Uncertainty in Renewable Energy Policy: How do Renewable Energy Credit markets and Production Tax Credits affect decisions to invest in renewable energy?

Derya Eryilmaz
Ph.D. Student
Department of Applied Economics
University of Minnesota
1994 Buford Avenue
St. Paul, MN 55108
eryil001@umn.edu

Frances Homans
Professor
Department of Applied Economics
University of Minnesota
1994 Buford Avenue
St. Paul, MN 55108
fhomans@umn.edu

Selected Paper prepared for presentation at the Agricultural & Applied Economics Associations 2013 AAEA & CAES Joint Annual Meeting, Washington, DC, August 4-6, 2013.

Uncertainty in Renewable Energy Policy: How do Renewable Energy Credit markets and Production Tax Credits affect decisions to invest in renewable energy?

Abstract

This paper examines the impacts of uncertainties in the US renewable energy policy on the investment decisions of renewable electricity producers. We develop a dynamic optimization model to understand how investment in wind energy depends on market and policy uncertainties in renewable energy markets. These uncertainties include the stochastic prices in the market for Renewable Electricity Credits (RECs) and the federal government's uncertain decision about continuation of Production Tax Credit (PTC) program. Results contribute to our understanding of the impact of the REC market and policy decisions on the profitability threshold required for investors to commit to renewable energy investments. Uncertainty about the renewable energy policy raises the threshold to invest in renewable energy. This paper also examines the relationship between two important renewable energy policies and their impacts on these investments. This paper has the potential to significantly contribute to the existing renewable energy development debate because the RECs prices are introduced explicitly as a random factor in a model of investment in renewable energy.

1 Introduction

Renewable energy resources have significant potential to supply energy, support energy security goals and contribute to less carbon-intensive energy production. The United States, the largest electricity consumer in the world (EIA 2012), has been successful in increasing the share of electricity produced from renewable sources. In 2011, the renewable energy share was 14% of the total energy produced (EIA 2012). This significant increase in renewable energy investments can be attributed, in part, to supportive government policies at both state and the federal levels.

Despite supportive federal and state policies, electricity production from renewables is still only a small fraction of the total energy supply in the United States. There are several possible reasons. First, renewable energy may simply not be cost-competitive with energy from non-renewable sources given current technology and prices. Second, uncertainties about future prices and technology may dampen current investment even though investment in renewable resources would be wise if the current prices and technology were sure to persist into the future. Third, if most of the incentives to invest in renewable energy come from government policy, investors may be concerned that these incentives may not last. This paper focuses on the third reason and asks how uncertainty in renewable energy policy affects investment decisions.

For the model framework, real options theory and the economics of investment under uncertainty (Arrow and Fischer 1974; Pindyck 1980, 1984, 1986, 2000, 2002) have been developed to highlight the importance of problems related to investing when the decision to invest is irreversible. A major finding from this framework is that there is value to delay exercising an option to invest when investments are irreversible and there is uncertainty in future benefits. A few recent studies used this framework to examine investments in renewable energy considering various sources of market and policy uncertainty: uncertainty in future carbon prices and climate policy (Fuss 2008), future fuel prices (Lou 2011), future pollution costs and pollution stock (Balikcioglu and Fackler 2011) and future renewable and non-renewable resource stock (Mosino 2012).

In our study, we build upon this previous work by investigating the impact of stochastic Renewable Electricity Credits prices and uncertainty about the federal energy policy on the renewable energy investment decisions. Our research questions include: (1) how do the level and volatility of Renewable Electricity Credits (REC) prices affect the decision to invest in renewable electricity, (2) how might these decisions change if this market was forecast to cease operation, and (3) how do these decisions depend upon the continuation of the Production Tax Credit (PTC) program? This paper contributes to an understanding of renewable investment portfolios of private power generating companies given the uncertainty about the future renewable energy policy. This is the first study that introduces price uncertainties of the RECs as a factor that influences investment in renewable energy. This paper also investigates the change in the investment decisions when there is uncertainty about the government's decision on the Production Tax Credits (PTC). Finally, this study contributes to the previous literature by identifying the relationship between the two major policies that affect the irreversible investment decisions in renewable energy.

This paper is organized as follows: background is given in section 2. The model framework and the parameters used for the model calibration are given in section 3. Results and policy implications of the results are presented in section 4 and section 5. Section 4 also includes sensitivity analysis and state-level analysis, which includes applications in selected states in different trading regions. Finally, section 6 concludes the paper. The appendix includes additional model details, data sources, and additional state-level analysis.

2 Background

State Renewable Portfolio Standards and the REC Market

Individual states have instituted Renewable Portfolio Standards (RPS) programs in which a certain fraction of total electricity must be produced using renewable sources. Applications of Renewable Portfolio Standards vary from state to state depending on the policy objectives such as reducing carbon emissions, promoting new investment in renewable energy, creating green jobs or innovating cleaner technology (Heeter et al. 2011). Another feature of RPS programs is the market for Renewable Electricity Credits (RECs). RECs are tradable commodities that are used to facilitate compliance with the renewable energy requirements provided by RPS. Almost all states have RPS programs and different mandatory requirements that must be met by producing energy from various renewable energy resources (e.g. solar, wind, hydro, and biomass). In the compliance markets, RECs are earned by producing electricity from renewable sources as an attribute of the generated renewable electricity. One credit is usually equivalent to one-megawatt of electricity production. A renewable power generating facility must be registered with the state-monitoring agency in order to obtain the credit. Each REC receives a unique tracking number that represents the renewable attributes of the electricity generated (Brown 2012). There is a compliance penalty associated with REC supply shortages (Heeter and Bird 2012). Voluntary markets allow trading in green energy in states that do not have RPS or that have already reached RPS goals (Heeter and Bird 2011). Both the compliance and voluntary markets for RECs fosters development of wind projects and provide additional revenue for these projects (Brown 2012).

Research by the Department of Energy showed that government incentives have been essential for reaching the renewable electricity production targets in the states (Wiser 2007). Among the many renewable energy resources, wind has benefited the most from federal and state incentives in the last decade (Brown 2012). Approximately 81% of the new capacity installed to produce renewable electricity was from wind power in 2010 and wind has significantly contributed to the renewable power markets (NREL 2010).

Federal Production Tax Credits

The federal government promotes renewable energy through Production Tax Credits (PTC). These credits are tax benefits for renewable energy investors to produce renewable energy from biomass, wind, hydro, geothermal or solid waste. For example, investment in wind power is subsidized at $23 per megawatt-hour during the first ten years of the new renewable energy facility's operation, which covers almost one-third of the initial installment cost (Brown 2012). National cumulative wind energy capacity has significantly increased (from 894 MW to 48.611 MW) since 1992 when the PTC policy was initially enacted (Lou 2011; EIA 2012, Brown 2012). The PTC policy was set to expire in December 2012 but was extended for another year. However, the government's future policy on PTC is uncertain for future wind projects (Brown 2012).

3 Model Framework and Parameters

In this section we describe the assumptions we make for the analytical model. Second, we present the analytical model. Finally, we provide our empirical methodology for estimating model parameters.

Model Assumptions

We model the decision to invest in renewable electricity using a discrete-choice dynamic optimization problem. The decision to invest in renewable electricity production from wind energy is considered to be irreversible. We assume that the representative investor is a price taker; the capacity of the wind turbine we model is not large enough to affect electricity prices or REC market prices. The investor knows the current REC prices and that the RPS goals needs to be met by 2020 (i.e. 30% of renewable electricity produced by renewables by 2020). We have assumed that REC prices follow a binomial process and that the investor knows the probability of up and down movements as well as their magnitudes. The representative investor sells RECs for each unit of his renewable energy production investment. In our model, 1MWh electricity production is equivalent to 0.7 RECs. RECs are earned by the amount of energy contracted to the grid per production (i.e. utilities). Our assumption implies that 70% of the generated power from a single windmill is sold to the grid. This is a technical assumption to consider the possible curtailment required by the grid. Most of the purchasing contracts between the producers and the purchaser account for the amount of the required curtailments in production.

We solve our model over a 20-year time horizon, which is the average lifespan of a 1.5MW windmill (NREL 2011). The uncertainties in the model are as follows: (1) annual prices of Renewable Electricity Credits (RECs) follow a stochastic process; (2) the federal government may or may not choose to continue the PTC incentive when it expires; and (3) the compliance RECs market may vanish if the policy that maintains RPS is discontinued.

Model Framework

In our model, the representative investor maximizes the expected profits of a private power generating company from producing wind energy. In each period, the investor can take two possible actions: invest in the renewable electricity production at any time t ($x_t = 1$), or not ($x_t = 0$), preserving the option to invest in future periods. The investor starts with $s_t = 0$, where the investment has not yet taken place. If the investor decides to invest in renewable electricity, he bears the sunk cost of investment (C^{SUNK}) at the time he decides to invest. Once energy production starts, one year after the investment decision has been made, the investor receives revenue from electricity production and RECs sold in the market for Renewable Electricity Credits and pays for the fixed annual operating and maintenance costs (C). Therefore, in the next time period, $s_{t+1} = 1$ and $x_{t+1} = 0$. If the investor does not invest and has not invested, the current reward equals zero. We assume that the investor has only one option to invest. Once the option has been exercised, it cannot be exercised again: x_t and s_t cannot take the value of 1 in the same time period.

The optimization problem of the representative investor is formulated as follows:

$$\max_{x_t(q_t,\alpha_t),t} \sum_{t=0}^{T=20} \frac{1}{(1+r)^t} E[\pi(x_t, s_t, q_t, \alpha_t)] \tag{1}$$

subject to

$$\pi(s_t(q_t,\alpha_t), x_t(q_t,\alpha_t)) = s_t[p * N + q_t * R_t - C] + x_t[\alpha_t(\tau * N_t) - C^{SUNK}] \tag{2}$$

$$s_{(t+1)} = s_t + x_t \tag{3}$$

$$s_t + x_t \leq 1 \tag{4}$$

$$x \in (0,1) \tag{5}$$

$$s \in (0,1) \tag{6}$$

$$\alpha \in (0,1) \tag{7}$$

T=20

The investor also receives tax credits (τ) if the government decides to continue the PTC policy (if $\alpha_t = 1$), but the government's decision on continuing the PTC policy is not known to the investor until after the investment decision is made. The investor knows whether the PTC policy will be continued or not with some probability and these probabilities of the PTC policy are independent across time intervals. For the initial time period, it is assumed that the investor will receive the revenue from the PTC if he decides to invest in the initial time period t_0. By investing when the PTC is in place, the investor locks in a stream of payments worth $\tau * N_t$ each year for 10 years. We include this revenue in the year of investment as the present value of the future income stream (NPV_t).

$$NPV_{(t)} = \sum_{s=t}^{t+10} \frac{1}{(1+r)^{t-s}}(\tau * N_t) \tag{8}$$

The expected benefits from investment depend on expected REC prices and expected federal PTC incentives. We assume that REC prices and electricity prices will remain fixed after the end of the time horizon. The terminal value received at time T+1 (V(T+1)) is the present value of the stream of revenues from RECs and electricity at the prices in place at time T+1. Optimal investment decisions can be derived by recursively solving Bellman's equation of optimality. The terminal value of the problem is:

$$V_{T+1}(s_{T+1}, \alpha_{T+1}, q_{T+1}; T+1) = (\frac{1}{1+r}) s_{T+1} * [p * N + q_{T+1} * R_{T+1} - C] \tag{9}$$

The value function can be written in the form of Bellman's equation as follows:

$$V_t(s_t, \alpha_t, q_t; t) = \max{}_{(x_t)}[\pi(x_t, s_t, q_t, \alpha_t) + \beta E V_{t+1}(s_{t+1}, q_{t+1}, \alpha_{t+1}; t+1)] \tag{10}$$

Probabilities

In the optimization problem, REC prices are introduced as random and we discretize the REC prices where prices follow a Markov process: REC prices move up or down according to a Bernoulli process. Using actual data on the daily spot REC Prices, we estimate the probability of the price of the REC increasing in the next period based on the "event probability" estimation (Fair 1993). A crucial assumption for this estimation is that the error term, which is normally, identically and independently distributed. The Markov assumption implies that the REC prices in the next period are only function of the prices in the previous time period. Therefore, the event in our study is the probability of the future prices of REC increasing compared to the prices in the previous time period. First, we randomly sample the consequent quarters of observations from the data and calculate the cumulative frequencies of the number of predicted REC prices (q_{t+1}) that are higher than the REC prices (q_t) in the previous time period. Results show that discretized prices moving up or down with constant volatility (σ) and with the probabilities $\sum_{\mu} \Gamma^{\mu}$=1 as follows:

$$Prob(q_{t+1} = q_t * \sigma \mid q_t) = \mu = 0.66 \tag{11}$$

$$Prob(q_{t+1} = \frac{q_t}{\sigma} \mid q_t) = (1 - \mu) = 0.34 \tag{12}$$

The probability of the RECs prices being higher in the next time step than the previous time step is 66% (μ). Similarly, the probability of the RECs prices being lower in the next time step than the previous time is 34% ($1 - \mu$).

We also examine the historical compliance market prices to see whether our discretized prices are reasonable for the simulations. According to our analysis on the historical REC prices do seem to follow a random walk; in fact, our prices include simplified version of the random walk process matching with the discretized Markov probability matrix. Therefore, our assumption about the REC prices is reasonable. [1]

The probability distribution of the future REC prices depends on the REC prices today and the volatility of the REC prices (Miranda and Fackler 2002). We compute the annual volatility (σ) of the REC prices using the following formula that is also used for the volatility of the natural gas spot prices by Mastrangalo (2007): Using the natural logarithm of the prices, we compute the relative change in the daily prices $\log(q_t/q_{t-1})$ and finally calculate the standard deviation for each time period (Mastrangalo 2007).

$$\sigma = Volatility = \frac{\sqrt{(\sum_{t=1}^{N_t}(\Delta q_t - \bar{q})^2}}{(N_T - 1)} * \sqrt{N_T} \tag{13}$$

$$\Delta q_t = \log(q_t/q_{t-1}) \tag{14}$$

$$N_T = \text{Number of Trading Days} \tag{15}$$

$$q_t = \text{RECs Prices} \tag{16}$$

$$\bar{q}_t = \text{Average RECs Prices} \tag{17}$$

T=Trading Days Between May 25, 2006 - November 22, 2012

[1]A graph of the REC prices and details of the empirical analysis are in the Appendix.

This is a common formula that calculates the standard deviation of the relative changes in the daily prices. We then convert the daily volatility into annual volatility by using the annual total number of trading days (T=252). The annual volatility for the RECs prices $\sigma = 3.86$.

For the PTC policy, the probability of the federal government maintaining the PTC policy is assumed to be 70% (p) in the next time period whereas the probability of the federal government removing the PTC policy is assumed to be 30% (1-p). We have assumed that the probability of the federal government continuing the PTC policy is higher than the probability of the federal government allowing the policy to lapse based on the historical decisions of the government.[2] To date, the government has continued the PTC policy. However, the PTC policy is set to expire and the decision to extend has been the subject of contentious debate in congress. In addition, economists (Palmer et al. 2005; Fell et al. 2012) have shown that it is not a cost effective policy. Continuation of the PTC policy is introduced as a binary random variable $\{\alpha_t\}_{t\geq 1}$. Once the government removes the PTC policy during any time period, we assume that there is no chance that the PTC policy can be enacted again.

$$Prob(\alpha_{t+1} \mid \alpha_t) = \begin{cases} p & \text{if } \alpha_t = 1, \alpha_{t+1} = 1; \\ (1-p) & \text{if } \alpha_t = 1, \alpha_{t+1} = 0 \\ 1 & \text{if } \alpha_t = 0, \alpha_{t+1} = 0; \\ 0 & \text{if } \alpha_t = 0, \alpha_{t+1} = 1. \end{cases}$$

Model Parameters

We use several data sources to obtain our model parameters: REC prices, cost of installation, operating and maintenance costs of a 1.5MW wind mill, and annual electricity prices. Table 1 summarizes the sources of our data and the parameters that are used in the numerical estimation of our optimization model. Our model framework is linear and the time step is annual. Since wind energy is intermittent in nature, we incorporate a capacity factor of 38% and the total amount of energy produced in the private utility is adjusted based on this capacity factor (NREL 2010). Our model does not account for the energy storage factor. [3]

Finally, revenues from the Production Tax Credits (PTC) are included into the model as function of the time of investment. If the government maintains the PTC policy at the time that the investor decides to install the windmill, the investor receives \$23MWh (τ) per unit of renewable energy production (N_t) based on the time of his investment decision for the next ten years of energy production. If the PTC policy is not enacted at the time that the investor decides to invest, then he will not receive any payments. The value of the payments in each period are calculated as follows although we included the PTC as sum of the discounted values of these payments in our model (NPV_t).

[2] Wiser 2007 and Lou 2011 provide the legislative history of the PTC policy, and note that the cumulative frequency of the government's decision to enact the PTC policy is 70% since 2002.

[3] Detail description of the model parameters can be found in the Appendix section.

$$PTC(\alpha_t) = \begin{cases} \tau * N_t & \text{if } \alpha_t = 1; \\ 0 & \text{if } \alpha_t = 0. \end{cases}$$

Table 1: Model Parameters and Calibration.

Parameter Name	*Parameters*	*Value*	*Source of Data*
Annual Average Electricity Prices ($/MWh)	p	98.3	EIA 2012
Power Capacity of the Windmill (MW)	M	1.5	EIA 2012
Annual Energy Production (MWh/year)	N	$M_t * k * hrs$	NREL 2011
Average RECs Prices ($/MWh)	q_t	56	Spectron Group 2012
Price Volatility in RECs	σ	3.96	Mastrangalo 2007
Amount of RECs Generated	$R_t = (1-\theta) * N_t$	$0.7 * 3,345$	DSIRE 2012
Sunk Cost of Windmill Installation ($/MWh)	C^{SUNK}	2.098	NREL 2011
Operating and Maintenance Cost ($/MW/year)	C	$1.5 * 350,000$	NREL 2011
Federal Production Tax Credits ($/MWh)	τ	23	DSIRE 2012
Capacity Factor (%)	k	38%	NREL 2010
Probability that the Government Maintains the PTC	p	0.7	Estimated
Estimated Probability of REC price increases	μ	0.67	Estimated
Annual Discount Factor	β	$\frac{1}{1.08}$	NREL 2011
Total hours in a year	h	$8760hrs$	$24hours * 365days$

Note 1: 1 MWh (Megawatt -hour) = 1000 kWh (kilowatt-hour)

Note 2: Capacity factor(k) is an efficiency unit because the windmill does not operate 24 hours/day

4 Results

Initially, we solve a deterministic version of our model. In this case, we find that the optimal decision of the investor is investing at or above a specific REC price. The optimal REC price threshold is $71.6MWh with the PTC incentive and $80.8 MWh without the PTC. The investor requires higher REC prices without the federal PTC incentive.[4] Under the stochastic REC prices and the federal government's decision about the PTC policy, our results show that the investor's decision to invest is affected by the policy uncertainties. With uncertainty in both policies, the investor may choose not to bear the large sunk cost of investment because of the lack of information about the future REC prices and the federal PTC policy.

Figure 1 and Figure 2 shows the optimal threshold of REC prices for the investment when there is the PTC policy and when there is no PTC policy. The decision to invest depends on whether the REC prices reach the threshold for the given time period and on whether the PTC policy is in force. REC prices are shown on the y-axis and the time left until the end of the horizon is shown on the x-axis. The investment boundaries show the threshold for REC prices for investment and this threshold price depends on time. The threshold for investment also divides the space into two regions: invest and not invest. The investment boundary is a step function when there is no

[4]Simulations from the deterministic case can be found in the Appendix section.

PTC policy and the region above the boundary is the price region for investment. Without the PTC policy, the lower bound of the RECs prices is $74.5MWh and it represents the lowest REC price that will spur the investment at any given time (t) in the horizon. However, the investment boundary is concave when there is the PTC policy. One of the striking findings from these results is that the lower bound of the optimal RECs price threshold for investment is about 30% lower with the PTC policy ($52MWh) compared to when there is no PTC policy ($74.5MWh).

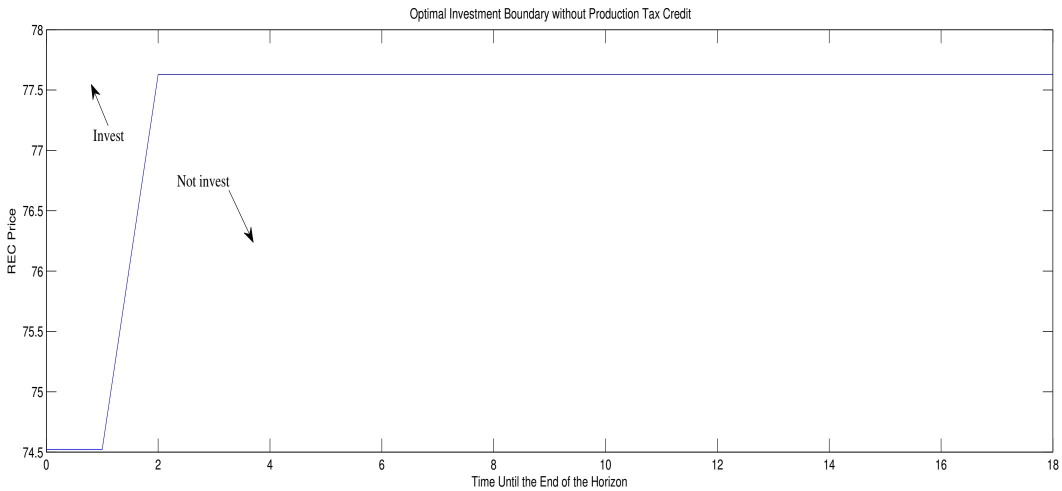


Figure 1: Optimal Investment Boundary when PTC=0

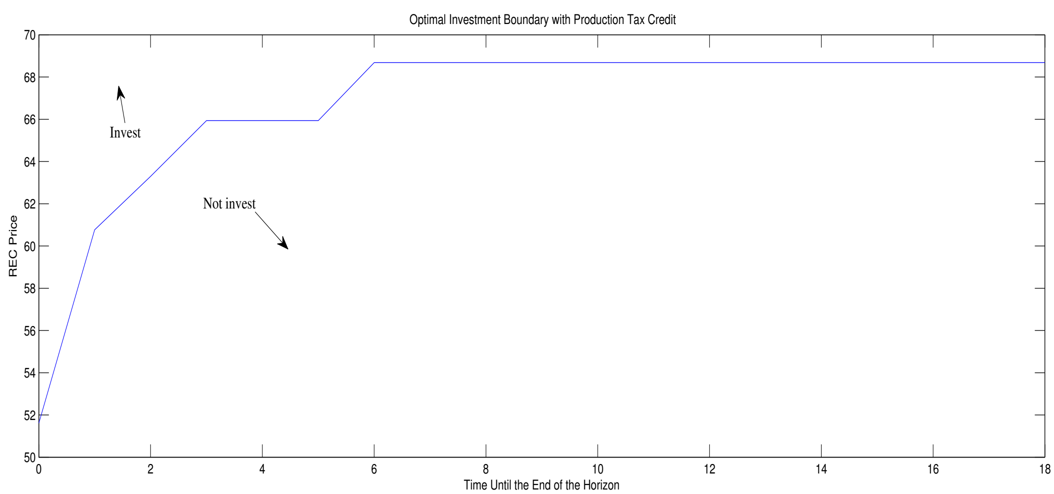


Figure 2: Optimal Investment Boundary when PTC=1

Stochastic REC prices affect the decision of investment and there is variability in the investor's decision to invest in renewable energy with the calibrated values. The critical REC prices for investment are within a smaller range ($74.5MWh and $77.6MWh) when there is no PTC policy compared to the critical REC prices for investment ($52MWh and $69MWh) when there is the PTC policy. The existence of the PTC policy also considerably affects the critical REC price boundary for investment and it allows more variability in the critical REC prices threshold for investment. Without the PTC policy, the investor requires higher REC prices for investment and with the PTC policy, the investor prefers to invest in the lower REC prices. The PTC policy significantly reduces the initial investment costs; therefore, the investor does not require high REC prices to compansate for the costs of investment. The investor is able to invest in lower REC prices at any time when there is the PTC policy. However, in order to compensate for the investment costs under uncertain REC prices, the investor prefers higher REC prices when the PTC policy is not enacted.

We also simulate the case where REC prices are random and whether the federal PTC policy is in force with certainty. The investor chooses to invest starting at \$40.5MWh. This result clearly shows that uncertainty in the federal PTC policy affect the investment threshold: The REC threshold is lower when the federal PTC policy is known with certainty (\$40.5MWh) compared to when there is uncertainty in the PTC policy (\$52MWh). Figure 3 shows the REC price threshold for investment when REC prices are volatile and when there is the PTC policy.

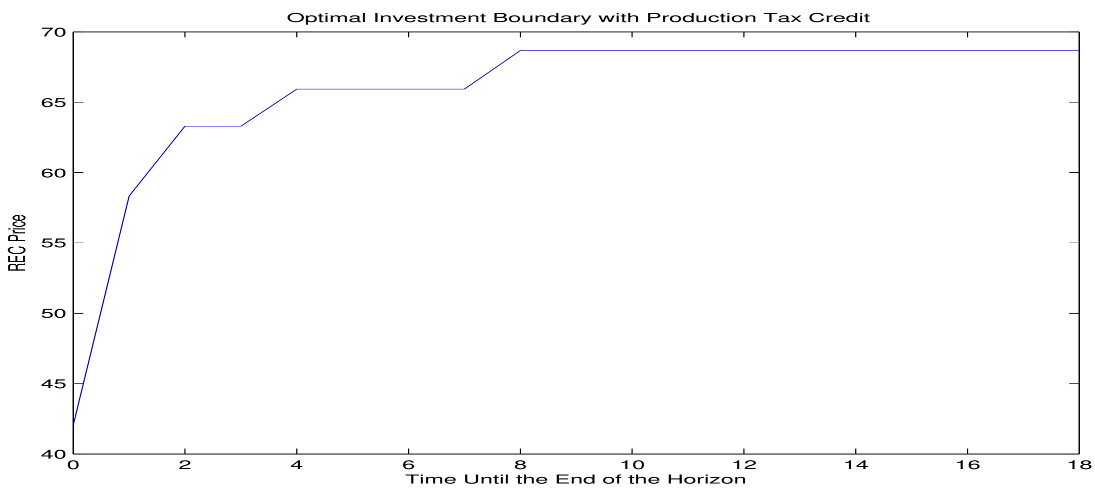


Figure 3: Optimal Investment Boundary when REC is stochastic and the PTC is known

4.1 Sensitivity Analysis

We perform sensitivity analysis to check how sensitive our model is to the parameters and assumptions we make. First, with a very large initial investment cost (C^{SUNK}), the representative investor never chooses to invest. Therefore, the investor should be able to generate sufficient revenue to compensate for the sunk cost between the time he decides to invest and the end of the time horizon. This also suggests that our model responds to the level of initial investment cost.

Second, we change the parameters that affect the REC market and we check whether the investment decision is responsive to the REC prices. We first change the probability of the prices increasing to $\mu = 0.87$ from the estimated probability of 0.67. The critical REC prices boundary for investment is still concave and the lower bound is \$51.8MWh. The REC price threshold for investment is almost the same with our initial results when there is the PTC policy (\$52MWh).

Moreover, the lower bound of the critical price for investment is still \$74.5MWh when there is no PTC policy and the investor only invests at this price level. With a higher probability of increase in REC prices, there is not a considerable difference in the optimal REC price threshold for investment. Figure 4 shows the optimal REC price boundary for investment with a higher probability of an increase in the REC prices when there is the PTC policy.

However, when we allow for a very small probability ($\mu = 0.17$) that the REC prices increase, the critical REC price for investment increases for both cases where the PTC is available (\$54.8MWh- \$88 MWh) and when the PTC is not available (\$77.8MWh- \$95MWh) compared to our results. The investor may prefer to invest within a higher critical REC price threshold regardless of if there is the PTC policy. These results show that probability of a decrease in REC prices increases the minimum REC price at which the investor decides to invest. These results also vary when there is the PTC policy and when there is no PTC policy. However, the implications of the PTC policy is still consistent with our initial results: without the PTC policy, the optimal REC price threshold for investment is higher compared to the case with the PTC policy. Figure 5 shows the optimal investment boundary with lower probability of an increase in the REC prices:

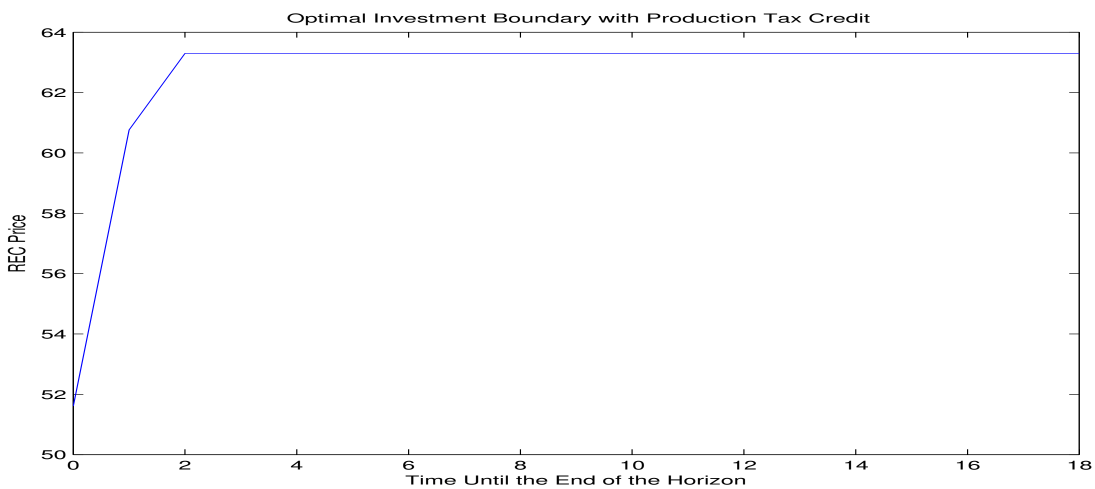


Figure 4: Optimal Investment Boundary with a Higher Probability of an Increase in REC Prices ($\mu = 0.87$) when PTC=1

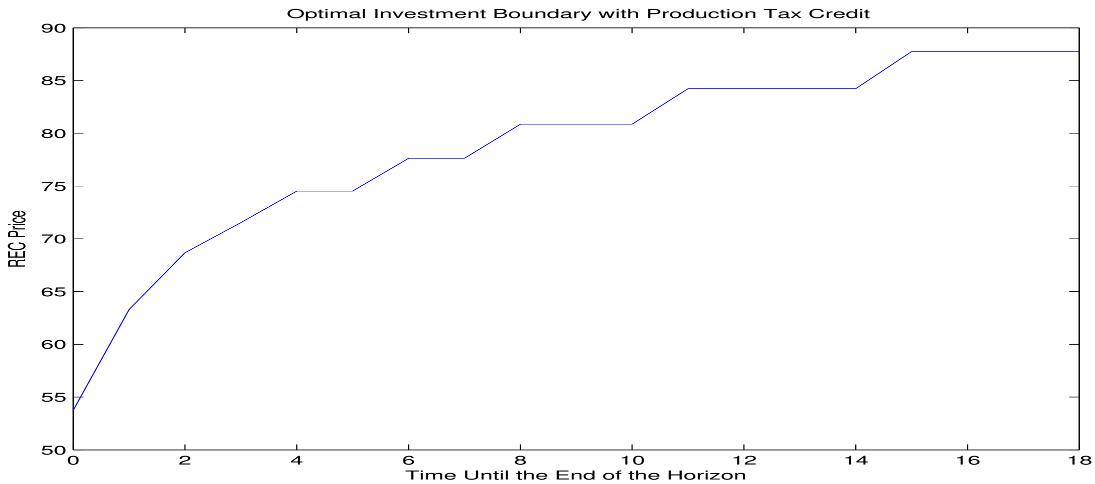


Figure 5: Optimal Investment Boundary with Lower Probability of an Increase in REC Prices ($\mu = 0.17$) when PTC=1

We check the effect of the different volatility of REC prices. We set the volatility (σ) as REC prices are moving towards zero over time. Our findings show that the investor does not invest at any time of the horizon without the PTC; thus there is no REC price threshold for investment. However, if there is the PTC policy, the investor only invests at the price of $14.2MWh, which is considerably lower than our initial results. There is not variability in the REC price threshold for investment when the REC prices are set to decrease to zero. The sensitivity analysis on a severe reduction in the REC prices show that prices of the market for RECs significantly affect the investment decision about renewable energy. Figure 6 shows the optimal REC price threshold for investment when there is the PTC policy and there is a severe reduction in REC prices:

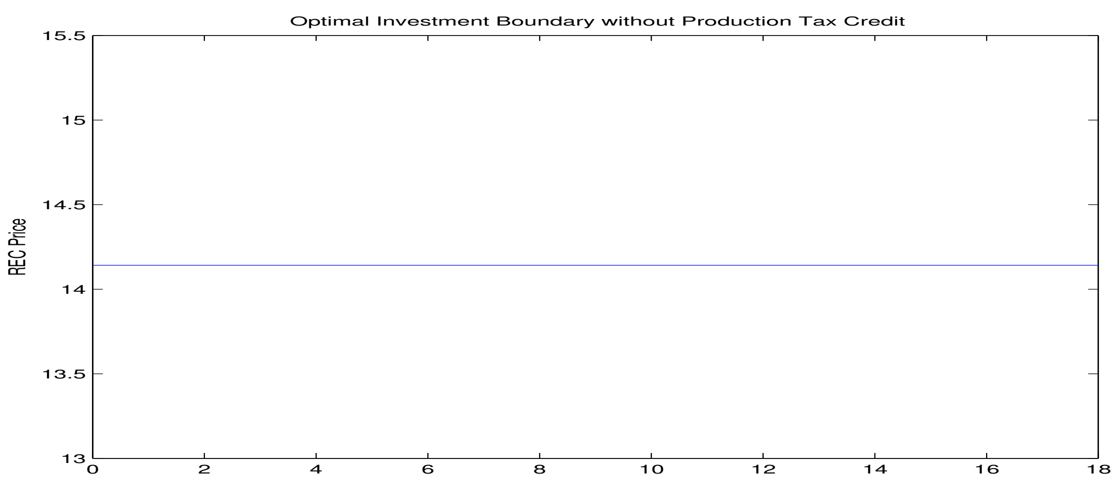


Figure 6: Optimal Investment Boundary with a Severe Reduction in REC Prices when PTC=1

We also change the probability of the federal government's decision to maintain the PTC policy to observe the responsiveness of our model to the PTC policy. We initially set the probability of maintaining the PTC at 0.7 but when we decrease the probability of maintaining the PTC to 0.3 holding other parameters, the investor's optimal investment boundary includes higher critical REC prices with the PTC policy. The minimum REC price threshold increases to \$63.5MWh. Without the PTC policy, the optimal investment boundary is between \$74.5MWh and\$77.6 MWh which is the same as our initial simulations. The investor receives zero revenues from credits if the government does not maintain the PTC policy, therefore; the REC price threshold stays same without the PTC. The sensitivity analysis on the PTC policy shows that a lower probability in the government's decision on continuing the PTC policy also increases the investor's optimal REC price threshold for investment. Figure 7 shows the higher critical REC prices for investment when there is a lower probability of the federal government maintaining the PTC policy.

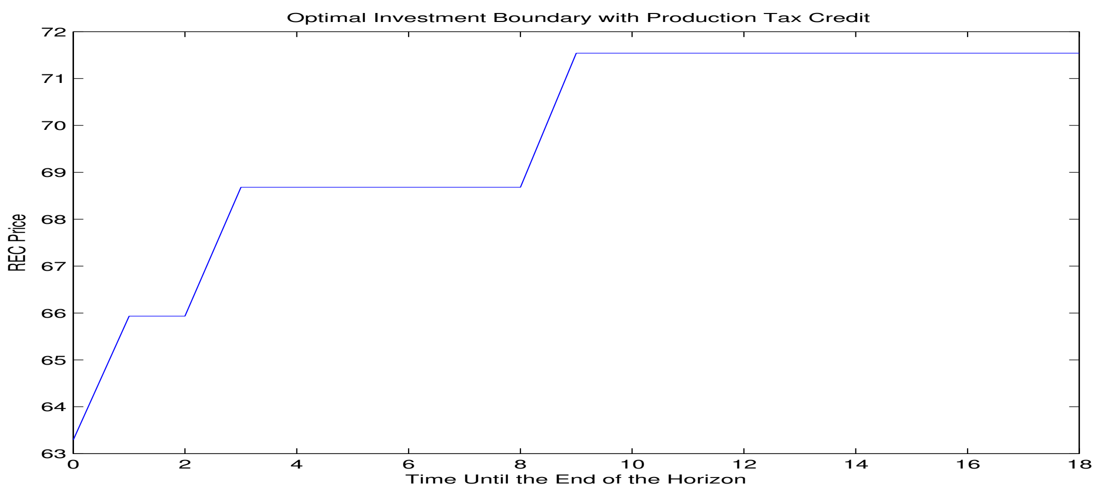


Figure 7: Optimal Investment Boundary with a Lower PTC Probability ($p = 0.3$) when PTC=1

4.2 State-Level Analysis

Similar to our initial analysis, we repeat the simulations for different states, which have different RPS goals; therefore, different REC prices and electricity prices based on the location of their operating electricity markets. We include three representative states from different electric power market regions: NEPOOL, PJM and Midwest. We select the states that we obtain REC market data and are located in these different trading regions.

Massachusetts is in NEPOOL, Delaware is in PJM and Michigian is in the Midwest REC trading region. In the state of Massachusetts, annual average electricity prices (\$142.6MWh) are the highest compared to Delaware and Michigan. Delaware has the highest average REC prices (\$80.05MWh) and the average electricity price is \$117.9MWh. The Midwest has the lowest electricity (\$98.8MWh) and REC prices (\$6.83MWh). Calibrating the REC and electricity prices into the model for three regions, we obtain different results in terms of the optimal REC price threshold for investment. We also estimate the probability of the REC prices increasing as well as the volatility for each state using the same methods described in the previous section. Table 2 includes the parameters for each representative state from different regions:

Table 2: State-Level Analysis: Parameters and Calibration.

Parameter / States	*Massachusetts* (NEPOOL)	*Delaware* (PJM)	*Michigan* (Midwest)
Annual Average Electricity Prices ($/MWh)	142.6	117.9	98.8
Power Capacity of the Windmill (MW)	1.5	1.5	1.5
Annual Energy Production (MWh/year)	4862	4862	4862
Average RECs Prices in 2012 ($/MWh)	32.70	80.05	6.83
Price Volatility in RECs	3.18	4.23	1.40
Amount of RECs Generated	$0.7 * 4862$	$0.7 * 4862$	$0.7 * 4862$
Sunk Cost of Windmill Installation ($/MWh)	2.098	2.098	2.098
Operating and Maintenance Cost ($/MW/year)	$350000 * 1.5$	$350000 * 1.5$	$350000 * 1.5$
Federal Production Tax Credits ($/MWh)	23	23	23
Capacity Factor (%)	37%	37%	37%
Probability that the Government Maintains the PTC	0.7	0.7	0.7
Estimated Probability of REC price increase	0.60	0.56	0.55
Annual Discount Factor	1/1.08	1/1.08	1/1.08
Total hours in a year	8760	8760	8760

Note 1: 1 MWh (Megawatt -hour) = 1000 kWh (kilowatt-hour)
Note 2: Average REC prices are based on the trading regions: NEPOOL, PJM, Midwest

An investor in Massachusetts with the highest electricity prices has the REC price threshold for investment starting at $14.5MWh with the PTC policy. Without the PTC, in fact, the minimum critical REC price is $22.65MWh in Massachusetts. However, the lower bound of the critical REC prices for investment in Delaware is $57.75MWh without the PTC policy. With the PTC, for the investor in Delaware, the critical price for investing starts at $41.8MWh. The investor in Michigan prefers to invest at the lowest REC price threshold. This is due to the lowest electricity and REC prices. When there is no PTC policy, the optimal REC price threshold is $14.7MWh and the investor in Michigan invests at this REC price without the PTC. However, with the PTC, the lower bound of the REC price threshold starts at $3.5MWh. Therefore, with a lower electricity price and REC price, the REC price threshold for investment is lower in Michigan compared to Delaware and Massachusetts. In fact, in Massachusetts, which has the highest average electricity price, the investor also does not require high REC prices threshold for the investment as well. In particular, with the PTC policy, minimum REC price for investment is as low as Michigan where both the average electricity and REC prices are the lowest.

In sum, our simulations for different states with different electricity and REC prices show differences in the minimum REC price for investment about the same renewable energy technology. The range of REC prices for investment vary in different states that are operating in different trading regions. All of the state-level results are also consistent with the initial results and the sensitivity analysis with respect to the implications of with and without the PTC policy: without the PTC, the investor requires a higher REC price threshold to invest. In addition, for all states, REC prices threshold for investment is lower when the PTC policy is active because the investor receives additional benefits from the PTC.[5]

[5]Simulations related to the state-level simulations are in the Appendix 7.4.

5 Policy Implications

Findings of this study have significant renewable energy policy implications. First, uncertainty about the renewable energy policies affect the decision to invest. Without considering the uncertainty in both policies, we show that REC price threshold for investment that depends on time is higher ($71.5MWh when PTC=1 and $80.8MWh when PTC=0). However, the change in the policy decisions do not necessarily affect the decision to invest in renewable energy when the investor has complete information about these policies. The deterministic case, in fact; is similar to the stochastic case with respect to the impact of the PTC policy on the REC price threshold. The REC price threshold for investment is lower when there is the PTC policy compared to when there is no PTC policy.

Uncertainty in renewable energy policy has considerable impact on the investment decisions: although the PTC policy provides a large amount of subsidy for renewable energy investors, uncertainity about the PTC policy affects clean energy capacity installations. Similarly, the RPS standards are set to expire in 2020 and we expect that new regulations for cleaner energy will be implemented. After the goals are met, the RPS design is uncertain. The new goals will determine the prices in the REC market. If there are higher mandatory goals set for the states, this will promote investment in cleaner energy. However, the future prices in the REC market may decrease. This will be a disincentive for renewable energy investments in the long run. Furthermore, the relationship between federal and state-level policies is usually ignored. However, in our study, we show that continuation and discontinuation of the federal policy affect the REC price threshold for investment. Without the PTC policy, the minimum REC price that will spur the investment is higher compared to when there is the PTC policy. Hence, the PTC policy provides a considerable incentive for renewable energy investments.

We also examine three different states with REC market of each state in a different trading region: Michigan in the Midwest, Delaware in PJM and Masachussets in NEPOOL. Each state has different electricity prices, different REC prices, different volatility of the REC prices and different probability of a REC price increase. Our results for the state-level analysis show that different market prices affect the investment decision on the same renewable energy technology. The PTC policy plays an important role on the investment decision through affecting the REC price threshold. With the PTC policy and lower average REC prices, the threshold for investment starts at a lower REC price (e.g., Michigan) compared to a state with higher average REC prices (e.g., Delaware). The investor may prefer to receive additional revenue from the PTC when the REC prices are low. The existence of the PTC policy decreases the minimum REC price threshold for investment. This is consistent for all cases considered in this paper. However, in Massachusetts the minimum REC price threshold is also low due to high electricity prices. States with different RPS goals, RECs trading and electricity markets vary with respect to their REC price threshold for investment with and without the PTC policy. Thus, investment decisions in different states may also vary with the changes in the REC market and the federal government's decision on the PTC policy. In states where the REC prices are lower, federal government's decision on the PTC policy may have a considerable impact on the decision to invest in renewable energy whereas in other states the impact may be negligible due to high REC and electricity prices.

Another important policy implication is what happens if the REC market ceases operation after the mandatory goals are met. This implies that the price of RECs gradually decrease to zero over time. This has two major implications. First, the REC prices have a considerable impact on the investment decisions in renewable energy. Although uncertainty affects the investment threshold, higher REC prices promote investment. Second, the PTC policy plays a critical role when REC prices decrease drastically to zero. If REC prices became zero, the PTC policy would still stimulate investments and the existence of a federal policy would become crucial for investment decisions. However, investment decisions are limited by positive REC prices without the PTC policy. If there were very low REC prices and no federal PTC policy, renewable investments is more likely be postponed. Thus, our research supports previous research (Wiser 2007) by suggesting that clearly defined state and federal goals and continuation of the state and federal-level policies are important for reaching the renewable energy development targets of the US.

6 Conclusions and Future Research

This paper solves the problem of investor's decisions to invest in renewable energy over a 20-year time horizon. A discrete choice optimization model is employed for a price-taker investor who makes the decision to invest in a 1.5 MW capacity windmill. Our model includes two sources of uncertainty: 1) Uncertainty about the Renewable Electricity Credits (REC) prices and 2) Federal government's decision to maintain the Production Tax Credits (PTC) policy. We solve our model using dynamic programming. We provide a REC price threshold for investment that changes over time. Our results show that the uncertainty in the federal government's decision about the PTC policy affects this threshold.

If the government makes the PTC available through the PTC policy, the investor receives revenues from these credits. However, depending on the REC price threshold for investment and the uncertainty about the future REC prices, the decision to invest in renewable energy may vary. This can be attributed to the investor compensating for the cost of investment by receiving the PTC and not requiring higher REC prices or selling these RECs to compensate for their costs when the PTC policy is not enacted. If there is no PTC available, the investor expects higher REC prices in order to invest. The PTC reduces the cost of investment by about 30% and therefore the investor does expect higher REC prices to make the decision to invest. Thus, uncertainty about the PTC policy affects both the value of the investment and the REC price threshold for investment.

Our paper contributes to the literature by examining the effects of uncertainties about policy on the investor's decision to invest in renewable energy. It also examines the relationship between the federal and the state policy that affect the investment decisions in renewable energy under uncertainty. We plan to extend this study in several ways: First, we would like to relax our assumption on REC prices following a jump up and down process. We would define a more realistic price function for RECs and compare with our findings. This would improve the applicability of our results significantly. Second, so far we have assumed constant annual electricity prices; however, we would like to introduce randomness in the electricity prices as well. This requires us to consider the joint distribution of the REC prices and electricity prices. Finally, we have assumed that the probability of the federal government's decision on the PTC policy is independent from the probability of the REC price increase or decrease. Introducing a joint distribution for federal and state policies may provide a more explicit interdependent relationship between these two policies.

References

[1] Arrow, Kenneth J. and Fischer, Anthony C. 1974. Environmental Preservation, Uncertainty and Preservation. *Quarterly Journal of Economics*, 88(2), May, 312–319.

[2] Balikcioglu, M., Fackler, P.L. and Pindyck, R.S. 2011. Solving optimal timing problems in environmental economics. *Resource and Energy Economics*, 33, 761–768

[3] Brown, P. 2012. *US Renewable Electricity: How Does the Production Tax Credit (PTC) Impact Wind Markets?* CRS Report for Congress, Congressional Research Service. `www.crs.gov` (Accessed December 24, 2012).

[4] Dixit, A.K. and R.S. Pindyck. 1993. *Investment Under Uncertainty.* Princeton University Press. New Jersey, United States of America.

[5] Fair, C. Ray (1993). Estimating Event Probabilities from Macroeconometric Models Using Stochastic Simulation. In James H. Stock and Mark W. Watson (eds), Business Cycles, Indicators and Forecasting (pg 157-178). University of Chicago Press.

[6] Fell, H. J. Linn, and C. Munnings 2012. Designing Renewable Electricity Policies to Reduce Emissions. *Resources For Future*, December Washington DC. `http://www.rff.org/RFF/Documents/RFF-DP-12-54.pdf` (Accessed March 8, 2012).

[7] Fuss, Sabine, Jana Szolgyaova, Michael Obersteiner and Mykola Gusti 2008. Investment under market and climate policy uncertainty. *Journal of Applied Energy*, 85 (2008), 708–721.

[8] Fuss, Sabine, Jana Szolgyaova, Nikolay Khabarov and Michael Obersteiner 2012. Renewables and climate change mitigation: Irreversible energy investment under uncertainty and portfolio effects. *Journal of Energy Policy*, 40 (2012), 59–68.

[9] Heeter, J., P. Armstrong, L. Bird 2012. *Market Brief: Status of the Voluntary Renewable Energy Certificate Market (2011 Data).* National Renewable Energy Laboratory NREL.

[10] Heeter J. and L. Bird 2011. *Status and Trends in US Compliance and Voluntary Renewable Energy Certificate Markets (2010 Data).* National Renewable Energy Laboratory (NREL).

[11] Lou, Chenlu 2011. *Generation Portfolio Optimization under Wind Production Tax Credit and Renewable Portfolio Standard.* Graduate Theses and Dissertations, Iowa State University, Paper 11202.

[12] Mastrangelo, Erin 2007. *An Analysis of Price Volatility in Natural Gas Markets. Office of Oil and Gas*, Energy Information Administration (EIA).

[13] Miranda, M.J., P.L. Fackler 2002. *Applied Computational Economics and Finance.* The MIT Press, Cambridge Massachussets.

[14] Mosino, Alejandro 2012. A real options evaluation model for the diffusion prospects of new renewable power generation technologies. *Journal of Resource and Energy Economics*, 34, 413–430.

[15] Palmer, K and D. Burtraw 2005. Cost-Effectiveness of Renewable Electricity Policies. *Journal of Energy Economics*, 27, pg. 873–894.

[16] Pindyck, R.S., 1980. Uncertainty and exhaustible resource markets. *The Journal of Political Economy*, 88, 1203-1225.

[17] Pindyck, R.S., 1984. Uncertainty in the theory of renewable resource markets. *The Review of Economic Studies*, 51, 289-303.

[18] Pindyck, R.S., 1988. Irreversible investment, capacity choice, and the value of the firm. *The American Economic Review*, 78, 969-985.

[19] Pindyck, R.S., 2000. Irreversibilities and the timing of environmental policy. *Resource and Energy Economics*, 22, 233-259.

[20] Puterman, M.L 1994. *Markov decision processes: discrete stochastic dynamic programming.* John Wiley Sons, Inc. New York, NY, USA.

[21] US Energy Information Administration (EIA) 2012. `http://www.eia.gov` (Accessed December 23, 2012).

[22] Tegen, S., M. Hand, B. Maples, E. Lantz, P. Schwabe and A. Smith 2010. *2010 Cost of Wind Energy Review.* National Renewable Energy Laboratory.

[23] Wiser, R. 2007. *Wind Power and Production Tax Credit: An Overview of Research Results. Lawrence Berkley National Laboratory.* `http://eetd.lbl.gov/ea/emp/reports/wiser-senate-test-4-07.pdf` (Accessed December 23, 2012).

7 Appendix

7.1 Model Parameters

p: Electricity Prices
R_t: Amount of RECs bought/sold where $R_t = (1-\theta)N_t$
M: Capacity of the windmill
N: Kilowatt/hours renewable electricity produced / year
θ: Proportion of Electricity Produced (30%)
q_t: REC Prices (stochastic)
C^{SUNK}: Sunk Cost of Investing in Renewable Energy
C: Variable (Operating and Maintenance) Cost of Renewable Energy Production
r: Discount Rate
$\beta = \frac{1}{(1+r)}$
$NPV(t)$: Discounted Production Tax Credits Payments
$PTC(t) : \tau * N_t$, PTC payments in each period
$\tau : 2.3 cents/kWh (= \$23 MWh)$
σ: REC Price Volatility
T: 20 years ahead when the RPS goals should be achieved
$Capacity factor : 38\%$

Action 1: Invest/Not Invest
$x \in (0, 1)$
$x_t = 1 \rightarrow$ invest
$x_t = 0 \rightarrow$not invest

Action 2: Have invested/ Not yet invested
$s \in (0, 1)$
$s_t = 1 \rightarrow$ invest
$s_t = 0 \rightarrow$ not invest

State for keeping/removing PTC (stochastic)
$\alpha \in (0, 1)$
$\alpha_t = 1 \rightarrow$ Government keeps the PTC
$\alpha_t = 0 \rightarrow$ Goverment removes PTC

7.2 Model and Parameter Estimations

We obtain the REC price data from Spectron Group between 05.25.2006 and 11.22.2012. The data includes the daily spot prices of the RECs for compliance and voluntary markets. We only present the compliance market in here. We have estimated the following simple AR(1) model and employed a Dickey-Fuller Test for each to check for existence of random walk in the price data. The historical REC prices follows a random walk process. The AR(1) and test results are presented in the Table 1 below:

$$REC_t = \alpha_1 * REC_{t-1} + \epsilon_t$$

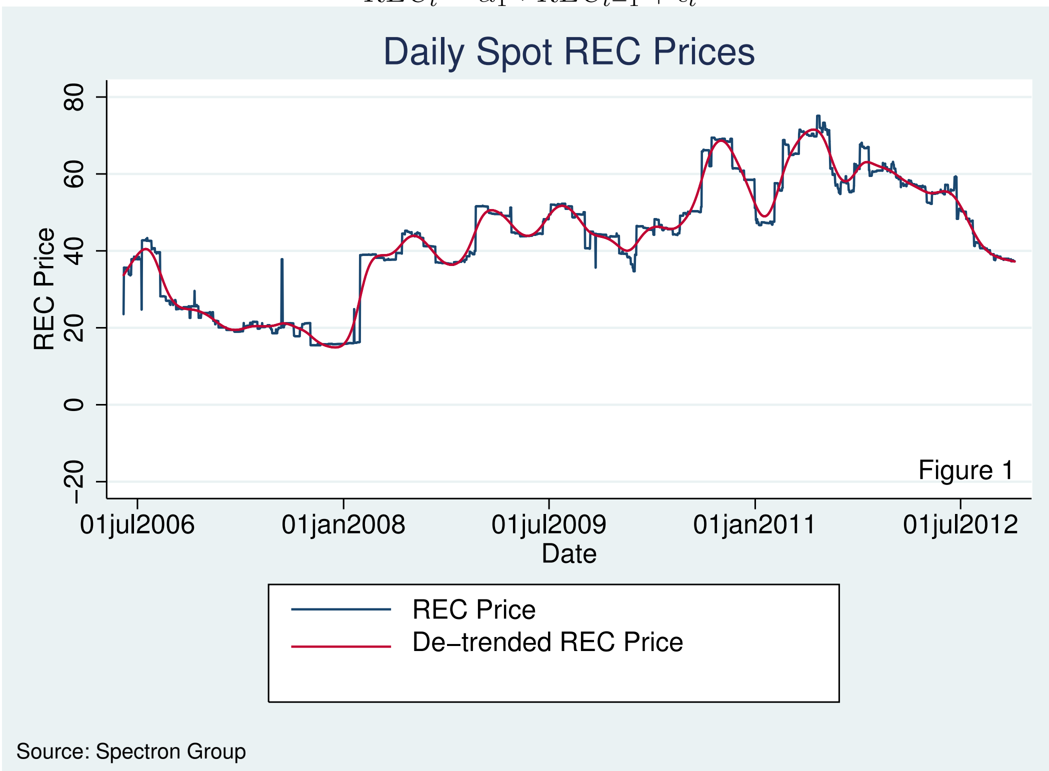


Figure 8: Daily REC Prices Follow Random Walk

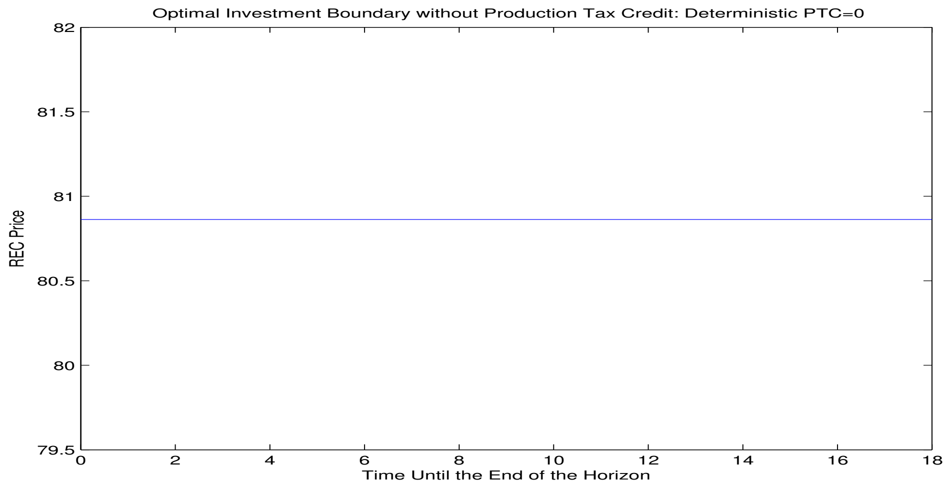
	(1)	(3)
	AR(1)	DF t-test
REC_{t-1}	0.999***	-1.253
	(0.001)	(0.652)
N	1627	1626

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

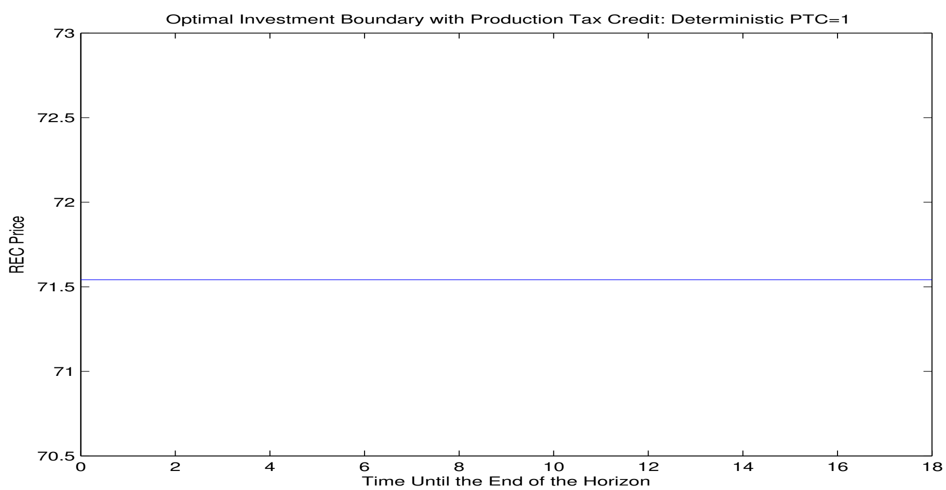
Table 3: Results for Random Walk

7.3 Simulations from Deterministic Case

The federal government removes the PTC policy for certainty for 20 years



The federal government maintains the PTC policy for certainty for 20 years



7.4 Simulations from State Level Analysis

Massachusetts (NEPOOL)

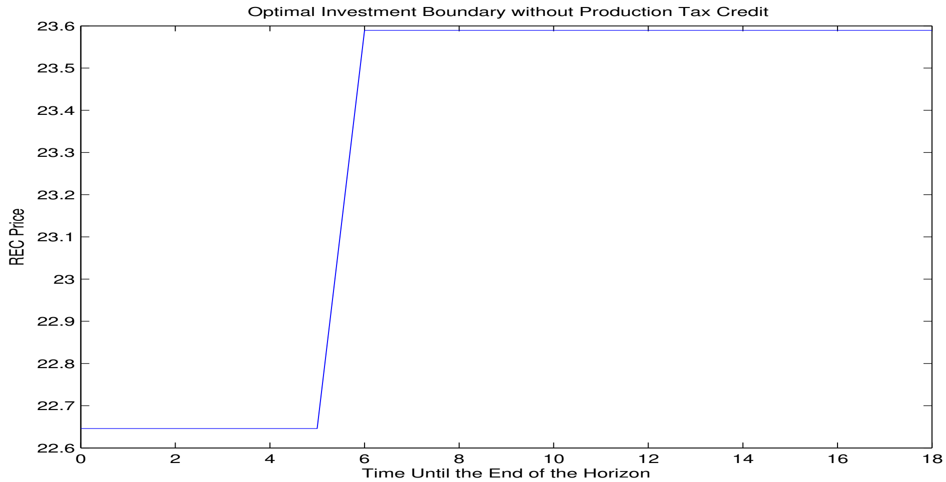


Figure 9: Investment Boundary When PTC=0

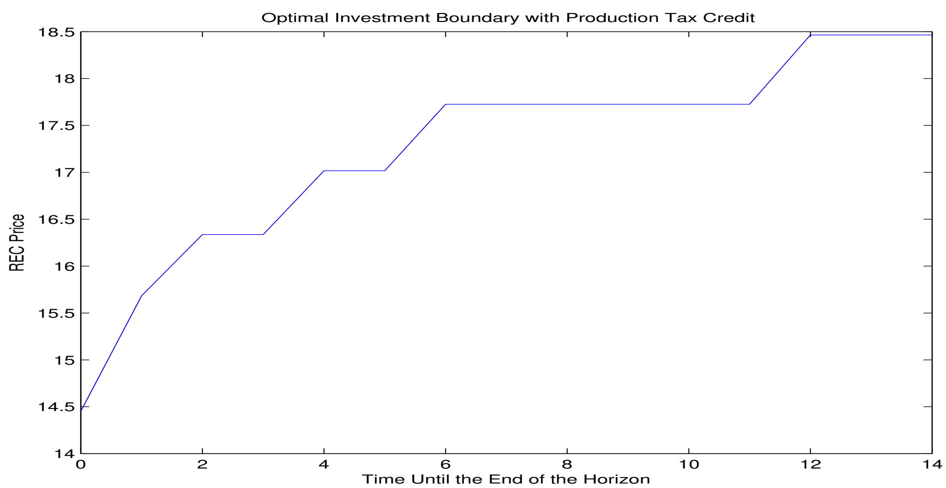


Figure 10: Investment Boundary when PTC=1

Delaware (PJM)

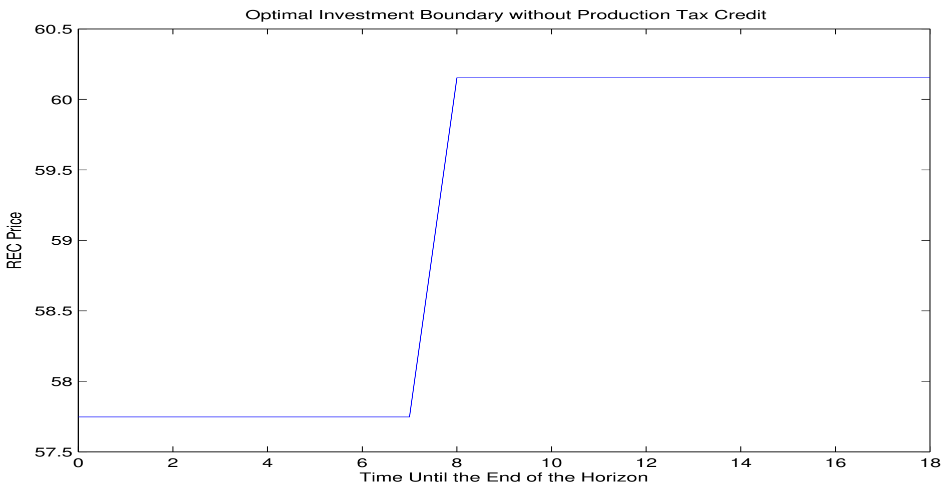


Figure 11: Investment Boundary When PTC=0

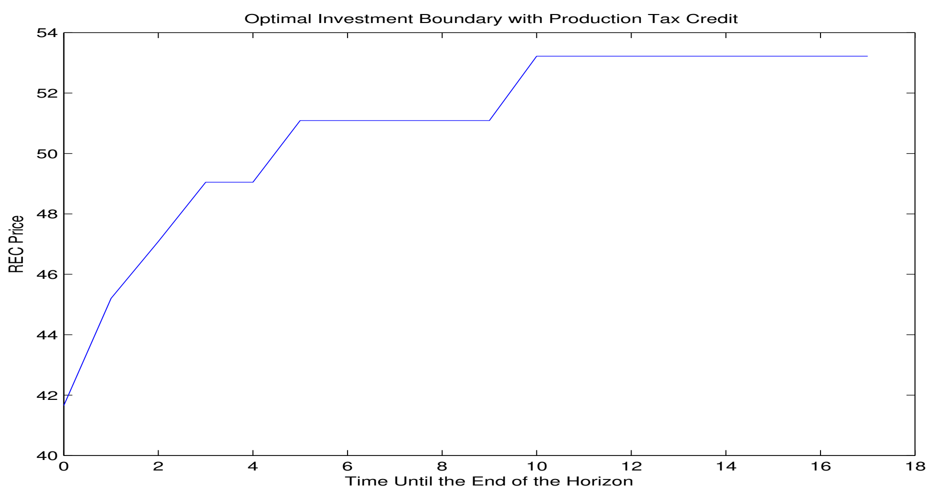


Figure 12: Investment Boundary when PTC=1

Michigan (Midwest)

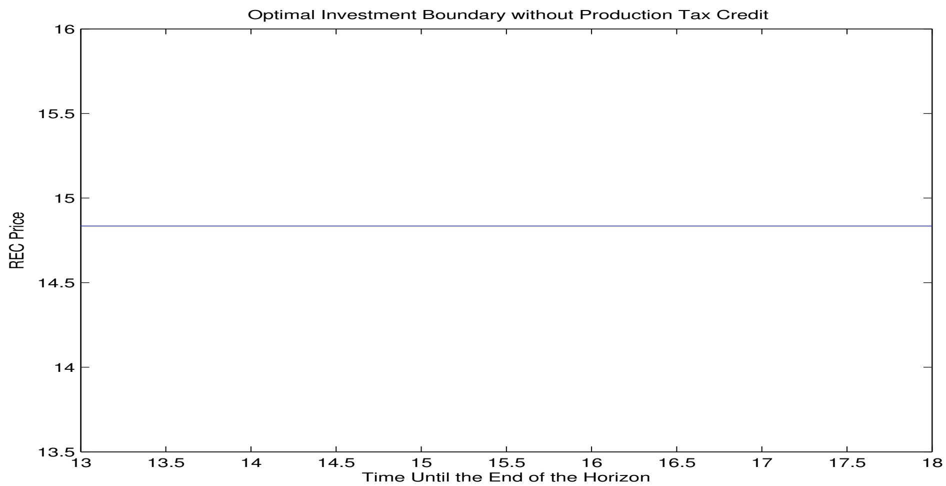


Figure 13: Investment Boundary When PTC=1

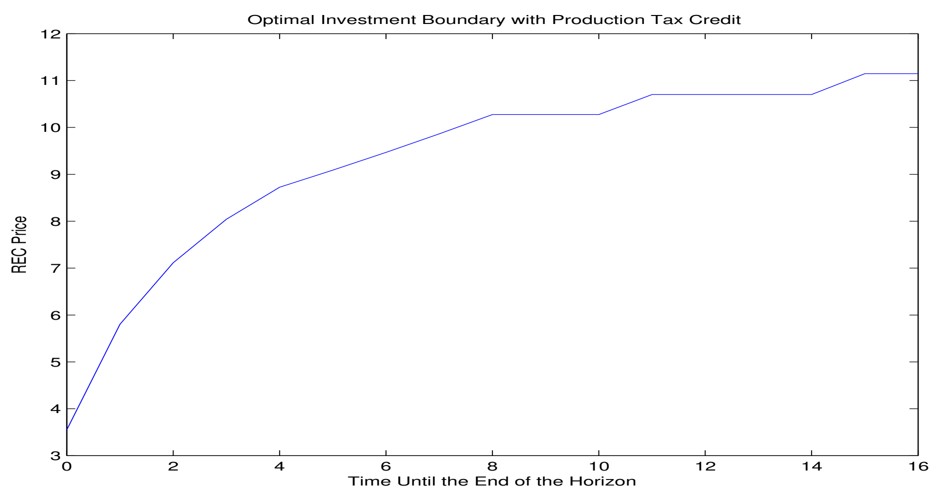


Figure 14: Investment Boundary When PTC=1