ABSTRACT

Title:	DID STATE RENEWABLE PORTFOLIO STANDARDS INDUCE TECHNICAL CHANGE IN METHANE MITIGATION IN THE U.S. LANDFILL SECTOR?
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Landfill gas (LFG) projects use the gas created from decomposing waste, which is approximately 49% methane, and substitute it for natural gas in engines, boilers, turbines, and other technologies to produce energy or heat. The projects are beneficial in terms of increased safety at the landfill, production of a cost-effective source of energy or heat, reduced odor, reduced air pollution emissions, and reduced greenhouse gas emissions. However, landfills sometimes face conflicting policy incentives. The theory of technical change shows that the diffusion of a technology or groups of technologies increases slowly in the beginning and then picks up speed as knowledge and better understanding of using the technology diffuses among potential users. Using duration analysis, data on energy prices, State and Federal policies related to landfill gas, renewable energy, and air pollution, as well as control data on landfill characteristics, I estimate the influence and direction of influence of renewable portfolio standards (RPS). The analysis found that RPS positively

influences the diffusion of landfill gas technologies, encouraging landfills to consider electricity generation projects over direct sales of LFG to another facility. Energy price increases or increased revenues for a project are also critical. Barriers to diffusion include air emission permits in non-attainment areas and policies, such as net metering, which promote other renewables over LFG projects. Using the estimates from the diffusion equations, I analyze the potential influence of a Federal RPS as well as the potential interaction with a Federal, market based climate change policy, which will increase the revenue of a project through higher energy sale prices. My analysis shows that a market based climate change policy such as a cap-and-trade or carbon tax scheme would increase the number of landfill gas projects significantly more than a Federal RPS.

DID STATE RENEWABLE PORTFOLIO STANDARDS INDUCE TECHNICAL CHANGE IN METHANE MITIGATION IN THE U.S. LANDFILL SECTOR?

By

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Acronyms

BACT	Best Available Control Technology
CFR	Code of Federal Regulations
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EIA	Energy Information Agency
GHG	Greenhouse Gases
GWP	Global Warming Potential
KM	Kaplan-Meier test
kWh	Kilowatt Hour
LFG	Landfill Gas
LMOP	Landfill Methane Outreach Program
Mg	Mega grams
$MMTCO_2E$	Million Metric Tons of Carbon Dioxide Equivalent
MSW	Municipal Solid Waste
MWh	Megawatt Hour
NAAQS	National Ambient Air Quality Standards
NGOs	Non-Governmental Organizations
NMVOCs	Non-Methane Volatile Organic Compounds
NO_2	Nitrogen Dioxide
NOx	Nitrogen Oxides
NRDC	National Resource Defense Council
NSPS	New Source
O_3	Ozone
PURPA	Federal Public Utility Regulatory Policies Act
R&D	Research and Development
RCRA	Resource Conservation and Recovery Act
REPI	Renewable Energy Production Incentive
RGGI	Regional Greenhouse Gas Initiative
RPS	Renewable Portfolio Standard
SF_6	Sulfur Hexafluoride
SIP	State Implementation Plan
SWANA	Solid Waste Association of North America
Tg	Tera grams
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
VOCs	Volatile Organic Compounds
WGA	Western Governors Association

Dedication

To my husband who had to live with me through this and to my parents who haven't figured out why I bothered.

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Chapter 1: Introduction

Over the last decade, many policy analysts have focused on national and international activity (or lack thereof) on climate change and renewable energy policy. Significant activity at the State level has overshadowed the focus on what is not being done by the Federal government on climate change and has limited progress at the Federal level to promote alternative sources of fuel. The focus of policy analysis on State climate change initiatives has increased due to expanded media attention and the establishment of regional initiatives led by progressive states such as California. According to Barry Rabe of the PEW Center on Global Climate Change, "Collectively, they [State policies] constitute a diverse set of policy innovations rich with lessons for the next generation of American climate change policy."[1]

The focus of this dissertation is to study the influence of current environmental policies on reducing greenhouse gases through encouraging or discouraging the use of greenhouse gas reduction technologies. Specifically, this study looks at the affect of renewable energy policies on the diffusion of methane capture-and-use technologies in the landfill sector. Identifying the obstacles, as well as the incentives to landfill gas projects, is a key element to designing and implementing a successful future climate change policy.

Air emission issues in the US were addressed first at the State level before becoming Federal regulations.[2] States provide laboratories for various policies to enable the Federal government to address issues and which later provide it with the ability to analyze effects of specific policies before they become regulations and to choose from a diverse menu of options already tried at the State level. One of the most widely used State level tools to reduce climate change and encourage renewable energy production is the renewable portfolio standard (RPS).[3] The states provide data and a basis for analysis to determine whether or not a Federal RPS is feasible and desirable.

Landfill gas is a key sector for any climate change policy, whether the focus is increasing energy from renewable sources or reducing direct emissions of a greenhouse gas. Landfills are the largest emitter of methane, a greenhouse gas 23 times more potent than carbon dioxide (CO_2) in trapping heat in the atmosphere. It is also a sector where reduction technologies are a known quantity. The capture-and-use of methane can generate enough revenue to cover the cost of the reductions, making reductions in the sector significantly cheaper than reductions in CO_2. Landfills also provide a cheaper source of renewable energy than wind farms or solar installations.

Despite some success with the RPS, states are now considering, or are in the process of implementing, other climate change policies such as cap-and-trade programs. In the absence of a climate policy and, in some cases, the absence of an RPS, many landfills in the US currently run landfill gas projects. These projects are economically viable because the gas they recover can be sold as energy. However, experts agree that there are a significant amount of projects, an estimated 600 landfills, that are economically viable but that are not being implemented. Several theories have been forward as to why this occurs, including information constraints, conflicting and confusing policy environments, and problems securing energy sales.

The continued presence of these problems could hinder the effectiveness and potentially raise the cost of a climate change policy in the future.

Identifying and understanding the current incentives and disincentives to technology adoption in the landfill gas sector is critical to understanding the response of the sector to a climate change policy. Several studies on climate modeling[4,5] state that climate policy will induce technical change, both innovation and the diffusion of technologies, based on the past experience of other environmental policies. Proponents of this theory point to empirical studies correlating technology change to non-climate change environmental policies and higher energy prices as evidence of a future climate policy's ability to significantly induce technology change. What they do not consider in any of these meta-analyses is the current effect of environmental policies in both the energy and non-energy sectors of the economy and the potential for distortion of the policies when a climate change regime is imposed on top of the current policy structure.

The majority, if not all, of empirical studies that estimate rates of technical change or the effects of policies on induced technical change have also focused exclusively on the energy sector, changes in either the supply of or the demand for energy. These studies often refer to the energy shock of the 1970s or energy related environmental policies such as appliance standards, air quality policies, or energy taxes. Little has been done to evaluate the potential effect of a climate policy on technical change in non-energy sectors, yet reduction technologies for non- CO_2 greenhouse gases such as methane, have been implemented for over a decade.[6,7,8] These technologies are particularly important to study because the diffusion of these technologies is assumed to be able to reduce the cost of a climate change policy by 30 to 60 percent.[9 10]

The Setting

Methane from municipal solid waste (MSW) facilities is the largest human-generated source of methane emissions in the US, releasing 135 million metric tons of CO_2 equivalents ($MMTCO_2E$) in 2003, with approximately 116 $MMTCO_2E$ captured-and-used, flared, or oxidized.[11] Landfill gas is created through an anaerobic process where bacteria in decomposing garbage generate methane and other organic compounds. Landfill gas is approximately 49 percent methane and, therefore, a valuable energy resource.

Table. 1: Emissions from Landfills in $MMTCO_2E$[12]
(million metric tones of CO_2 equivalent)

	1990	1995	2000	2001	2002	2003	2004	2005
MSW Landfills	188.7	204.7	217.3	221.4	227.2	234.9	242.4	249.6
Industrial Landfills	12.9	13.9	15.4	15.6	1537	15.9	16.0	16.1
Recovered								
Gas-to-Energy	(17.6)	(22.3)	(49.0)	(54.3)	(54.4)	(54.9)	(57.1)	(58.6)
Flared	(5.0)	(21.8)	(37.1)	(40.8)	(43.7)	(46.0)	(54.4)	(60.4)
Oxidized	(17.9)	(17.5)	(14.7)	(14.2)	(14.5)	(15.0)	(14.7)	(14.7)
Total	**161.0**	**157.1**	**131.9**	**127.6**	**130.4**	**134.9**	**132.1**	**132.0**

Source: USEPA, 2007; Note: parentheses denote reductions in emissions.

Net methane emissions are increasing in the US. Estimates of methane oxidization, flaring, and use as energy are increasing over time, helping to counteract increases in waste disposal and methane generation rates. The largest source of the reductions is attributed to the New Source Performance Standard (NSPS), also called the Landfill Rule. The Landfill Rule is an air pollution reduction requirement that mandates landfills that emit 50 mega grams (Mg) or more per year of non-methane volatile organic carbons (NMVOCs) to begin collecting landfill gas and flaring the gas.[13] This also destroys the methane in the landfill gas. The number of gas-to-energy projects is increasing, and it is theorized that the number of landfills that trigger the Federal Landfill Rule is also increasing.[14]

The total number of landfill gas projects has increased significantly from 50 projects in 1986 to 350 in 2003.[15] Today, 424 of landfills have gas recovery projects, while 500 landfills flare the gas instead of venting it into the atmosphere.[16] Total energy recovered has increased from 371 million metric tons of methane or tera grams (Tg) of methane to 1212 million metric tons. Total energy flared has increased from 210 million metric tons of methane to 1466 million metric tons over the same time period.

Benefits of Landfill Gas Projects

According to US Environmental Protection Agency's (USEPA) Landfill Methane Outreach Program (LMOP) literature, there are several motivations for installing landfill gas recovery and use projects:

- Methane can be used to offset the use of a non-renewable fossil fuel (coal, oil, natural gas);
- Projects help reduce local air pollution by also destroying non-methane organic compounds that create smog in local areas;
- Projects create revenues for local landfills or reduce costs of environmental compliance, particularly as natural gas and electricity prices rise; and
- Projects reduce safety risk from fires and explosions due to migration of methane in the landfill.

Landfill policies generally focus on potential environmental benefits. Landfills are highly regulated for their environmental impact since they can potentially harm water quality, soils, and air quality. The benefits of landfill gas projects are primarily air quality benefits.

Reduction of Greenhouse Gases

Greenhouse gases allow incoming solar radiation to pass through the atmosphere and reach the earth, but they absorb the infrared radiation that is re-emitted from the ground. This keeps the heat (radiation) trapped in the atmosphere instead of releasing it into space, creating a "greenhouse" effect.

Table 2: Examples of Global Warming Potentials

Gas	Lifetime	GWP
Carbon Dioxide (CO_2)	50-120 years	1
Methane (CH_4)	12	23
Nitrous Oxide (N_2O)	114	296
HFC- 143a	52	4,300
CF_4	50,000	5,700
SF_6	3,200	22,200

Source: IPCC Third Assessment Report, 2001

Each greenhouse gas has a different impact on global warming, based on its effectiveness in absorbing radiation and its lifetime in the atmosphere. Methane traps 23 times more radiation than CO_2. The potencies of greenhouse gases are compared using a global warming potential (GWP) index. The GWP of a gas is an index relative to CO_2 , comparing the warming contribution of a kg of CO_2 compared to a kg of the indexed gas. The GWPs of greenhouse gases vary widely, ranging from 23 times to 22,200 times more potent than CO_2.[17] Table 2 above summarizes the GWPs of the major greenhouse gases.

Methane (CH_4) is an important greenhouse gas. Methane emissions account for approximately 9 percent of all greenhouse gas emissions in the US. The largest methane sources in the US include: landfills (33 percent of total anthropogenic methane emissions in the US); livestock enteric fermentation (20 percent); leakage from oil production and natural gas production, processing, and transmission/distribution (19 percent); coal mining (10 percent); and livestock manure management (6 percent).[18]

Air Pollution Reductions

Landfill gas contains volatile organic compounds (VOCs) and nitrogen oxides (NOx). VOCs and NOx are precursors to the formation of ground level ozone and smog. Ozone is a criteria air pollutant and can have an adverse effect on respiratory health, including reduced lung function and aggravation of asthma. Ground-level ozone (O_3) is not emitted, but it is formed through the chemical reaction of its precursors in sunlight.[19] Recent studies have suggested that controlling methane, particularly at landfills, is an effective way of reducing local, background ozone as well as tropospheric ozone formation.[20] Local air quality strategies have previously focused on the shorter-lived more reactive precursors to ozone, such as NOx and Non-Methane Volatile Organic Compounds (NMVOCs). However, more recent work suggests that methane may also quickly lead to significant reductions in ozone.[21]

Safety Benefits

Methane mitigation also addresses safety concerns surrounding the migration of landfill gas and the high potential for landfill fires fueled by landfill gas. Establishing a system of wells during the design and filling of a landfill cell safely collects landfill gas and allows owners to manage where the gas flows and its disposal.

Policy Issues

Non- CO_2 greenhouse gases like methane are unlikely to be directly regulated under a climate change policy.[22] Most legislation that has been proposed in the US focuses on capping CO_2 emissions from utilities, which can then buy "offsets" from other sectors such as landfills. The appeal of this scheme is that utilities could buy cheaper reductions from other sectors, lowering the overall cost of the regulation. However, if landfills would have reduced their methane emissions without a climate policy in place, then these "offsets" would not be real reductions in total greenhouse gas emissions. If the reductions would have taken place without the climate policy, the reductions would be "anyway tons" (tons that would have been reduced without the policy) and should not be counted as a reduction under the climate change policy. Understanding what the diffusion rate is in the absence of a climate policy would determine the amount available for offsets and, in turn, the true cost of meeting a greenhouse gas target.

The US landfill gas sector is an important case study in how non-climate change environmental regulations may affect the outcome of a stringent climate change policy. Many developing countries are starting to manage their waste through a system of landfills, moving away from the open dumping that is currently prevalent. Developing countries are also starting to enact some of the same air quality and renewable energy polices as the US and the EU in attempt to reduce smog and increase access to energy, particularly in their poorer populations. Understanding the role of air quality and renewable energy policies in inducing technical change in the

US landfill gas sector will help understand the barriers to implementing landfill gas projects in other countries.

Objectives

The objective of this study is to try to determine the effects of State level renewable energy policies on technology change in the landfill gas sector, as well as Federal renewable energy policies, air quality policies, and energy prices while controlling for the individual characteristics of the landfills. The end result will be estimates of the effect of these policies on the diffusion of technologies and the choice of technologies used in landfill gas projects. The basic concepts behind what drives technical change are introduced in Chapters 2, and Chapter 3 reviews the methodology used to estimate technical change in this thesis. Chapters 4 and 5 analyze rates of diffusion and technology choice, respectively. Chapter 6 analyzes the potential policy implications of these estimations. Finally, Chapter 7 reviews the relevance of this research in devising future policies to meet climate change goals.

Chapter 2: Review of Basic Concepts

Diffusion is the process by which a technology spreads among individuals or firms in an economy.[23] Diffusion of technology has many aspects, including the speed and variation of diffusion, variations in the rates of acceptance of different types of technologies by similar firms, and the acceptance of innovative processes, including those technologies which "spillover" from other countries, sectors, and the like.

The concepts of technological diffusion and technological learning have been widely used since their introduction by economist Edwin Mansfield.[24] Empirical studies of diffusion (adoption over time of a technology) have focused on the speed in the diffusion, the choice between technologies, the variation in acceptance of technologies, and the characteristics of the technologies and adopters that explain the speed and acceptance of one technology over another. Mansfield produced the seminal work in the area of technology diffusion. His work on the diffusion of robotics showed a firm's perceived adoption costs, rate of return, and the risk associated with technology investments.[25] His framework used the general premise that technical information diffuses throughout an industry (or industries) and reduces costs. The standard adoption curve is an S-shaped distribution, where adoption is slow at first, accelerates as it spreads through the population, and then slows as the market becomes saturated.[26] The shape of the curve has been empirically tested using a variety of statistical techniques and is considered the standard. This curve represents not only the firms' decision whether or not to adopt, but also their choice between adopting now or deferring adoption until another time period.[27]

Diffusion policy or policies that encourage the diffusion of specific technologies or sets of technologies are widely used in the US. Until recently, most policy regimes have focused on the encouragement of invention and innovation through public research and development (R&D), grants, and subsidies. This also reflects the literature on the subject.[28] Only a small number of studies have focused on the success of policies in the diffusion of technologies.

Theoretical Factors Influencing Adoption and Technology Choice

Economists and sociologists form the two schools of thought on variables affecting technology diffusion. While the two schools focus their attention on separate issues, discounting the concerns of the other school, most of the factors that influence diffusion are considered as relevant by both schools and overlap. Economists consider more than just financial variables, and sociologists consider economic factors in their analyses. For the purpose of the following discussion, the two schools are separated, even though the variables considered are the same in many cases. For this study, variables from both schools are considered in the analysis.

Sociological Factors

Sociologists assume that money making is not the primary goal of an adopter, even if it is considered part of the decision making process. The sociologists' school of thought focuses on adoption as a social process, where the decision-maker and the decision process are the key to understanding diffusion. Within this process, decisions are based not only on the characteristics of the firm (the decision-maker), but also on how the decision-maker evaluates technology, social networks, and the social and cultural environment in which the decision-maker acts.

The theoretical backbone of the sociologists' theory is described as a multi-stage process where social and individual factors play different roles at different stages in the adoption process. The stages of diffusion can be summarized as a five stage dynamic process:

1. Knowing that the technology exists and that its application is relevant to the decision-maker;
2. Non-trial evaluation of the technology or the stage where the decision-maker begins to collect information which may or may not lead to an actual trial of the technology;
3. Small-scale or full-scale trial evaluation of the technology;
4. Adoption of the technology on a full scale; and
5. Non-adoption or dis-adoption of a technology because results from the trial are not encouraging. [29]

Within this dynamic process, several key characteristics play a role in influencing adoption. In particular, the characteristics of the technology itself, the firm's characteristics, and social and cultural norms are influential within the framework.

Technology Characteristics

Several criteria exist for deciding whether or not to adopt a technology. If one of these criteria is not met, creating a barrier to adoption, the decision-maker will not adopt the technology. [30] The first criterion is the performance of the technology, which relates to the benefits or the revenue generated by the technology, as well as the engineering efficiency. The second is the cost of the technology in terms of fixed costs, operation and maintenance costs, opportunity costs, and training costs, as well as other costs born by the company when a specific technology is chosen. The third is the consumer acceptance of the technology, which also includes acceptance by the consumer of the final product but may also include the community's acceptance as a whole. The fourth is the safety of using the technology. The fifth is the enabling infrastructure for the technology, or how well the technology works with the technologies or infrastructure the company already has in place. The sixth is whether or not the technology always compels the firm to comply with the current or foreseen regulatory environment. The last is the environmental impact of the technology, which is also related to the regulatory structure of the industry and consumer acceptance.

E. M. Rogers, an economist at Stanford University, lists five categories that influence the adaptors decision-making related to technologies.[31] These include:

1. The relative advantage of the innovation;
2. The compatibility with current technology used by the adaptor and with social norms;
3. The complexity of the technology, (relating to cost, complementary investment, relative advantage, and the benefit/cost ratio of adopting a new technology);
4. The ease of testing the technology; and
5. The ease of observing and evaluated the technology.

Some of these criteria overlap with the industry decision-maker criteria above, particularly the relative advantage of the technology, its compatibility with current technology, and the cost of the technology. But, Rogers' focus is not only on specific criteria used in the evaluation of the technology. He also stresses the ease of evaluating the technology, suggesting that even the best of technologies will not be adopted unless the technologies can be easily tested or demonstrated on a large scale.

Landfill gas technologies are a special case in the sense that they are developed for another sector, tried and tested in other sectors, and then adapted to the landfill gas sector. The complexity of potential landfill gas technologies varies. The reciprocating engine is the most understood, and newer technologies like fuel cells are the least understood by the industry. Testing of the technology occurs in the primary sector where the early adaptor in the form of developer or company can observe and evaluate the technology for the landfill gas sector. Evaluation of the technology is generally easy (the technology usually is not a new technology), but using the technology in the landfill gas sector is a new use for an old technology. If the technology seems suitable for use with landfill gas, the technology becomes a spillover; and the first use of the technology in the landfill gas sector occurs. Then the diffusion becomes an intra-sectoral spillover. The relative advantages of the technology, as defined above, then determine the adoption pattern.

Many, including Rogers, assume that technologies don't change over time and that the new technology is always better than the old. Nathan Rosenberg, another economist from Stanford University who has written extensively about diffusion of technologies, challenges this. He argues that technologies improve with user experience and that competitive pressure could actually boost the improvement of an old technology and slow the diffusion of the new technology.[32] This argument may hold true in the landfill gas sector. User experience in the primary sector may mean that landfill owners are more likely to adopt the old technology because more is understood about issues relating to the adaptation of the technology to landfill gas. Experience with and improvements in an old technology may provide significant advantages over a newer, lesser-known technology in the eyes of the landfill owner/operator.

Firm Specific Characteristics

Many empirical studies of technology diffusion have incorporated information on firms as a factor in the diffusion patterns. Firm heterogeneity is considered a major factor in the "uneven" diffusion of a given technology. A firm's characteristics reflect the firm's ability to "take-up" a technology available to them. However, it should be noted that technology change is a dynamic process; the firm's heterogeneity not only influences technology adoption, but it is also influenced by past technology adoption patterns.

An empirical study on diffusion of multiple technologies concluded that the variables traditionally considered in the literature on diffusion are confirmed by their study of flexible automation in the Italian metal working industry. [33] Plant size, type of production, use of the technology is the same geographic region, interdependencies, and cumulative learning-by-using effects were the key determinants of a plant's adoption behavior. The study points out that the experience a plant gained by using previously available technologies is crucial to the adoption of the new technology. The conclusion of the study states that individual innovations should not be studied in isolation. The authors note that heterogeneity in firms is endogenous to the diffusion process; in other words, firms are different because of their adoption decisions.

Additionally, Rogers considers four firm-specific issues other than firm size and plant-type that may affect the ease of adoption.[34] These include: who makes the decision to adopt, how information is acquired about a technology, the norms in the adaptor's social system, and the extent to which the sellers can efficiently promote the technology within the sector. Again, these variables are not always clearly distinguishable from each other. Firm size, for instance, may be correlated with the decision structure within the firm and how information is required. Social or cultural norms within the society may also correlate with plant-type.

Social and Cultural Factors

Evaluation of a technology or project may be influenced by the society in which the decision-maker lives. Most economic text books explain the relationship between increases in aggregate income and education levels and increased environmental protection. However, several studies have gone beyond the income and education variables and looked at the decision-maker's role within society and society's attitudes towards economic activity in the sector.

A literature review covering the various influences of the adoption of conservation technology in the farming sector summarized a handful of journal articles into four relevant factors in the evaluation of information by the decision maker (in this case, the rural landholder).[35] The factors were: material wealth and financial security; environmental protection and enhancement beyond that related to person financial gain; social approval and acceptance; and personal integrity and high ethical standards. Two of the categories relate directly to the social norms of the society and the individual.

Another example of social norms and their influence on adoption can be found in a study of the diffusion of organic horticultural practices in the UK.[36] The study uses the physical characteristics of the farm, the characteristics of the farmer, current farming techniques, farm level economic indicators, the farmer's sources of information, membership in associations, and attitudes towards environmental issues as explanatory variables for diffusion. The study found that the gender of the farmer was of particular importance. However, the belief that environmental concerns and sustainability of food system were important also meant that adoption was more likely. The study confirmed the importance of non-economic factors, particularly attitudes, on diffusion. At the same time, the study found negative results (e.g., that education and income did not affect the time taken to adopt).

While there is obviously a difference between a family run farm and a landfill run by a large waste management company or a local government, there are commonalities which have not been researched. In particular, there are two areas of interest in the above studies that apply to landfills. The first is the existence of social networks within the landfill industry, and the second is the attitude towards greenhouse gas issues.

The existence of social networks in the case of landfills is in the form of Solid Waste Association of North America (SWANA) or the LMOP program, where each association actively promotes the use of landfill gas as a fuel source. Both organizations hold up examples of continued successful and financially profitable examples of landfill gas recovery projects as examples of profit making, environmentally friendly decisions to spur the interest of other landfills. This may have a large impact on the way landfill management views landfill gas projects. There are also the relationships among landfills within a particular geographic area and the potential for the diffusion of information through these relationships, by word-of-mouth. This diffusion of knowledge, whether passively obtained or directed towards landfills through an information programs like LMOP or SWANA, may be an important factor contributing to the increase in number of landfill gas recovery projects and may promote better operation of the technologies.

Increasing public awareness of climate change concerns, whether associated with landfill gas directly or as overall awareness of climate change increase, may increase the likelihood that projects are implemented. In areas where environmental concerns in general and climate change concerns specifically are considered high priority, such as California, landfill gas projects may diffusion more quickly. While higher awareness may influence government and firm decision-making, no concrete evidence of this exists.

Economic Factors

While sociologists and organizational behaviorists focus on the external environment, economists favor the approach of rational behavior by a series of individuals based on the incremental benefits of adopting a new technology against the cost of adopting said technology. This analysis is characterized by uncertainty (risk) and/or limited by information. Many economic studies encompass the determinants of diffusion from the sociologists' point of view, though economists tend to place more emphasis on economic factors such as profit and risk. Economic theories on diffusion also look at diffusion from the point of view of the adaptor of the technology, as well as how diffusion may also be influenced by the suppliers of the technology in terms of reduced costs over time. A major subset of the diffusion literature concerns the effect of energy prices and environmental policies on the process of diffusion within several of the economic structures.

In the 1960s and 1970s attention focused on technical change in terms of changes in demand and in relative factor prices.[37] Zvi Griliches, an economist from Harvard University, is credited with being the first to look at the issue of adoption from an economist's, not a sociologist's, point of view.[38] Griliches began the trend with his study on the diffusion hybrid maize in which he showed the role of demand for maize in determining the timing and location of the innovation.[39] Mansfield built on Griliches' work and hypothesized that imperfect information constrained adoption; but he added that as knowledge was disseminated, the innovation itself was more widely disseminated. These conclusions received more support from empirical studies.[40][41] Later studies showed that both demand and supply factors were important.[42] At the same time, others put forward the idea that relative prices explained innovation since firms were focused on reducing costs.[43]

In the 1980s, the focus shifted to the idea of endogenous technical change and path-dependency. Two types of models were developed: one a growth theoretic model[44] and the other a microeconomic model.[45] In the growth model, analysis is done in terms of the effect of changes in relative factor shares, between capital and labor, and not in terms of relative factor prices. However, this model is severely criticized by William Nordhaus, an economist from Yale University.[46] Nordhaus felt that in the reallocation of factor shares there is no reallocation towards innovation, the net effect being growth theory with exogenous technological change instead of endogenous technical change. The microeconomic model is based on the concept of an innovation-possibility curve where, given the right amount of R&D expenditure, a firm could maximize output based on labor and capital. Both models are confined to the standard two-factor neoclassical model. While this has limitations in the terms of understanding natural resources, the theories fit well into the framework of larger climate economic models used to analyze climate policy today. The issue with this approach is that it ignores social feedback effects or externalities that could encourage one firm to adopt or discourage another firm from adopting the same technology.

To those modeling climate/economic interactions, neoclassical analysis of the issue is most prominent in the sense of being the "mainstream" economic thought. Induced technical change in neo-classical economic modeling is manifested in production functions.[47] To date, policy considerations have not been introduced into the induced technical change functions of the models. Instead, all policy representation has been exogenously applied to the model as a whole (i.e., air pollution regulation and carbon taxes constrain the model instead of being endogenously represented in the model).

In line with neo-classical thought, empirical and theoretical studies that have focused on the production function assume induced technical change is a function of energy prices and cumulative production.[48] This has advantages and disadvantages. The production function is based on prices, so including non-price variables in the production function is not straightforward. A recent dissertation work on the influence of regulations and economic incentives on technology change, in particular the increase in energy efficiency of appliances and other technology characteristics, and the decrease in prices of these appliances over time, is one example of a study which tries to incorporate policies endogenously into the production function structure as well as including technical characteristics.[49] However, non-market based approaches, such as information policies, are difficult to incorporate into the framework.

Instead of relying on the neoclassical profit maximizing behavior model, two Yale economists, Richard Nelson and Sidney Wilson, defined evolutionary theory.[50] Their theory is based on the idea of decision rules which are applied over an extended period of time. The idea is that the production function is replaced by the concept of "routine," defined as specified technical routines of the firm, procedures for hiring and firing, ordering inventory, research and development, advertising, or business strategies, etc. The activities leading to technical changes are: local search for technical innovations, imitation of other firms, and satisfying economic behavior. However, little has been done to validate this framework.[51]

Another argument that has been put forward is that technology change is "path dependent." In other words, technology choice is locked-in, based on historical choices. The classic example of this idea is the typewriter keyboard, studied by Stanford University Economist Paul David.[52] David explored the historical reasons why a typewriter with a QWERTY layout became the standard despite the fact that the layout is considered inefficient today. The reasons for the lock-in were the linkage between the design of the keyboard and the typists skill at using it, the decline in costs of the QWERTY system relative to other systems, and the quasiirreversibility of investment in both learning the skill. These network externalities occur when a technology is more useful to the adopter if others are using the same technology (e.g., fax machines). Path dependency or lock-in occurs when the standard has been chosen (e.g., Microsoft) and when the barriers to switching to another technology are high.

Energy Prices

The economic literature on diffusion of technologies has focused heavily on the effect of energy prices on adoption and innovation. Increasing energy prices will decrease the overall cost of the project because of cost offsets from revenue generation. However, sharply increasing energy costs may raise the cost of production of the technology and actually raise the cost of the technology during the time period. There may also be an effect on adoption and predicted or expected costs and benefits if energy prices are volatile, as can be the case with natural gas prices. This could make a firm more cautious about implementing a project.

Several empirical studies show a strong relationship between energy prices and patenting activity for energy technologies between 1970 and 1993.[53] [54] Using patents as a proxy for solar powered technologies, these studies show that innovation of technologies such as solar power responded quickly and strongly to the particularly high energy prices during the 1970s energy crisis. Alternately, a similar empirical study which also uses patent data to estimate the effect of energy prices on energy-efficiency innovations does not find a significant positive impact on innovation activity. The study instead found a correlation between energy taxes (as a percentage of energy prices) and patent activity.[55] The two results may not be inconsistent. Long-term expected high energy prices may in fact be related to increases in patent activity.[56]

The diffusion of landfill gas projects is likely to be influenced by volatile or long-term electricity and gas prices as well as oil prices. Diffusion would also be affected by the ability of a landfill to sell the electricity at a close to market rate or sell the gas at a rate pegged to the oil price. The premise behind State regulations such as net metering and renewable portfolio standards is that renewable resources such as landfill gas would not be a reliable source of electricity for a wholesale rate. The regulations were enacted in order to encourage this behavior. On the natural gas side, low natural gas prices in the 1980s were assumed to hinder direct use projects at landfills. With increasing and volatile prices, industry found long-term contracts for landfill gas pegged on the price of oil more and more appealing.[57] However, this effect has not been studied.

Environmental Policy

There are a variety of policy instruments that can affect adoptions – providing information, command-and-control regulations, subsidizing adoption of key technologies or government purchase of the technology. Several theoretical studies support the premise that environmental policy provides an efficient incentive for innovation and diffusion.[58] [59] [60] The studies have looked at market-based approaches such as taxes/subsidies or cap-and-trade programs, information dissemination, and regulation. The general conclusion of these studies has been that market-based environmental policies provide incentives for innovation and diffusion because they provide revenues or reduce costs. This is believed to be the case for information dissemination as well.[61] Direct regulation, however, is believed to inhibit innovation and only force diffusion to those directly regulated and not the wider economy. Once the standard has been reached, the industry will not bother to continue improvements.

What is not well understood is how a sector will respond to a combination of environmental regulations. The landfill sector is faced with a variety of overlapping policies at both the State and Federal level. A landfill wanting to install an engine to combust landfill gas to produce electricity faces regulations related to the State Implementation Plan (SIP) to reduce air pollution emissions from fuel combustion, a Federal NSPS permitting process, and potentially net metering regulations, interconnection standards and an RPS. Applying a climate policy on top of these policies and regulations may distort the effectiveness of one or more of the policies.

Learning-by-Doing and Learning-by-Using

Learning-by-doing and learning-by-using are critical components of the diffusion process. Learning-by-doing and learning-by-using are the representation of the learning and experience gained by producing and installing a technology that feeds back into the innovation process, allowing for revisions of the technology and increased diffusion. Kenneth Arrow, a Nobel Prize winning economist, introduced the concept of technological learning-by-doing into the literature in 1962. [62] Learning-by-doing represents the reduction in costs and improvement in technical efficiency associated with production of a technology (i.e., the more the firm produces, the better the firm is at producing the technology). Learning-by-using is focused on the adopter where the adopter's experience in using the technology over time allows the adopter to reap addition gains. Empirical studies have supported these theories. While the impact of learning on costs is not disputed, the size of the effect is still in question.

Learning-by-doing curves are typically estimated based on previous production (i.e., the more production in the previous period, the higher on the learning curve the firm finds itself). Learning curve effects are defined as the reduction in costs associated with cumulative production. As manufacturers repeatedly perform specific tasks, workers learn from the cumulative experience and can perform the tasks more efficiently. This means the suppliers of the technology reduce their costs of production over time though learning-by-doing. The landfill gas sector, as a small buyer of natural gas fueled technologies, takes improvements in the cost and efficiency of technologies as given from the primary sector.

On the technology-user side, learning-by-using curve effect is the decrease in costs (particularly labor costs) associated with continued use and maintenance of a technology. These curves incorporate the effects of training, technical improvements, and better management. The curves may also include reductions in costs or efficiency gains associated with adapting a particular technology to a firm or sector specific use. Learning-by-using in the landfill gas sector is assumed to be the primary innovation within this sector.

Empirical Studies

Reviewing the empirical literature confirms many of the conclusions in the theoretical pieces. Empirical studies show ambiguous results when analyzing whether environmental standards may inhibit or encourage innovation. "End-of-pipe" type command and control regulations seem to stymie innovation by requiring a firm to choose a mandated technology and not innovate, while energy efficiency standards seemed to have stimulated technology innovation.[63] Regulated auto fuel efficiency standards in the US are effective, but other studies have shown that other regulations have either no discernable effect, such as the case of building standards; or have a negative impact where the regulation has postponed the retirement of older, less efficient installations.[64]

Another example of the effect of environmental regulations on industry is an empirical study of whether or not environmental regulations had an impact on two aspects of investment decisions at paper mills.[65] The study found that State regulations have a weak impact on technology investment and choice and questioned, but did not answer, whether or not this was due to the fact that older plants, ones that would require a large investment to meet environmental regulations, were exempt from the regulations or grandfathered under the rule. The study implied, but did not confirm, that minimum standards and direct regulation are not the only considerations in technology investment.

Other studies focus on empirically estimating induced innovation in energy-saving technologies from the producer's point of view. One study analyzed the impact of energy prices and energy saving regulations on technological innovations in energy efficient appliances like gas water heaters.[66] The analysis found that approximately 62 percent of the overall change in energy efficiency of these appliances was due to autonomous factors and not induced factors (such as energy prices and energy efficiency standards). Of the 38 percent effect of endogenous change, energy prices had the largest effect due to increased commercialization or supply of new models and retirement of old models. The study is based on the premise that if the price of energy is relative to other goods, demand will shift to energy-saving appliances and producers will introduce into the market innovative goods. Within this framework, energy efficiency standards are introduced. The study showed that both high energy prices in the late 1970s and early 1980s, as well as the energy efficiency standards set by the government, have a significant impact on the product menu.

Studies exploring the effect of market-base mechanisms strongly support the theory that these mechanisms promote innovation and diffusion.[67] One example of this is a paper on innovation in pollution control under the Clean Air Act of 1990.[68] The analysis shows that requiring or regulating plants constructed before 1990 to install scrubbers would lead to innovation that would lower the cost of compliance. However, the SO_2 cap-and-trade program provided incentives to install scrubbers with higher removal efficiencies as well as lower costs. The analysis concluded by asking whether or not command-and-control regulation actually leads to innovations aimed at avoiding the costs of compliance as opposed to increasing the efficiency or the benefits of the technology to society.

Other empirical analyses have assumed green policies induce change and have actually used a measure of this change as a proxy measurement for the stringency of a policy. For example, one study uses the rate of patenting in related technology fields, itself a proxy for induced innovation, as a proxy for the stringency of environmental regulation in that field.[69] Another study finds a significant correlation between expenditures of R&D and pollution abatement expenditures. [70] However, they do not find a significant correlation between pollution control expenditures and patents.[71]

While the conclusion that a stringent climate change policy will induce technical change in the affected sectors is hard to prove in absence of a climate change policy to study, there is some evidence that a climate change policy will encourage diffusion. A technical review of climate policy models and the representation of environmental policy in economic models states that "available evidence on induced technological change by environmental polices and/or higher energy prices seems to support the hypothesis that (future, stringent) climate policies will encourage the innovation and diffusion of new technologies that will address the issue of controlling global warming in a more cost-effective way." [72] The statement is qualified by saying: a) in the short-term, the diffusion will be of off-the-shelf products as R&D will be slower to respond to the signal; b) induced change may or may not reduce the overall cost of the policy; and c) the theory does not say anything about what mix of policy instruments would be the most effective in meeting a target. The report also goes on to say that it is not enough to rely on a policy to induce technical change; there should be a specific technology policy to promote innovation and diffusion as well.

Landfill gas technologies have been in place since 1975 and have been diffusing through the industry. The diffusion of these methane capture-and-use technologies have followed a typical S-shaped curves as described by Mansfield. In the late 1970s and early 1980s, the diffusion process was slow. Since the early to mid-1990s, the diffusion process has increased. It is not well understood how sociological and economic factors are influencing diffusion and the choice of technologies, nor have these factors been analyzed for their potential influence on future policies. Despite the introduction of new technologies such as microturbines and fuel cells, the majority of projects continue to adopt mature technologies such as reciprocating engines. Better understanding of what is driving diffusion and technology choice will help design a more effective "offsets" policy.

Chapter 3: Duration Modeling

One of the most important insights from the wide variety of historical empirical studies done on diffusion of individual technologies is the extent to which diffusion enhances innovation through the feedback of information about the utility and the operation of the technology, also called learning-by-using and learning-by-doing.[73] In order to capture this effect, the literature has been moving away from bivariate analysis at the firm level, where adoption is measured at a point in time, in order to understand the causes of diffusion. The dichotomy between diffusion as a process and adoption due to firm heterogeneity is artificial.[74] Diffusion is the aggregate of the firm's adoption decisions. Time may change the factors that affect a firm's decision as well as the firm's characteristics. Because of this dynamic aspect of diffusion, more analysts are focusing on modeling the cumulative affects of adoption over time through techniques such as duration analysis and epidemic learning.

A literature review of empirical studies on induced innovation in agriculture and industry find few studies that try to directly measure induced innovation.[75] The majority of empirical studies using neoclassical techniques focus instead on supporting the idea of induced technical change, but has not in fact separated the effects of technical change from factor substitution in the production functions used. Later studies separate out these effects. Of the eight studies that attempt to test for induced technical change specifically, findings from only half of the studies are consistent with the theory of induced innovation. In the other half, the findings are ambiguous, or the signs of the parameters are clearly the opposite of what the theory predicts.

The less-than-convincing results of the neoclassical studies and the limitations of studying the dynamics of change within the neoclassical structure has led researchers to move towards other models of induced technical change. One alternative mathematic model is the epidemic model. The epidemic model is used more by the sociological and marketing fields, but it is also used in some economic studies of technology diffusion. The model assumes that all adopters have the same preference for the technology and that the cost of the technology is constant over time. The difference is that not all adopters have the same information about the technology. As the technology is adopted, the information about the technology (learning-by-using) is spread and increases the rate of adoption until the market is saturated. This model also generates an S-shaped curve as predicted in diffusion theory. Mansfield pioneered the use of the epidemic model based on profit and proportion of non-users. The model has been used empirically to study overall rate of diffusion, inter-firm diffusion, intra-firm diffusion, and international diffusion of a technology.[76]

Duration analysis is a statistical means of identifying factors that have an effect on the length of time between two points. When analyzing diffusion, the starting point can be the patent date, the date of the first use in the natural gas industry, or the date of the first use in the landfill gas industry. The end date can be the date of the first use in the landfill gas industry or the date adopted by the specific firm.

Duration analysis has become popular with researchers in diffusion studies after economists derived a theoretical approach to diffusion of technologies using duration analysis.[77] [78] Adoption is based on the current price of the technology, movements in the prices expected to occur in the future for the technology, and expectations of obsolescence. This theoretical exercise shows that if the industry supplying the technology is competitive with a large number of firms, there will be slower diffusion, because of expectations that prices will fall over time. Another study using duration analysis finds that the main factors affecting the diffusion of technology in a UK engineering study are endogenous learning, firm size, industry growth rates, cost of the technology, and expected changes in the cost of technology.[79]

Another trend in the literature is analyzing the simultaneous diffusion of two or more technologies throughout a sector. Using duration analysis, one study looks at the complementary role between various technologies and learning at Italian metalworking firms. It finds that learning due to the adoption of one technology has an impact on the adoption of the next technology.[80] A similar study analyzes the diffusion of two new technologies, specifically numerically controlled machine tools and coated carbide tools in the UK engineering and metal working industries, using a probit model.[81] The study concludes through both a theoretical and empirical approach that the adoption of one technology is affected by the explanatory variables related to the technology as well as the variables related to the technology the firm did not adopt.

Duration Analysis is a relatively new technique in the economic field.[82][83] It is based on a technique used by epidemiologists to model the survivorship of patients exposed to a certain disease. In the case of technology adoption, survivorship means that the firm or entity has not adopted the technology; death of the patient is equivalent to adoption of the technology. The technique has been used on a wide range of issues.

In the early 1970s, economists began using the technique to analyze issues such as the duration of unemployment. Later, policy scientists began using the technique in the study of issues such as periods of war or peace in various regions.[84]

Duration Analysis

Duration analysis, or epidemic modeling techniques, is well documented.[85] [86] [87] [88] There are two basic types of duration analysis: proportional analysis and accelerated failure time analysis. Proportional models compare the survival of different groups. Log linear survival time models are accelerated failure time models where the effect of the covariate is multiplicative over time.[89]

Duration analysis, or survival analysis, is the modeling of time to event data. The technique identifies factors that have a statistically significant effect on the length of time between an entity's entry into a specific state and the exit or entry into a new state. In epidemiology, survival analysis focuses on the survival of people who contract a disease or are exposed to a disease and the length of time before the person becomes sick or dies from the disease. In the context of this study, the spell is the difference between the first demonstration of a landfill gas project or opening of the landfill (whichever comes later) and the adoption of a landfill gas technology.

The basic survival function is denoted S, which is defined as:

$S(t) = Pr(T<t)$

where t is some time, T is the time of death (in this case, the time of adoption of a landfill gas project), and "Pr" stands for probability. The survival function is the probability that the time of death (adoption) T is later than time t, or in the case of this study, the probability that a landfill will *not* adopt a landfill gas project at time t. The survival function is non-increasing over time, since the probability of death, (or in the case of landfills – non-adoption), increases over time.

Given that S(t) decreases over time, the lifetime distribution function, usually denoted F is defined as follows:

$$F(t) = \Pr(T \leq t) = 1 - S(t)$$

In this study, F(t) is defined as the probability that a landfill will adopt a landfill gas technology. The density function of the lifetime distribution can be estimated by taking the derivative of F (denoted as f),

$$f(t) = \frac{d}{dt} F(t)$$

where f is called "the event density," which is the rate of death or failure events per unit of time. The function f(t) is assumed to be a continuous probability density of the random variable T, where t is the realization of T and is the length of the spell.

The event rate at time t conditional on survival up to time t is the hazard function.

$$h(t) = \lim_{\Delta \to 0} \frac{\Pr(t \leq T \leq t + \Delta \mid T \geq t)}{\Delta}$$

$$h(t) = \lim_{\Delta \to 0} \frac{F(t + \Delta) - F(t)}{\Delta S(t)}$$

$$h(t)dt = f(t)/S(t)$$

The hazard function is nonnegative, $\lambda(t) \geq 0$, but may be increasing or decreasing, nonmonotonic, or discontinuous. It represents a continuous time equation of a sequence of conditional probabilities of adoption.

The cumulative hazard function can be defined as:

$$H(t) = \int_0^t h(u)du = \int_0^t [f(u)/S(u)]du = \int_0^t [1/S(u)]\{d/du\, S(u)\}\, du = -\ln\{S(t)\}$$

Therefore:

$$S(t) = \exp\{-H(t)\}$$

$$F(t) = 1-\exp\{-H(t)\}$$

$$f(t) = h(t)\exp\{-H(t)\}$$

When a specific hazard function is specified, the equations can be further defined. An example is the Weibull model which will be used in this analysis. The Weibull hazard function is defined as:

$$h(t) = pt^{p-1}$$

where p is a shape parameter that is estimated using the dataset given in the analysis. Given the Weibull hazard form, the survivor, cumulative distribution, and probability density functions become:

$$F(t) = 1- \exp(-\gamma tp)$$

$$S(t) = \exp(-\gamma tp)$$

$f(t) = \gamma pt(p-1)\exp(-\gamma tp)$

$h(t) = \gamma tp$

Once the hazard function is defined, the covariates can be analyzed using the maximum likelihood technique. The likelihood function is the joint probability distribution of a sample with a vector of parameters θ. The likelihood function can be written as:

$$L(\theta) = \sum \ln f(t_i,\theta)$$

$$i=1 \text{ to } n$$

Since the duration of the observations is at least z_i where z_i is the time censored for i, the likelihood function is:

$$L(\theta) = \sum di \ln f(t_i{*},\theta) + \sum(1-d_i)\ln S(z_i,\theta)$$

$$= \sum d_i \ln \lambda(t_i,\theta) + \sum \ln S(t_i,\theta)$$

Where $t_i = \min (t_i{*}, z_i)$. After this, explanatory variables, or covariates can be introduced into the survivor and hazard functions above; and the maximum likelihood procedure can be used to estimate the vector of parameters.

Hazard Specification

The hazard specification represents the underlying increase in diffusion due to an “epidemic learning.” Under adoption theory, this "epidemic learning" can be defined as learning-by-using, learning-by-doing, and/or information dissemination.

Cox proportional hazard model

To avoid a parametric assumption concerning a baseline hazard rate, a Cox model can be used. The Cox proportional regression estimates are the probability of failure at time t without reporting a baseline hazard rate. Cox proportional models assume that the hazard does not depend on time and, therefore, that the proportional hazard is constant over time. The Cox model is probably the most basic proportional hazard model because a parametric baseline does not have to be assumed by the modeler.

Exponential

If failures occur randomly and the firms or individuals studied do not change or "age" over time, then it is appropriate to use the exponential distribution.[90] In the case of landfills, this does not necessarily seem to be the best fit. Landfills do "age" over time, decreasing their landfill gas output and making a landfill gas project less profitable and, therefore, less likely over time.

The exponential distribution for a parameter $\gamma>0$ yields the following survivor and hazard functions:

$$F(t) = 1- \exp(-\gamma t)$$

$$S(t) = \exp(-\gamma t)$$

$$f(t) = \gamma \exp(-\gamma t)$$

$$h(t) = \gamma$$

Weibull

The Weibull distribution is a more general form of the exponential distribution and seems the most likely candidate for the underlying parametric distribution. The Weibull distribution has two parameters. If the distribution shape parameter (p) in the Weibull distribution all equal 1 then the Weibull becomes an exponential distribution. If the shape parameter is greater than 1, then the hazard is increasing over time. Likewise, if p is less than one, the hazard is decreasing over time.[91] If the Weibull distribution is the best fit for adoption in this sector, it is likely that that the shape parameter would be increasing over time.

Given these two parameters, the survival and hazard functions for the Weibull distribution are as follows:

$F(t) = 1- \exp(-\gamma tp)$

$S(t) = \exp(-\gamma tp)$

$f(t) = \gamma pt(p-1)\exp(-\gamma tp)$

$h(t) = \gamma tp$

Log-Logistic

The log-logistic parametric shape increases and then decreases over time. This shape does not fit with the theoretical idea of technology adoption where adoption increases over time and then flattens out at some optimal point. However, the shape of this distribution may have more significance when considering specific technologies where one technology may dominate then wane as another new technology dominates.

The log-logistic distribution is also a two parameter distribution. When $p>1$ the hazard first increases with time, then decreases. If $0<p\leq 1$ the hazard function decreases with duration.

$F(t) = 1 – [1/(1 + \gamma tp)]$

$S(t) = 1/(1 + \gamma tp)$

$f(t) = \gamma pt(p-1)/(1 + \gamma tp)2$

Others

There are several other parametric distributions, which for theoretical reasons were rejected. These include the Poisson, Gamma, and Gompertz. The shapes of these distributions do not follow the theory of technology adoption. For example, with the Poisson distribution, the assumption is that each event (adoption) would occur independently of each other with a constant probability. The assumption that each adoption is independent of each other does not fit with the information gathered from interviews and the literature on information dissemination, project demonstrations, etc., leading to development of new projects.

Alternatives to Duration Analysis

Several alternatives to the epidemic model exist: the generalized static model, dynamic modeling, vintage and stock adjustment models, threshold of probit models, learning models such as the Baysian learning approach, the game theoretic approach, and duration analysis. A generalized static model builds on the epidemic/logistic model in the sense that it incorporates information from one constant source as well as information from word-of-mouth and other economic variables such as product prices. It divides the population into more than two groups, allowing for the rejection of the innovation altogether by a specific group. While this model provides a flexible mathematical way of studying diffusion, it does not allow for any change in the population of adopters or for post-innovation improvements in the technology or application of the technology.

A dynamic model allows for the declining real costs of technology due to cumulative improvements, learning by doing/using, and vintaging of capital over time, and for the reduction of risk due to the spread of information about the technology.[92] An example of this is a study using a system of two equations to evaluate the relationship between innovation output and market structure in an industry.[93] It supports the theory that both innovation activity and market structure are endogenous variables as well as variables of firm size and labor characteristics.

Vintaging models are designed to allow capital stock turn-over to drive the adoption of new technology. The premise is that firms will delay adoption until the old capital equipment needs to be replaced, at which time, the firm will buy the newer technology to replace the old. Generally these studies are based on an epidemic or logistic model and adjusted to represent the dynamic process of replacing capital equipment.[94]

Threshold of probit models are static probit (or logit) models where the explanatory variables change over time. These exogenous variables explain adoption; and as they change with time, the proportion of the population that decides to adopt increases. These models are based on actual explanatory variables instead of some proxy (usually time).

Learning models have been developed in an attempt to explicitly model the effect of learning on the diffusion process. The models, mostly tested in the area of agricultural innovation, have produced what can be described as "sensible results;" but the models have been criticized for using various learning mechanisms without explicitly justifying why the mechanism was used.[95] Bayesian learning seems to be the leading mechanism used, and it has been applied to both agricultural diffusion and industrial diffusion among firms and across sectors. The models focus on learning, profitability and cost, attitudes towards risk, and initial uncertainty.

The game theoretic approach assumes that even if all firms have exactly the same information about a technology, the behavior of each firm could lead to different adoption dates. The difference in the adoption dates of each firm thus creates a diffusion curve.

Chapter 4: Analysis of Diffusion

Landfill gas capture-and-use projects are considered by some to be a critical means of reducing greenhouse gas emissions, reducing ground-level ozone, increasing profits at landfill sites, and increasing the local energy supply. A number of Federal and State policies encourage the capture-and-use of landfill gas. However, there is a debate as to whether or not these policies are necessary to increase the adoption of landfill gas capture-and-use technologies. Many argue that the price of electricity or natural gas is sufficient to encourage adoption. Others argue that the majority of landfill gas capture-and-use projects are only marginally profitable and, without Federal and State incentives, would not be worth pursuing.[96]

This chapter studies the effects of both policies and prices on the adoption of landfill capture-and-use projects. The models reflect issues or variables raised in the interviews with developers, companies, associations, and consultants, as well as issues raised in the literature on landfill gas projects (see appendix A for interview coverage). Variables identified by the research on the landfill gas sector fall within the sociological and economic categories identified in the theoretical literature review. Using the variables identified from these experts, several forms of epidemic models are applied to the data. First, the analysis looks at whether or not the example of landfill gas projects fits the epidemic model of adoption, or, more specifically, which baseline hazard function is appropriate. Second, the analysis then looks at the correlation between the variables identified by experts and the literature on landfill gas projects with the outcome, adoption.

Model Specification

An essential conclusion of current diffusion theory is that potential adopters have different or preferred adoption dates.[97] In the literature, the reasons for the difference in preferred adoption dates are due not only to the spread of information (epidemic effects), but also to firm characteristics, policy structure, and prices faced by the firm.

In the case of landfill gas capture-and-use projects, several studies have been funded by the USEPA to identify general barriers to adoption.[98] The models in this study rely on responses from intensive interviews with landfill gas project developers and landfill owners to identify the following factors in deciding whether or not to pursue a landfill gas project. Experts identified what they felt were the most critical issues, and their responses fell within the literature. Relying on information from these experts, I identified sixteen variables as key to whether or not to adopt a project. Ten of the variables identified were related to environmental policies at the Federal and State levels, two variables were price related, one variable was technology specific, and three variables were related to the characteristics of the landfill. In order to isolate the effects of the renewable energy policy and the price effects in the model, the remaining fourteen variables were used as control variables.

Policies Related to Landfill Gas Collection and Emissions

The first landfill gas capture-and-use project was installed in 1975, prompted by the energy crisis. Interest seemed to wane once energy prices decreased. More recently, however, interest has increased due to Federal regulation of emissions from landfills.

The focus of regulation has primarily been on reducing air pollution, mainly NMVOCs, and other safety concerns.[99]

Landfills have used landfill gas projects as a way to recover costs while meeting Federal regulations. Cost recovery and profit play a key role, but are not sufficient to explain the patterns of implementation. Many regulated landfills, specifically those that must combust the gas, could do so economically by selling the energy produced, yet they opt to flare rather than capture the gas and sell the gas as energy. LMOP staff has identified hundreds of landfills that could make money from capture-and-use technologies, but have not installed the technologies. In addition, not all landfill with landfill gas projects fall under the Federal regulations.

The final decision to install a capture-and-use project is influenced by a multitude of factors, including State renewable energy policies, Federal renewable energy and air pollution policies, energy prices, economics, and public opinion.[100] Some mitigation options are profitable or attractive even without an environmental policy impetus; but other policy issues (at both the Federal and State levels), the availability of an end user, and lack of technical knowledge may hinder a firm's ability to implement even profitable options.

Many states have enacted RPS rules. Most states consider landfill gas, if not a clean source of energy, at least a renewable source. Renewable energy developers have also found that landfill gas is cheaper and easier to install than wind farms or solar farms. Some states, in order to encourage more renewable energy projects, have also enacted rules and regulations that make it easier for operators generating electricity to sell the electricity back to the grid at a reasonable price. States have enacted other policies that promote renewables, including net metering, green power provisions, disclosure rules about the mix of fuels being used for electricity in an area, and financing provisions. Currently, 38 states have interconnection standards, 41 have net metering regulations, 24 have RPS standards, and 10 have green power purchasing programs.[101]

Federal regulations on air quality at landfills encourage landfill gas projects, but State requirements to comply with NOx, O_3, and carbon monoxide (CO) standards may actually create an administrative burden to the landfill. Reducing landfill gas by venting or leaking to the atmosphere reduces ozone levels and odor problems. Collecting landfill gas to be used as energy or to feed a flare significantly reduces the amount of gas that could fuel a landfill fire. However, power generating technologies also produce volatile organic compounds (VOCs) and NOx, the precursors to O_3. Permitting power generation technology may be difficult for landfills, particularly in areas where the US government has classified the area as a “non-attainment” area. Other barriers may include lack of information or experience with landfill gas technologies or the inability to finance the project.

Federal Policies

Section 29 and Section 45 under the IRS Code

Several experts note that all landfill gas projects, including flaring, take advantage of tax credits, specifically those credits laid out in Section 29 and Section 45 of the IRS Tax Code.[102] Experts feel that the tax credits are necessary to continue production of landfill gas as an energy source. Higher energy prices help the economics of a project, but when comparing landfill gas to coal, landfill gas is still considerably more expensive.

Facilities that use biomass to convert to gas before use as a fuel qualify for a tax credit of 99.3 cents per million Btu or 1 cent per kilowatt hour under Section 29 of the Internal Revenue Code. The credit is adjusted each year for inflation. The Section 29 tax credit started in 1979 and was extended to 1996 by the Energy Policy Act of 1992. The tax credit has been renewed twice since to cover the period between 1992 and 1998 as well as extend beyond the 1998 time period. The credit is divided between large and small landfills; larger landfills getting $2 per barrel oil equivalent for 4 years of 200,000 cubic feet per day production and small landfills getting $3 per barrel oil equivalent for 4 years of 200,000 cubic feet per day production (2002 dollars).[103]

However, a great deal of uncertainty is associated with the tax credits. The tax credit was designed so that only the producer (Genco) could use the tax credit and the energy had to be sold to a third party. In 1996, of the approximately 140 LFG capture-and-use projects running, approximately half of them used the tax credits.[104] After two years of annual extensions, Section 29 was instated to 2007.[105] The limited coverage of the tax credits, four years of production, and only 200,000 cubic feet per day, coupled with the uncertainty of whether or not the tax credits would exist in the future, limited the tax credits' influence on a firms' decision making. In addition to the uncertainty, the tax credits were designed not to help the landfill, but to help the Gasco (the company which owns the gas). Section 29 tax credits were based on the sale of the LFG to the Genco. The Gasco (not the owner or the Genco) filed for and received the tax credits. Many private companies spun off Gascos from their companies in order to take advantage of the tax credits.

These same landfills which are eligible for the Section 29 tax credit are also eligible for the new Section 45 tax credit. Under Section 45, the tax credits for generating electricity go to the Genco. The Section 45 tax credit is worth 1.2 cents per kilowatt hour for the first five years of electricity generation (which is roughly equivalent to $1.20 per million Btu).[106] Section 45 is considered important to the development of current projects. The waste management industry associations lobbied for the tax credit and lobbied to have it apply to the Genco.

Section 29 is not represented in this analysis. The use of a dichotomous policy variable for Section 29 would mean a value of one for all years of the analysis. A numerical value for the policy does not capture the uncertainty surrounding the policy during the mid-1990s, the most critical time in the development of landfill gas projects. Section 45 was not enacted in 2004 and is, therefore, beyond the scope of this analysis.

Renewable Energy Production Incentive (REPI)

The Renewable Energy Production Incentive (REPI), part of the Energy Policy Act of 1992, was enacted to promote renewable fuel use to generate electricity through tax incentives to State and local facilities. The policy began in 1993 and lasted until 2003. Qualifying facilities received the equivalent of 1.5 cents per kilowatt hour in 1993. While this represents a significant increase in potential revenue for projects, payments to qualifying landfills depended on sufficient appropriations by Congress.

In the first two years of the REPI program, there were sufficient appropriations to make full payments to owners of all qualifying landfills. After that point, only partial payments or no payments could be made to landfills that qualified for the program.[107]

New Source Performance Standards (NSPS)

In addition to tax credits and energy policies, environmental regulations may also have a positive or negative impact on adoption of capture-and-use projects at landfills. Under the Clean Air Act, the NSPS regulation or Landfill Rule requires that landfills over a 2.5 million Mg of MSW test their landfill gas emissions. If gas emissions are above 50 mega grams per year of landfill gas (LFG), the landfill is required to put in a collection system for the gas. While the original regulation which declared MSW emissions a pollutant was passed in 1991, the 1996 regulation finalized the actual emissions standards. NSPS is focused on limiting NMVOCs in landfill gas emissions because they are precursors to ground level O3 as well as CO. Unfortunately, states are still at different levels of understanding about the standards and do not always coordinate their waste and air regulations. This leads to the misunderstanding that a landfill gas capture-and-use project is an additional source of pollution, not a reduction technique.[108]

The Landfill Rule requires large landfills to collect their landfill gas and flare or produce energy. While flaring reduces local air pollution and addresses safety concerns caused by the flammable gas migrating through the landfill, it does not capitalize on the value of the landfill gas as an energy source. Flaring also does not offset air pollution and greenhouse gas emissions caused by displacing coal or oil use.

LMOP literature also notes that collection systems with flares are not as closely maintained as those that produce landfill gas for sale, creating more emissions or leakage from the collection system.[109] Flaring is not considered a landfill gas project in this analysis; only capture-and-use projects are considered. When a large landfill is required to flare but instead opts for a capture-and-use project, this reduces the overall cost of the project since the gathering system is already in place.

Under the LMOP program (below), USEPA promotes landfill capture-and-use projects as a way to recover costs of meeting the NSPS regulation. Landfills over a certain size are required to install a gathering system for the gas and, at a minimum, flare the gas under the regulation. Many companies see this as a sunk cost, making capture-and-use projects more attractive.

Landfill Methane Outreach Program (LMOP)

Studies on the effectiveness of information provision policies illustrate that these policies can increase use of a technology, particularly in the case of imperfect information networks.[110] [111] The Landfill Methane Outreach Program (LMOP) is a Federal program administered by the USEPA to disseminate information about landfill gas capture-and-use projects. The program was created to address four critical areas:

- lack of information and the perception that LFG projects are high risk by disseminating information on project opportunities and the environmental, energy and economic benefits of LFG projects;
- Costly permitting and other regulatory hurdles by working with Federal and State regulators to increase their understanding of the issues;

- Poor rate of return on project investment by working with utilities and other energy purchasers to increase recognition of the benefits of LFG projects; and
- Misperception that projects are not profitable through workshops, site visits and case studies of projects that are cost-effective.

The program also enrolls partner organizations, such as State organizations, NGOs, developers, and vendors into the partnership to help facilitate information exchange. Experts also cite LMOP as being extremely useful in educating local and State officials on the benefits of projects, smoothing the permitting process.[112] The literature on the effectiveness of success of voluntary policies is available, though no specific study focuses on the LMOP program. [113] [114]

State Policies

State policies are geared towards encouraging renewable energy projects in general. Interviews with experts were split as to whether or not these policies encourage landfill gas capture-and-use projects. A 1996 report by the Department of Energy's (DOE) Energy Information Agency (EIA) on Renewable Energy states that, "The reach of State and local environmental regulations is expanding at an increasing rate. According to industry sources, the costs for LFG [landfill gas] energy recovery projects of complying with all pertinent regulations are escalating faster than the inflation rate and the original financial assumptions."[115] In the same report, EIA states that, "State incentives in the form of favorable utility contracts for electricity projects have contributed to the development of LFG energy recovery projects more than any other government incentive program [no study cited]." However, this is a mixed blessing. Landfill developers are faced with diverse rules across states, particularly pertaining to air quality permits, which sometimes add to the transaction costs of the project. These policies may actually make other renewable energy projects more attractive than landfill gas projects.

<u>Renewable Portfolio Standards (RPS) and Green Power</u>

Renewable Portfolio Standards (RPS), which include landfill gas projects, have been adopted in over 20 states since the mid-1990s. RPS is a market-oriented policy used to encourage renewable resources into the electric sector. An RPS introduces a schedule for the minimum amount of renewable electricity (as a percent of total electricity production) for each electricity producer. Each producer is forced to comply either by purchasing enough renewable energy to meet the percentage standard or by buying credits from producers that exceed their standard. This trading system provides a least-cost approach to reaching the State-wide target. The State monitors and verifies the crediting system.

The issue with RPS is whether or not the State in question would have met the standard in the absence of the policy. In other words, to what extent does the standard increase renewable energy in the State? One case is Maine, where the RPS standard seems particularly high at 30 percent.[116] Considering that 45 percent of Maine's electricity already comes from renewables, this is misleading. In general, states choose a standard above their current rate and then tighten the standard over time. Announcing the policy ahead of time and the gradual tightening of the standard allow the industry to respond to the standard without spikes in energy prices.

Another issue with RPS is what is defined as a renewable energy source. Many people would immediately think of "clean" energy sources such as wind or solar.

Some states also include renewable sources that are not considered "clean," such as waste incineration and landfill gas. These sources of energy tend to be cheaper than traditional renewables and also have co-benefits if managed properly.

States with RPS specify the percentage or amount of renewable energy generation they want operating by a specific date. Many states have yearly targets over a ten to fifteen year period. In addition to the RPS standard in percentage terms, some states are requiring specific megawatt standards for renewable energy. Texas is requiring 2000 MW of renewables by 2009.[117] Each state has a specific mix of renewable fuels and technologies which they target. Generally, a state creates a system where the generation of renewable energy earns credits that are certified by the state. Energy providers or utilities purchase the credits from renewable generators. At the end of each year, each energy provider is required to hold a certain number of credits.

Some experts noted that State RPS programs helped push projects in the absence of the Federal Tax credits, though this view not shared by all. Other experts also noted that RPS credits are not hard contracts, but a soft incentive, unlike the tax credits. Ownership of the generated credits is somewhat of an issue, because many landfills have three parties involved (the owner, Gasco and Genco). In some states, it is not clear which party receives the benefit from the sale of the credits to the provider. Some programs (e.g., Massachusetts) have to be renewed on an annual basis, and this creates a paperwork burden on the Genco. Despite the problems, many of the projects relied on RPS in absence of the tax credit. LMOP representatives could not think of a project that was not done with RPS when Federal tax credits were suspended.[118]

Green power purchasing is also gaining acceptance in some states. In some states customers are willing to pay a slightly higher price for electricity in order to increase the amount of electricity generated from renewables. Eight states require that a specific percentage of electricity purchased for government buildings come from green power sources such as landfill gas, wind power, or solar power. Twenty cities have formed green power "buying blocks." Green power can be bought via utility pricing programs, green power marketers, or green power contracts. Four states require some utilities to offer customers the option of purchasing green power. [119] These programs are still too new to analyze with the current data set.

Net metering

Net metering generally means that excess electricity produced by a consumer is given to the utility or is bought by the utility at a rate usually lower than the retail price of electricity in the area. As of 2000, 18 states had net metering statutes that required utilities to buy electricity that the utility customer does not use. As of June 2003, 33 states had net metering (or net billing) regulations. By 2005, 39 states or territories had net metering laws. [120]

The Federal Public Utility Regulatory Policies Act (PURPA) in 1978 provided the basic framework for State net metering laws. Net metering laws allow customers to sell the power they generate themselves (using technologies such as photovoltaic panels) back to the utility at the utilities "avoided cost." The law greatly simplifies the purchase of renewable energy generated by customers. For independent power producers such as a landfill gas project, the process is more complicated and requires that a utility sign a net purchase and sale agreement which must be negotiated.

Interconnection standards

State interconnection standards simplify the interconnection process through standardized forms and rules. Each company applies for interconnection during the development phase of the project, and each state and/or utility has a different set of rules for interconnection. Developers (Genco) may face a variety of standards when working across states. Despite this, Gencos still must negotiate a contract with the utility. In this analysis, the presence of a State interconnection standard is represented by a dichotomous variable indicated when the standard was implemented in a specific state.

Financial Instruments

All states currently have financial incentives to increase production of renewable energy. These incentives include:

- Corporate tax credits or deductions for installing or using renewable energy (16 states have state run programs);
- Grant programs to encourage the development and use of renewable energy (24 states, 8 privately funded options in 5 states, 5 local governments);
- Low or no-interest loans for residential, commercial, or industrial purchase of renewable energy technology (17 states, 10 utilities in 4 states, 8 local governments);
- Production incentives or cash per unit of electricity produced (7 states, 11 utilities in 10 states, 2 local programs in 1 state, 54 privately funded programs in 49 states);

- Exemptions, exclusions, or credits on property taxes for installing a renewable energy project (25 states);
- Rebates for installing renewable energy technology (11 states, 41 utility run programs in 12 states, 3 local programs in 3 states, and 1 privately funded program);
- Exemption on sales tax when purchasing renewable energy equipment (15 states); and
- Recruitment by states and local government of renewable energy providers (7 states and 1 locality).[121]

The above financing options will apply to landfill gas depending on the wording of the State or local policy. Some policies may apply only to solar and/or wind power.

Most states have financial incentives to promote renewable energy projects, including landfill gas projects. Instruments include loans, tax credits, production incentives, grants, purchasing agreements, and rebate incentives. The experts interviewed stated that few projects use the State grants and loan programs offered.[122]

Environmental Compliance

Landfill gas project developers encounter difficulties in obtaining air permits, particularly in ozone NOx and CO non-attainment areas. Non-attainment areas are those counties that fail to meet the National Ambient Air Quality Standards (NAAQS). Permits can require lengthy negotiations with State representatives. The more stringent the air requirement and whether or not the landfill is located in a non-attainment area may influence whether or not a landfill decides to develop a landfill gas project.

The Resource Conservation and Recovery Act (RCRA) requires compliance with the Clean Air Act limiting NOx and CO in ozone non-attainment regions. Many areas are still considered in “non-attainment” areas by Federal air pollution laws, requiring State permits to install any type of power project.

Until very recently, air permits have been a hurdle to landfill gas capture-and-use projects. Landfill gas projects were seen as a potential source of air pollution and developers had difficulty gaining permits, particularly in areas with low air quality thresholds, until a ruling by EPA declared landfill gas “recycled” which let it be treated differently under NSPS.[123] Despite this, problems obtaining air permits have not prevented projects, but instead have increased the time and cost of developing the project. Delays and increased costs have turned a few landfill projects from capture-and-use projects to flaring.

Energy Prices

The economics of a landfill gas project is largely influenced by the revenue stream produced by the project. Landfill gas is purchased by an end user in a direct use project for a negotiated price over a long time period and pegged to the national average oil price.[124] This guarantees the industry buyer a long-term, local supply of fuel and protects them from the volatile price of natural gas. Because untreated landfill gas has various other gases mixed into it, the buyer must compensate for the “dirty” mixture through higher maintenance costs. The buyer then negotiates a less than market price to cover the higher maintenance costs.

Landfills also enter into long-term electricity contracts with utilities for an electricity generation project. In states where net metering laws exist, the electricity utility has access to electricity from small, individual producers at the "avoided cost" to the utility. To compete with this price, the landfill gas project may end up negotiating a lower price in order to get the long-term contract. These contracts can make or break a landfill gas project.

Revenue from projects can be low enough that even mature technologies may be too expensive to operate. Local utilities consider only cost (not the reduction of environmental externalities) when negotiating contracts. Low energy prices also limit the market for landfill gas generated energy. Experts noted that there are other issues that must be dealt with during the process of developing a project. However, if the economics are right (i.e. the revenue is high enough relative to the cost), other issues such as air permits, financing, etc. can be overcome.

US Landfill Characteristics

Landfills are engineered sites permitted to receive non-hazardous solid wastes, including household trash, construction debris, and sludge from sewage treatment. Each landfill is managed to prevent leachate (the liquid produced when water percolates through the waste) from entering ground water; to reduce smells, rodents, and other potential health hazards; and to prevent excessive air pollution.

Modern landfills in the US are lined with plastic or bentonite clay to prevent toxic leachate from migrating into groundwater. To reduce smells, health issues from rodents, and other health hazards, a layer of soil is spread over each layer of garbage, usually at the end of each operating day. In addition, large landfills are regulated to safely collect landfill gas that is approximately 49% methane and highly flammable. Combustion, or flaring, destroys the methane along with other organic compounds that can be hazardous or cause odor. The gas also carries toxics and other air pollutants that can be destroyed through flaring or through combustion as an energy source.[125]

Municipal solid waste landfills produce methane when bacteria decompose the organic wastes such as paper products, food, and yard wastes under anaerobic conditions. The amount of methane produced at a landfill depends on the quantity of the organic material, the nutrients available to the methane-producing bacteria, the moisture content of the landfill, the depth of the landfill (which regulates the temperature), and the pH of the landfill. The process requires six months to two years to start producing methane and continues for approximately 30 years, depending on the amount of organic waste in the landfill and other conditions such as temperature and pH. Methane is released into the atmosphere when the methane migrates through the soil of the landfill cover.[126]

Between 1980 and 2003, the amount of waste disposed in landfills increased 50% to 236 million tons of waste per year. The per capita rate of 4.5 pounds per person per day has stayed relatively stable since the early 1990s. The largest component of this waste is organic materials that break down to produce landfill gas: paper products - 35 percent of municipal solid waste; wood - 6 percent; yard trimmings - 12 percent; food scraps - 12 percent; glass, metals, and plastics - about 24 percent; and rubber, leather, textiles, and other goods - about 10 percent. The amount of organic materials in the total waste sent to landfills continues to decrease due to recovery, recycling, and incineration. Approximately 30 percent of total waste is recovered through recycling, composting, and other recovery programs. The remaining two-thirds of municipal solid waste produced is disposed in approximately 2,300 municipal solid waste landfills.[127]

Several non-policy and non-economic variables influence the diffusion of technology and must be controlled for in the model. Methane generation potential of the landfill is a function of the landfill's size, the climate, the composition of the solid waste, and the age of the landfill. The amount of methane generated has a large impact on whether or not a project is feasible. In addition, the ownership of a landfill may encourage landfill gas. Private ownership is thought to be more innovative and, therefore, more likely to adopt a project. Lastly, the model is also controlled for the variances in State cultures towards both environmental issues and landfill projects specifically.

Landfill Ownership and the Structure of a Project

Approximately 78 percent of all landfills are owned by State and local authorities, while 20 percent are owned by private companies. Most of the privately owned landfills are owned by a few national waste management companies. The rest are federally owned facilities.[128]

There are a limited number of national waste companies. The largest is Waste Management with 235 landfills in 49 states, 72 of which have landfill gas projects in approximately 22 states.[129] Waste Management became the largest waste service provider in 1998 when USA Waste Services, Inc., merged with Waste Management, Inc. The company is traded on the New York Stock Exchange and operates in 13 countries outside of North America.

The second largest company in the US, Allied Waste Services (formerly BFI) currently runs 177 landfills in 37 states, 167 of which are still active. The third largest company, Republic Services, runs 52 landfills in 20 states. The fourth largest company, Onyx, runs 26 landfills in 11 states. IESI and Waste Connections run 6 and 5 landfills in 4 and 3 states respectively. Various departments within the US Federal government run 56 landfills in the US. [130]

Whether or not the firm is privately owned influences the flexibility of the gas project ownership structure. A private firm is more able to restructure or spin off parts of the company in order to maximize tax credits and generation revenues; they can, therefore, receive more benefits from a landfill gas project. The structure of a landfill gas project is defined by the IRS tax credit system. The landfill owner leases the landfill gas (LFG) development rights to the LFG developer. In return, the owner receives lease payments and royalties. The landfill owner is responsible for the maintenance of the landfill, including LFG migration control.

Separate from the landfill owner, the Gasco is the developer who sets up the LFG collection system. The Gasco pays the landfill owner production payments, royalties, etc., and is responsible for constructing operating and maintaining the LFG collection system. The Gasco then sells the LFG to a separate legal entity, the Genco who generates electricity from the fuel. The Genco is responsible for the construction and maintenance of the power generation facility.

Under this ownership structure, different tax credits go to different entities. A private company can spin off a development company and a generating company and maximize on tax credits. A public organization can not receive tax benefits. This also creates a structure where the privately owned companies have their own development companies whose job it is to look for LFG project development opportunities across the company's portfolio of landfills. This may drive diffusion of these projects through the private sector.

Size, Age, Composition, and Precipitation

The size of the landfill in terms of volume of waste, the age of the landfill, the composition of the waste put into the landfill, and the precipitation in the area where the landfill is sited determines the amount of landfill gas produced by the landfill. The gas output is a key factor in the economics of a landfill gas project. Landfills with high potential volumes of methane generation are more attractive to end users of the fuel who prefer a guaranteed long-term price and supply of the fuel.

CA Dummy Variable

A recurring topic in the interviews and literature is the difference between California and the rest of the US. Experts noted several issues, including the 34 air districts where each district has its own rules and procedures, high demand for renewables, popular attitudes which promoted environmental ideals, an innovative culture ready to take risks on new technologies, and the business attitude of an early adopter.[131] The complicated government structure and strict environmental guidelines can hinder certain projects, but attitudes towards alternative energy and environmentally sound technologies can encourage projects. A dummy variable was introduced to the equation to capture these effects, because other states do not have air districts to implement their air quality standards and because of the striking difference between California and other states on environmental issues including climate change and renewable energy.

Variable Specification

The data set used in this analysis is panel data based on the LMOP database, DSIRE State renewable database, EIA energy data, NASA weather data, and a variety of US and State government reports. In addition to collecting data and the literature review, I conducted a series of interviews with developers, landfill owners/operators, experts and associations. Developers and landfill owners/operators interviewed are associated with 25% of all landfill gas projects and have projects in 41 states (see appendix A for coverage information).

Approximately 1145 landfills are considered in the analysis during the time period from 1978 to 2003. All data described below is lagged two years before the start date of the project. From interviews with experts and a review of the LMOP literature on decision making process of the landfill, I found that the decision to build a project, including policy and financial analyses, happens on average two years in advance of the project. Because most project decisions are made two to three years in advance of the actual start date of the project, all variables are lagged.

The data set is restricted to those landfills which are considered "candidate" landfills for a project. This means a pre-feasibility economic analysis has been done to show that a landfill gas project could be done cost-effectively at the landfill. Because of this, cost data for individual technologies are not included to avoid double counting.

Below is a description and discussion of the variables in the data set. For data summary statistics, see appendix B.

Table 3: Variable Specification and Data Sources

Variable	*Description*	*Source*	*Validation (if necessary)*
Federal Policies			
Renewable Energy Production Incentive (REPI)	Dichotomous variable where the value 1 indicates the program was implemented.	EIA reports	Code of Federal Regulations (CFR)
New Source Performance Standard (NSPS or "Landfill Rule")	Variable equal to 0 before 1996, variable equal to 1 after 1996, variable equal to 2 for landfills required to flare after 1996.	CFR	EPA summaries
Landfill Methane Outreach Program (LMOP)	Number of members in a state by year. Members include landfill managers, state and local officials, vendors and NGOs. A proxy for the spread of information among networks.	LMOP Program data	Interviews; LMOP program reports
State Policies			
Renewable Portfolio Standards (RPS)	Variable equal to 1 if state has an RPS standard for that year which includes LFG; 0 otherwise.	DSIRE database	State websites; EIA reports
Net Metering	Variable equal to 1 if state has a net metering rule for that year; 0 otherwise.	DOE/EERE reports	DSIRE database
Interconnection Standards	Variable equal to 1 if state has an interconnection standard for that year; 0 otherwise.	DOE/EERE reports	DSIRE database
Financial Instruments	Total number of financial instruments available in the state related to LFG technologies.	DSIRE Database	State websites
Air Pollution standards by county for non-attainment areas	Variable has value of 0 if landfill located in a county meeting the air pollution standard; 1 if county in non-attainment with target level of 100; 2 if in non-attainment with target level of 50; 3 if target level is 25 and 4 if target level 10.	USEPA summaries	State Implementation Plans (SIPs)
Energy Prices			
Electricity prices	Cents per kilowatt hour (2005 dollars)	EIA	
Oil prices	Dollar per barrel (2005 dollars)	EIA	

<u>Control Variables</u>			
Methane Potential	size as measured by waste-in-place variable x precipitation variable	See below:	
Waste-in-Place	The variable ranged from 1 to 6 depending on the size category of the landfill.	LMOP	Landfill reports
Climate data (precipitation)	The variable is equal to 1 if sufficient rainfall available in the state for methane generation; 0 otherwise.	NASA	
Private ownership	The variable is equal to 1 if the landfill is privately owned; 0 otherwise.	LMOP database	company literature review; interviews
CA dummy variable	The variable is equal to 1 if landfill is located in CA; 0 otherwise.	LMOP database	
<u>Technology Characteristics</u>			
NOx Emissions	Pound per megawatt hour equivalent.	Engineering reports on specific technologies	

The REPI tax credit bill specified that the tax credit increase over time at the rate of inflation, so the real value of the credit was the same for all years. Because of this, the presence of the REPI tax credit is denoted by a dichotomous variable which has the value of 1 after 1993 to represent the presence of the tax credit in those years.

NSPS is represented by a variable that is equal to 0 before 1996, is equal to 1 after 1996, and is equal to 2 if the landfill has tested emissions under NSPS and must capture and flare/use methane emissions. The variable is divided into three parts, instead of using a dichotomous variable similar to the REPI variable; because the threat of legislation or future regulation seems change behavior even at landfills that have not reached the Landfill Rule cut-off point. Many landfills below the 2.5 Mg standard are designing and building their landfills with wells in order to meet a future regulation.[132]

In order to capture the LMOP programs' information network and reach, the variable for LMOP represents the number of partners in a given state in a given year. This measurement is the metric LMOP uses to measure success and best represents the spread of information through information networks in the sector.

An analysis of the targets for RPS above and beyond what is already in place shows that many of the RPS targets are actually similar increases, with little deviation among them, though an exact comparison is difficult because of the different time frames and focus of the standards (see Appendix B for mean and standard deviation of the RPS annual increase in stringency variable) . For the nine states with RPS in place during the analysis period, the RPS standards translated roughly into increases of 1 percent per annum, with two of the states having already exceeded their targets (Maine and Iowa).[133] Most RPS standards start off with low targeted increases in the beginning. Some RPS have annual increases held constant over several years or have a percentage goal for a given year where it is expected that the amount of renewable energy will slowly increase over time. The ultimate targets in this case are generally stated in terms of a 2015 to the 2025 goal. In the period covered by this analysis, that translates into only soft, modest targets.

Because of the complexities in comparing the standards and the similarity among the standards in the early years of RPS, the variable used in the model does not reflect the strength of the RPS standard but instead reflects the presence of an RPS rule in the state. The presence of an RPS rule in a state after the year it was promulgated is denoted by a dichotomous variable. RPS rules that did not include landfill gas as an option were not included in the variable.

The variable for net metering laws and interconnection standards are dichotomous variables which equal one in the years the legislation applies to the state where the landfill is sited.

State financial incentives, including loans, grants, and taxes, are mostly based on technology (i.e., grants for the use of fuel cells). While these technologies can be used for landfill gas projects, the original intention of most of the financial incentives is to promote solar and wind projects. In looking at these incentives, I ran the adoption model with these incentives broken out by type (taxes, grants, loans). I found that loans were insignificant in the analysis; taxes were significant but had a negative affect on adoption; and grants had a significant positive affect. However, the break out of this variable significantly increased the frailty of the model. Therefore, I used a variable which measure the number of instruments available to a developer in a given state. The idea is that if a variety of instruments covering several different types of technologies exist, a developer is more likely to develop a project. The financial instruments variable is the total number of State financial instruments available to a landfill.[134]

The air permit and non-attainment variables in the equations are an interaction between whether or not the area was in non-attainment (by county) and the level of the State standard. For example, if a landfill has the value 0 if located in a county in attainment; I used the value 1 for areas in non-attainment with a standard of 100 tons/year specified under the State Implementation Plan (SIP) as the standard for non-attainment areas; the value 2 is used for areas in non-attainment with a standard of 50 tons/year; a value of 3 is used for areas in non-attainment with a standard of 25 tons/year; and a value of 4 is used for areas in non-attainment with a value of 10 tons/year for the specific pollutant.[135] Originally I considered using the actual target pollutant levels, but the variable values were orders of magnitude higher than other variables in the equation.

I used two variables to represent revenue from the landfill gas project: electricity prices and natural gas prices over time. Price data are EIA data in 2005 US dollars and are reported in cents/kWh and $/barrel for electricity and oil prices, respectively.

The variable representing the potential methane production from the landfill is a function of the size, by category, and sufficient precipitation in the state the landfill is located, a dichotomous yes/no variable. The amount of waste-in-place determines the size of the landfill. Each landfill is then categorized by size according to the LMOP program standard size categories for LFG projects. Sufficient levels of precipitation are determined by an average annual rainfall of greater than 40 inches per year.[136]

Private ownership is a dichotomous variable that is equal to 1 for privately owned firms.

I introduced the CA dummy variable to capture the effects of the complicated environmental governance structure of the State and the innovative and progressive attitudes of the mainstream in California. I originally considered trying to using polling data on environmental issues across all states over time to pull out the effect of attitudes by state. However, this data are unavailable over the time period considered. Instead, both of these effects are lumped into the geographical dummy variable, making it impossible to pull apart why a landfill in California is more likely to have a project even after controlling for policies, prices, and landfill characteristics.

NOx emissions levels for each technology are from engineering studies of electricity generation technologies and boilers. I converted the emission measurements into pounds per megawatt hour (lbs/MWh) equivalence using a Btu to megawatt hour ratio. I only use this variable in the models presented in Chapter 5 because it is relevant to choices between technologies.

Baseline Hazard Specification

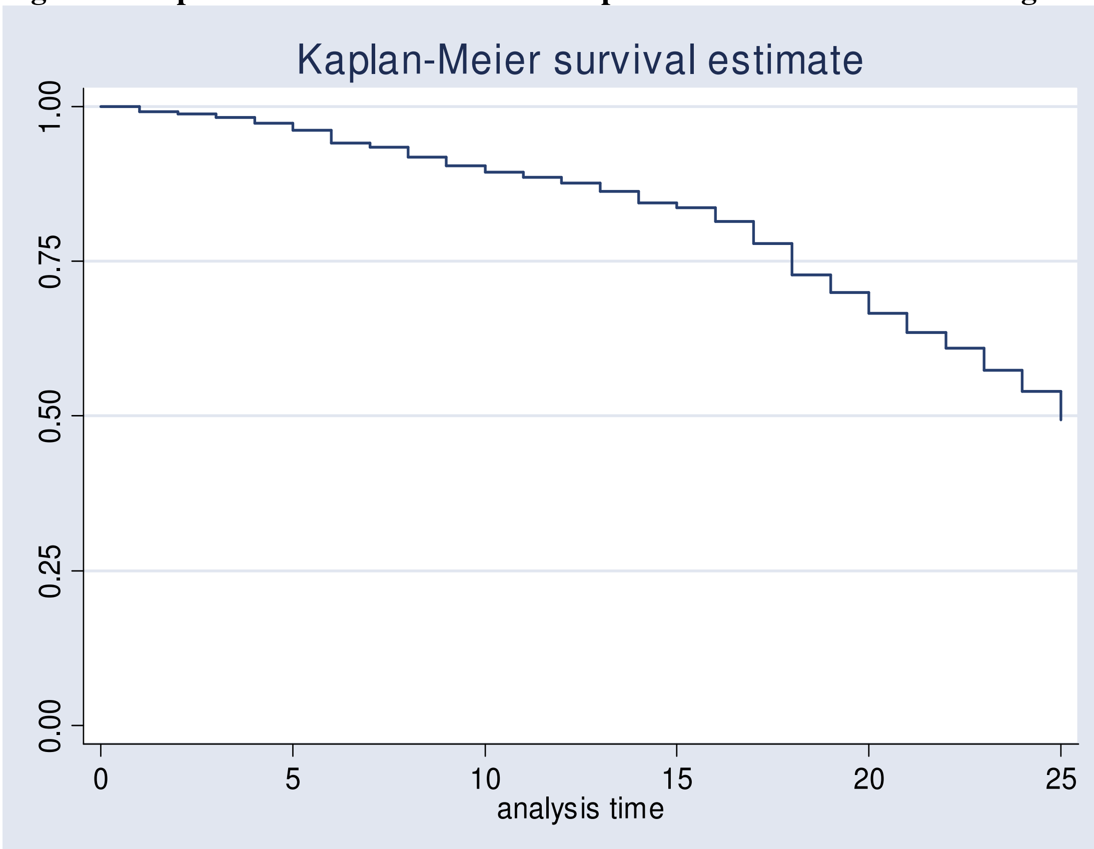
Mansfield hypothesized that information dissemination imperfections constrained adoption during the initial phase of adoption, but were slowly eliminated as the technology became more widely used.[137] This led to the use of the 'contagion' or 'epidemic' model to mimic the diffusion of information and adoption of a technology over time. Duration analysis is a statistical technique that assumes a baseline hazard function, representing the dissemination of information and learning over time, and calculates the influence an independent variable beyond this baseline. Because this technique was pioneered in the study of epidemiology, the terms (such as baseline hazard function, failure, etc.) refer to a patient contracting a disease. In this analysis, the baseline hazard function refers to baseline information distribution, which flows among firms in the same way that a cold disseminates among people; and failure means the firms adopts a specific technology, analogous to a person contracting a cold.

The duration model structures used in this analysis are a combination of conventional proportional hazard frameworks and accelerated hazard frameworks. In both frameworks, a specific hazard function is defined for assessing the probability of observing an event at time t, in this case adoption of a landfill gas project. Dependent variables in the model alter the baseline hazard in a proportional or accelerated manner for all t for all landfills 'at risk' of adopting a landfill gas project. In order to assess the most appropriate baseline hazard, I considered and tested a variety of baseline hazards.

Kaplan-Meier Estimation

The theory of technology diffusion assumes that the probability of failure (i.e., adoption of a technology) increases over time. Evidence that adoption of landfill gas projects over time conform to this theory is seen in the Kaplan-Meier Survivor Function for the dataset (see figure 1 below) also shows a curved survival estimate, graphically demonstrated increased hazard over time.

Figure 1: Kaplan-Meier Estimation for Adoption of Landfill Gas Technologies



In order to test the theoretical shape of the underlying distribution, I calculated five distributions using the full model including Cox, Weibull, Exponential, Log-Logistic, and Poisson.

Hazard Function

There are several underlying functions which can be used to specify the distribution of the hazard function. The exponential form and the Weibull distribution are common in the limited literature on duration analysis in technology diffusion. The exponential form means the hazard function is a constant. This means that the conditional probability of a change (adoption) does not depend on the duration.[138] With the Weibull distribution, the hazard varies with the duration and the direction of the dependence. This distribution would be used if future duration spells are expected to change at a given point forward and are dependent on the duration of the spell. For example, it may be useful to use the Weibull distribution if it is expected that a landfill that has not adopted a landfill gas project over the last ten years is less likely to do so because they have lost the ability to capture ten years worth of gas. For descriptions of hazards functions, see chapter 3.

Estimation Results

The following table lists the estimated coefficients from the specified model for adoption of landfill gas projects. I estimated the model using five different underlying hazard models in order to assess the most appropriate distribution for the underlying learning curve.

Table 4: Model Results for Five Baseline Hazard Functions as Applied to the Adoption of Landfill Gas Projects

	Cox	Exponential	Weibull	Log-Logistic	Poisson
REPI	43040.3(0.991)	1.262(0.365)	0.776(0.343)	0.104(0.466)	0.735(0.000)
NSPS	2.573(0.000)	1.633(0.000)	1.537(0.000)	-0.235(0.000)	1.464(0.000)
LMOP	1.952(0.001)	2.067(0.000)	1.849(0.001)	-0.164(0.141)	1.593(0.000)
RPS	1.735(0.001)	1.787(0.000)	1.514(0.008)	-0.253(0.014)	1.255(0.000)
Net Metering	0.493(0.000)	0.446(0.000)	0.482(0.000)	0.284(0.003)	0.502(0.000)
Interconnection Standard	1.256(0.226)	1.289(0.113)	1.073(0.669)	0.025(0.818)	1.042(0.402)
Financial Instruments	1.041(0.062)	1.036(0.075)	1.035(0.092)	-0.014(0.229)	1.032(0.000)
Ozone non-attainment	0.985(0.766)	1.015(0.762)	0.977(0.627)	0.017(0.556)	1.015(0.319)
CO non-attainment	0.910(0.126)	0.937(0.243)	0.904(0.070)	0.064(0.127)	0.928(0.000)
NO_2 non-attainment	0.689(0.015)	0.684(0.013)	0.684(0.013)	0.193(0.013)	0.980(0.399)
Electric Prices	1.109(0.021)	1.143(0.001)	1.202(0.000)	-0.141(0.000)	1.115(0.000)
Oil Prices	5.599(0.000)	0.992(0.316)	1.012(0.243)	-0.015(0.002)	0.998(0.616)
CA Dummy	1.669(0.004)	1.558(0.014)	1.617(0.011)	-0.305(0.004)	2.214(0.000)
Methane Potential	1.348(0.000)	1.386(0.000)	1.424(0.000)	-0.155(0.000)	1.162(0.000)
Private Ownership	1.148(0.159)	1.201(0.051)	1.221(0.039)	-0.010(0.041)	1.127(0.000)
Wald Test	245.5(0.000)	497.1(0.000)	293.1(0.000)	171.2(0.000)	
Goodness-of-fit					10524.2(1.000)
Shape Parameter			1.959[1.634; 2.347]	0.346[0.306; 0.391]	
Constant				4.953(0.000)	
Frailty test	1.000	1.000	0.280	1.000	n.a.
Log Likelihood	-2902.4366	-630.2776	-616.74104	-629.41868	-9944.12

Coefficients are reported as hazard ratios, not the original hazard function coefficients, except for log logistic and Poisson. Hazard ratios greater than one corresponds to an increased probability of adoption relative to the hazard baseline. Hazard ratios less than one correspond to a decreased probability of adoption relative to the baseline. A hazard ratio of one means there is not corresponding effect. The log-logistic estimates are reported as coefficients, and Poisson estimates are reported as incidence rate ratios. The significance level is reported in the parentheses. The 95 percent confidence ratio is reported between brackets for the shape parameters p and gamma. To estimate the frailty test for the Cox model, the data was grouped by state.

Diagnostics

Frailty

One assumption I made when estimating an accelerated hazard model is that the underlying hazard distribution and explanatory variables account fully for differences among firms, i.e., there is no unobserved heterogeneity present. If unobserved heterogeneity is present, estimates could be estimated incorrectly. If relevant variables are missing from the equation, included variables coefficients are biased towards zero.

In order to test for unobserved heterogeneity, I ran the model using a frailty model. A frailty model incorporates an unmeasured "random" effect in the hazard function to account for the heterogeneity.[139] The "random" effect follows a gamma distribution with a mean equal to one and a variance parameter of theta.

The literature suggests, though no conclusive theorem currently exists, that data are more sensitive to the underlying hazard distribution than to that of the choice in underlying distribution of the added variable.[140] I ran the models, therefore, using a gamma distribution in order to estimate the effect. The tests were similar across the Weibull and Exponential distributions. When the full models were tested for frailty, the test suggested there was a marginally significant problem of unobserved heterogeneity in the Weibull model. The exponential, log logistic and Cox model test indicated frailty, though this may correspond to the data not fitting the hazard functions used in these models.

Heteroscadasticity

In order to test for heteroscadasticity in the models, I ran the models estimating both robust and general estimates and compared. In addition, I graphed the residuals of each model over time. Neither test showed heteroscadasticity issues. The robust estimates varied little from the general estimated model.

Test for proportional hazard

A test for proportional hazards assumption shows that the proportional hazard in the Cox model is not constant over time. Using the Scheonfeld residuals, I ran a test on individual variables as well as a global test to see if whether or not the variables interact with time. The results of the test suggested that the data are multiplicative over time and is evidence that the Cox and exponential models are not appropriate for the trends seen in the dataset.

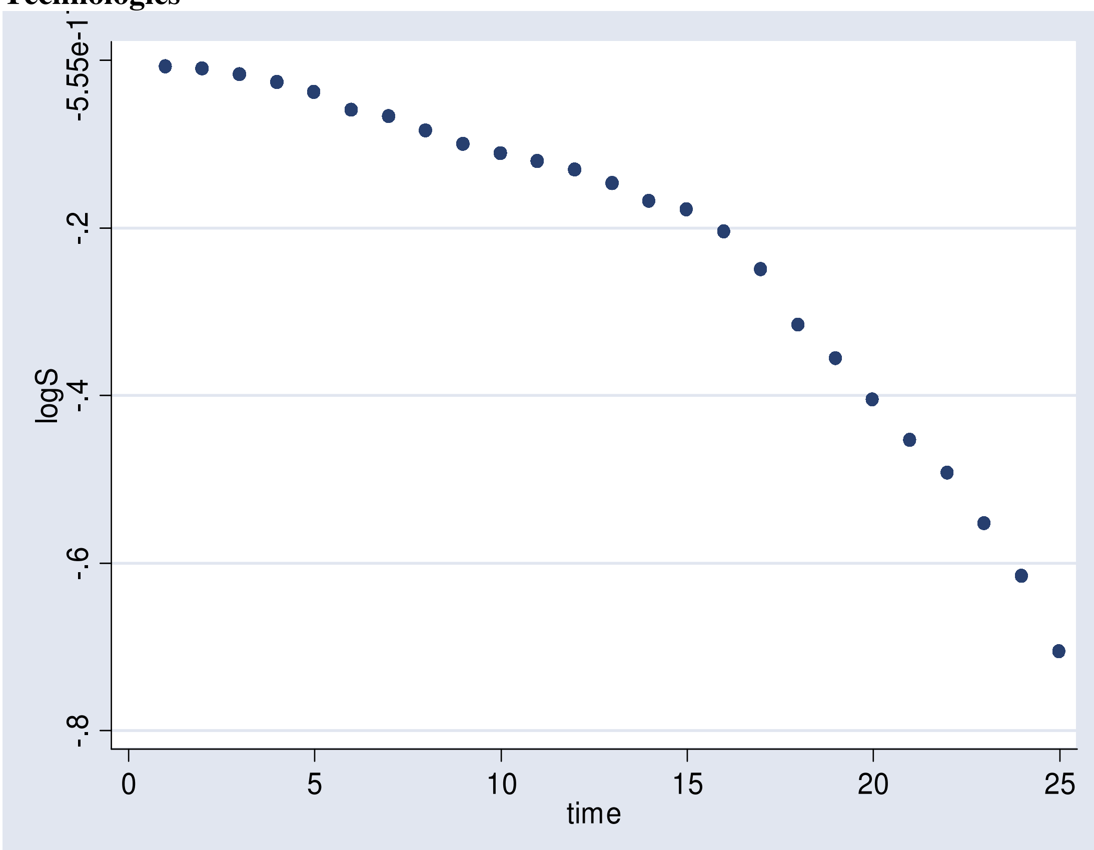
Shape parameter test

I tested the shape parameter of the Weibull model against the exponential shape pattern. Mathematically, the Weibull distribution is equivalent to the exponential distribution if the shape parameter is equal to 1. The shape parameter for the Weibull was significantly greater than one, indicating a Weibull distribution with an increasing hazard ratio over time was the best fit for the underlying data. A shape parameter between 0 and 1 for the log-logistic model suggests that Weibull is a better fit for the data.

Log Observed Outcomes vs. Time

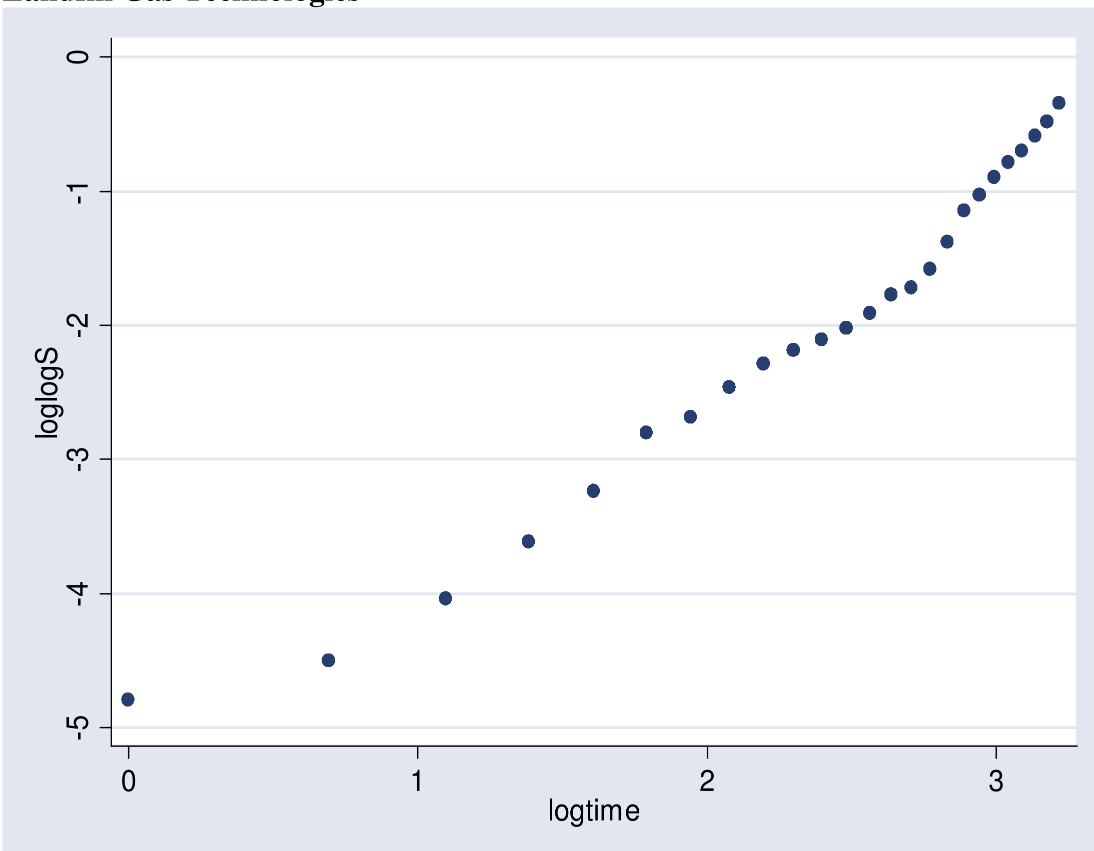
Graphical evidence for use of the Weibull model can be seen when graphing the log of the survival function against time. The Weibull distribution implies that ln(-ln(S(t)))), where S(t) is the survival function or underlying baseline hazard, is a linear function of time.

Figure 2: Log of survival time over time of Adoptions of Landfill Gas Technologies



Graphing the ln(-ln(S(t))) against ln(t) shows that the data does fit the Weibull distribution. A Weibull distribution appears curvilinear in a plot of ln(S(t)) versus t, but it is linear in a plot of ln(-ln(S(t))) versus ln(t). An exponential distribution, on the other hand, would be linear in both plots and have a slope equal to 1 in the ln(t) plot.[141]

Figure 3: Natural log of logged survival time over the log of time for Adoption of Landfill Gas Technologies



Goodness-of-fit for the Poisson Distribution

The goodness-of-fit tests, both the pseudo R^2 and the Chi-squared test that the independent variables explain the outcome, show that the model is not a good fit for the data. I rejected the Poisson distribution as a possible underlying distribution for the data. This, along with the evidence from the other tests, seems to suggest that an accelerated time model is a more appropriate fit.

I rejected the possibility that the data does not "age" with time and the possibility that the data do not have an underlying parametric hazard baseline. The exponential form is rejected because the Weibull results show that the shape parameter is not constant, but increasing. The log logistic form is rejected because of the issues with frailty of the model and the fact that when the shape parameter for the log logistic equation is between 0 and 1, as is with this case, the shape of the log logistic distribution is very similar to that of the Weibull distribution. The results of the diagnostic tests suggest that the Weibull distribution is the most appropriate underlying distribution for the data.

Sensitivity of Results across Models

A test of the sensitivity of the results is to look at the coefficients across all models. Most variables are consistently significant (or insignificant) across models. The variables NSPS, RPS, net metering, CA dummy variable, methane potential, and electricity prices are all significant across all model types. Interconnection Standards and ozone non-attainment areas are insignificant across all models. LMOP, nitrogen dioxide (NO_2) non-attainment areas, financial instruments, and private ownership are significant across four of the five models. REPI is insignificant in four of the models, and CO non-attainment areas and oil prices are insignificant in three of the models.

The overall results from the models indicate that the Weibull model is the best fit for the data. Using this model, I can state the following results about what influences adoption of landfill gas projects.

After the establishment of the LMOP program, the data suggests that landfills were 85 percent more likely to adopt a project. This is also reflected in interviews with the developers who praised LMOP for their work on information dissemination to state and local officials, smoothing the way for air permits and for general acceptance of projects at the State and local levels.

The effect of the REPI incentive was not significantly different from the baseline hazard. This is due to the uncertainty surrounding the Congressional appropriations. Even though the legislation was in place after 1993, the credit was not always fully funded each year.[142] An electricity project might take advantage of additional revenue from the credit, but the project had to be cost-effective without the credit in order to survive.[143]

After the implementation of NSPS, the data shows that landfills who fall under the NSPS rule were 54 percent more likely to adopt. This fits with the theory that landfills are faced with a costly regulation to destroy the gas and are searching for a way to recover the cost of these projects by selling the gas or using it to create electricity.

The presence of an RPS standard is significant in the Weibull model. In states with RPS that includes LFG as a renewable, landfills are 51 percent more likely to adopt a landfill gas project. This result fits with the fact that states find landfill gas projects cheaper relative to traditional renewable projects. It also reflects to some extent the states attitudes towards promoting renewable energy in general.

Results for the presence of a net metering law suggests that competition with other producers, namely individual customers, reduces the likelihood of adoption by almost half. I found in interviews with experts that companies occasionally have more difficulty negotiating electricity contracts with utilities that cover landfill gas project costs in states with net metering laws due to the fact the utility is already paying a specific rate for other individual consumers. Also, utilities are only required by many states to purchase a fixed amount of electricity from outside of the utility. Net metering laws may bias some utilities to buy the required amount from individual producers.

Interconnection standards were not significant in the Weibull model. Under the Federal law, PURPA requires that all utilities make standard power purchase contracts available to qualifying facilities less than 100kW. State interconnection standards provide a standardized agreement to connect with the utility. Standard interconnection agreements tend to be based on technology instead of fuel type, so a limited number of landfill gas projects would qualify for the standard agreement. Interconnection standards may have more of an effect on technology choice as presented in the next chapter.

Adoptions of projects at landfills which reside in counties in an ozone non-attainment area are no more likely than those in attainment areas. Landfills residing in a CO non-attainment are 10 percent less likely to adopt. This is due to states misperceptions about the technologies as cited by experts interviewed. In reality, capturing landfill gas reduces ground level ozone and CO as it combusts NMVOCs. Counties which are in NO_2 non-attainment are also 32 percent less likely to adopt. Burning methane as a fuel is a source of NOx, and installing a generator in a non-attainment area requires the developer to endure a difficult permitting process.

I found that state financial instruments had a slight, but significant affect on adoption. The experts I interviewed said that very few projects took advantage of State financial instruments. A few cited the fact that the state financial instruments took a great deal of time to learn about and to process the paperwork through the state system. As with State air permits, once a firm had learned how the process works, it was normally not applicable in the future as firms tend to work in different states. While these instruments may help a single landfill gas project, they are may not be instrumental in diffusion of landfill gas projects.

The dummy variable for landfills in California had a large effect on the outcome in the model. The models suggest that a landfill in California is 62 percent more likely to adopt than one outside of the State. Interviewers all mentioned California as being a completely different place to work than the rest of the country. The 34 air districts made it more complicated to get the necessary permits to build a project, but the State and the attitudes of the population helped pushed projects forward.

Private ownership of a landfill also had an effect on adoption. The models suggest that privately owned landfills are 22 percent more likely to adopt. This is expected since privately owned landfills tend to have more than one landfill, unlike publicly owned organizations; and they tend to reduce their information costs for each project adopted over time. Once a private company demonstrates the usefulness of a project or technology, it is easier for it to gain the internal financial support needed to replicate the project at another site.

The size and potential for producing methane is also significant in the model. An increase in size from one landfill size category to the next means the landfill is approximately 42 percent more likely to adopt a project. This reflects the need for a steady, long-term stream of gas to fuel a project.

For a one cent per kilowatt hour increase in the lagged state electricity price, a landfill was 20 percent more likely to adopt a landfill gas project. Oil prices are not significant in the model, though they may have more influence in choice of technology, as reviewed in the next chapter.

Chapter 5: Technology Choice

In this section, the analysis focuses on the effect of State policies on technology choice for landfill gas projects. My review of the literature found a few studies which relate Federal and State regulation, particularly environmental regulation on investment decisions.[144] [145] [146] This analysis considers State level air pollution permitting and renewable energy policies influence when considering which technology is chosen by a landfill interested in utilizing landfill gas.

Since Mansfield in 1961, numerous empirical studies have reviewed and analyzed industry-specific determinants of diffusion.[147] Building on this body of research, others have analyzed a firm's optimal adoption decision between two substitute technologies that are simultaneously available to the firm. [148] [149] A small number of studies have focused on technology choice and environmental regulations or other policy variables using Logit analysis.[150]

This section addresses determinants of diffusion of specific technologies, including policy variables, firm characteristics, prices, and learning-by-using as a foundation for understanding future adoption choices. In addition, this analysis lays a foundation for better understanding spillover effects of technologies into the landfill sector, specifically new or niche technologies, and their rates of diffusion.

My analysis seeks to investigate the determinants of successful adoption of specific capture-and-use technologies in the landfill gas sector by analyzing the landfill characteristics, policy influences, and price determinants behind adoption. In addition to the determinants reviewed in the previous chapter, this chapter also includes technology specific determinants such as the cost of the technology and NOx emission levels of each technology. Again, the dependent variables of the model reflect lags in the adoption decision, in this case 2 years. Using duration analysis, I determined the appropriate hazard function; and the results were analyzed by comparing the outcomes of the duration analysis to that of the interviews and literature review.

The use of duration analysis allows for the distinction between duration dependence from calendar time dependence in the estimation of adoption probability. Typically, duration dependence is interpreted as endogenous learn-by-using and flows of knowledge throughout the population. This occurs in an epidemic pattern and is illustrated by the hazard function. Calendar dependence is associated with the independent variables that change over the time period of the analysis.

Model Specification

The differences in technologies have important environmental and energy provision consequences. Technologies vary in terms of electrical efficiency (amount of electricity produced per unit of fuel) and emissions of CO and NOx. The stringency of air pollution regulations could influence the choice of technology a firm chooses.

The technologies also vary in terms of energy provision; roughly half of the technologies used at landfills generate electricity either for the landfill or for provision to the grid, while the other half are a substitute for natural gas either in vehicles, industrial boilers, or other commercial applications. Shortages or volatile prices of electricity vs. natural gas may play a key role in decision making.

Substantial differences in the types and numbers of technologies can be seen across states, indicating some State policy regimes may encourage certain types of technologies while other regimes do not. The table below shows the variation in technologies across states.

Table 5: Technology Variation by State
(Summary table projects ever done by state as of 2006)

State	Types of Technologies (as listed in LMOP database)	Number of Technologies	Total Number of Projects
AL	Direct use; direct thermal; boiler; unknown	3	14
AR	High Btu; reciprocating engine; direct thermal	3	4
AZ	Steam engine; Stirling Engine; microturbine; reciprocating engine	4	5
CA	Alternative vehicle fuel; boilers; cogeneration; combined cycle; direct thermal; gas turbine; Leachate treatment; liquefied natural gas; microturbine; reciprocating engine; steam engine	11	112
CO	Reciprocating engine; direct thermal	2	4
CT	Reciprocating engine; fuel cell; gas turbine	3	4
DE	Reciprocating engine; steam engine; condensate evaporation	3	4
FL	Leachate treatment; combined cycle; reciprocating engine; microturbine; boiler; direct thermal; steam engine	7	27
GA	Direct thermal; reciprocating engine	2	11
HI	Cogeneration	1	1
IA	Direct thermal; reciprocating engine; steam engine	3	5
ID	Leachate treatment; reciprocating engine	2	2
IL	Cogeneration; combined cycle; direct thermal; gas turbine; organic Rankine cycle; reciprocating engine; unknown direct	7	42
IN	Reciprocating engine; direct thermal; Leachate treatment; microturbine; boiler; greenhouse; gas turbine	7	25
KS	Direct thermal; high Btu; boiler	3	4
KY	Reciprocating engine; boiler	2	6
LA	Boiler; high Btu	2	4
MA	Fuel cell; gas turbine; direct thermal; steam engine; reciprocating engine; medium Btu	6	25
MD	Reciprocating engine; boiler; Leachate; unknown direct use	4	9
MI	Boiler; cogeneration; combined cycle; gas turbine; greenhouse; high Btu; Leachate treatment; reciprocating engine; Stirling engine	9	42
MN	Reciprocating engine; combined cycle; Stirling engine	3	8
MO	Direct thermal; boiler; Leachate treatment;	7	9

	reciprocating engine; greenhouse; cogeneration; high Btu		
MS	Boiler	1	1
MT	Leachate treatment	1	1
NC	Reciprocating engine; boiler; direct thermal; gas turbine	4	23
ND	Boiler	1	1
NE	Reciprocating engine	1	2
NH	Reciprocating engine; Leachate treatment; gas turbine	3	6
NJ	Boiler; cogeneration; combined cycle; gas turbine; greenhouse; LNG; medium Btu; reciprocating engine; steam engine	9	28
NM	Microturbine	2	1
NY	Alternative vehicle fuel; cogeneration; direct thermal; gas turbine; high Btu; Leachate treatment; reciprocating engine	7	41
OH	High Btu; reciprocating engine; combined cycle; microturbine; Leachate treatment; medium Btu; boiler; direct thermal	8	24
OK	Direct thermal; alternate vehicle fuel; boiler	3	6
OR	Reciprocating engine; direct thermal; Leachate evaporation	3	6
PA	Boiler; cogeneration; direct thermal; gas turbine; high Btu; Leachate treatment; reciprocating engine; steam engine;	8	42
RI	Reciprocating engine	1	4
SC	Reciprocating engine; cogeneration; direct thermal; gas turbine	4	8
TN	Reciprocating engine; boiler; Leachate treatment; high Btu	4	10
TX	Reciprocating engine; direct thermal; organic Rankine cycle; cogeneration; Leachate treatment; boiler; high Btu; steam engine; gas turbine	9	27
UT	Reciprocating engine; direct thermal	2	4
VA	Boiler; direct thermal; Leachate treatment; reciprocating engine	4	27
VT	Reciprocating engine	1	5
WA	Reciprocating engine; Leachate treatment; gas turbine; boiler	4	9
WI	Boiler; cogeneration; direct thermal; gas turbine; microturbine; reciprocating engine	6	36

Technology Characteristics

Landfill gas provides a low cost, renewable, local alternative fuel source for industry, hospitals, schools, and other institutions. In addition, local utilities can participate in landfill gas projects, take advantage of a renewable energy source, potentially improving customer relations and broadening their resource bases. [151]

Generally, experts agreed that they preferred the simplest technology possible. This is substantiated by the sheer number of reciprocating engines and direct gas projects. They seemed to feel that the more complicated the technology, the less kilowatt hours (kWh) will be generated, even though the newer technologies tend to have less air pollution emissions. What specific technology a developer will use also depends on what the landfill owner wants locally: whether or not there is a local buyer near by for direct use, or if the landfill itself would like to use some of the electricity the gas generates.[152]

Different types of technologies were available at different periods during the analysis. As can be seen in the table below, boilers, reciprocating engines, gas engines, and direct use of the gas as high-Btu grade gas was available throughout the analysis period. Newer technologies, such as fuel cells, were not considered viable options until after 2000.

Table 6: Number of Technologies Used over Time

Type of Technology	1985	1995	2005
Biodiesel/vehicle fuel	0	1	2
Boiler	1	6	45
Cogeneration	0	2	12
Combined Cycle	0	2	6
Leachate Evaporation	0	0	21
Direct Thermal	0	7	37
Fuel Cell	0	0	2
Gas Turbine	2	16	26
Greenhouse	0	1	4
High Btu/ Liquefied Natural Gas	1	4	14
Medium Btu	0	0	1
Microturbines	0	0	16
Reciprocating Engine	15	76	254
Steam engine/ Organic Rankine cycle	0	7	20
Sterling engine	0	0	1

Note: this table lists only open projects in the given year.

In the above table, the same landfill can have more than one technology running, based on how much each cell (or division of the landfill) produces. As each cell is closed to additional waste, the gas for the well can be added to a current project or directed to a new project depending on the amount of gas produced by the cell and the size of the landfill gas project. Larger landfills may have several projects that cover internal needs such as leachate treatment, as well as selling gas or electricity externally.

The most common methane mitigation projects at landfills are electricity generation using a reciprocating internal combustion engine, directly piping landfill gas to an industrial boiler, or for use as direct thermal heat. However, over the years, the diversity of projects has increased.

The technologies in this analysis have been grouped into several categories; electricity generation technologies, direct use technologies, and niche technology (less than 6 applications by 2005) are the major categories. In addition, electricity generation was broken into reciprocating engines (which compose the majority of electricity generation projects) and other engines and turbines (Stirling engines, microturbines) which do not fit into the niche technologies category (like fuel cells). Categories could not be broken down further because of the difficulty of estimating the equations.

The following technologies are considered in the analysis:

- *Reciprocating engines* are commercially available and achieve high electrical and total efficiencies. However, they have higher emissions than other engines, depending on catalyst/engine technology and maintenance. They are a mature technology and are economically viable.

- *Stirling engines* are lower in emissions and have high fuel flexibility (can easily use bio-fuels). They also have the potential to achieve high total efficiency and moderate electrical efficiency. They are low cost, but have only been introduced into the commercial market in the last five years.

- *Fuel cells* are still in the research and development phase with demonstration projects currently under study. Potentially, fuel cells offer the highest electrical efficiency and almost zero emissions, but questions remain about overall efficiency and costs once the technology is commercialized.

- *Gas Turbines* are slightly more expensive than reciprocating engines and are also commercially available. However, electrical efficiency is lower than the reciprocating engines. NOx emissions tend to be lower with the gas turbine than with the reciprocating engine even without emission control technologies.

- *Microturbines* are low emissions, but relatively higher cost when compared with reciprocating engines and gas turbines. Only a small number of units are in commercial operation so reliability has not been fully assessed. The potential is high because of the basic design and low number of moving parts,. Their electrical efficiency is comparable to that of a gas turbine.

- The electrical efficiency of *Steam turbines* depends on the size of the plant, varying from a high compared to a reciprocating engine for a large plant to a low well below other turbines for a small plant. Small sized team turbines (less than 2MW) have a relatively small market and are not economically attractive in most cases. Emissions are low relative to reciprocating engines.

- *Combined Cycle Systems* have the potential to produce steam and electricity at higher efficiency rates and lower capital costs than traditional systems. CC also has lower particulate and NOx emissions than traditional systems.

- All of the above technologies can be combined into *Cogeneration* options were the total efficiency is based on electrical efficiency plus the efficiency of the condensing boiler.

- *Direct use projects* include using the gas to heat greenhouses, using the gas as medium Btu fuel, cleaning the gas and using it as vehicle fuel, liquid natural gas or high Btu natural gas, using the gas in an industrial boiler or in a direct thermal heating system. Emissions are similar across applications; however, they are dependent to some extent on the composition of the landfill gas and the cleaning process. The cost of these applications largely depends on whether or not the fuel is processed before use and whether or not a pipeline is necessary to transport the fuel to the end user.

- Some landfills use the landfill gas to power *Leachate Treatment Systems* onsite. Raw leachate, which is the water that percolates through a landfill, can contain environmental hazardous materials such as heavy metals. Leachate is created through a series of biological, physical, and chemical processes and must be treated to reverse these processes before the water can be put back into the environment. This can be costly to a landfill. In order to reduce these costs, some landfills use the landfill gas to combust the evaporated leachate using a flare.

Electricity Generation

EPA estimates that approximately 847 million metric tons of methane could be reduced cost-effectively (i.e., the revenue from selling energy covers the cost of installing the project from electricity generation and direct use projects.). This reduction would mean a 20% decrease in emissions from US landfills.[153]

Reciprocating internal combustion engines are cheap and appropriate for smaller sized landfills. These engines generally produce between 1 and 3 megawatts (MW) of electricity per project with costs ranging from 2 to 5 million dollars per project, respectively.[154] Electricity projects are the most likely to be effected by renewable energy policies, particularly RPS, net metering, and disclosure policies.

Gas fueled turbines are the leading technology for new electric power generation in the US. They have far lower greenhouse gas (GHG) and air pollution emissions per kWh than coal fired technologies. Gas turbines are based originally on jet engines developed for the military. Since the 1940s, military research and development has led to large improvements in design and significantly improved performance of the engines. In the 1970s, the technology became cost-effective for use in the commercial power generation sector. In the 1980s, reductions in production costs and low natural gas prices increased the diffusion of gas turbines from the electric utility sector in to the industrial sector. At this time, industry and utilities began using cogeneration, utilizing the turbine exhaust as space heat. In the late 1990s, microturbines were produced for off-grid and stand-by power generation.[155]

Despite these advances, the reciprocating engine is by far the most popular choice for electricity generation projects. In 2003, there were approximately 175 operational reciprocating engines installed and another 100 under construction or planned. At the same time, only about 40 other types of projects existed, including microturbines, cogeneration, steam turbines, and gas turbines.[156]

Waste Management, Inc., has been one of the leaders in electricity generation projects. Their first project started in the mid-1980s, and they own and operate 30 landfill gas electricity plants in the U.S. which generated approximately 1.2 billion kWh of electricity in 2000.[157]

Direct Use Projects

Landfill gas can be directly used in boilers, as direct thermal heat, as medium or high Btu, or as liquefied natural gas. In these cases, the landfill gas is piped directly to the nearby customer. Customers beyond a five-mile radius are less attractive because the cost of a long pipeline is prohibitive. Onsite, the gas can be used in a leachate evaporation system or as vehicle fuel for landfill trucks or fleet vehicles. As natural gas prices have increased, landfill gas has become an attractive alternative. This option, however, is more cost effective at larger landfills. On average, a landfill with 100,000 metric tons of waste-in-place can collect gas for direct use for approximately $55/Btu collected. At a landfill with 11 million metric tons of waste-in-place, the cost drops to $1.35/Btu collected.[158]

One example of a direct use project is with Lucent Technologies. In Columbus, Ohio, the Beford landfill is supplying Lucent Technologies with landfill gas directly to a boiler system to generate steam for space heating and hot water. The 20-year fuel contract began in 1992; and the gas is sold through SBM Energy, a landfill gas developer. The cost of the landfill gas is approximately 10 to 20 percent less than the market price of natural gas. Lucent Technologies estimates that the projects save the company $100,000 per year on fuel costs. The landfill gas project is estimated to reduce 162,000 tons of carbon equivalent in greenhouse gases per year, equal to taking 23,000 cars off the road.[159]

Niche Technologies

The Niche Technologies category includes a variety of technologies which have been tried at less than 6 sites. These include applications that are more specific to landfill gas, such as purifying the gas to create liquid natural gas, as well as new technologies like fuel cells which are general to small, natural gas applications and still in the demonstration phase.

In the last decade, considerable efforts have been made to further develop technologies such as fuel cells and microturbines for independent power production. State level financing and some net metering and interconnection standards target fuel cells and microturbines in order to encourage these technologies specifically.

Fuel cells are one of the most promising examples of new technologies. They are still in the demonstration phase, but to date have shown promising results. For example, in a joint effort, the USEPA and ONSI Corporation developed a fuel cell project in Connecticut. The project used a new gas cleanup technology to allow LFG to be used as a fuel in high-efficiency, low-emission fuel cells. Prior to development of the gas cleanup technology designed and used in this project, use of landfill gas to power fuel cells was not possible due to contaminants in the gas such as sulfur and halides. USEPA and ONSI Corporation demonstrated the gas cleaning technology and fuel cell project at the Flanders Road Landfill. The demonstration project was encouraging. The fuel cell currently provides 140 kilowatts of electricity to the Connecticut Light and Power Company.[160]

NOx Emissions from Technologies Using Landfill Gas

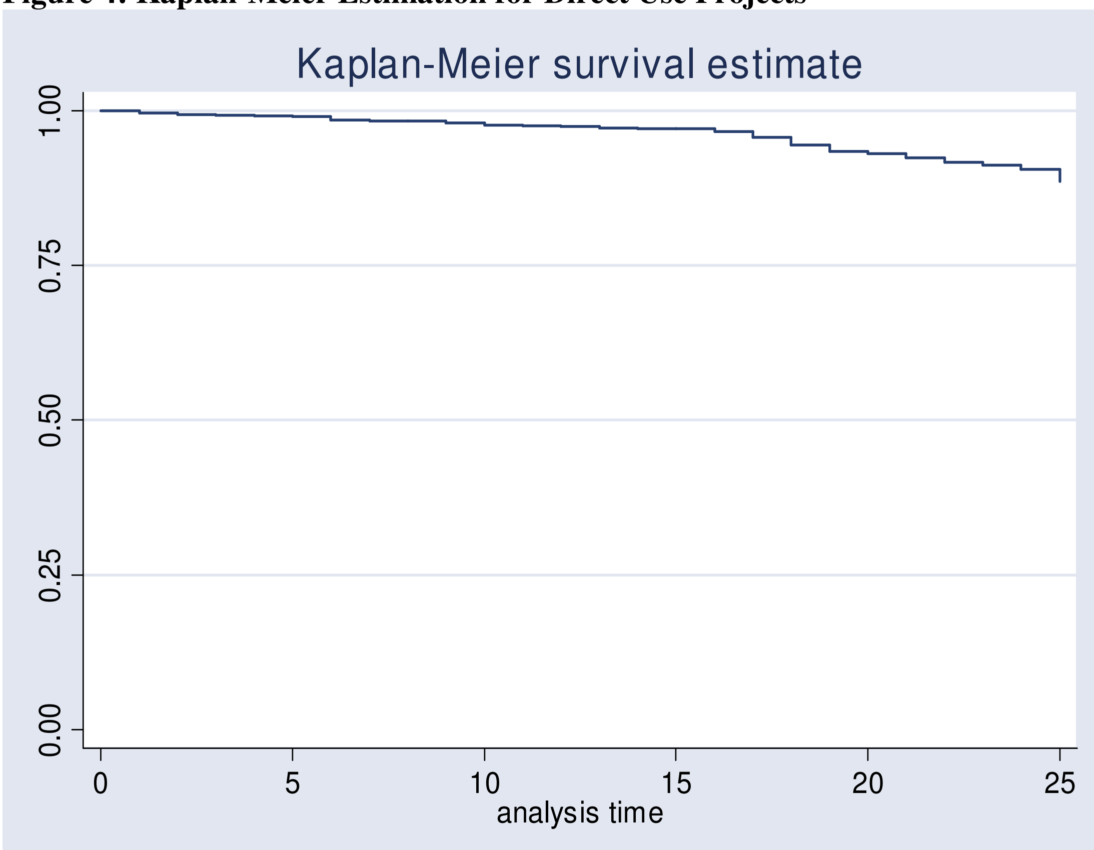
The independent variables are the same as in Chapter 4 with one addition; a NOx emissions variable by technology. The new variable is considered in the literature and by experts as a critical aspect to the decision making process. Average NOx emissions were taken from the technology descriptions in various published documents in terms of lbs/MWh and used as an explanatory variable (See Chapter 4 for variable specification details). In the direct use model and the reciprocating engine model, NOx emissions variable were not considered. This is because both variables have the same value over time for all observations, causing problems with estimation and providing no added value to the understanding of the decision process.

As in Chapter 4, cost of each technology was considered and rejected as an explanatory variable. It is important to remember that all landfills in this sample are roughly cost-effective based on pre-feasibility studies. Experts' state that the revenue generated from the project relative to that cost was more important than the overall cost of the project. If revenues, in this case based on oil and electricity prices, are high enough, the project is cost-effective. Therefore, for this data set, specific estimates of relative costs between projects are not as important in choosing *which* technology to implement as the revenue stream. For example, high oil prices in the area may mean it is more profitable to build a long pipeline than it is to install electric generation capacity.[161]

Kaplan-Meier Estimation

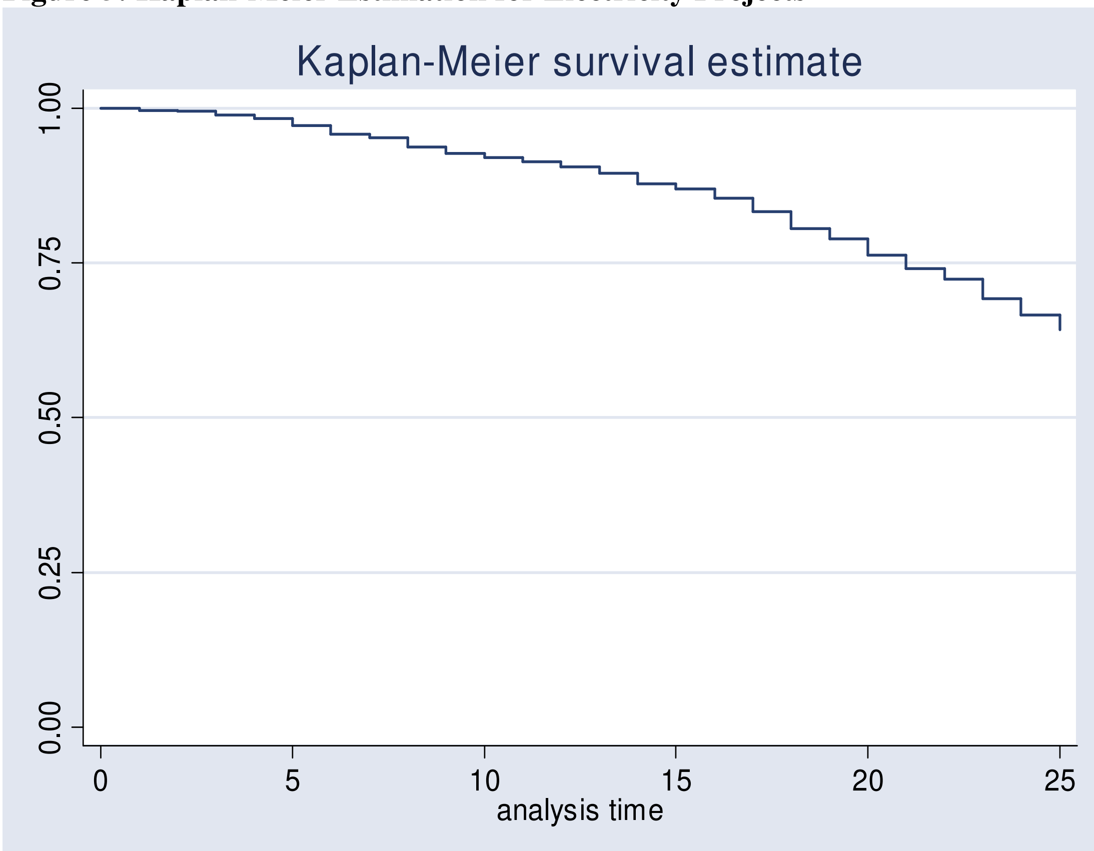
I plotted the proportion of landfills which have not adopted a specific technology. Figures 4 and 5 compare the survivor function of direct use and electricity generation at an aggregate level. They show higher survivor rates (no-adoption) for niche technologies. In other words, fewer niche projects have been installed.

Figure 4: Kaplan-Meier Estimation for Direct Use Projects



Notice that while the number of direct use projects is increasing, as shown by the slightly downward line of the KM curve, the slope of the curve is fairly flat indicating that direct use adoption is not increasing at the same rate as overall adoptions. This can also be seen in the KM estimation for the electricity projects. Compared to the downward slope of direct use projects, adoptions of electricity projects are increasing at a faster rate.

Figure 5: Kaplan-Meier Estimation for Electricity Projects



Estimation Results

I estimate each technology group separately and then compare them to the overall adoption estimates in Chapter 4. In table 7, all results are reported in terms of hazard ratios with the significance of each in parentheses.

Table 7: Duration Analysis Results for Technology Choice Models

Full Models	**Electric Projects**	**Direct Projects**	**Reciprocating Engines**	**Other Engines and Turbines**	**Niche Technologies**
REPI	0.648(0.009)	3.116(0.047)	0.631(0.142)	0.665(0.419)	0.515(0.825)
NSPS	0.934(0.331)	1.236 (0.368)	1.287(0.101)	0.807(0.397)	0.261(0.203)
LMOP	1.250(0.105)	0.633(0.233)	2.464(0.000)	2.143(0.066)	2.099(0.774)
RPS	1.248(0.041)	0.241(0.003)	1.667(0.027)	1.737(0.176)	2.136(0.343)
Net Metering	0.765(0.044)	1.351(0.322)	0.619(0.022)	0.521(0.116)	0.387(0.417)
Interconnection Standard	1.269(0.075)	0.714(0.302)	0.742(0.228)	2.594(0.011)	2.318(0.297)
Financial Instruments	0.985(0.455)	1.125(0.002)	0.974(0.443)	0.918(0.322)	1.018(0.908)
Ozone non-attainment	0.954(0.165)	0.716(0.006)	0.984(0.828)	0.950(0.650)	1.008(0.977)
CO non-attainment	0.919(0.089)	1.049(0.821)	0.877(0.087)	0.782(0.074)	0.986(0.973)
NO_2 non-attainment	0.824(0.149)	1.014(0.961)	0.700(0.059)	0.017(0.000)	0.025(0.000)
Electric Prices	1.098(0.000)	1.049(0.549)	1.203(0.002)	1.275(0.018)	1.061(0.833)
Oil Prices	0.994(0.312)	1.052(0.015)	1.003(0.832)	0.948(0.022)	1.061(0.511)
Methane Potential	1.058(0.221)	1.827(0.000)	1.058(0.314)	1.250(0.046)	0.940(0.880)
Private Ownership	1.120(0.158)	0.463(0.000)	1.727(0.000)	1.648(0.109)	0.752(0.735)
CA Dummy	1.560(0.002)	0.195(0.026)	2.555(0.000)	2.012(0.117)	0.497(0.628)
NOx emissions from technologies	3.728(0.000)			0.249(0.000)	0.189(0.000)
Shape parameter	1.545 (1.310;1.822)	1.960 (1.386;2.775)	1.693 (1.270;2.258)	0.789 (0.238;2.612)	1.379 (0.164;11.575)
Wald Test	534.9(0.000)	101.9(0.000)	112.4(0.000)	2015.6(0.000)	1369.4(0.000)
Baseline Hazard	Weibull	Weibull	Weibull	Exponential	Weibull
Frailty test	0.001	1.000	0.000	0.000	0.000
Log Likelihood	368.69498	-276.07584	-551.89132	-94.108408	-28.475295

Diagnostics

All models underwent the same diagnostic tests as in Chapter 4 to confirm the use of the Weibull distribution, check for unobserved heterogeneity in the landfills, and check for issues with heteroscadasticity.

Frailty

None of the models except the direct use model showed signs of frailty. However, when I ran the direct use model with gamma frailty, the hazard ratios did not change for any of the variables and the significance level of the variables changed little. None of the variables I considered significant in the original model were insignificant in the frailty model, and none of the insignificant variables became significant in the frail model.

A significant probability that frailty exists in the direct use model suggests that a variable has been left out of the equation. According to experts interviewed, this is most likely the availability of a near-by customer for the gas. Many developers have commented that when evaluating a project, one of the first steps is to drive around a landfill and look for industrial plants. In order for direct use projects to be cost-effective, pipelines must be less than 20 miles long, but data on the availability of direct use consumer in close proximity to the landfill is not available and cannot be added to the model.

Heteroscadasticity

In order to test for heteroscadasticity in the models, I ran the models estimating both robust and general estimates and compared them. In addition, the residuals of each model were graphed over time. Neither test showed heteroscadasticity issues. The robust estimates varied little from the general estimated model.

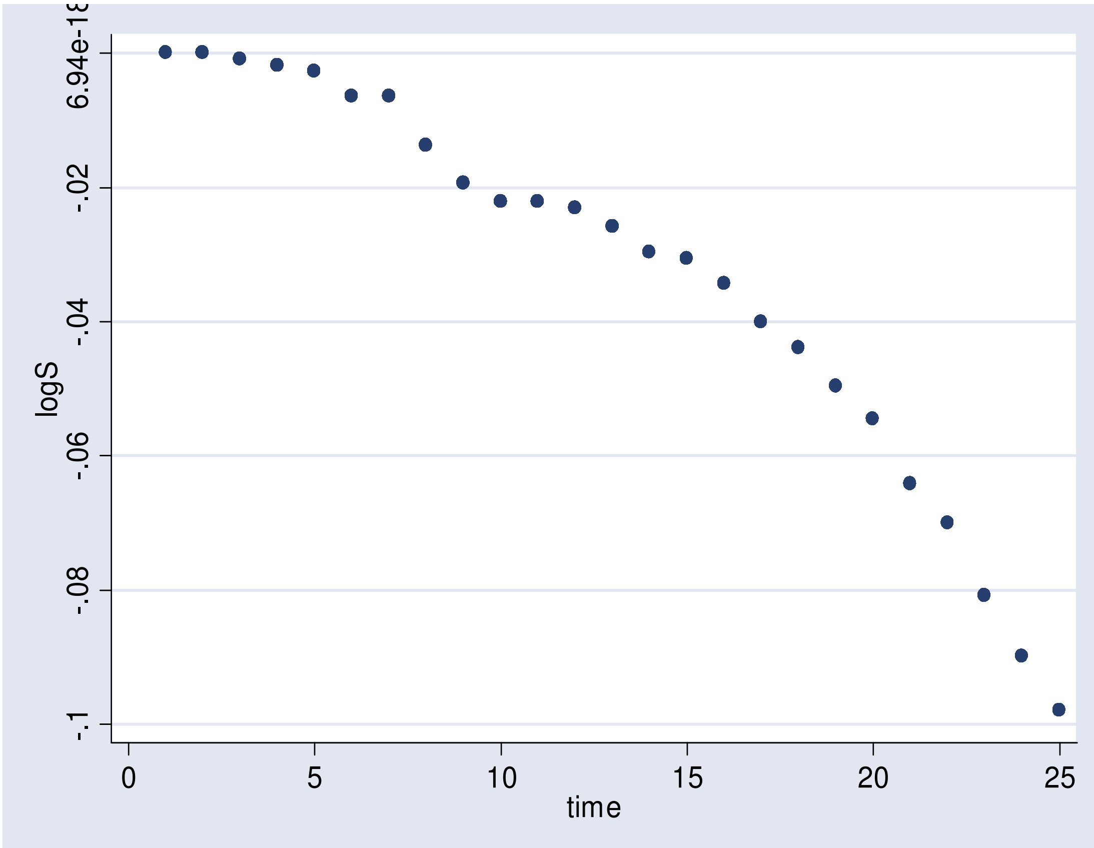
Shape parameter test

I tested the shape parameter of the Weibull models against the exponential shape pattern. Mathematically, the Weibull distribution is equivalent to the exponential distribution if the shape parameter is equal to 1. The shape parameter for the electric generation, direct use, reciprocating engines and niche technologies is significantly greater than one, indicating a Weibull distribution with an increasing hazard ratio over time is a good fit for the underlying data. For the non-reciprocating engines and turbines, the shape parameter is less than one. For this study, I re-estimated the model using the exponential hazard function. The results are reported in the table above.

Log Observed Outcomes vs. Time

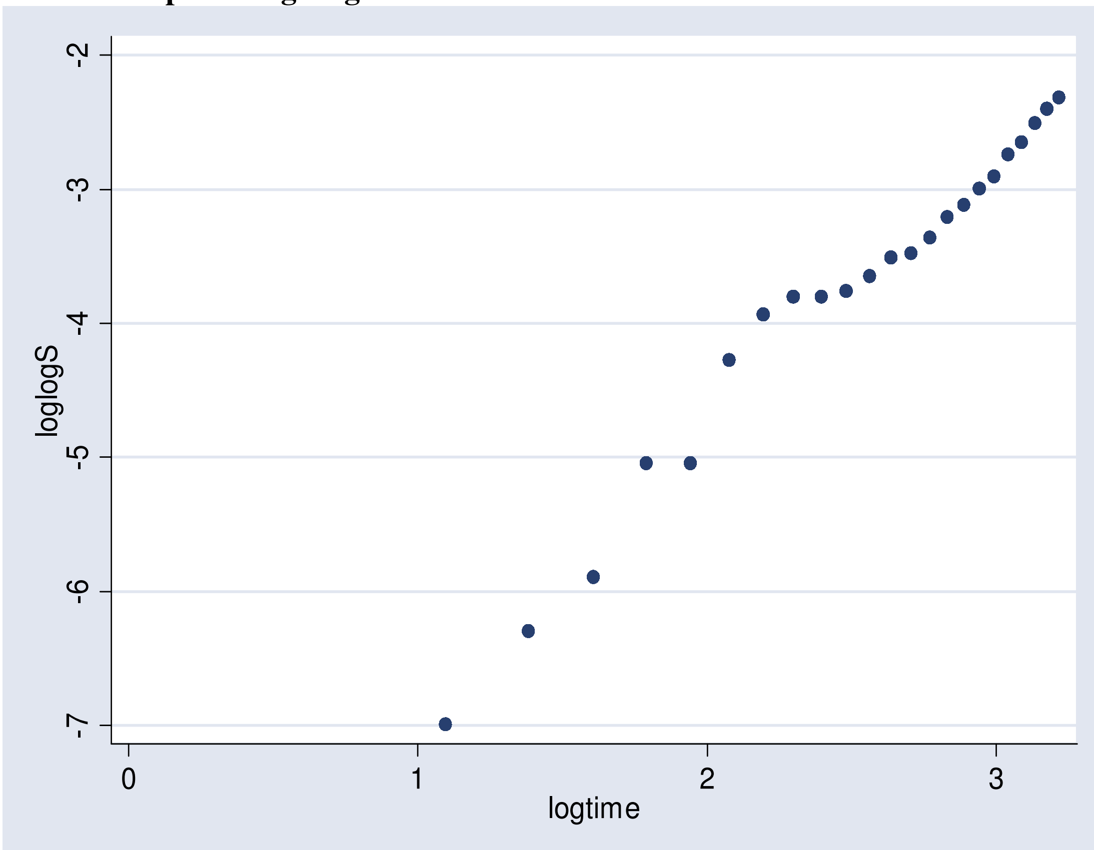
Graphical evidence for use of the Weibull model can be seen when graphing the log of the survival function against time. The Weibull distribution implies that ln(-ln(S(t)))), where S(t) is the survival function or underlying baseline hazard, is a linear function of time. In the graph below, which graphs the ln(-ln(S(t)))) for non-reciprocating engines and turbines, is consistent with the Weibull distribution graphed in Chapter 4.

Figure 6: Log survival time over time for Adoption of Non-Reciprocating Engines



Graphing the ln(-ln(S(t))) against ln(t) shows that the non-reciprocating engines and turbines data does fit the Weibull distribution as well as the adoption date shown in Chapter 4. The date plotted above is more linear than the adoption data. A Weibull distribution appears curvilinear in a plot of ln(S(t)) versus t, but is linear in a plot of ln(-ln(S(t))) versus ln(t). An exponential distribution, on the other hand, is linear in both plots and has a slope equal to 1 in the ln(t) plot.[162] This would seem to support a Weibull distribution despite the shape test outcome.

Figure 7: Natural log of logged survival time over the log of time for Adoption of Non-Reciprocating Engines



Results by Technology

Adoption of Electricity Projects

In the electricity generation model, I found that 8 of the 16 variables considered are significant. Unlike the adoption model in Chapter 4, the REPI variable is significant in the model and suggests that projects were less likely to occur with these incentives, 35 percent less likely. When I compared these results to the results of the direct use projects, a clearer picture emerges. REPI credits were variable at best. Whether or not the credit was available in a given year depended on that year's appropriation bill in Congress. Electricity projects, which are more expensive than direct use and are more likely to need the extra income to be cost-effective, could not rely on the credits to provide them with sufficient revenue. Therefore, REPI had a negative effect on electricity projects, creating an incentive for developers to build direct use projects instead.

In states with an RPS standard covering LFG projects, the adoption of an electricity generation project was 25 percent more likely than in states without an RPS standard or with one that did not include landfill gas. Adopting an electricity generation project was 24 percent less likely states with net metering laws. This is likely due to increased competition from individual producers of electricity in states with net metering laws. Interconnection standards are significant with a 27 percent increased likelihood of adoption of an electricity project in states with the standard.

Landfills which reside in counties which are in CO non-attainment areas are 8 percent less likely to adopt an electricity project as the state air quality standard becomes more stringent. The inclusion of a significant dummy variable for California showed that California tends to encourage electricity generation, perhaps due to its' high electricity demand. Landfills in California were 56 percent more likely to adopt electricity projects.

Higher electricity prices also meant increased adoption of electricity projects. A 1cent/kW increase meant landfills were 10 percent more likely to adopt an electricity project. NOx emissions from specific technologies also had an effect on choosing electricity generation. High emission engines were almost 4 times more likely to be adopted by landfills. This may be due to the significantly higher cost of low emission options.

Direct Use Projects

Eight of the sixteen variables were significant in the direct use model. In contrast to the adoption model in Chapter 4, the REPI incentive is significant. The REPI results showed that landfills were approximately 3 times more likely to adopt a direct use project under the REPI incentive regime over an electricity project, holding all other variables constant. As discussed above, the issue is that these credits were not reliable and were subject to appropriation bills.[163] Because the credit could not be counted on to help fund a relatively more expensive electricity generation project, developers looking at a project site were more likely to go with a direct use project.[164]

The RPS variable was also found significant; it showed that the presence of an RPS in the state meant a landfill was 76 percent less likely to adopt a direct use project. RPS standards apply to the generation of electricity. When comparing this result to the electricity generation model, the presence of an RPS rule steers projects toward electricity generation and away from direct use.

O_3 non-attainment areas decreased the likelihood of a direct use project by 28 percent, most likely because the gas is not combusted at the landfill, directly destroying the NMVOCs. CO and NOx non-attainment variables are not significant, probably due to the fact that the gas in a direct use project is being sold for combustion by another firm. In most cases, this firm is already combusting a comparable amount of fossil fuels. Therefore, there is no net gain in air pollution from the project. State financial incentives for landfills increased the likelihood of a direct use project by 13 percent.

Privately owned landfills and landfills located in California are less likely to adopt a direct use project. Privately owned companies have more knowledge and experience in operating and maintaining electricity generation systems and are not intimidated by these technologies. The demand in California for electricity is strong and encourages projects to generate electricity over direct use. Increased size of the landfill, which translates into increased and long-term gas flow, increases the likelihood of adopting a direct gas use project by 83 percent.

Many direct use projects have contracts with the end user based on the price of oil, not natural gas. A one dollar increase in the price of a barrel of oil increased the likelihood of a direct use project by 5 percent.

The results of the direct use model must be used with caution, however. The test for frailty showed that it is a strong likelihood that a variable is omitted. One variable that experts mentioned as crucial to a project is whether or not there was an end-user willing to buy the gas in the vicinity of the landfill. This is nearly impossible to add to the analysis and, therefore, biases the analysis.

Reciprocating Engines

I found that participation in the LMOP program made landfills two and a half times as likely to adopt reciprocating engines, and the presence of an RPS standard increases the likelihood of adoption by 67 percent. The data also suggests that the presence of net metering laws made a landfill less likely to adopt a reciprocating engine.

Landfills in a CO non-attainment area were 12 percent less likely to adopt a reciprocating engine in states with less stringent permitting requirements. Landfills in a NO_2 non-attainment area were 30 percent less likely to adopt a reciprocating engine as standards became more rigid.

California has a large number of reciprocating engines, and private ownership and intra-firm diffusion of knowledge seems to encourage the use of reciprocating engines. Electricity prices influences the adoption of reciprocating engines. A 1 cent/kWh increase in average State price meant a landfill was 20 percent more likely to adopt a reciprocating engine.

Others Engines and Turbines

Reciprocating engines are by far the dominant electricity generation technology used at landfills. The choice of using other mature electric generation technologies is studied in the model for other engines and turbines. Participation in the LMOP program doubled the likelihood of adoption of a non-reciprocating engine or turbine. The presence of an interconnection standard in the state made it more than twice as likely a landfill would adopt one of these technologies. This may be due to the fact that interconnection standards, which in many cases are focused on specific technologies such as turbines and Stirling engines, would help ease negotiations with utilities when using technologies that deviate from the typical reciprocating engine.

A landfill in a CO non-attainment area is 22 percent less likely to adopt a non-reciprocating engine or turbine. NO_2 non-attainment in a county meant that a landfill was 98 percent less likely to adopt one of these technologies most likely due to the fact that the NOx emissions have not been thoroughly tested for all of these technologies. Increased methane generation potential increases the likelihood a non-reciprocating engine would be adopted by 25 percent.

A 1 cent/kWh increase in average State price means a landfill was 28 percent more likely to adopt a non-reciprocating engine or turbine. A 1$ per barrel increase in the oil price decreases the likelihood of adoption by 5 percent. This likely reflects the fact that an increase in the oil price would increase the cost of a project to an end-user based on a contracted rate pegged to the oil price. These projects relative to direct use and reciprocating engines have smaller profit margins and are more sensitive to increased costs to the end user. An increase of 1lb/MWh of NOx emissions from the technology mean the technology are 74 percent less likely to be adopted.

Niche Technologies

Only two variables are significant in the model for niche technologies: NO_2 non-attainment and NOx emissions from the technology. In areas with a non-attainment problem and strict standards for NO_2, niche technologies are 97 percent less likely to be adopted. This may be because emissions from these technologies are still untested or under studied, making it difficult to get permits. For every increase in lb/MHz of emissions of the technology, a landfill is 81 percent less likely to use the technology. Several experts note that they generally used niche technologies because of their low emissions properties, in response to the permitting issues.

Chapter 6: Turning State Policies into Federal Policies

Introduction

Over the last two to three years, more than thirty states have joined six regional initiatives to reduce carbon dioxide emissions from power plants and increase renewable energy generation. These initiatives include the Western Regional Climate Action Initiative, the Powering the Plains initiative, the Regional Greenhouse Gas initiative (RGGI), the Western Governors' Association (WGA) Clean and Diversified Energy Initiative, East Coast Governors' Global Warming Initiative, New England Governors Climate Change Action Plan, and the Southwest Climate Change Initiative. As with many other environmental issues, the states in these regional initiatives are providing the basis for what may become a Federal system.

The 110th Congress has proposed over 125 different climate related bills and a record number of cap-and-trade policies since its change over to Democratic leadership.[165] Representative Lover (D-MA) and Senators Lieberman (I-CT), Feinstein (D-CA), and Kerry (D-MA) have all proposed separate cap-and-trade legislation during the 110th Congress. In addition to the climate change policies debated in Congress, the Energy Policy Act of 2005 focused on increasing renewable energy in the U.S. Under the Act, the Federal government is required to increase the purchase of renewable power from 3% in 2007 to 7.5% in 2013.[166] This goal is on the lower end of the State RPS goals.[167] During this debate, Congress also considered enacting a Federal RPS, but that was later cut from the bill. In addition to the increase in renewable power purchased by the Federal government, the Energy Policy Act also extended REPI credit of 1.9 cents per kWh for the first ten years of operation of a renewable project.

Other congressional concerns have focused on promoting energy independence or energy security by proposing ways of encouraging alternative fuels (biomass, biofuels, coal-to-liquid fuels, etc.). The 110th congress introduced 7 bills focused on providing incentives to develop and use alternatives to foreign oil.[168]

Encouraging landfill gas projects as a climate change reduction strategy or renewable energy promotion strategy has been considered for over a decade. Federal policies provide tax credits as an incentive to adopt these projects, though funding has been insufficient to make significant changes. NSPS provides a regulation scheme to encourage projects, which I argue in this study, is successful in encouraging LFG projects. Other options have also been considered. In terms of promoting renewable energy, one option that was discussed in several of the Energy Bill debates is a Federal RPS standard. Options focused on reducing climate change include using landfill gas capture-and-use projects as a potential "offset" to a CO_2 cap-and-trade regime or taxing carbon, which would increase energy prices and lead to large increases in revenue for landfill gas projects. In Chapter 4 and 5, I point out that RPS and increased revenue through energy prices have been significantly large influences on adoption and technology choice. Building on this information, the analyses in this chapter look at which of these schemes is more potent in influencing adoption.

Climate Change Reduction Policies

Environmental groups and economists advocate the use of offset under a cap-and-trade program for CO_2 as a way to reduce the cost of reductions to a power generator. A cap-and-trade system would allow the government to set an environmental target (a cap on greenhouse gas emissions) and then use the market to determine the price of compliance. A tax on carbon, another commonly discussed policy option, could be adjusted to meet an environmental goal over time; but it would not allow utilities to seek reductions outside their industry, which would reduce the short-term cost of the policy. Non-market policy options also exist. Two options which could be implemented are a best available control technology (BACT) standard or an energy efficiency standard. A BACT standard is difficult to implement when technologies such as carbon capture and storage are still in the development stages. Industry would prefer to choose for themselves which technologies are best for their operations, whether the technologies reduce emissions at the end-of-the-pipe or improve efficiency. One of the main advantages of a cap-and-trade policy is the ability of a firm to by offsets or reductions from a firm that is not being capped. Offsets are generally reductions from industries producing non-CO_2 greenhouse gases and are not covered by the cap-and-trade program. Because the reductions are of non-CO_2 greenhouse gases, a ton of reduction can be equivalent to 20 to 20,000 tons of carbon dioxide, depending on the gas and the gases GWP. In addition, several of the gases, including sulfur hexafluoride (SF_6) and CH_4, have a market value and can be captured and sold as a way to offset all or most of the cost of reduction. Since there is no market for CO_2 in the quality and quantity that is being released from a power plant, CO_2 reductions do not have a way to generate revenue through capture-and-use. Lastly, technology currently exists to reduce these emissions. Industries emitting these gases need a price signal to make further reductions. For these reasons, offsets are generally cheaper to implement.

However, offsets present a baseline definitional issue. Under a cap-and-trade program, there is a target level of CO_2 reductions. If part of these reductions are met through offsets of another gas (e.g., reductions of CH_4 at a landfill), how can the agency monitoring the program or the company purchasing the offsets be sure that these reductions are "real" and would not have happened in absence of the cap-and-trade program? This is generally referred to as a question of additionality - whether or not the reductions are additional to a business-as-usual baseline.

Timing of the reductions becomes a crucial aspect of this question. Diffusion theory states that just because a technology is cost effective to implement does not mean that the technology is instantly diffused. I have confirmed this for the landfill gas industry in this thesis. Given a future climate policy and the current diffusion of technologies over time, what is the actual baseline five or ten years from now? Like any prediction, additionality can only be estimated. Some have argued that it does not matter; any reduction is beneficial whether it is additional or not. Others are concerned that without a way to monitor additionality, the target becomes less stringent and will not meet the environmental goals related to stopping further climate change.

The question becomes, "Is the additionality issue large enough to design a complex system of bureaucratic investigation (i.e. a financial analysis of whether or not the project would be cost effective without the carbon credits) by the governing agency in charge of the cap-and-trade system, or is it minor and should be ignored?"

Offset policies are potentially tricky to implement. The major concern about an offset policy is that it will count “anyway tons" towards an emissions cap. In other words, reductions that would have happened “anyway,” without the pollution policy will be applied to the goal, reducing the reductions beyond the business-as-usual baseline. In order to analyze this issue, the analyses in this chapter will look at proposed non-climate legislation, in this case a Federal RPS policy, and compare it to reductions in the business as usual case and the pollution scenario where revenues are higher.

Landfill Gas as an Alternative Fuel Source

In addition to pollution and climate change concerns, states have promoted renewable energy for a variety of other reasons. RPS debates at the State level have mainly focused on the energy interest of the State; pollution and climate change benefits are deemed an important, but secondary, benefit in many cases. Some states are concerned about electricity supply and reliability and use RPS to diversify their fuel supply. Some states are frustrated with the sharp increase in natural gas prices in the last five years and want to promote alternatives. Some states are concerned with air emissions from coal-burning and use RPS to diversify. States have used RPS to compliment other programs such as tax credits, grants, and cheap loans that encourage specific renewable technologies.

The US seems to be moving towards a de facto National RPS as more and more states adopt it as a standard. Currently 30 states have RPS with RPS goals ranging from a 4% target in 2009 to a 25% target by 2025.[169] Several environmental groups have advocated for a Federal RPS to compliment or replace the fluctuating and uncertain

Federal production tax credit. RPS could also compliment a future cap-and-trade scheme if designed to appropriately take into account credit for early action and additionality issues.

Post-Estimation Analyses for Parametric Models

Using the estimated models in Chapter 4 and 5, the influence of additional policies or energy price increases on adoption (i.e., failure) can be predicted.[170] Predictions can be made using the mean or median values of the independent variables which are not directly analyzed and can be made using either the time to failure or the logged time to failure. This analysis will focus on changes in a specific variable or set of variables, using the mean value of the remaining variables, and predicting the time to failure.

The expected value of time T_j, the time to failure for a random observation with covariates x_j is given by:

$$E(T_j|x_j) = \int_0^\infty t f(t|x_j)\, dt$$

$$= \int_0^\infty S(t|x_j)\, dt$$

where f() is the probability density function of T and S() is the survivor function. Both of these equations are reliant on the chosen hazard function for the model. Using Weibull as the example, the survivor function becomes:

$$S(t|x_j) = \exp[-\{\exp(-\beta_0 - x_j\beta_j)\, t\}^p]$$

It follows that the probability that a landfill will adopt at time T_j given x_j is

$$F(t|x_j) = 1 - \exp[-\{\exp(-\beta_0 - x_j\beta_j)\, t\}^p]$$

This estimation provides the mean value of the covariates. In order to analyze the change in predicted outcome based on a change in one covariate, the covariate's value can be changed, while using mean values for the remaining covariates. This way, the vector of covariates x_j can be modified to look at the influence of one or more variables on the survivor function.

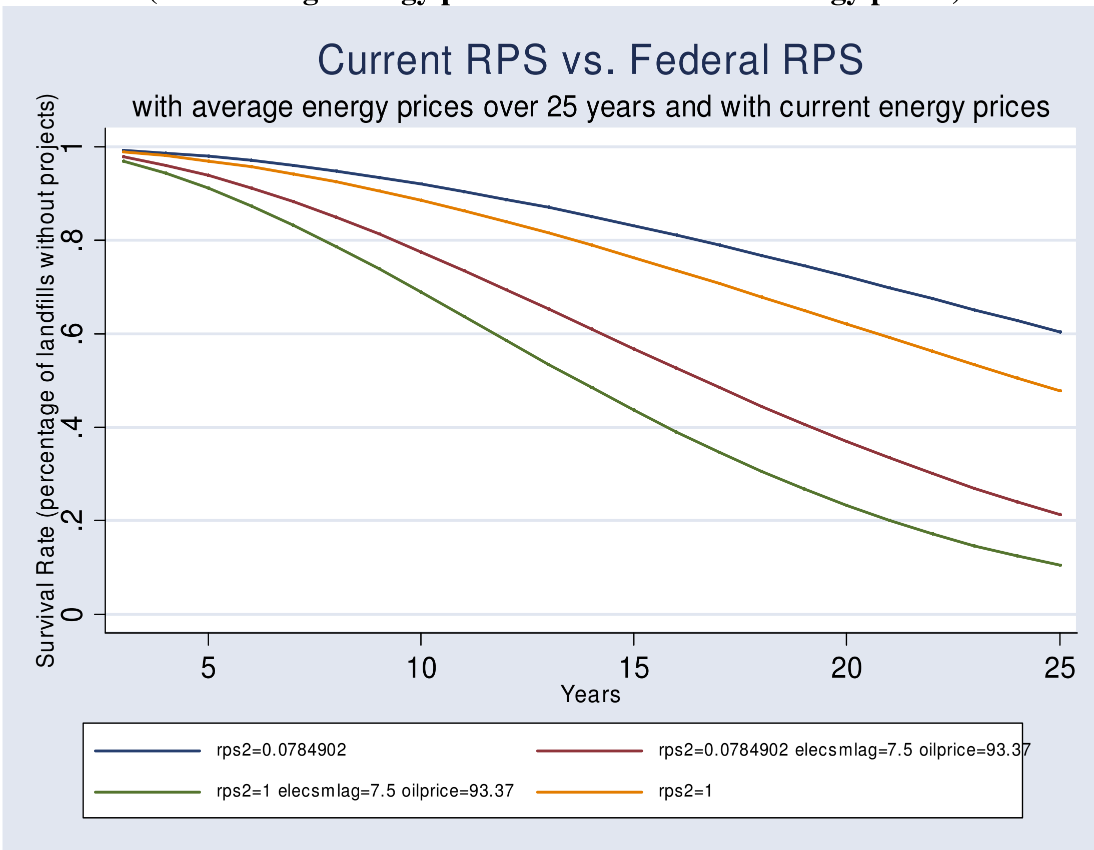
Post-estimation of the Diffusion Model

Based on the empirical analysis presented in Chapter 4, the rate of adoption can be analyzed given various policy scenarios. First, the analysis estimates the difference between no RPS standards, the current RPS standards, and a Federal RPS standard. Second, the analysis compares current policies to a Federal RPS and a potential revenue increase from a domestic cap-and-trade system that uses CH_4 from the landfill sector as an offset to reductions in CO_2 or a carbon tax scheme which increases domestic electricity prices and oil prices.

Federal RPS Analysis

In order to simulate a Federal RPS in the model, I ran the model for RPS=1 for all states. All other variables were represented by their mean values in the model. The mean value for the RPS covariate is 0.0784902. This value is used as the business-as-usual baseline for these analyses.

Figure 8: Current RPS standards in place vs. Federal RPS standards (with average energy prices and with current energy prices)



Note that this figure is a representation of the survivor function, or the percentage of landfills which do not adopt landfill gas projects. To calculate the percentage or number in the sample which do, the failure rate or adoption rate is simply 1-survivorship.

As can be seen in the Figure 8, a domestic RPS standard would increase adoption over a 25 year timeframe from about 40 to slightly above 50 percent. If you compare this to today's electricity and oil prices, the sharp increase in energy prices since 2003 (the end year of the analysis) increases adoption of projects beyond the predicted adoption rate of a Federal RPS.[171] The combination of increased energy prices and a Federal RPS yields the steepest curve indicating the fastest rate of diffusion.

Climate Change Reduction Policy Analysis

As can be seen above, the critical factor in promoting landfill gas projects is the increase in the electricity price or oil price (i.e., revenue). This can be accomplished through a market-based climate change policy such as a cap-and-trade program or through a carbon tax scheme. The revenue from increased energy prices under a tax scheme or the increased energy price plus the revenue earned from companies buying the offsets would determine the rate of adoption of landfill gas projects. RPS would open up a market to sell the energy by forcing utilities to buy electricity from LFG projects.

To look at the effect of a carbon price on diffusion of landfill gas projects, I selected a range of carbon prices and added the carbon price to the current energy price. Table 8 below summarizes the energy prices at $10, $25, $50, $100 and $200 per ton of carbon. In this analysis, there is no difference between a carbon tax scheme and a cap-and-trade program. Both policies increase the energy price in the model.

Table 8: Energy Prices Associated with Various Levels of Potential Carbon Prices[172]

Carbon Price	Additional Cost Due to Carbon Price ($/barrel for oil; cents/kWh for electricity)	Carbon Price plus Current Energy Price ($/barrel for oil; cents/kWh for electricity)
$10/ton of Carbon - Oil	$28.61	$121.98
$10/ton of Carbon - Electricity	¢0.39	¢7.89
$25/ton of Carbon - Oil	$71.53	$164.90
$25/ton of Carbon - Electricity	¢0.96	¢8.46
$50/ton of Carbon - Oil	$143.05	$236.42
$50/ton of Carbon - Electricity	¢1.925	¢9.43
$100/ton of Carbon - Oil	$286.10	$379.47
$100/ton of Carbon - Electricity	¢3.85	¢11.35
$200/ton of Carbon - Oil	$572.20	$665.57
$200/ton of Carbon - Electricity	¢7.7	¢15.2

The effect of a range of carbon prices on the diffusion rate of landfill gas projects can be seen in Figure 9 below. The analysis shows that at $25 per ton of carbon, all candidate landfills would adopt a project over the next 25 years. At $100 per ton of carbon, the rate of diffusion increases to full adoption in approximately 7 years.

Figure 9: Carbon Price Scenarios with a State RPS

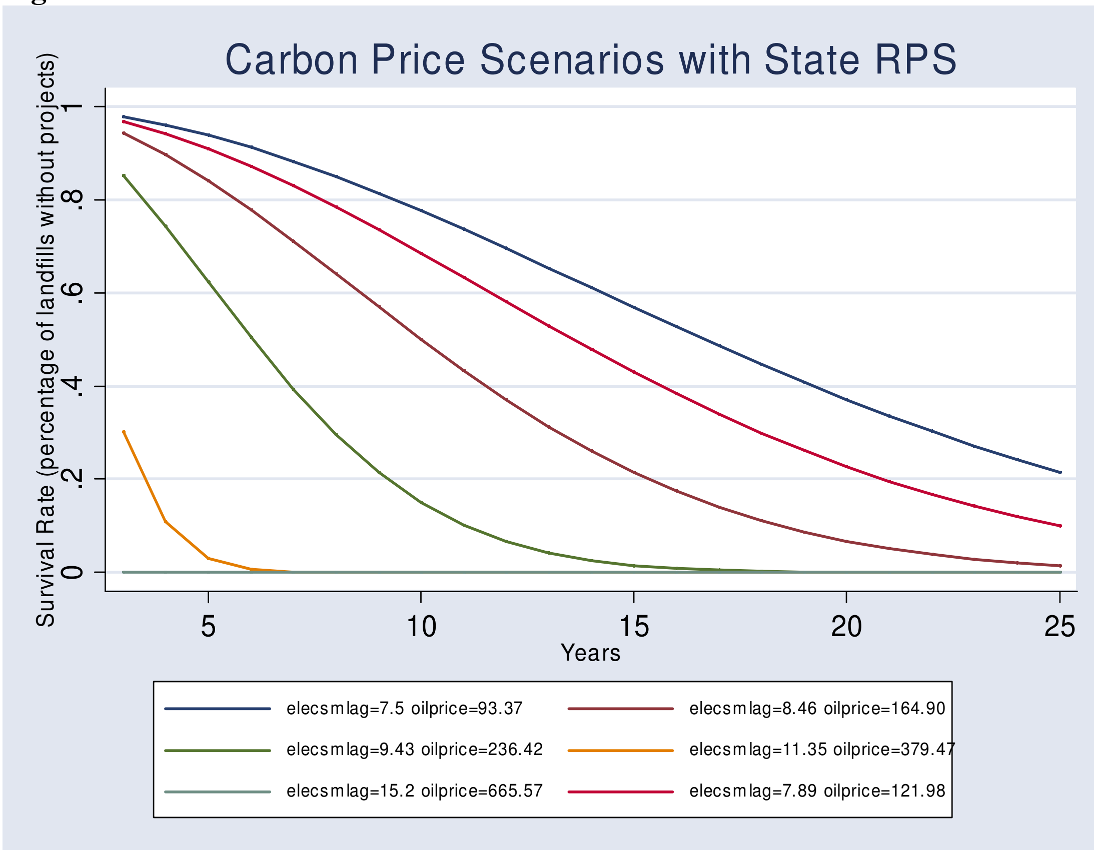
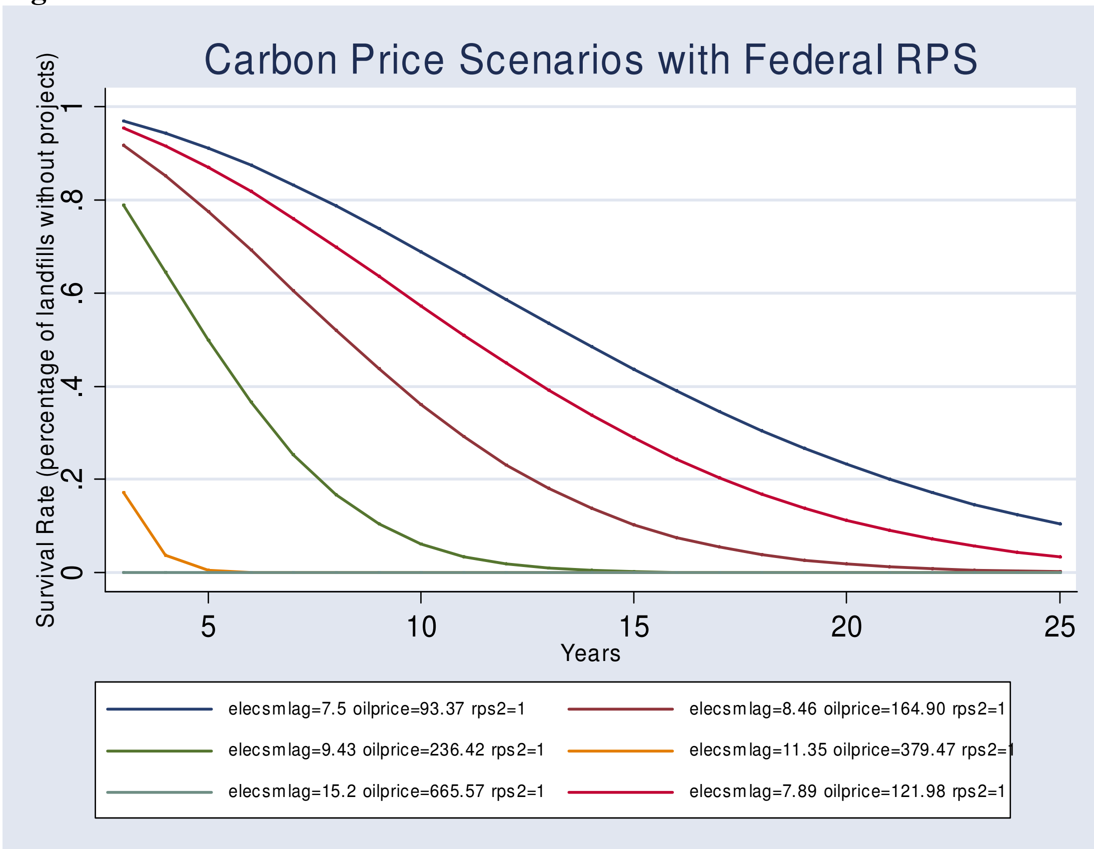


Figure 10 below is the same analysis, but includes a Federal RPS. As can be seen in the graph, the combined carbon price and Federal RPS accelerates the rate of diffusion. However, the acceleration is limited to a few years. At $25 per ton, full adoption occurs at roughly 24 years instead of 25 years. At $100 per ton of carbon, full adoption occurs at roughly 5 years instead of 7 years.

Figure 10: Carbon Price Scenarios with a Federal RPS



The level of the carbon price has a dramatic effect on the rate of diffusion in the analysis. In order to compare this to a potential climate change policy, one that could realistically be promulgated, I reviewed potential cap-and-trade schemes which have been introduced into Congress and choose the Lieberman-McCain Climate Stewardship Act of 2003 as a basis of comparison. While this bill is not among those currently debated on the Hill, it is similar to seven currently proposed bills and has the advantage of being widely analyzed by the Federal government, think tanks, and Universities. The results of these analyses are published and available to the public. The currently proposed bills have been analyzed to various extents by the Federal government, but the results have not been published. The Climate Stewardship Act is also considered the model for many of the State programs now being considered including the REGGI program.

A range of potential costs from the Climate Stewardship Act are available from reports from the National Resource Development Council, MIT University, and USDOE's Energy Information Agency. Below is a summary of the carbon prices from each of these analyses.

Table 9: Cost of the Leiberman-McCain Climate Stewardship Act

$/ton of Carbon

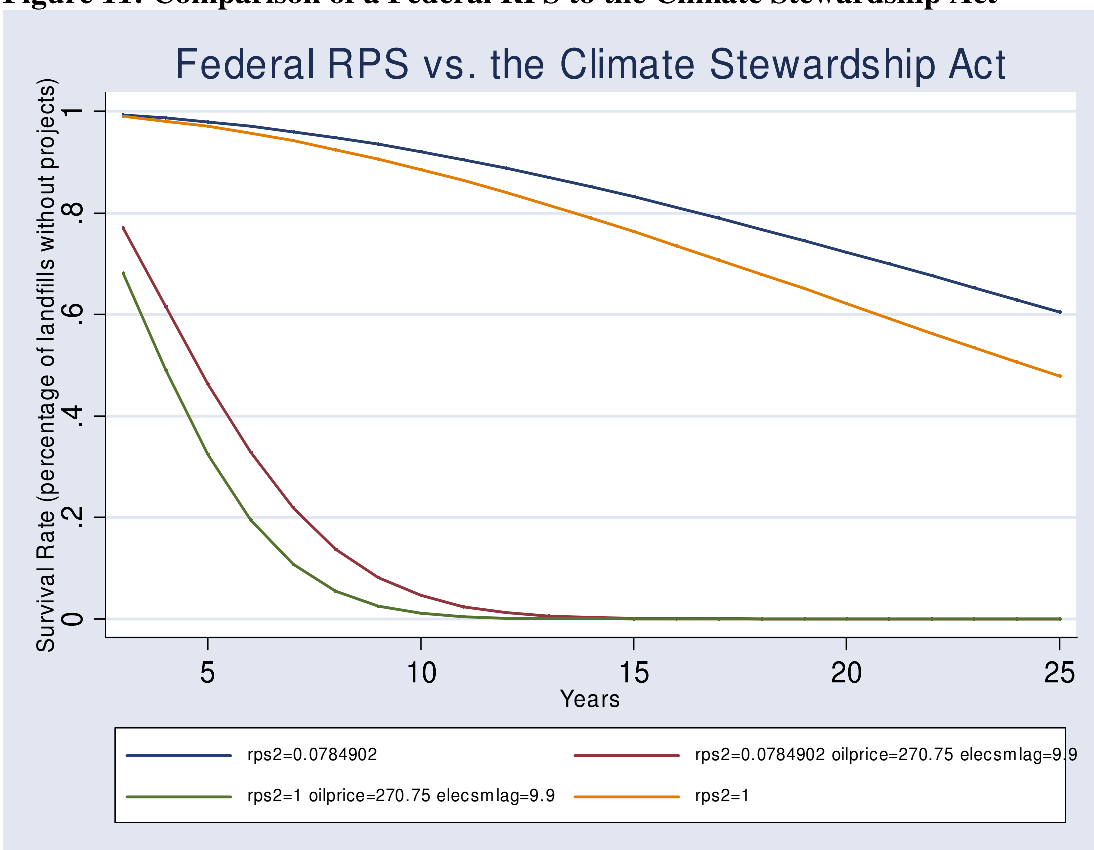
	NRDC	MIT	EIA
2010	29	62	79
2015	66	81	119
2020	81	103	178

Source: Pew Climate Center

NRDC and EIA both represent biased positions on the issue, giving a range of costs. The most unbiased estimate from a policy agenda perspective is the MIT estimate, which, as expected, lies somewhere in between the two extremes. In order to analyze these costs in the duration models used in this thesis, I converted the MIT cost estimates to energy prices based on the carbon content of coal used to generate electricity and oil.[173] Using the conversion methodology recommended by the UN Intergovernmental Panel on Climate Change to estimate emissions from energy, I could estimate the amount of carbon per unit of energy. [174] Building on this, the price per unit of carbon can then be converted to price per unit of energy.[175] Using these conversions, the carbon prices from 2010 in the MIT analysis roughly translates into a 2.4 cents/kWh and 177.38 dollars per barrel increase in energy prices.

In figure 11, the survivorship function or predicted non-adoption of the business-as-usual scenario (where RPS equals the mean), a Federal RPS standard, a climate change policy, and a climate change policy with a Federal RPS standard is compared. In this analysis, the RPS standard was assumed to cover all states. The energy prices increased to 9.9 cents/kWh and $270.75/barrel of oil for electricity and oil prices, respectively. These prices reflect the current energy price as of November 15, 2007, plus revenue from a carbon price and the national average oil price per barrel for November 15, 2007, plus revenue from a carbon price.

Figure 11: Comparison of a Federal RPS to the Climate Stewardship Act



The model shows the strong response of the industry to increases in energy prices. The response is much stronger than creating a Federal RPS standard of similar strength to the current State standards. The analysis also shows that the additionality problem relative to the overall increase is small, approximately 10 percent. Compared to the RPS standard, the increase in energy prices due to a cap-and-trade or tax scheme will increase adoption of landfill gas projects to the point where all landfills that have projects that are technically feasible will adopt in 14 years. A combination of a Federal RPS standard and cap-and-trade program will speed up adoption, and all technically feasible projects will be implemented in approximately 12 years.

From the analysis it can be seen that the RPS standard coupled with higher revenue from the climate change policy gives the most reductions in the shortest period of time. This argues for ignoring the additionality issue and concentrating on more overall reductions of CH_4.

Post-estimation of the Electricity Projects Adoption Model

Another potential policy goal in the renewable energy and climate change arenas is to ease the demand on coal, if only slightly, buy using alternative fuels to create electricity. While using landfill gas is in no way a "magic bullet" to solve this problem, it can contribute to a solution. This analysis looks at effective policy options to maximize the use of landfill gas to generate electricity. Note that when looking at an electricity project, tradeoffs between electricity generation projects and direct use projects are taken into account.

Figure 12: Current RPS vs. Federal RPS in the Adoption of Electricity Projects

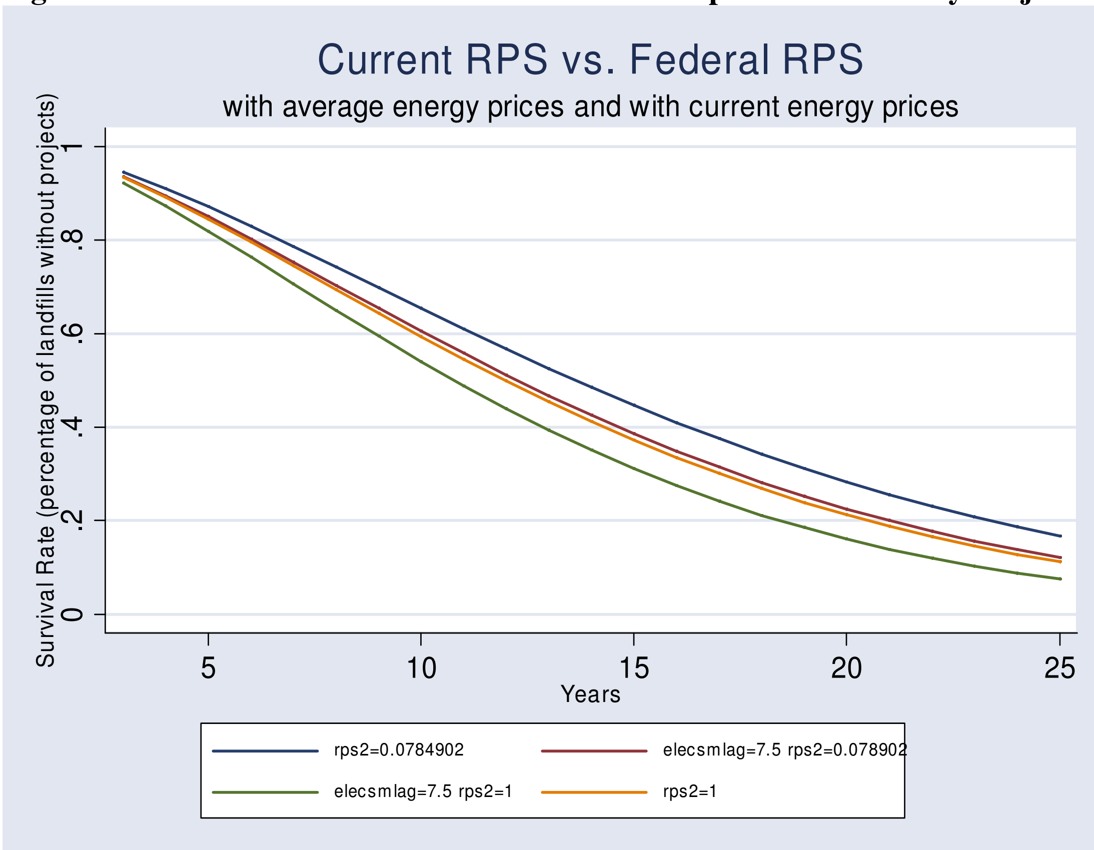


Figure 12 illustrates the effect of a national RPS program on adoption of electricity prices. Electricity projects increase from 85 to 90 percent of overall adopted projects with current energy prices or with a Federal RPS. The combination of the current energy prices and a Federal RPS increased adoption to approximately 95 percent over the 25 year timeframe.

Figure 13: Comparison of Federal RPS and the Climate Stewardship Act in the Adoption of Electricity Project

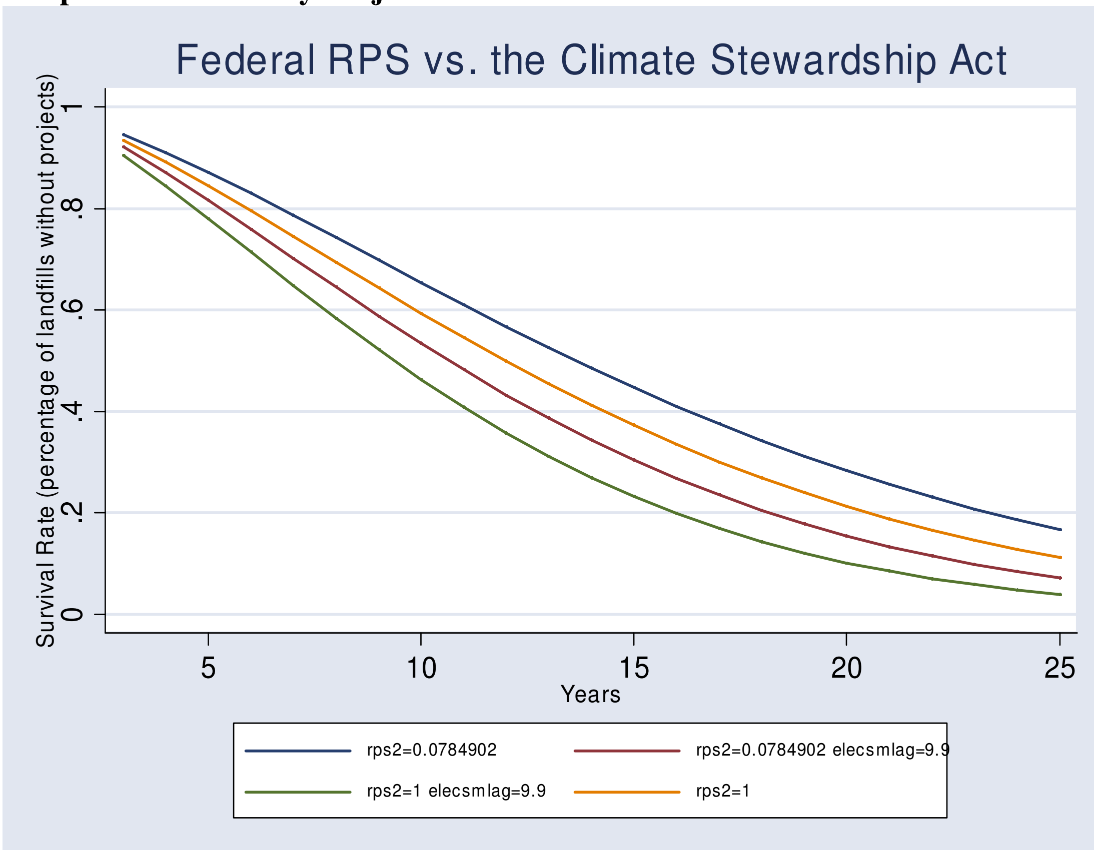


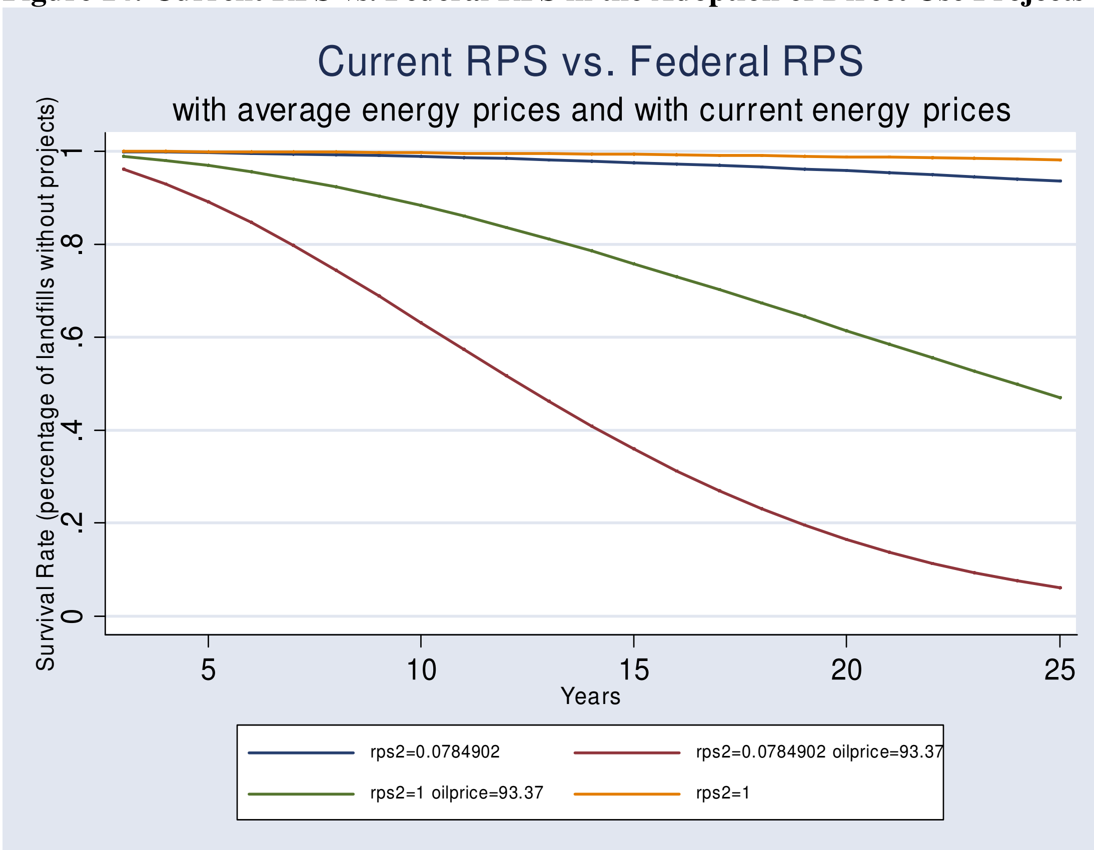
Figure 13 shows the same overall pattern as the adoption model as electricity projects make up the majority of projects adopted overall. A combination of a Federal RPS and climate change program pushes this to almost 100 percent of all adoptions being electricity projects in 25 years, a few percentage points above a climate-change-only regime.

Post-estimation of the Direct Use Adoption Model

When looking at the rate of adoption of direct use projects, a Federal RPS and cap-and-trade scheme combined would be less effective in encouraging direct use projects than a climate change policy alone. RPS skews the distribution of technologies towards electricity generation projects, away from direct use. This leads to the

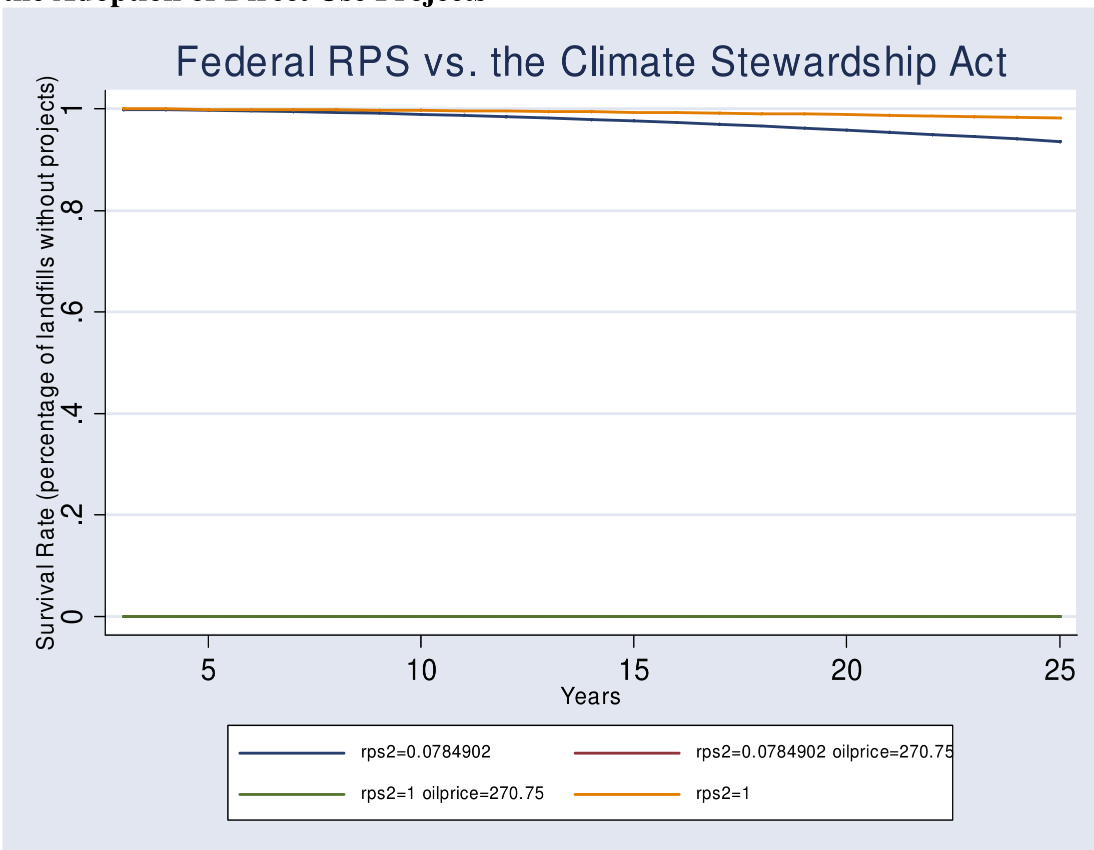
Federal RPS standard increasing the number of electricity projects. However, the increased energy prices continue to make some direct use project attractive in the short term.

Figure 14: Current RPS vs. Federal RPS in the Adoption of Direct Use Projects



Compared to figure 12, figure 14 shows an opposite trend in direct use projects under a Federal RPS program. Direct use projects decrease from approximately 5 percent of total adoptions under the current RPS regime to a total of approximately 2 percent of all adopted projects under a Federal RPS. The current oil price makes direct use projects dramatically more attractive. Approximately 90 percent of candidate landfills would adopt direct use projects over the 25 year period at the current oil price. If a moderate price increase is combined with a Federal RPS standard, the adoption rates of direct use projects is restricted; and landfills adopt electricity projects.

Figure 15: Comparison of a Federal RPS and the Climate Stewardship Act in the Adoption of Direct Use Projects



As can be seen in figure 15, a combination of RPS and carbon price will have little effect because the oil price is sufficiently high to diffuse direct use projects almost immediately.

Post-estimation of the Niche Technologies Adoption Model

Niche technologies are not significantly affected by either policy, although the number of niche applications continues to increase. Concerns about NOx emissions continue to drive adoption of these technologies. The experts I interviewed noted that while energy prices were not currently high enough to make a difference in choosing niche technologies over more mature technologies, under a potential future cap-and-trade program, they expected this to change. The basic niche technology model does not reflect this because this phenomenon (high enough energy prices to cover the cost of niche technologies) cannot be found in the historical data. Despite the inability of the historical data to estimate this trend, it is expected that higher energy prices will lead to a steady if not increasing use of niche technologies. A Federal RPS standard is predicted to skew this towards fuel cells and other electricity related technologies.

Chapter 7: Summary and Conclusions

I began this analysis to answer whether or not State renewable energy portfolio standards influenced the adoption of landfill gas projects. It is important to learn from the experience of the RPS programs and use this experience to design an optimal policy at the national level to address climate change and renewable energy issues.

Did RPS increase the rate of diffusion?

This analysis confirms the explanatory power of the independent variables traditionally considered in the literature on diffusion. By far, the most influential State policy was the RPS standard. Experts gave the relevance of a renewable portfolio standard a mixed review. While a few of the experts indicated that RPS standards kept projects going during the years when Federal incentives were uncertain or unavailable, others felt that the RPS credits were too unreliable to count on as part of the basic economics of a project. Some noted that as time goes on, issues with the RPS standards are working themselves out; and they felt that in the future strict RPS standards could help promote projects. However, the modeling exercise showed that RPS rules already have a more significant affect on adoption than the experts perceived them to have. As the stringency of RPS increases over time, it is likely that RPS will increase diffusion rates.

In other areas, experts, the literature and the modeling agreed. For example, states with low emission standards and non-attainment areas have difficult permitting procedures and push companies towards more expensive projects with lower profits.

Developers seem to shy away from projects in NOx and CO non-attainment areas because of the additional NOx and CO emissions from the projects. Despite this, companies will go through the sometimes lengthy process of obtaining the permits, if a project is deemed profitable enough to justify a more expensive, cleaner technology. This is shown in the modeling by a hazard ratio of less than one, indicating that in states with non-attainment issues and low air standards it is less likely a project will be adopted. Permitting in ozone non-attainment areas were either not an issue or the perception was they did not apply to landfill gas projects.

The literature, particularly USDOE/EIA reports, stated that State provisions such as net metering and interconnection standards have had an impact on landfill gas projects.[176] The statistical analysis and experts disagree. Interconnection standards do not seem to have any influence on the development of landfill gas projects, and net metering actually seems to have a negative effect by encouraging utilities to find renewable sources of energy elsewhere. The effect of net metering on discouraging LFG projects is a particularly interesting result. These policies are designed to encourage renewable energy projects other than LFG, creating competition. In terms of a national renewable energy goal or greenhouse gas reduction goal, these policies do not necessarily have a negative consequence overall. More information on the success of these policies in encouraging residential and commercial solar or other renewable projects is needed to determine if these policies support national renewable and climate change goals.

As expected, NSPS and energy prices have a positive effect on the diffusion of LFG projects. NSPS encourages large landfills to switch to a capture-and-use project in order to cover the cost of the regulation. Increased energy prices mean projects are more profitable. The results of the LMOP variable confirm the importance of information networks in the diffusion of technologies.

Did State Renewable Portfolio Standards Influence Technology Choice at Landfill Gas Projects?

State Renewable Portfolio Standards positively influenced the adoption of electricity projects, particularly reciprocating engine projects. The standards had a negative impact on direct use projects, providing enough of an incentive to generate electricity that landfills shifted away from direct use projects in these states.

The overall results of the technology models complement the results of the interviews and literature search, and further clarify the contradictory nature of the experts' view s of RPS with the view of the literature. Developers generally felt that RPS did not encourage LFG projects, noting that RPS projects would have been developed even without the RPS. What the analysis of technical choice shows is that RPS may have provided the developer with an incentive to develop an electricity project over a direct use project. At landfills with large amounts of gas available over several decades, the economics of a project looks good on paper but is useless unless a buyer can be found. RPS creates a market for electricity sales, a critical factor in the decision to develop a project, particularly if there is not a nearby industrial park or institution nearby to buy the landfill gas directly.

RPS did not encourage the use of innovative technologies nor did it promote demonstration of new technologies. Instead, air pollution issues, specifically NOx emissions, were a strong factor in encouraging the use of innovative technologies.

Projects in NO_2 non-attainment areas were less likely to be adopted. Engines and turbine technologies with low NOx emissions, which have been introduced as an innovative substitute to a reciprocating engine, are more likely to be adopted in most cases.

Another important result of the technical choice analysis was the influence of the REPI. While REPI applies to electricity generation projects, the analysis shows it is insignificant in the electricity projects diffusion model. In contrast, REPI is a significant and positive factor in the direct use diffusion model. This result suggests that the lack of reliable funding for the incentive made it ineffective at promoting the targeted electricity generation projects; instead, it encouraged landfills to opt out of electricity generation and develop a direct use project. Because REPI has been renewed under the latest energy bill, a thorough investigation of the usefulness of this policy should be conducted.

Energy variables in the model are predictably related to the type of project; electricity projects were significantly influenced by electricity prices, and direct use projects were significantly influenced by oil prices.

Is RPS a stringent enough policy to accelerate diffusion and meet climate change and renewable energy targets?

Post-estimation analysis of the parametric models shows the hypothetical impact of a Federal RPS standard on adoption of landfill gas technologies overall, as well as diffusion of specific types of technologies. While a nation-wide RPS standard can increase adoption by 10 percentage points overall, this could be a small increase compared to proposed climate change legislation or even a more modest increase in energy prices. RPS programs also skew what types of projects are adopted, since they apply only to electricity generation projects.

Combining a Federal RPS standard with a market based climate change policy could have a beneficial effect in increasing overall diffusion of landfill gas technologies. At lower carbon prices, combining a climate change policy with a Federal RPS will increase the diffusion rate of landfill gas technologies. The number of direct use projects will continue to increase under this scheme, but at a lower rate than with a climate change only policy. At higher carbon prices, RPS may not be needed to create a market for the electricity sales. The lower price of producing electricity using LFG compared the high price of oil or natural gas under a climate change policy increases market share of electricity from LFG beyond the market mandated by current RPS.

Recommendation for future studies

My interviews with developers and landfill owners alone lead to the conclusion that RPS programs are only marginally successful at encouraging landfill gas projects. Developers interviewed felt that the price received for the electricity produced under the program was not high enough to pay for projects that were not profitable outside of the program. The literature on RPS, mainly produced by State governments and environmental NGOs, reflects a different point of view. Some NGOs are even concerned that the RPS programs go too far in encouraging landfill gas and should be restricted to clean, traditional sources of renewable energy such as solar or wind power.

The results of the analyses in this dissertation suggest several areas of research beyond the scope of this dissertation. As mentioned previously, net metering policies and their success in encourage small scale renewable electricity generation should be studied in greater detail to provide more information about how these policies should fit into national renewable energy and climate goals. Another policy that needs to be looked at in great detail is the success of the REPI in encouraging electricity generation projects. This analysis suggests that it has not been successful in promoting electricity generation from LFG. Because this is most likely due to the nature of the incentives funding process, other types of electricity generation projects may be similarly affected.

Another area of interesting research is the role of attitudes and State government institutional structure on diffusion of environmental technologies. In this analysis, California is seen as a significantly different culture in which to work than any other of the states because of the complicated State government structure (i.e., the 34 separate air districts) and the innovative nature of the society. An in-depth look at these issues would be informative in how other states could encourage the diffusion of environmental technologies.

Lastly, the effect of green power provision in developing the market for renewable energy sales and the new Section 45 tax credit effect on encouraging LFG projects would be useful once the data becomes available. Neither of these policies existed during the time period analyzed in this study.

Endnotes

[1] Barry G. Rabe, *Greenhouse and Statehouse: The Evolving State Government Role in Climate Change*, (Washington, DC: Pew Center on Global Climate Change Policy Series, November 2002), pg. iii in the Executive Summary, http://www.pewclimate.org/global-warming-in-depth/all_reports/greenhouse_and_statehouse_/
[2] Paul R. Portney and Robert N. Stavins, *Public Polices for Environmental Protection*, 2nd edition, (Washington, DC: Resources for the Future, 2000), 78.
[3] Barry G. Rabe, *Race to the Top: The Expanding Role of the U.S. State Renewable Portfolio Standards*, (Washington, DC: Pew Center on Global Climate Change Policy Series, June 2006), page iii in the Forward by Eileen, Claussen, http://www.pewclimate.org/global-warming-in-depth/all_reports/race_to_the_top/.
[4] J.P.M. Sijm, "Induced Technological Change and Spillovers in Climate Policy Modeling," *ECN Working Paper Series* No. ECN-D-04-073 (The Netherlands: ECN, 2004): Chapter 4: Does Climate Policy Induce Technological Change?
[5] John A. Alic, David C. Mowery, Edward S. Rubin, *U.S. Technology and Innovation Policies: Lessons for Climate Change*, (Washington, DC: Pew Center on Global Climate Change Policy Series, 2003), http://www.pewclimate.org/global-warming-in-depth/all_reports/technology_policy/.
[6] USEPA, *Turning a Liability into an Asset: A Landfill Gas-to-Energy Project Development Handbook*, EPA 430-B-96-0004, (Washington DC: US Environmental Protection Agency, September 1996).
[7] USDOE/EIA, *Renewable Energy Annual, 1976-1996*, (Washington DC: US Department of Energy, Energy Information Agency, 1999), Chapter 10, http://www.eia.doe.gov/cneaf/solar.renewables/renewable.energy.annual/chap10.html
[8] USEPA, *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions*, EPA 430-R-99-013, (Washington DC: US Environmental Protection Agency, September 1999), Chapter 2.
[9] USEPA, *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions*, EPA 430-R-99-013, (Washington DC: US Environmental Protection Agency, September 1999), Chapter 2.
[10] USEPA, *Global Mitigation of Non-CO_2 Greenhouse Gases*, EPA 430-R-06-005, (Washington DC: US Environmental Protection Agency, June 2006), Chapter III.1 on Landfills.
[11] USEPA, *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2005,* EPA 430-R-07-002 (Washington, DC: US Environmental Protection Agency, April 2007), Chapter 8: Municipal Solid Waste.
[12] USEPA, *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2005,* EPA 430-R-07-002 (Washington, DC: US Environmental Protection Agency, April 2007), Chapter 8: Municipal Solid Waste, table 8-3.
[13] USEPA, *Fact Sheet: Final Federal Plan for Municipal Solid Waste Landfills*, http://www.epa.gov/ttn/atw/landfill/lndfpfs.pdf
[14] Personal communication with landfill methane emissions modeling team, USEPA.
[15] USEPA, *LMOP Accomplishments,* http://www.epa.gov/lmop/accomplish.htm (accessed 2006)
[16] USEPA, *LMOP landfill database,* www.epa.gov/lmop/res/index.htm#5 (accessed 2005)
[17] UNIPCC, *Summary for Policy Makers, Third Assessment Report* (Geneva: United Nations Intergovernmental Panel on Climate Change, 2001), Executive Summary.
[18] USEPA, *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2003,* EPA 430-R-05-003, (Washington, DC: US Environmental Protection Agency, April 2005), Chapter 8: Municipal Solid Waste.
[19] Susan M. Bernard, Jonathan M. Samet, Anne Grambsch, Kristie L. Ebi and Isabelle Romieu, "The Potential Impacts of Climate Variability and Change on Air Pollution-Related Health Effects in the United States," *Environmental Health Perspectives*, vol. 109, supplement 2, (May 2001): 199-209.
[20] Dina Kruger, "Methane Control: Transferring Experience from the Climate Arena to Tropospheric Ozone Strategies," *Environmental Management* (December 2003).

[21] A.M. Fiore, Jacob, D.J., Field, B.D., Streets, D.G., Fernandes, S.D., Jang, C., "Linking Ozone Pollution with Climate Change: The Case for Controlling Methane," *Geophys, Res. Lett*. 29 (2002): 25.

[22] As of September 2007, the cap-and-trade proposal considered in Congress use landfill gas as an offset. See http://www.pewclimate.org/policy_center/congressional for a summary of the current bills.

[23] Bronwyn H. Hall, "Innovation and Diffusion," *NBER Working paper series*, working paper number 10212 (2003), Http://www.nber.org/papers/w10212.

[24] E. Mansfield, "Intra-firm Rates of Diffusion of an Innovation," *The Review of Economics and Statistics* XLV, (1963): 348-359.

[25] E. Mansfield, "The Diffusion of Industrial Robots in Japan and the United States," *Research Policy* 18, (1989): 183-192.

[26] E. Mansfield, "Intra-firm Rates of Diffusion of an Innovation," *The Review of Economics and Statistics* XLV, (1963): 348-359.

[27] Bronwyn H. Hall, "Innovation and Diffusion," *NBER Working paper series*, working paper number 10212 (2003), pg.8, Http://www.nber.org/papers/w10212.

[28] Paul Stoneman and Paul Diederen, "Technology Diffusion and Public Policy," *The Economic Journal*, 104 (July 1994): 929.

[29] David J. Pannell, Graham R. Marshall, Neil Barr, Allan Curtis, Frank Vanclay, and Roger Wilkinson, "Understanding and Promoting Adoption and Conservation Technologies by Rural Landholders," Unpublished manuscript, submitted to *Australian Journal of Experimental Agriculture*, (2005), 3, http://www.general.uwa.edu.au/u/dpannell/dp0502.htm.

[30] Brian P. Flannery and Haroon S Kheshgi, "An Industry Perspective on Successful Development and Global Commercialization of Innovation Technologies for Greenhouse Gas Mitigation," IPCC Expert Meeting on Industrial Technology Development, Transfer and Diffusion 21-23 September 2004, Tokyo, Japan.

[31] E. M. Rogers, *Diffusion of Innovations*, 5th ed., (New York: The Free Press, 1995).

[32] N. Rosenberg, “Learning by Using" in *Inside the Black Box*, ed. N. Rosenberg (Cambridge: Cambridge University Press,1982), 120-140.

[33] Massimo G. Colombo and Rocco Mosconi, "Complementarity and Cumulative Learning Effects in the Early Diffusion of Multiple Technologies," *The Journal of Industrial Economics*, Vol. 43, No. 1 (March 1995): 44-45.

[34] E.M. Rogers, *Diffusion of Innovations*, 4th ed., (New York: The Free Press, 1995).

[35] David J. Pannell, Graham R. Marshall, Neil Barr, Allan Curtis, Frank Vanclay and Roger Wilkinson. "Understanding and Promoting Adoption and Conservation Technologies by Rural Landholders," Unpublished manuscript, submitted to *Australian Journal of Experimental Agriculture*, (2005), http://www.general.uwa.edu.au/u/dpannell/dp0502.htm.

[36] Michael Burton, Dan Rigby and Trevor Young, "Modeling the Adoption of Organic Horticultural Technology in the UK using Duration Analysis," *The Australian Journal of Agricultural and Resource Economics*, 47:1, (2003): 29-54.

[37] Vernon W. Ruttan, "Sources of Technical Change: Induced Innovation, Evolutionary Theory, and Path Dependence," *Technological Change and the Environment*, ed. Arnulf Grubler, Nebojsa Nakicenovic and William D. Nordhaus, (Washington, DC: Resources for the Future and the International Institute for Applied Systems Analysis (IIASA), 2002), 364-388.

[38] Paul A. David, "Zvi Griliches on Diffusion, Lags and Productivity Growth…Connecting the Dots," Prepared for the Conference on R&D, Education and Productivity, Held in Memory of Zvi Griliches (1930-1999).

[39] Zvi Griliches, "Hybrid Corn: An Exploration in the Economics of Technological Change," *Econometrica*, 25 (1957): 501-522.

[40] R.E. Lucas, Jr., "Tests of a Capital-theoretic Model of Technological Change," *Review of Economic Studies*, 34 (1967): 175-180.

[41] U. Benzion and V.W. Ruttan, "Aggregate Demand and the Rate of Technical Change," in *Induced Innovation: Technology Institutions and Development*, H.P. Binswanger, and V.W. Ruttan, eds, (Baltimore, MD: The Johns Hopkins University Press, 1978), 261-275.

[42] Colin G. Thirtle and Vernon W. Ruttan, "The Role of Demand and Supply" *Generation and Diffusion of Technical Change*, (Switzerland: Harwood Academic Press, 1987).

[43] For a discussion of Fellner's work, see V.W. Ruttan, "Sources of Technical Change: Induced Innovation, Evolutionary Theory, and Path Dependence," *Technological Change and the Environment*, eds. Arnulf Grubler, Nebojsa Nakicenovic and William D. Nordhaus, (Washington, DC: Resources for the Future and the International Institute for Applied Systems Analysis (IIASA), 2002), 364-388.
[44] C. Kennedy, "Induced Bias in Innovation and the Theory of Distribution," *Economic Journal*, 74 (1964), 541-547.
[45] S. Ahmad, "On the Theory of Induced Innovation," *Economic Journal*, 76 (1966): 344-357.
[46] W. D. Nordhaus, "Some Skeptical Thoughts on the Theory of Induced Innovation," *Quarterly Journal of Economics*, 87 (1973): 208-219.
[47] Leon E. Clark and John P. Weyant, "Modeling Induced Technological Change: an Overview." *Technological Change and the Environment*, eds, Arnulf Grubler, Nebojsa Nakicenovic and William D. Nordhaus, (Washington, DC: Resources for the Future Press, 2002), 320-363.
[48] Winston W. Chang, "The Neoclassical Theory of Technical Progress." *The American Economic Review*, Vol. 60, No. 5 (Dec., 1970): 912-923.
[49] R.G. Newell, "Environmental Policy and Technological Change: the Effects of Economic Incentives and Direct Regulation on Energy-Saving Regulation," (PhD dissertation, Harvard University, 1997).
[50] R.R. Nelson and S. G. Winter, *An Evolutionary Theory of Economic Change*, (Cambridge, MA: Harvard University Press, 1982).
[51] V. W. Ruttan, "Sources of Technical Change: Induced Innovation, Evolutionary Theory, and Path Dependence," *Technological Change and the Environment*, eds. Arnulf Grubler, Nebojsa Nakicenovic and William D. Nordhaus, (Washington, DC: Resources for the Future and the International Institute for Applied Systems Analysis (IIASA), 2002), 364-388.
[52] Paul A. David, "Clio and the Economics of QWERTY," *American Economic Review* 76 (1985): 332-337.
[53] D. Popp, "Induced Innovation and Energy Prices," *American Economic Review*, Vol. 92, No. 1, (2002): 160-180
[54] D. Popp, "Lessons from Patents: Using Patents to Measure Technological Change in Environmental Models," *NBER Working Paper 9978*, (Cambridge, MA: National Bureau of Economic Research, 2003).
[55] S. Schmitz, "Do Energy Prices Induce Progress in Energy-related Technology? An Empirical Study," *HWWWA Discussion Paper* No. 147, (Hamburg: Hamburg Institute of International Economics, 2001).
[56] J.P.M. Sijm, "Induced Technological Change and Spillovers in Climate Policy Modeling," *ECN Working Paper Series* No. ECN-D-04-073 (The Netherlands: ECN Publications, 2004), Chapter 4: Does Climate Policy Induce Technological Change?
[57] Interviews with developers, owners and industry associations.
[58] Chulho Jung, Kerry Krutilla, and Roy Boyd, "Incentives for Advanced Pollution Abatement Technology at the Industry Level: An Evaluation of Policy Alternatives," *Journal of Environmental Economics and Management* 30 (1996): 95-111.
[59] A. Marin, "Firm Incentives to Promote Technological Change in Pollution Control: Comment." *Journal of Environmental Economics and Management* 21 (1991): 297-300.
[60] Scott R. Milliman and Raymond Prince, "Firm Incentives to Promote Technological Change in Pollution Control," *Journal of Economics and Management* 13 (1989): 301-312.
[61] N. Ireland and P. Stoneman, "Technological Diffusion, Expectations and Welfare," *Oxford Economic Papers*, new Series, Vol. 38, No. 2 (Jul., 1986): 283-304.
[62] K.J. Arrow, "The Economic Implications of Learning by Doing," *Review of Economic Studies*, Vol. 29, (1962): 153-173.
[63] A. R. Jaffe, R. Newell, and R. Stavins, "Technological Change and the Environment," *NBER Working Paper Series*, Working paper 7970, (Cambridge, MA: National Bureau of Economic Research, 2000), www.nber.org/papers/w7970.
[64] A. Jaffe, R. Newell, and R. Stavins, "Technological Change and the Environment," *NBER Working Paper Series*, Working paper 7970, (Cambridge, MA: National Bureau of Economic Research, 2000), www.nber.org/papers/w7970.

[65] Wayne B. Gray and Ronald J. Shadbegian, "Environmental Regulation, Investment Timing, and Technology Choice." *The Journal of Industrial Economics*, Vol. 46, No. 2, Inside the Pin-Factor: Empirical Studies Augmented by Manager Interviews: A Symposium (Jun., 1998): 235-256.
[66] Richard G. Newell, Adam B. Jaffe, and Robert N. Stavins., "The Induced Innovation Hypothesis and Energy-Saving Technological Change," *Technological Change and the Environment*, eds., Arnulf Grubler, Nebojsa Nakicenovic and William D. Nordhaus, (Washington, DC: Resources for the Future and the International Institute for Applied Systems Analysis (IIASA), 2002), 97-126.
[67] John A. Alic, David C. Mowery, Edward S. Rubin, *U.S. Technology and Innovation Policies: Lessons for Climate Change*, (Washington, DC: Pew Center on Global Climate Change Policy Series, 2003), http://www.pewclimate.org/global-warming-in-depth/all_reports/technology_policy/.
[68] D. Popp, "Induced Innovation and Energy Prices," *American Economic Review*, Vol. 92, No. 1, (2002): 160-180.
[69] J. Lanjouw, and A. Mody, "Innovation and the International Diffusion of Environmental Responsive Technology," *Research Policy*, Vo. 25, No. 4, (1996): 549-571.
[70] A. Jaffe, and K. Palmer, "Environmental Regulation and innovation," *Review of Economics and Statistics*, Vol. 79, No. 4, (1997): 610-619.
[71] The pros and cons of using patent data compared to R&D expenditures as a proxy for innovation is beyond the scope of this paper since I will not be using either in this analysis. For a summary of the pros and cons, see J.P.M. Sijm, "Induced Technological Change and Spillovers in Climate Policy Modeling," *ECN Working Paper Series* No. ECN-D-04-073 (The Netherlands: ECN Publications, 2004).
[72] J.P.M. Sijm, "Induced Technological Change and Spillovers in Climate Policy Modeling," *ECN Working Paper Series* No. ECN-D-04-073 (The Netherlands: ECN Publications, 2004), 25.
[73] Bronwyn H. Hall, "Innovation and Diffusion," *NBER Working paper series* 10212, (Cambridge, MA: National Bureau of Economic Research, 2003), 6, Http://www.nber.org/papers/w10212
[74] Michael Burton, Dan Rigby and Trevor Young, "Modeling the Adoption of Organic Horticultural Technology in the UK using Duration Analysis," *The Australian Journal of Agricultural and Resource Economics*, 47:1, (2003): 29-54.
[75] Colin G. Thirtle and Vernon W. Ruttan, *The Role of Demand and Supply in the Generation and diffusion of Technical Change* (Switzerland: Harwood Academic publishers, 1987).
[76] Bronwyn H. Hall, "Innovation and Diffusion," *NBER Working paper series* 10212, (Cambridge, MA: National Bureau of Economic Research, 2003), Http://www.nber.org/papers/w10212
[77] Christopher Palmberg, "Successful Innovation, the Determinants of Commercialization and Break-even Durations of Innovations," *VTT Group for Technology Studies*, (Finland: VTT Publications, 2002).
[78] N. Ireland and P. Stoneman, "Technological Diffusion, Expectations and Welfare," *Oxford Economic Papers*, new Series, Vol. 38, No. 2 (Jul., 1986): 283-304.
[79] Massoud Karshenas and Paul L. Stoneman, "Rank, Stock, Order, and Epidemic Effects in the Diffusion of New Process Technologies: an Empirical Model." *The RAND Journal of Economics*, Vol. 24, No. 4 (Winter, 1993): 503-528.
[80] Massimo G. Colombo, and Rocco Mosconi, "Complementarity and Cumulative Learning Effects in the Early Diffusion of Multiple Technologies," *The Journal of Industrial Economics*, Vol. 43, No. 1 (Mar., 1995): 13-48.
[81] Paul Stoneman and Myung-Joong Kwon, "The Diffusion of Multiple Process Technologies," *The Economic Journal*, Vol. 104, No. 423 (Mar., 1994): 420-431.
[82] Michael Burton, Dan Rigby and Trevor Young, "Modeling the Adoption of Organic Horticultural Technology in the UK using Duration Analysis," *The Australian Journal of Agricultural and Resource Economics*, 47:1,(2003): 29-54.
[83] Massoud Karshenas, and Paul L. Stoneman, "Rank, Stock, Order, and Epidemic Effects in the Diffusion of New Process Technologies: an Empirical Model." *The RAND Journal of Economics*, Vol. 24, No. 4 (Winter, 1993): 503-528.
[84] Scott D. Bennett, "Parametric Models, Duration Dependence and Time-Varying Data Revisited," *American Journal of Political Science*, Vol. 43, No. 1 (Jan., 1999): 256-270.
[85] Tony Lancaster, "The Econometric Analysis of Transition Data," *Econometric Society Monographs*, No. 17, (Cambridge, MA: Cambridge University Press, 1990).

[86] Mario A. Cleves, William W. Gould, and Roberto G. Gutierrez, *An Introduction to Survival Analysis Using Stata*, Revised Edition, (College Station, TX: STATA Corporation, 2004).
[87] David W. Hosmer and Stanley Lemeshow, *Applied Survival Analysis: Regression Modeling of Time to Event Data*, (New York, NY: Wiley Series in Probability and Statistics, 1999).
[88] Nicholas M. Kiefer, "Economic Duration Data and Hazard Functions," *Journal of Economic Literature*, Vol. 26, No. 2 (Jun., 1988): 646-679.
[89] David W. Hosmer and Stanley Lemeshow, *Applied Survival Analysis: Regression Modeling of Time to Event Data*, (New York, NY: Wiley Series in Probability and Statistics, 1999).
[90] Lawrence C. Hamilton, *Statistics With STATA*, (Belmont, CA: Duxbury/Wadsworth Group, 2003).
[91] Lawrence C. Hamilton, *Statistics With STATA*, (Belmont, CA: Duxbury/Wadsworth Group, 2003).
[92] Colin G. Thirtle and Vernon W. Ruttan, *The Role of Demand and Supply in the Generation and diffusion of Technical Change*, (Switzerland: Harwood Academic publishers, 1987).
[93] C. Timothy Koeller, "Innovation, Market Structure and Firm Size: A simultaneous Equations Model," *Managerial and Decision Economics*, Vol. 16, No. 3 (May-Jun., 1995): 259-269.
[94] P. Stoneman, *The Economic Analysis of Technological Change*, (London: Oxford University Pres, 1983).
[95] Colin G. Thirtle and Vernon W. Ruttan. *The Role of Demand and Supply in the Generation and diffusion of Technical Change*, (Switzerland: Harwood Academic publishers, 1987), 114.
[96] Interviews with developers, owners and industry associations.
[97] Massoud Karshenas and Paul L. Stoneman, "Rank, Stock, Order and Epidemic Effects in the Diffusion of New Process Technologies: An Empirical Model," *The RAND Journal of Economics*, Vol. 24, No. 4 (Winter, 1993): 503-528.
[98] For example: USEPA, *Landfill Gas Energy Utilization Experience: Discussion of Technical and Non-Technical Issues, Solutions, and Trends*, EPA-600/R-95-035, (Washington, DC: US Environmental Protection Agency, March 1995).
[99] USEPA, *Federal Plan Requirements for Municipal Solid Waste Landfills*. 40 CFR Part 62, Federal Register 64:215 (60689-60706) (Washington, DC: National Archives and Records Administration, 1999).
[100] Interviews with developers, owners and industry associations.
[101] Database of state incentives for renewable energy (DSIRE). Interstate Renewable Energy Council. www.dsireusa.org (accessed 2005).
[102] Interviews with developers, owners and industry associations.
[103] Global Energy, *IRS Section 29 (redesignated to IRS Section 45J and IRS Section 45K) Nonconventional Fuel Credits,* http://www.section29info.com/
[104] SCS Engineers, "Comparative Analysis of Landfill Gas Utilization Technologies," Prepared for Northeast Regional Biomass Program, *CONEG Policy Research Center, Inc. Hall of the States*, File No. 0293066 (Washington DC, March 1997).
[105] Global Energy, *IRS Section 29 (redesignated to IRS Section 45J and IRS Section 45K) Nonconventional Fuel Credits,* http://www.section29info.com/.
[106] USDOE/EIA, *Analysis of Five Selected Tax Provisions of the Conference Energy Bill of 2003,* No. SR-01AF/2004-01, (Washington, DC: US Department of Energy, Energy Information Agency, 2004), http://www.eia.doe.gov/oiaf/servicerpt/ceb/fuel.html.
[107] USDOE/EIA, *Federal Energy Market Interventions 1999: Primary Energy*. (Washington, DC: US Department of Energy, Energy Information Agency, 1999), http://www.eia.doe.gov/oiaf/servicerpt/subsidy/pdf/appendix_b.pdf.
[108] Interviews with developers, owners and industry associations.
[109] USEPA, *Turning a Liability into an Asset: A Landfill Gas-to-Energy Project Development Handbook*, EPA 430-B-96-0004, (Washington DC: US Environmental Protection Agency, September 1996).
[110] Paul L. Stoneman and Paul A. David, "Adoption Subsidies vs. Information Provision as Instruments of Technology Policy," *The Economic Journal*, Vol. 96, Supplement: Conference Papers (1986): 142-150.
[111] Paul Stoneman and Paul Diederen, "Technology Diffusion and Public Policy," *The Economic Journal*, Vol. 104, No. 425 (July, 1994): 918-930.
[112] Interviews with developers, owners and industry associations.

[113] Julio Videras and Anna Alberini, "The Appeal of Voluntary Environmental Programs: which Firms Participate and Why?" *Contemporary Economic Policy* Vol. 18, No. 4, (Oct., 2000): 449-461.
[114] National Research Council, *New Tools for Environmental Protection: Education, Information and Voluntary Measures*, eds., Thomas Dietz and Paul C. Stern, (Washington, DC: National Academy Press, 2002).
[115] F.P. Wong, *Alternative Energy and Regulatory Policy: Till Death Do We Part* (Commerce, CA: Pacific Energy, March 1992), quoted in USDOE/EIA, *Renewable Energy Report, 1996*. (Washington, DC: US Department of Energy, Energy Information Agency, 1999), http://www.eia.doe.gov/oiaf/servicerpt/subsidy/pdf/appendix_b.pdf.
[116] John Dernbach, "Moving the Climate Change Debate from Models to Proposed Legislation: Lessons from State Experience," *Environmental Law Reporter*, 30 ELR 10933, (Washington, DC: Environmental Law Institute, 2000).
[117] John Dernbach, "Moving the Climate Change Debate from Models to Proposed Legislation: Lessons from State Experience," *Environmental Law Reporter*, 30 ELR 10933, (Washington, DC: Environmental Law Institute, 2000).
[118] Interviews with developers, owners and industry associations.
[119] Database of state incentives for renewable energy (DSIRE). Interstate Renewable Energy Council. www.dsireusa.org (accessed 2005).
[120] Database of state incentives for renewable energy (DSIRE). Interstate Renewable Energy Council. www.dsireusa.org (accessed 2005).
[121] Database of state incentives for renewable energy (DSIRE). Interstate Renewable Energy Council. www.dsireusa.org (accessed 2005).
[122] Interviews with developers, owners and industry associations.
[123] Interviews with developers, owners and industry associations.
[124] Interviews with developers, owners and industry associations.
[125] USEPA, *Fact Sheet: Frequently Asked Questions About Landfill Gas and How it Affects Public Health, Safety and the Environment October 2006,* http://www.epa.gov/lmop/faq-3.htm.
[126] USEPA, *Fact Sheet: Frequently Asked Questions About Landfill Gas and How it Affects Public Health, Safety and the Environment October 2006,* http://www.epa.gov/lmop/faq-3.htm.
[127] USEPA, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2003*, http://www.epa.gov/msw/pubs/msw05rpt.pdf.
[128] USEPA, LMOP Landfill Database, http://www.epa.gov/lmop/proj/index.htm#1.
[129] Waste Management, Inc., *Waste Management, Inc. 2002 Annual Report*. www.wm.com.
[130] USEPA, LMOP Landfill Database, http://www.epa.gov/lmop/proj/index.htm#1.
[131] Interviews with developers, owners and industry associations.
[132] Interviews with developers, owners and industry associations.
[133] Union of Concerned Scientists, *Powerful Solutions: Seven Way s to Switch America to Renewable Electricity*, January 1999 (tables updated October 2005), www.ucsusa.org/clean_energy.
[134] Database of state incentives for renewable energy (DSIRE). Interstate Renewable Energy Council. www.dsireusa.org (accessed 2006).
[135] CFR, *Determining Conformity of General Federal Actions to State or Federal Implementation Plans; Final Rule,* 40 CFR Parts 6, 51 and 93, (Washington, DC: Code of Federal Regulation, November 30, 1993).
[136] USEPA, *Turning a Liability into an Asset: A Landfill Gas-to-Energy Project Development Handbook*, EPA 430-B-96-0004, (Washington DC: US Environmental Protection Agency, September 1996).
[137] E. Mansfield, "Technical Change and the Rate of Imitation," *Econometrica*, vol. 29, (October 1961): 741-766.
[138] Michael Burton, Dan Rigby and Trevor Young, "Modeling the Adoption of Organic Horticultural Technology in the UK using Duration Analysis," *The Australian Journal of Agricultural and Resource* Economics, 47:1, (2003): 29-54.
[139] David W. Hosmer Jr. and Stanley Lemeshow, *Applied Survival Analysis: Regression Modeling of Time to Event Data,* (New York, NY: Wiley Series in Probability and Statistics, 1999).
[140] Nicholas M. Kiefer, "Economic Duration Data and Hazard Functions," *Journal of Economic Literature*, Vol. 26, No. 2 (Jun., 1988): 646-679.

[141] Lawrence C. Hamilton, *Statistics With STATA*, (Belmont, CA: Duxbury/Wadsworth Group, 2003).
[142] USDOE/EIA, *Federal Energy Market Interventions 1999: Primary Energy*. (Washington, DC: US Department of Energy, Energy Information Agency, 1999), http://www.eia.doe.gov/oiaf/servicerpt/subsidy/pdf/appendix_b.pdf.
[143] Interviews with developers, owners and industry associations.
[144] T.J. Bartik, "The Effects on Environmental Regulation on Business Location in the United States," *Growth and Change*, 19 (Summer, 1988): 22-44.
[145] W. B. Gray, "Manufacturing Plant Location: Does State Pollution Regulation Matter?" *NBER Working Paper Series*, No. 5880, (Cambridge, MA: National Bureau of Economic Research, 1997).
[146] Wayne B. Gray and Ronald J. Shadbegian, "Environmental Regulation, Investment Timing, and Technology Choice," *The Journal of Industrial Economics*, Vol. 46, No. 2 Inside the Pin-Factory: Empirical Studies Augmented by Manager Interviews: A Symposium (Jun., 1998): 235-256.
[147] Bronwyn H. Hall, "Innovation and Diffusion," *NBER Working paper series*, Working paper number 10212, (Cambridge, MA: National Bureau of Economic Research, 2003), Http://www.nber.org/papers/w10212
[148] Massimo G. Colombo and Rocco Mosconi, "Complementarity and Cumulative Learning Effects in the Early Diffusion of Multiple Technologies," *The Journal of Industrial Economics*, Vol. 43, No. 1 (Mar., 1995): 13-48.
[149] Paul Stoneman and Myung-Joong Kwon, "The Diffusion of Multiple Process Technologies," *The Economic Journal*, Vol. 104, No. 423 (Mar., 1994): 420-431.
[150] Wayne B. Gray and Ronald J. Shadbegian, "Environmental Regulation, Investment Timing and Technology Choice," *The Journal of Industrial Economics*, Vol. 46, No. 2, Inside the Pin-Factory: Empirical Studies Augmented by Manger Interviews: A Symposium (Jun., 1998): 235-256.
[151] USEPA, *Turning a Liability into an Asset: A Landfill Gas-to-Energy Project Development Handbook*, EPA 430-B-96-0004, (Washington DC: US Environmental Protection Agency, September 1996).
[152] Interviews with developers, owners and industry associations.
[153] USEPA, *U.S. Methane Emissions 1990–2020: Inventories, Projections, and Opportunities for Reductions,* EPA 430-R-99-013, (Washington, DC: US Environmental Protection Agency, 1999).
[154] USEPA, *U.S. Methane Emissions 1990–2020: Inventories, Projections, and Opportunities for Reductions,* EPA 430-R-99-013, (Washington, DC: US Environmental Protection Agency, 1999).
[155] John A. Alic, David C. Mowery, Edward S. Rubin, *U.S. Technology and Innovation Policies: Lessons for Climate Change*, (Washington, DC: Pew Center on Global Climate Change Policy Series, 2003), http://www.pewclimate.org/global-warming-in-depth/all_reports/technology_policy/.
[156] USEPA, LMOP Landfill Database, http://www.epa.gov/lmop/proj/index.htm#1.
[157] USEPA, *Case Study on Waste Management*, http://www.epa.gov/lmop/res/wmi.htm.
[158] USEPA, *Turning a Liability into an Asset: A Landfill Gas-to-Energy Project Development Handbook*, EPA 430-B-96-0004, (Washington DC: US Environmental Protection Agency, September 1996).
[159] USEPA, LMOP Accomplishments, http://www.epa.gov/lmop/accomplish.htm.
[160] USEPA, *Fuel Cells: Demonstrating the Power of Landfill Gas*, http://www.epa.gov/lmop/res/fuelcell.htm.
[161] Interviews with developers, owners and industry associations.
[162] Lawrence C. Hamilton, *Statistics With STATA*, (Belmont, CA: Duxbury/Wadsworth, 2003).
[163] USDOE/EIA, *Federal Energy Market Interventions 1999: Primary Energy*. (Washington, DC: US Department of Energy, Energy Information Agency, 1999), http://www.eia.doe.gov/oiaf/servicerpt/subsidy/pdf/appendix_b.pdf.
[164] Interviews with developers, owners and industry associations.
[165] Pew Center on Global Climate Change, *Legislation in the 110th Congress Related to Global Climate Change*, http://www.pewclimate.org/what_s_being_done/in_the_congress/110thcongress.cfm.
[166] Pew Center on Global Climate Change, *Summary of the Energy Policy Act of 2005*, http://www.pewclimate.org/policy_center/analyses/hr_6_summary.cfm
[167] Union of Concerned Scientists, *Powerful Solutions: Seven Way s to Switch America to Renewable Electricity*, January 1999 (tables updated October 2005), www.ucsusa.org/clean_energy

[168] Pew Center on Global Climate Change, *Legislation in the 110th Congress Related to Global Climate Change*, http://www.pewclimate.org/what_s_being_done/in_the_congress/110thcongress.cfm.
[169] Database of state incentives for renewable energy (DSIRE). Interstate Renewable Energy Council. http://www.dsireusa.org/documents/SummaryMaps/RPS_Map.ppt (accessed November 2007).
[170] For a discussion on post-estimation techniques, see: Mario A. Cleves, William W. Gould and Roberto G. Gutierrez, *An Introduction to Survival Analysis Using STATA*, revised edition (College Station, TX: Stata Press, 2004).
[171] Electricity and oil prices used in the analysis are 11/15/07 average US prices from USDOE/EIA's website, www.eia.doe.gov (accessed 11/17/07).
[172] Using IPCC methodology, the conversion from carbon price ($/ton of Carbon) to electricity price ($/kWh):
C = (44/12)*CO2 = (44/12)*[(production of coal in metric tons)*(Oxidation factor)*(amount of carbon)]
= (44/12)*[(1 ton of coal)*(0.982)8(0.746)]
1 ton of coal = 2.686 tons of carbon
1 ton of coal produces approximately 6976.191 kWh of electricity
2.686 tons of carbon = 1 ton of coal = 6976.191 kWh
1 kWh of electricity = 0.000385 tons carbon
Therefore,
$50/ ton of Carbon = $0.01925/kWh
Using the IPCC methodology, the conversion of carbon into barrel of oil:
1 barrel of oil = (44/12)*[(production of one barrel)*(oxidation factor)*(carbon content)]
= (44/12)*[(1)*(0.918)*(0.85)]
= 2.861 tons of carbon/barrel of oil
Therefore,
$50/ton of carbon = $143.05/barrel of oil

[173] Using IPCC methodology, the conversion from carbon price ($/ton of Carbon) to electricity price ($/kWh):
C = (44/12)*CO2 = (44/12)*[(production of coal in metric tons)*(Oxidation factor)*(amount of carbon)]
= (44/12)*[(1 ton of coal)*(0.982)8(0.746)]
1 ton of coal = 2.686 tons of carbon
1 ton of coal produces approximately 6976.191 kWh of electricity
2.686 tons of carbon = 1 ton of coal = 6976.191 kWh
1 kWh of electricity = 0.000385 tons carbon
Therefore,
$62/ ton of Carbon = $0.02387/kWh
Using the IPCC methodology, the conversion of carbon into barrel of oil:
1 barrel of oil = (44/12)*[(production of one barrel)*(oxidation factor)*(carbon content)]
= (44/12)*[(1)*(0.918)*(0.85)]
= 2.861 tons of carbon/barrel of oil
Therefore,
$62/ton of carbon = $177.382/barrel of oil

[174] G. Marland and R.M. Rotty, *Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-1981*, (U.S. Department of Energy, Washington, DC: DOE/NBB-0036, TR003, 1983).
[175] Uncertainty of these estimates can range from +-3 to +-4 percent.
[176] For Example, Mark Gielecki, Fred Mayes, Lawrence Prete*, Incentives, Mandates and Government Programs for Promoting Renewable Energy*, (Washington, DC: US Department of Energy, Energy Information Agency, 2001), http://www.eia.doe.gov/cneaf/solar.renewables/rea_issues/incent.html

Appendix A: Interview Coverage

Developers, landfill owners/operators, experts and associations:

- **Companies formally interviewed represent 30 percent of the total projects over the time period of the study.**
- **These companies have facilities in 41 states; these 41 states account for approximately 92% of all LFG Projects.**

Formal Structured Interviews	States covered:
Waste Management, Inc ○ Waste Management (owns and operates landfills and transfer stations) ○ Wheelabortor (development company under Waste Management)	LFG Facilities owned by WM or partnership in CA, CT, FL, GA, IA, IL, IN, MI, MO, NH, NY, OH, OR, PA, TN, TX, WI WM sells LFG to third party facilities in FL, GA, IL, IN, KY, MA, MD, MI, MN, MS, NE, OH, SC, PA, TX, VA, WA
Enerdyne, Inc	NC, PA, VA
Gas Recovery Systems (GRS), Inc.	CA, HI, IL, IN, MA, MI, MN, NC, NY, TX, VA
DTE Biomass Energy	AL, AZ, CA, FL, IL, KS, MA, MI, NC, OH, OK, TX, UT

National Partnerships Formally Interviewed:
Landfill Methane Outreach Program, USEPA
Solid Waste Association of North America

Landfill Tours:	Montgomery County Landfill, MD
	Fairfax County Landfill, VA

I would also like to thank representatives from the following companies who provided informal comments on my dissertation:

AEA Technologies	OWT, Inc.
Landfill Strategies, Inc.	Firm Green Energy

Appendix B: Summary Statistics for Observation Year 2003

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
Observation Year	1093	2003	0	2003	2003
REPI	1093	1	0	0	1
NSPS	1093	1.461116	.4987139	1	2
LMOP	1093	13.16102	8.076311	0	27
RPS rate	1093	.2241537	.3818242	0	3
Dichotomous RPS	1093	.3641354	.4814072	0	1
Net Metering	1093	.2854529	.4518366	0	1
Interconnection Standard	1093	.441903	.4968406	0	1
Financial Instruments (number)	1093	1.353156	2.115199	0	9
Tax	1093	.1665142	.3727121	0	1
Loan	1093	.0914913	.2884385	0	1
Grants	1093	.2159195	.4116471	0	1
Ozone county attainment*State target	1093	.9835316	1.514794	0	4
CO country attainment*State target	1093	.2031107	.86386	0	4
NO2 county attainment*State target	1093	0	0	0	0
Electricity Price	1085	5.355094	1.970603	2.966747	11.39855
Oil Price	1093	27.56	0	27.56	27.56
Landfill Name	1093				
County	1093				
State	1093				
Size	1076	2.405204	1.028583	1	7
Precipitation	1093	.9423605	.2331672	0	1
Methane Potential	1076	2.261152	1.153202	0	7
Private Ownership	1065	.4544601	.4981557	0	1
CA Dummy	1093	.116194	.3206041	0	1
NOx Emissions by Technology	550	2.143904	1.050719	.001	3.1
Adoption	1093	.5068618	.5001818	0	1
Electricity Projects	391	1	0	1	1
Direct Use Projects	124	1	0	1	1
Reciprocating Engine Projects	289	1	0	1	1
Non-Reciprocating Engine Projects	102	1	0	1	1
Niche Technology Projects	11	1	0	1	1

Glossary

Million Metric Tons	1,000,000 kilograms which is equivalent to 1 Tera gram
Tera grams	10^12 grams which is equivalent to a Million Metric Ton
Mega grams	10^6 grams
Additionality	The issue of whether or not a specific amount of reduction occurred because of a climate change policy (additional tons). If the reductions are not additional, or due to the climate change policy, in other words, they would have occurred anyway, there is an additionality issue.
Anyway Tons	Reductions that would occur without a climate change policy and should be considered in a business-as-usual baseline.
Diffusion	"the word diffusion is commonly used to describe the process by which individuals and firms in a society/economy adopt a new technology, or replace an older technology with a new technology." Hall, 2004 pg. 2
Global Warming Potentials	An index based on the heat trapping ability of a gas where CO2 is the reference and has a GWP of 1. See table 2.
Offsets	Reductions purchased from a sector that is not directly under a cap-and-trade cap.

Bibliography

Abbring, Jaap, H. and Gerard J. van den Berg. "The Unobserved Heterogeneity Distribution in Duration Analysis." *Tinbergen Institute Discussion Paper*, TI 2006-059/3. Amsterdam: Vrije Universiteit Amsterdam and Tinbergen Institute, 2006.

Ahmad, S. "On the Theory of Induced Innovation," *Economic Journal*, 76 (1966):344-357.

Aidt, Toke S., and Jayasri Dutta. "Transitional Politics: Emerging Incentive-based Instruments in Environmental Regulation." *The Fondazione Eni Enrico Mattei Note di Lavoro Series*, October 2001. http://www.feem.it/web/activ/_activ.html.

Alic, John A., David C. Mowery, and Edward S. Rubin. "U.S. Technology and Innovation Policies: Lesson for Climate Change." *Pew Center on Global Climate Change Policy Series*. Washington, DC: Pew Center, 2003. http://www.pewclimate.org/global-warming-in-depth/all_reports/technology_policy/.

Anderson, D. "Technical Progress and Pollution Abatement: An Economic Review of Selected Technologies and Practices." *Imperial College Working Papers*. London: Imperial College, 1999.

Anderson, D., M. Grubb, and J. Kohler. "Induced Technical Change in Energy/Environmental Modeling: Analytic Approaches and Implications." *Imperial College Working Papers*. London: Imperial College, 2000.

Arrow, K. "The Economic Implications of Learning-by-Doing." *Review of Economic Studies* 29 (1962): 155-73.

Bartik, T.J. "The Effects on Environmental Regulation on Business Location in the United States." *Growth and Change,* 19 (Summer, 1988): 22-44.

Bennett, D. Scott. "Parametric Models, Duration Dependence, and Time-Varying Data Revisited." *American Journal of Political Science* 43, no. 1 (1999): 256-70.

Bernard, Susan M., Jonathan M. Samet, Anne Grambsch, Kristie L. Ebi and Isabelle Romieu. "The Potential Impacts of Climate Variability and Change on Air Pollution-Related Health Effects in the United States." *Environmental Health Perspectives*, vol. 109, supplement 2, (May 2001): 199-209.

Blossfeld, Hans-Peter, Katrin Golsch, Gotz Rohwer. *Event History Analysis with STATA*. Mahwah, NJ: Lawrence Erlbaum Associates, Publishers, 2007.

Binswanger, Hans P., and Vernon W. Ruttan. *Induced Innovation: Technology, Institutions and Development*. Baltimore and London: The Johns Hopkins University Press, 1978.

Box-Steffensmeier, Janet M., and Bradford S. Jones. *Event History Modeling: A guide for Social Scientists.* Cambridge, MA: Cambridge University Press, 2006.

Burton, Michael, Dan Rigby, and Trevor Young. "Modeling the Adoption of Organic Horticultural Technology in the UK Using Duration Analysis." *The Australian Journal of Agricultural and Resource Economics* 47, no. 1 (2003): 29-54.

CFR. *Determining Conformity of General Federal Actions to State or Federal Implementation Plans; Final Rule,* 40 CFR Parts 6, 51 and 93. Washington, DC: Code of Federal Regulation, November 30, 1993.

Chang, Winston W. "The Neoclassical Theory of Technical Progress." *The American Economic Review*, Vol. 60, No. 5 (Dec., 1970): 912-923.

Cleves, Mario A., William W. Gould, and Roberto G. Gutierrez. *An Introduction to Survival Analysis Using Stata.* College Station, TX: STATA Press, 2004.

Colombo, Massimo G., and Rocco Mosconi. "Complementarity and Cumulative Learning Effects in the Early Diffusion of Multiple Technologies." *The Journal of Industrial Economics* 43, no. 1 (1995): 13-48.

Corrocher, Nicoletta, and Roberto Fontana. "Expectations, Networks Effects and Timing of Technology Adoption: Some Empirical Evidence from a Sample of SMEs in Italy." Paper presented at the DRUID Tenth Anniversary Summer Conference, Copenhagen, Denmark 2005.

Dadi, Leggesse, Leggesse Dadi, Michael Burton, and Adam Ozanne. "Duration Analysis of Technological Adoption in Ethiopian Agriculture." *Journal of Agricultural Economics* 55, no. 3 (2004): 613.

David, Paul A., and M. Thomas, eds. *The Economic Future in Historical Perspective.* Oxford: Oxford University Press, 2003.

David, Paul A. "Path Dependence, Its Critics and Quest for 'Historical Economics'." Paper presented at the European Association for Evolutionary Political Economy, Athens, Greece 2000.

David, Paul A. "Zvi Griliches on Diffusion, Lags and Productivity Growth…Connecting the Dots." Prepared for the Conference on R&D, Education and Productivity, Held in Memory of Zvi Griliches (1930-1999).

David, Paul A. "Clio and the Economics of QWERTY," *American Economic Review* 76 (1985): 332-337.

David, Paul A. *Technical Choice Innovation and Economic Growth: Essays on American and British Experience in the Nineteenth Century*. Cambridge, MA: Cambridge University Press, 1975.

Dernbach, John. "Moving the Climate Change Debate from Models to Proposed Legislation: Lessons from State Experience." *Environmental Law Institute* 30, no. ELR 10933 (2000).

DSIRE. *Database of State Incentives for Renewable Energy*. http://www.dsireusa.org.

Energy Nexus Group. *Technology Characterization: Fuel Cells*. Prepared for USEPA. Washington, DC: April 2002.

Energy Nexus Group. *Technology Characterization: Microturbines*. Prepared for USEPA. Washington, DC: March 2002.

Energy Nexus Group. Technology *Characterization: Gas Turbines*. Prepared for USEPA. Washington, DC: February 2002.

Energy Nexus Group. *Technology Characterization: Steam Turbines*. Prepared for USEPA. Washington, DC: March 2002.

Energy Nexus Group. *Technology Characterization: Reciprocating Engines*. Prepared for USEPA. Washington, DC: February 2002.

Faria, Ana, Paul Fenn, and Alistair Bruce. "A Count Data Model of Technology Adoption." *Journal of Technology Transfer*, Vol. 28 (2003): 63-79.

Feldman, Maryann P., and Richard Florida. "The Geographic Sources of Innovation: Technological Infrastructure and Product Innovation in the United States." *Annals of the Association of American Geographers* 84, no. 2 (1994): 210-29.

Flannery, Brian P., and Haroon S Kheshgi. "An Industry Perspective on Successful Development and Global Commercialization of Innovation Technologies for Greenhouse Gas Mitigation." IPCC Expert Meeting on Industrial Technology Development, Transfer and Diffusion 21-23 September 2004, Tokyo, Japan.

Fiore, A.M., Jacob, D.J., Field, B.D., Streets, D.G., Fernandes, S.D., Jang, C. "Linking Ozone Pollution with Climate Change: The Case for Controlling Methane." *Geophys, Res. Lett*. 29 (2002): 25.

Fiorino, Daniel J. *Making Environmental Policy*. Berkeley, CA: University of California Press, 1995.

Frondel, Manuel, and Christoph M. Schmidt. "Evaluating Environmental Programs: The Perspective of Modern Evaluation Research." *IZA Discussion Paper* No. 397. Bonn: Institute for the Study of Labor (IZA), November 2001. http://papers.ssrn.com/abstract =290905.

Gerlagh, Reyer, and Wietze Lise. "Induced Technological Change Under Carbon Taxes." Unpublished manuscript from the Institute for Environmental Studies, Faculty of Earth and Life Sciences, Vrije Universiteit, Amsterdam, the Netherlands, 2003.

Gielecki, Mark, Fred Mayes, and Lawrence Prete. *Incentives, Mandates and Government Programs for Promoting Renewable Energy*. Washington, DC: U.S. Department of Energy, Energy Information Agency, 2001. http://www.eia.doe.gov/cneaf/solar.renewables/rea_issues/incent.html

Global Energy, Inc. *IRS Section 29 (redesignated to IRS Section 45J and IRS Section 45K) Nonconventional Fuel Credits.* http://www.section29info.com/

Goulder, Lawrence H. and Koshy Mathai. "Optimal CO_2 Abatement in the Presence of Induced Technological Change." *NBER Working Paper* 6494. Cambridge, MA: National Bureau of Economic Research, 1998.

Gray, Wayne B., and Ronald J. Shadbegian. "Environmental Regulation, Investment Timing, and Technology Choice." *The Journal of Industrial Economics*, Vol. 46, No. 2 Inside the Pin-Factory: Empirical Studies Augmented by Manager Interviews: A Symposium (Jun., 1998): 235-256.

Gray, W. B. "Manufacturing Plant Location: Does State Pollution Regulation Matter?" *NBER Working Paper Series*, No. 5880. Cambridge, MA: National Bureau of Economic Research, 1997.

Greene, William H. *Econometric Analysis*. New York, NY: MacMillan Publishing Company, 1990.

Griliches, Z. "The Search for R&D Spillovers." *Scandinavian Journal of Economics* 94 (1992): 29-47.

Griliches, Z. "Issues in Assessing the Contribution of Research and Development to Productivity Growth." *Bell Journal of Economics* 10, no. 1 (1979): 92-116.

Griliches, Z. "Hybrid Corn: An Exploration in the Economics of Technological Change." *Econometrica*, 25 (1957):501-522.

Grubb, M. "Economic Dimensions of Technological and Global Responses to the Kyoto Protocol." *Journal of Economic Studies* 27, no. 1/2 (2000): 111-25.

Grubb, M. "Technologies Energy Systems and the Timing of Co2 Abatement: An Overview of Economic Issues." *Energy Policy* 25 (1997): 159-72.

Grubb, M., and J. Kohler. "Induced Technical Change: Evidence and Implications for Energy-Environmental Modeling and Policy." In Report to the Deputy Secretary-General Organisation for Economic Cooperation and Development, Paris, 2000.

Grubler, A, and S. Messner. "Technological Change and the Timing of Mitigation Measures." *Energy Economics* 20, no. 5-6 (1998): 495-512.

Grubler, A, N. Nakicenovic, and D.G. Victor. "Modeling Technological Change: Implications for the Global Environment." *Annual Review of Energy and the Environment* 24 (1999): 545-69.

Grubler, Arnulf, Nebojsa Nakicenovic, and William D. Nordhaus, eds. *Technological Change and the Environment*. Washington, DC: Resources for the Future, 2002.

Hagedoorn, John. *The Dynamic Analysis of Innovation and Diffusion: A Study in Process Control*. London and New York: Pinter Publishers, 1989.

Hakkinen, Iida, and Roope Uusitalo. "The Effect of a Student Aid Reform on Graduation: a Duration Analysis." Unpublished manuscript from the Department of Economics, Uppsala University, Sweden, 2003.

Hall, Bronwyn H. "Innovation and Diffusion." *NBER Working Paper* No. 10212. Cambridge, MA: National Bureau of Economic Research, 2004. http://www.nber.org/papers/w10212

Hamilton, Lawrence C. *Statistics with STATA.* Belmont, CA: Duxbury/Wadsworth, 2003.

Hannan, Timothy H., and John M. McDowell. "The Determinants of Technology Adoption: The Case of the Banking Firm." *The RAND Journal of Economics*, Vol. 15, No. 3 (Autumn, 1984): 328-335.

Heckman, James J., and Christopher R. Taber. "Econometric Mixture Models and More General Models for Unobservables in Duration Analysis." *NBER Working Paper Series, Technical Working Paper* No. 157. Cambridge, MA: National Bureau of Economic Research, 1994.

Hosmer, David W., Jr., and Stanley Lemeshow. *Applied Survival Analysis: Regression Modeling of Time to Event Data*, Wiley Series in Probability and Statistics. New York, NY: John Wiley & Sons, Inc., 1999.

Industrial Economics, Incorporated. "Micro Hydrogen Fuel Cells." Washington, DC: US Environmental Protection Agency, 2004.

Ireland N. and P. Stoneman. "Technological Diffusion, Expectations and Welfare." *Oxford Economic Papers*, new Series, Vol. 38, No. 2 (Jul., 1986): 283-304.

Jaffe, A.R., R. Newell, and R. Stavins. "Technological Change and the Environment." *NBER Working Paper Series,* Working paper 7970. Cambridge, MA: National Bureau of Economic Research, 2000. www.nber.org/papers/w7970.

Jaffe, A., and K. Palmer. "Environmental Regulation and innovation." *Review of Economics and Statistics*, Vol. 79, No. 4, (1997): 610-619.

Jensen, Richard A. "Strategic Intrafirm Innovation Adoption and Diffusion." *Southern Economic Journal*, Vol. 68, No. 1 (Jul., 2001): 120-132.

Jorgensen, Rasmus. "A Duration Analysis of Danish Start-Ups." *CEBR Student Paper.* Copenhagen: Centre for Economic and Business Research, 2005.

Jung, Chulho, Kerry Krutilla, and Roy Boyd. "Incentives for Advanced Pollution Abatement Technology at the Industry Level: An Evaluation of Policy Alternatives." *Journal of Environmental Economics and Management* 30 (1996): 95-111.

Karshenas, Massoud, and Paul L. Stoneman. "Rank, Stock, Order, and Epidemic Effects in the Diffusion of New Process Technologies: An

Empirical Model." *The RAND Journal of Economics*, 24, no. 4 (1993): 503-28.

Katz, Michael L., and Carl Shapiro. "Technology Adoption in the Presence of Network Externalities." *The Journal of Political Economy*, Vol. 94, No. 4, (Aug., 1986): 822-841.

Kennedy, Charles. "Induced Bias in Innovation and the Theory of Distribution." *The Economic Journal* 74, no. 295 (1964): 541-47.

Kiefer, Nicholas M. "Economic Duration Data and Hazard Functions." *Journal of Economic Literature* 26, no. 2 (1988): 646-79.

Koeller, Timothy C. "Innovation, Market Structure and Firm Size: A simultaneous Equations Model." *Managerial and Decision Economics*, Vol. 16, No. 3 (May-Jun., 1995): 259-269.

Kostiuk, Peter F., and Dean A. Follmann. "Learning Curves, Personal Characteristics, and Job Performance." *Journal of Labor Economics* 7, no. 2 (1989): 129-46.

Kruger, Dina W. "Methane Control: Transferring Experience from the Climate Arena to Tropospheric Ozone Strategies." *Environmental Management* (2003).

Lancaster, Tony. "The Econometric Analysis of Transition Data." *Econometric Society Monographs*, Vol. No. 17. Cambridge UK: Cambridge University Press, 1990.

Lanjouw, J., and A. Mody. "Innovation and the International Diffusion of Environmental Responsive Technology." *Research Policy*, Vo. 25, No. 4, (1996): 549-571.

Loreti, Christopher P., William F. Wescott, Michael A. Isenber. *An Overview of greenhouse gas emissions inventory issues*. Washington, DC: Pew Center on Global Climate Change Policy Series, August 2000.

Loschel, Andreas. "Technological Change in Economic Models of Environmental Policy: A Survey." *Ecological Economics* 43, no. 2002 (2002): 105-26.

Lucas, R. E., Jr. "Tests of a Capital-theoretic Model of Technological Change." *Review of Economic Studies*, 34 (1967):175-180.

Magat, Wesley A. "Regulation and the Rate and Direction of Induced Technical Change." The *Bell Journal of Economics* 7, no. 2 (1976): 478-96.

Mahajan, Vijay, and Robert A. Peterson. "Innovation Diffusion in a Dynamic Potential Adopter Population." *Management Science*, Vol. 24, No. 15 (Nov., 1978: 1589-1597.

Maio, Michele Di. "Explaining Technological Change: A Survey." Paper presented at the DRUID Winter Conference, Aalborg, Denmark 2003.

Mansfield, E. "The Diffusion of Industrial Robots in Japan and the United States." *Research Policy* 18, (1989): 183-192.

Mansfield, E. "Intra-firm Rates of Diffusion of an Innovation." *The Review of Economics and Statistics* XLV, (1963): 348-359.

Mansfield, E. "Technical Change and the Rate of Imitation," *Econometrica*, vol. 29, (October 1961): 741-766.

Marland, G., and R.M. Rotty. "Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-1981." Washington, DC: U.S. Department of Energy, 1983.

Marin, A. "Firm Incentives to Promote Technological Change in Pollution Control: Comment." *Journal of Environmental Economics and Management* 21 (1991): 297-300.

McAleer, Michael, Daniel J. Slottje, and Pei Syn Wee. *Patent Activity and Technical Change in Us Industries*. Edited by D.W. Jorgenson, J. Tinbergen, B. Baltagi, E. Sadka and D. Wildasin. Vol. 272, Contributions to Economic Analysis. New York, NY: Elsevier, 2005.

McWilliams, Bruce, Yacov Tsur, Eithan Hochman, and David Zilberman. "Count-data Regression Models of the Time to Adopt New Technologies." *Applied Economics Letters* 5, (1998): 369-373.

Milliman, Scott R. and Raymond Prince. "Firm Incentives to Promote Technological Change in Pollution Control." *Journal of Economics and Management* 13 (1989): 301-312.

Nakicenovic, Nebojsa, Arnulf Grubler, and Alan McDonald. *Global Energy Perspectives.* Cambridge, MA: Cambridge University Press, 1998.

National Research Council. *New Tools for Environmental Protection: Education, Information and Voluntary Measures*. Eds., Thomas Dietz and Paul C. Stern. Washington, DC: National Academy Press, 2002.

Nelson, Richard R., and Sidney G. Winter. *An Evolutionary Theory of Economic Change*. Cambridge, MA: The Belknap Press of Harvard University Press, 1982.

Newell, R.G. "Environmental Policy and Technological Change: the Effects of Economic Incentives and Direct Regulation on Energy-Saving Regulation." PhD dissertation, Harvard University, 1997.

Nordhaus, W.D. "Some Skeptical Thoughts on the Theory of Induced Innovation." Quarterly Journal of *Economics,* 87 (1973): 208-219.

Palmberg, C. "Successful Innovation, the Determinants of Commercialization and Break-even Durations of Innovations." *VTT Group for Technology Studies*. Finland: VTT Publications, 2002.

Palmer, Karen, and Dallas Burtraw. "Electricity, Renewables, and Climate Change: Searching for a Cost-Effective Policy." Washington, DC: Resources for the Future, 2004.

Pannell, David J., Graham R. Marshall, Neil Barr, Allan Curtis, Frank Vanclay, and Roger Wilkinson. "Understanding and Promoting Adoption and Conservation Technologies by Rural Landholders." Unpublished manuscript, submitted to *Australian Journal of Experimental Agriculture*, (2005). http://www.general.uwa.edu.au/u/dpannell/dp0502.htm.

Pehnt, Martin, Martin Cames, Corinna Fischer, Barbara Praetorius, Lambert Schneider, Katja Schumacher, and Jan-Peter Voss. *Micro Cogeneration: Towards Decentralized Energy Systems*. New York, NY: Spriger, 2006.

Pew Center on Global Climate Change. "Climate Change Activities in the United States: 2004 Update." Washington, DC: Pew Center on Global Climate Change Policy Briefs, 2004.

Pew Center on Global Climate Change. *Legislation in the 110th Congress Related to Global Climate Change*. http://www.pewclimate.org/what_s_being_done/in_the_congress/110thcongress.cfm.

Pew Center on Global Climate Change. *Summary of the Energy Policy Act of 2005*. http://www.pewclimate.org/policy_center/analyses/hr_6_summary.cfm.

Pew Center on Global Climate Change. *State Energy Policies.* http://www.pewclimate.org/states.cfm.

Popp, D. "Lessons from Patents: Using Patents to Measure Technological Change in Environmental Models." *NBER Working Paper* 9978. Cambridge, MA: National Bureau of Economic Research, 2003.

Popp, D. "Induced Innovation and Energy Prices." *American Economic Review*, Vol. 92, No. 1, (2002): 160-180

Popp, D. "Pollution Control Innovations and the Clean Air Act of 1990." *NBER Working Paper Series*, No. 8593. Cambridge, MA: National Bureau of Economic Research, 2001.

Portney, Paul R., and Robert N. Stavins. *Public Polices for Environmental Protection*. 2nd ed. Washington, DC: Resources for the Future, 2000.

Rabe, Barry G. *Greenhouse and Statehouse: The Evolving State Government Role in Climate Change*. Washington, DC: Pew Center on Global Climate Change Policy Series, November 2002. http://www.pewclimate.org/global-warming-in-depth/all_reports/greenhouse_and_statehouse_/

Rabe, Barry G. *Race to the Top: The Expanding Role of the U.S. State Renewable Portfolio Standards*. Washington, DC: Pew Center on Global Climate Change Policy Series, June 2006. http://www.pewclimate.org/global-warming-in-depth/all_reports/race_to_the_top/.

Rogers, E. *The Diffusion of Innovation*. 5th Edition ed. New York, NY: Free Press, 2000.

Rogers, E. *The Diffusion of Innovation*. 4th Edition ed. New York, NY: Free Press, 1995.

Romer, P.M. "Endogenous Technical Change." *Journal of Political Economy* 98, no. 5 (1990): 71-102.

Rosenberg, Nathan. *Exploring the Black Box: Technology, Economics, and History*. Cambridge, MA: Cambridge University Press, 1994.

Rosenberg, Nathan. *Inside the Black Box: Technology and Economics*. Cambridge, MA: Cambridge University Press, 1982.

Rosenberg, Nathan. "Technology and the Environment: An Economic Exploration." *Technology and Culture*, Vol. 12, No. 4 (Oct., 1971): 543-561.

Rosenberg, Nathan. "The Direction of Technological Change: Inducement Mechanisms and Focusing Devices." *Economic Development and Cultural Change*, Vol. 18, No. 1 (Oct., 1969): 1-24.

Sahal, Devendra. "Generalized Poisson and Related Models of Technological Innovation." *Technological Forecasting and Social Change* 6 (1974): 403-36.

Schmitz, Simon. "Do Energy Prices Induce Progress in Energy-Related Technology? An Empirical Study." *HWWA Discussion Paper* 147. Hamburg: Hamburg Institute of International Economics, 2001.

SCS Engineers. *Comparative Analysis of Landfill Gas Utilization Technologies*. Prepared for Northeast Regional Biomass Program, CONEG Policy Research Center, Inc. Hall of the States, File No. 0293066. Reston, VA: March 1997.

SCS Engineers. *Helping Landfill Owners Achieve Effective, Low-Cost Compliance with Federal Landfill Gas Regulations*. Prepared for USEPA. Reston, VA: 1996.

Seebregts, Ad, and Bob van der Zwaan. "Endogenous Technological Change in Climate-Energy-Economic Models: An Inventory of Key Uncertainties." Paper for the International Conference 'Risk and Uncertainty in Environmental and Resource Economics,' Wageningen, the Netherlands, June 5-7, 2002.

Sijm, J.P.M. "Induced Technological Change and Spillovers in Climate Policy Modeling." *ECN Working Paper Series*, no. ECN-C--04-073. The Netherlands: ECN Publications, 2004.

Soderholm, Patrik, and Thomas Sundqvist. "Learning Curve Analysis for Energy Technologies: Theoretical and Econometric Issues." *International Institute for Applied Systems Analysis Working Paper*. Austria: IIASA, 2003.

Stoneman, Paul, and Myung-Joong Kwon. "The Diffusion of Multiple Process Technologies." *The Economic Journal* 104, no. 423 (1994): 420-31.

Stoneman, Paul and Paul Diederen. "Technology Diffusion and Public Policy." *The Economic Journal*, 104 (July 1994): 929.

Stoneman, Paul L. and Paul A. David. "Adoption Subsidies vs. Information Provision as Instruments of Technology Policy." *The Economic Journal*, Vol. 96, Supplement: Conference Papers (1986): 142-150.

Stoneman, P. *The Economic Analysis of Technological Change.* London: Oxford University Pres, 1983.

Thapa, Prem Jung, and Tue Gorgens. "A Duration Analysis of the Time Taken to Find the First Job for Newly Arrived Migrants in Australia." *Centre for Economic Policy Research, Discussion Paper* No. 527. Australia: The Australian National University, July 2006

Thirtle, Colin G., and Vernon W. Ruttan. "The Role of Demand and Supply in the Generation and Diffusion of Technical Change." In *Fundamentals of Pure and Applied Economics*, eds. Jacques Lesourne and Hugo Sonnenschein. Switzerland: Harwood academic publishers, 1987.

UNIPCC. *Summary for Policy Makers, Third Assessment Report.* Geneva: UN Intergovernmental Panel on Climate Change, 2001.

Union of Concerned Scientists. *Powerful Solutions: Seven Ways to Switch America to Renewable Electricity* Washington, DC: January 1999 (tables updated October 2005), www.ucsusa.org/clean_energy

USDOE/EERE. *Analysis of Energy Efficiency Investment Decisions by Small and Medium-Sized Manufacturers*. Washington, DC: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, March 1996.

USDEO/EIA. Average U.S. Electricity and Oil Prices for 11/15/07. www.eia.doe.gov (accessed 11/17/07).

USDOE/EIA. *Analysis of Five Selected Tax Provisions of the Conference Energy Bill of 2003,* No. SR-01AF/2004-01. Washington, DC: U.S. Department of Energy, Energy Information Agency, 2004. http://www.eia.doe.gov/oiaf/servicerpt/ceb/fuel.html.

USDOE/EIA. *Federal Energy Market Interventions 1999: Primary Energy*. Washington, DC: U.S. Department of Energy, Energy Information Agency, 1999. http://www.eia.doe.gov/oiaf/servicerpt/subsidy/pdf/appendix_b.pdf.

USDOE/EIA. "Renewable Energy Annual, 1976-1996." Washington, DC: U.S. Department of Energy, Energy Information Agency, 1999.

USEPA. *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2005*, EPA 430-R-07-002. Washington, DC: U.S. Environmental Protection Agency, April 2007.

USEPA. *Global Mitigation of Non-CO2 Greenhouse Gases*, EPA 430-R-06-005. Washington, DC: U.S. Environmental Protection Agency, June 2006.

USEPA. *LMOP Accomplishments*. http://www.epa.gov/lmop/accomplish.htm (accessed 2006)

USEPA. *Fact Sheet: Frequently Asked Questions About Landfill Gas and How it Affects Public Health, Safety and the Environment*. Washington, DC: U.S. Environmental Protection Agency, October 2006. http://www.epa.gov/lmop/faq-3.htm.

USEPA. *LMOP Landfill Database* www.epa.gov/lmop/res/index.htm#5 (accessed 2005)

USEPA. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003,* EPA 430-R-05-003. Washington, DC: U.S. Environmental Protection Agency, 2005.

USEPA. *Tennessee State Primer: A Primer on Developing Tennessee's Landfill Gas-to-Energy Potential*, EPA 430-R-04-002. Washington, DC: U.S. Environmental Protection Agency, 2004.

USEPA. *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2003*. Washington, DC: U.S. Environmental Protection Agency, 2003. http://www.epa.gov/msw/pubs/msw05rpt.pdf.

USEPA. *Mississippi State Primer: A Primer on Developing Mississippi's Landfill Gas-to-Energy Potential*, EPA 430-R-02-011. Washington, DC: U.S. Environmental Protection Agency, 2002.

USEPA. *Small Landfills=Untapped Energy Potential*, EPA 430-F-01-001. Washington, DC: U.S. Environmental Protection Agency, 2001.

USEPA. *Utah State Primer: A Primer on Developing Utah's Landfill Gas-to-Energy Potential*, EPA 430-R-01-003. Washington, DC: U.S. Environmental Protection Agency, 2001.

USEPA. *North Carolina State Primer: A Primer on Developing Utah's Landfill Gas-to-Energy Potential*, EPA 430-R-00-010. Washington, DC: U.S. Environmental Protection Agency, 2001.

USEPA. *Kentucky State Primer: A Primer on Developing Kentucky's Landfill Gas-to-Energy Potential*, EPA 430-R-00-003. Washington, DC: U.S. Environmental Protection Agency, 2000.

USEPA. *Florida State Primer: A Primer on Developing Florida's Landfill Gas-to-Energy Potential*, EPA 430-R-00-004. Washington, DC: U.S. Environmental Protection Agency, 2000.

USEPA. *Wisconsin State Primer: A Primer on Developing Wisconsin's Landfill Gas-to-Energy Potential*, EPA 430-R-99-006. Washington, DC: U.S. Environmental Protection Agency, 1999.

USEPA. *South Carolina State Primer: A Primer on Developing South Carolina's Landfill Gas-to-Energy Potential*, EPA 430-K-99-037. Washington, DC: U.S. Environmental Protection Agency, 1999.

USEPA. *Ohio State Primer: A Primer on Developing Ohio's Landfill Gas-to-Energy Potential.* Washington, DC: U.S. Environmental Protection Agency, 1999.

USEPA. *Georgia State Primer: A Primer on Developing Georgia's Landfill Gas-to-Energy Potential*, EPA 430-R-99-007. Washington, DC: U.S. Environmental Protection Agency, 1999.

USEPA. *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions*, EPA 430-R-99-013. Washington, DC: U.S. Environmental Protection Agency, September 1999.

USEPA, *Federal Plan Requirements for Municipal Solid Waste Landfills*. 40 CFR Part 62, Federal Register 64:215 (60689-60706) Washington, DC: U.S. Environmental Protection Agency, 1999.

USEPA. *Washington State Primer: A Primer on Developing Washington's Landfill Gas-to-Energy Potential*, EPA 430-B-98-000. Washington, DC: U.S. Environmental Protection Agency, 1998.

USEPA. *Air Pollution Operating Permit Program Update: Key Features and Benefits*, EPA 451-K-98-002. Washington, DC: U.S. Environmental Protection Agency, February 1998.

USEPA. *Turning a Liability into an Asset: A Landfill Gas-to-Energy Project Development Handbook.* Washington, DC: U.S. Environmental Protection Agency,1996.

USEPA. *Funding Landfill Gas Projects: A Guide to State, Federal and Foundation Resources*. Washington, DC: U.S. Environmental Protection Agency, 1996.

USEPA. *Landfill Gas Energy Utilization Experience: Discussion of Technical and Non-Technical Issues, Solutions, and Trends*, EPA-600/R-95-035. Washington, DC: U.S. Environmental Protection Agency, March 1995.

USEPA. *Landfill Methane and Clean Air Act Opportunities: Incentives from the Acid Rain Program*, EPA-430-K-94-014. Washington, DC: U.S. Environmental Protection Agency, November 1994.

USEPA. *Criteria for Solid Waste Disposal Facilities*, EPA-530-SW-91-089. Washington, DC: U.S. Environmental Protection Agency, March 1993.

USEPA. *Fact Sheet: Final Federal Plan for Municipal Solid Waste Landfills*. http://www.epa.gov/ttn/atw/landfill/lndfpfs.pdf

USEPA. *Case Study on Waste Management*. http://www.epa.gov/lmop/res/wmi.htm.

USEPA. *Fuel Cells: Demonstrating the Power of Landfill Gas*. http://www.epa.gov/lmop/res/fuelcell.htm.

Vega-Cervera, Juan A., Juan A. Vega-Cervera, and Isabel Cuadrado Gordillo. "Duration Analysis Applied to the Adoption of Knowledge." *Education Economics* 9, no. 1 (2001): 19.

Videras, Julio, and Anna Alberini. “The Appeal of Voluntary Environmental Programs: which Firms Participate and Why?” *Contemporary Economic Policy* Vol. 18, No. 4, (Oct., 2000): 449-461.

Waste Management, Inc. *Waste Management, Inc. 2002 Annual Report*. www.wm.com.

Whitford, Andrew B., and Andrew B. Whitford. "The Pursuit of Political Control by Multiple Principals." *Journal of Politics* 67, no. 1 (2005): 28.

Willke, Richard J., Henry A. Glick, Jim Z. Li, and Brian E. Rittenhouse. "Effects of Linezolid on Hospital Length of Stay Compared with Vancomysin in Treatment of Methicillin-Resistant Staphylococcus Infections." *International Journal of Technology Assessment in Health Care* 18, no. 3 (2002): 540-54.

Wong, F.P. *Alternative Energy and Regulatory Policy: Till Death Do We Part* (Commerce, CA: Pacific Energy, March 1992), quoted in USDOE/EIA, Renewable Energy Report, 1996. Washington, DC: US Department of Energy, Energy Information Agency, 1999. http://www.eia.doe.gov/oiaf/servicerpt/subsidy/pdf/appendix_b.pdf

Yin, Robert K. *Case Study Research: Design and Methods*. Edited by Leonard Bickman and Debra J. Rog. Vol. 5, Applied Social Research Methods Series. London: Sage Publications, 2003.

Yin, Robert K., and Karen A. Heald. "Using the Case Survey Method to Analyze Policy Studies." Administrative Science Quarterly, Vol. 20, No. 3 (Sep., 1975): 371-381.