA, ACP, and state grant |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| **Economic Variables** | | | | |
| RPS | 0.0148 | 0.0139 | 0.0190 | 0.0177 |
| | (0.0157) | (0.0156) | (0.0170) | (0.0170) |
| Electricity price | 0.141 | 0.155 | 0.0960 | 0.109 |
| | (0.115) | (0.115) | (0.118) | (0.118) |
| Gas price | 0.558*** | 0.569*** | 0.479*** | 0.496*** |
| | (0.172) | (0.172) | (0.178) | (0.177) |
| State grant | | -0.493* | | -0.560* |
| | | (0.295) | | (0.297) |
| Lagged state grant | 0.363 | 0.640** | 0.435* | 0.759** |
| | (0.257) | (0.306) | (0.263) | (0.315) |
| Investment tax credit | 0.557 | 0.567 | 0.500 | 0.492 |
| | (0.757) | (0.754) | (0.761) | (0.759) |
| Production tax credit | 0.599 | 0.586 | 0.548 | 0.534 |
| | (0.577) | (0.576) | (0.578) | (0.578) |
| Power purchase agreement | | | 0.116 | 0.207 |
| | | | (0.254) | (0.259) |
| Lagged power purchase agreement | | | -0.499 | -0.590* |
| | | | (0.309) | (0.313) |
| Alternative Compliance Payment rate | | | -0.0219* | -0.0218* |
| | | | (0.0133) | (0.0132) |
| Alternative compliance payment dummy | | | 1.100 | 1.078 |
| | | | (0.676) | (0.674) |
| **Control Variables** | | | | |

| | | | | |
|---|---|---|---|---|
| Waste in place | 1.23e-07* | 1.22e-07* | 1.25e-07* | 1.24e-07* |
| | (7.36e-08) | (7.29e-08) | (7.39e-08) | (7.35e-08) |
| Temperature | -0.00646 | -0.00638 | -0.00599 | -0.00595 |
| | (0.0145) | (0.0143) | (0.0144) | (0.0143) |
| Precipitation | 5.98e-07 | 5.89e-07 | 4.78e-07 | 4.65e-07 |
| | (3.19e-06) | (3.16e-06) | (3.19e-06) | (3.17e-06) |
| Interaction- waste & temperature | -1.05e-09 | -1.04e-09 | -1.09e-09 | -1.08e-09 |
| | (9.62e-10) | (9.53e-10) | (9.64e-10) | (9.58e-10) |
| Interaction – waste & precipitation | 0 | 0 | 0 | 0 |
| | (0) | (0) | (0) | (0) |
| Landfill age | 0.0779*** | 0.0765*** | 0.0782*** | 0.0768*** |
| | (0.0232) | (0.0230) | (0.0232) | (0.0232) |
| Landfill age squared | -0.00116*** | -0.00114*** | -0.00117*** | -0.00115*** |
| | (0.000331) | (0.000328) | (0.000332) | (0.000332) |
| Distance to power grid | -0.0757*** | -0.0747*** | -0.0748** | -0.0742** |
| | (0.0292) | (0.0290) | (0.0291) | (0.0291) |
| Public ownership | -0.777*** | -0.768*** | -0.780*** | -0.773*** |
| | (0.199) | (0.197) | (0.200) | (0.199) |
| Year fixed effect | Yes | Yes | Yes | Yes |
| State fixed effect | Yes | Yes | Yes | Yes |
| Individual landfill fixed effect | yes | yes | yes | yes |
| Observations | 27,318 | 27,318 | 27,318 | 27,318 |
| Number of landfills | 1,774 | 1,774 | 1,774 | 1,774 |

Note: Standard errors in parentheses. The asterisks indicate the significance levels of each coefficient estimation: *** p<0.01, ** p<0.05, * p<0.1. The waste, precipitation, and temperature data are not scaled in these models, unlike in the main model presented in chapter 5.

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