An Assessment of the Impacts of Government Energy Policy on Energy Technology, Innovation, and Security: The Case of Renewable Technologies in the US Electricity Sector

Edwin Garces and Tugrul Daim

Abstract Purpose The reduction of using natural gas and coal and the necessity of having different sources of energy are essential for the energy security in the USA. Renewable energy technologies are considered as the alternative, but these technologies are not yet reliable and cost effective. The objective of this paper is to identify the factors that results in technological change and to analyze the direction and effects of energy policies in the electricity sector.
Design/Methodology/Approach Based on the induced technological change theory, a co-integration analysis is done to evaluate the short- and long-run effects of the factors on renewable technology change by, focusing on the analysis of energy policies. An ex post quantitative policy evaluation is applied.
Findings The results of the empirical analysis show that the variables are associated in the long run, while the relationship between renewable energy technologies and the electricity market is not significant.
Practical Implications The federal and state energy policies, R&D investment, knowledge stock, and knowledge accumulation are not entirely connected to electrical market variables. These results indicate the importance of energy policies aiming at accomplishing the energy security objectives.
Originality/Value This paper focuses on understanding how policies impact the renewable energy technology and analyzing the relationships and directions of the effects among the variables. The empirical and quantitative analysis, focusing on a theoretical model and the practical analysis, aims to understand the long- and short-run policy effects to develop better technology plans and achieve the energy security objectives.

E. Garces (✉) • T. Daim
Department of Engineering and Technology Management, Portland State University, P.O. Box 751, ETM, Portland, OR 97207-0751, USA
e-mail: edwing@pdx.edu; tugrul@etm.pdx.edu

W. Leal Filho and V. Voudouris (eds.), *Global Energy Policy and Security*, Lecture Notes in Energy 16, DOI 10.1007/978-1-4471-5286-6_15,

Keywords US • Government energy policy • Energy security • Technology innovation • Renewable energy technology • Co-integration analysis • Induced technological change

1 Introduction

Recently, high conventional energy prices and the political and economic instability show the necessity of having different sources of energy. In this context, renewable energy technologies will contribute to achieve the government objectives of reducing foreign energy dependency and reduction of contaminant emissions.

The development of renewable energy power technologies is important for energy security as a part of national security. Energy security, defined by Bielecki (2002), implies the "reliable and adequate supply of energy at reasonable prices" (p. 237). In the US electricity sector, the major sources of energy come from natural gas and coal. However, these two sources are linked to concerns of foreign dependency and environmental pollution. In the case of coal, the source is abundant, inexpensive, and will last for a long time. However, since coal is associated with over-emission, replacing coal by clean sources for generating electricity is necessary (Wirth et al. 2003). In the case of natural gas, as Bielecki (2002) indicates, the problem is not availability but that concentration of the major reserves is outside the USA and is related to the complexity of distribution and transport of natural gas to markets (Bielecki 2002).

In order to reduce dependency on natural gas and reduce the risk associated with coal pollution, it is the objective of the government to promote renewable energy production and to eliminate imports of oil and gas by 2030 (Spector 2009; The White House 2002). However, the elimination or reduction of natural gas and coal use is complex since in the electricity market, supply levels need to be adjusted according to the demand levels. Accordingly, diversification is one of the options to reduce the foreign energy dependency, and all the options need to be considered with long-term programs that promote the improvement of efficiency (Bielecki 2002).

The new alternative source of energy comes from renewable resources. In the specific case of the electricity sector, electricity can be generated by renewable resources, such as wind, sun, tidal waves, and marine currents. However, renewable energy technologies are not taken as an integral part of the electrical grid system, because they are economically inefficient and technically unstable compared with conventional energy technologies. Considering reliability and price, the use of renewable energy on a large scale, like wind turbines, has many concerns. These renewable energy technologies are intermittent and their costs are not yet competitive with nonrenewable sources.

At present, electricity from renewable energy technologies does not represent a significant fraction of total production (Deutch et al. 2006). For example, in the "Economic Dispatch in the Electrical Power System," electrical plants using renewable resources are not included as base or marginal units. This concern is much more serious because energy scarcity and new environmental restrictions have appeared. Generating alternatives present challenges to be more reliable and capable to generate electricity in a large scale in a cost-efficient way, and increasing the reliability of these new generation alternatives presents challenges.

The US electrical market has changed during the last 10 years, showing that policy makers have given more priority to renewable energy. However, even as the use of renewable energy sources has been increasing, the penetration in the market is limited (Johnstone et al. 2010). One of the reasons for the limited adoption is the higher cost of renewable technologies, compared to substitute fossil fuel products (Johnstone et al. 2010).

The market adoption or diffusion of renewable technologies is associated with market failure, since the electricity market has the characteristics of a natural monopoly. This market failure in the electricity industry implies that investors do not adopt renewable technology, despite high electricity prices. Renewable technologies are not adopted because the amount and type that firms invest in knowledge is driven by private profit incentives from appropriate innovations (Loschel 2002).

Due to the market failure, the government has been applying and restructuring national and state policies in order to find an energy source that is clean and cost competitive, specifically in the electric industry. Since policy interventions affect the process of technological change (Kerr and Newell 2003) and to accelerate the adoption and diffusion of renewable energy technologies in the electricity market, the government has been applying different types of policies. The policies, such as certificates, feed-in tariffs, production quotas, and tax credits, aim at reducing production costs of using renewable energy (Johnstone et al. 2010). At present, the policies appear to have failed because renewable technologies are believed to be a second option in technology selection. The failure of policies is associated with controversial practices for promoting technologies such as the Energy Independence and Security Act of 2007 which does not include the Renewable Energy Portfolio Standard (RPS) (CRS 2007).

It is clear that policies lack comprehension of technological change and diffusion of technologies for renewable energy technologies. However, energy independence and environmental restrictions are factors that can be considered as the determinants of using and promoting renewable energy in the electricity sector (Bielecki 2002). Therefore, the necessity of generating electricity from clean resources is a government priority (Mignone 2007).

Unlike other studies analyzing only environmental or renewable policies, this paper examines the relationship between renewable technological change and policies associated with the electrical sector, including federal and state regulations.

Modeling technological change is an important issue for formulating policies regarding the environment and energy (Gillingham et al. 2007). Therefore, this paper will find answers for the following questions:

- How have government policies been affecting renewable technology change?
- What are effective policies that promote renewable energy technology change?
- What are the main factors causing technological change and causal relationships between them?

Considering the challenges of renewable technologies and policies in the electrical sector, the main objectives of this paper are:

- To identify the factors that results in technological change and to describe the effects of technology policies related to renewable technology innovation in the electricity sector.
- To analyze the direction and effects of energy policies in the electricity sector for inducing the change and adoption of renewable technologies by applying ex post quantitative policy evaluation.

It is important to understand how policies affect the renewable energy technology. Modeling technological change is essential to analyze the policies and their final effects, in order to develop optimal policies and economic models (Grubb et al. 2000). However, previous analyses had been focused on environmental strategies and environmental policy analysis as mentioned by Popp (1998). There are few studies specifically about renewable energy technology change and adoption in the electricity sector.

Finally, it is crucial to have empirical and quantitative analysis to understand the long- and short-run policy effects in order to formulate better technology plans. Empirical analysis is needed, because theories, such as the induced technology theory, explain how factors affect technological change; however, theories do not explain how new knowledge is developed (Popp 1998). Applying the endogenous growth theory gives an opportunity to analyze knowledge formation and accumulation as well as how the factors explain the knowledge accumulation and the direction of technological change. Therefore, understanding endogenous technological change is important since policies affect the evolution of technologies, costs, and outcomes (Weyant and Olavson 1999).

2 Theory and Literature Review

As cited by Loschel (2002) "Schumpeter (1942) distinguishes three stages in the process of technological change": Invention, innovation, and diffusion (p. 1). In the frame of induced innovation, technological change is explained by different methods and theories. Due to the motivation and objectives of this paper, technological change has been associated with the "induced technological change theory," which can be divided into the following theories:

2.1 Exogenous Technological Change

Using the Solow (1956) theory, in the energy and environmental field, technological change has been considered as an exogenous variable which implies an autonomous function of time. Technology follows two functions of time: a Hicks-neutral productivity following economic progress and the energy-saver approach (Gillingham et al. 2007). In this context, autonomous technological change depends on autonomous trends and government R&D. This differs from endogenous technological change, which considers technological change as dependent on corporate R&D in response to market conditions (Grubb et al. 2000).

2.2 Endogenous Technological Change

This model considers R&D investments as one of the main reasons for technological innovation which is a product of profit maximization. Endogenous technological change (ETC) incorporates the feedback of policies that alters the state and direction of technological change (Gillingham et al. 2007). Feedback takes the form of information from prices, research and development (R&D) or learning by doing (LBD).

The three most common models of endogenous technological change are the following: “direct price-induced, R&D-induced, and learning-induced” (Gillingham et al. 2007, p. 2738). Direct price-induced technological change implies that the changes of relative prices cause innovation because of the reduction of more expensive technologies (this is concordant with Hicks-induced innovation). R&D-induced technological change explains the change in rate and the direction produced by changes in R&D investments. Learning by doing (LBD) uses a unit cost of a technology as a decreasing function of cumulative output.

In the analysis of the relationship between energy, technology, and environment, there are two approaches: bottom-up and top-down models. Bottom-up models integrate the new technologies considering their cost and performance. In this context, technological change is a product of substitution of one technology for other technologies with better cost-efficiency performance (Loschel 2002). Since energy and price are regarded as exogenous, this analysis “may overestimate the potential penetration” (McFarland et al. 2004, p. 686).

Top-down models describe the energy sector in aggregate way by neoclassical theory. These models do not describe technologies (Loschel 2002), but represent technology in the aggregate production function.

The research associated with the theories described above focuses on environmental analysis. In this context, induced technological change has been explained by addressing environmental policies. Goulder and Mathai (2000) studied changes of technology (related to avoid CO_2 emissions—avoided cost) affected or induced by carbon-abatement policies. Their paper considers the R&D and learning by doing (LBD) approaches of knowledge accumulation. Using analytical and numerical models, the main conclusion is under the presence of induced technological change, the time profile of optimal taxes is lower.

There is a lot of research analyzing the relationship between policies and technological innovation focused on environmental policies. For example, Johnstone et al. (2010) use panel data patents among 25 countries to analyze the effects of environmental policies on technological innovation. This study uses a linear model where patents represent technological change as a dependent variable and policies, price, R&D, and consumption are the exogenous variables. Johnstone et al. (2010) conclude that there has been an increase in technological innovation among the 25 countries, and this improvement has been significant and positively affected by different environmental policies.

A theoretical review about induced technological change associated with energy, environment, and policy was made by Weyant and Olavson (1999). Also, Bosetti et al. (2006) use an endogenous model that emphasizes on learning by researching and learning by doing. Endogenizing technological change was empirically modeled by Pizer and Popp (2007) who focus on R&D process, learning by doing, and diffusion.

Theoretical analysis and empirical (statistical and econometrical) analysis have demonstrated that the government policies affect technological change following the endogenous theory. The empirical studies use the demand side and the supply side in order to explain technological change. In this context, empirical studies combine market analysis considering supply. Popp (1998) studies the impact of energy prices on technological innovation, specifically energy-efficiency innovation. Popp (1998) uses the number of patent citations in the USA to measure the state of knowledge and investigate market effects (demand- and supply-side factors). Additionally, Popp (1998) uses demand- and supply-side theories implying that technological change (energy-saving research) depends on the energy prices and the "usefulness of the existing stock of scientific knowledge" (p. 3). In this case, a linear relationship is used where the relative number of patent application is the dependent variable and the price of energy, marginal productivity, R&D investment, and other variables are determinant variables. The results show that energy price and the marginal productivity of R&D play an important role in technological innovation. Using the demand and supply side, Tsoutsos and Stamboulis (2005) argue that systematic innovation processes for diffusion of renewable technologies depend on successful policies.

Moreover, many researchers focused on the innovation of some specific technologies as the effect of renewable energy policies. For instance, Adelaja et al. (2010) analyze the case of the wind industry by using an empirical approach and focusing on state policies such as Renewable Portfolio Standards (RPSs). The results show that RPSs are not important drivers of wind technological change.

3 Methodology

In this chapter, an econometrical model, based on the induced endogenous technological innovation theory, has been developed. The empirical analysis is based on a theoretical model and then a co-integration analysis is done in order to analyze the short- and long-run patterns.

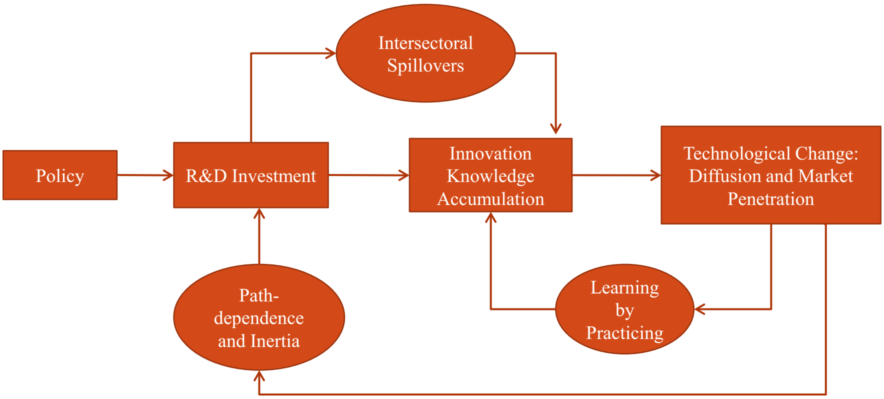

Fig. 1 Endogenous technological change. *Source*: Adapted from Weyant and Olavson (1999)

3.1 Theoretical Analysis

Formulated and based on induced endogenous technology change, there are indications that technological change is not exogenous but endogenous (Loschel 2002). In this context, the effects of policy and other variables are endogenously associated. The reason for not adopting an exogenous model is that exogenous assumptions of technological change are unresponsive to policy (Gillingham et al. 2007). Following an endogenous analysis, knowledge accumulation, research, and development expenditure are emphasized in the analysis, applying an additional endogenous function as shown below.

A top-down analysis is adopted since this model is appropriate for a long-run innovation analysis and gives important framework for knowledge accumulation and spillovers (Loschel 2002).

The dynamic process of technological change is shown by Weyant and Olavson (1999) as presented in Fig. 1.

Figure 1 shows that the technological change and market diffusion are preceded by knowledge accumulation, which interacts with the market by LBD. Policies and R&D investment affect knowledge accumulation first and then the technological change and technology adoption.

Adopting an endogenous analysis, R&D investment and policies play an important role in the knowledge accumulation, because R&D is an intangible asset to the firms' knowledge capital (Loschel 2002). In addition, electricity price is included in the model to analyze the relationship of this variable with technological change and knowledge accumulation. The main idea of the adoption of this variable is to analyze and prove the connection of this variable with endogenous modeling. Even though Gillingham et al. (2007) indicate that technological change does not follow an endogenous approach since policies and prices are historic, considering knowledge accumulation under different policies and market scenarios is important since there are retrofit effects.

Following the model of Goulder and Mathai (2000), the objective, as it is applied by Goulder and Mathai (2000), is to minimize the cost, choosing optimal patterns of abatement cost and R&D investment depending on knowledge accumulation. The objective function is represented as

$$\underset{A_t I_t}{\text{Min}} \int_0^a [C(A_t, H_t) + p(I_t)I_t)\mathrm{e}^{-rt}dt. \tag{1}$$

C represents the cost, A_t abatement, H_t knowledge stock, $p(.)$ real price of investment, I_t R&D investment, r interest rate, and t time.

The objective function depends on knowledge accumulation and it is subject to

$$\dot{H} = a_t H_t + k\varphi(I_t, H_t). \tag{2}$$

$\dot{H}$ is the knowledge accumulation and a_t and k the parameters.

This constraint is the function to focus on. Endogenous human knowledge capital accumulation is represented by the function φ and the autonomous part by αH_t.

H_t, the state of knowledge, can be represented by the number of patent applications. $\dot{H}$, the accumulation of knowledge or experience, can be represented by the cumulative number of applications of patents.

Therefore, the analysis is concentrated on (2). This Eq. (2) explains the transmission function where H and I determine the accumulation of knowledge through the function φ as represented below:

$$H, I \rightarrow \varphi \rightarrow \dot{H}$$

The function (2) is transformed and represented by a Cobb–Douglas function:

$$\dot{H} = H_t^a \, \varphi(I_t, H_t, Z)^k \tag{3}$$

Notice that the variable Z is added and represents other exogenous variables that can affect the knowledge change, such as policies or prices.

Applying natural logarithms to the function (3),

$$\text{In}\, \dot{H} = a_t \ln H_t + k \ln \varphi(I_t, H_t, Z) \tag{4}$$

Assuming that φ can be represented as Cobb–Douglas function as follows,

$$\varphi = M I_t^a H_t^b, Z_t^c \tag{5}$$

M is a parameter. Applying natural logarithms to (5),

$$\ln\, \varphi = \ln\, M + aI_{\mathrm{t}} + bH_t + Z_t \tag{6}$$

Replacing (6) in (4),

$$\ln\, \dot{H} = \propto \ln(H_t + k[\ln M + a \ln I_t +) b \ln H_t + c \ln Z_t]$$

Finally, grouping and renaming the parameters,

$$\ln\, \dot{H} = A \ln H_t + B \ln I_t + C \ln Z_t \tag{7}$$

It is important to notice that the parameters A, B, and C have different meaning comparing to the initial function. In this case, the knowledge accumulation depends on the stock of knowledge and R&D investment. This last relationship is linear and a co-integration analysis is recommended.

The variable Z_t represents other exogenous variables as price. Price-induced innovation is a theory which has been used to explain that changes in relative factor prices induce technology change, because of avoiding the use of more expensive inputs. This theory has microeconomic foundations explaining that there is a dynamic change in the production function caused by the changes in relative prices (Liu and Shumway 2009). The influence of prices is also explained by the demand-pull theories of innovation, for example, Popp (1998) mentioned that energy price makes new technology in energy efficiency more valuable. Therefore, higher energy prices from an efficient point of view will motivate to create or invent new technologies, which include renewable energy technologies.

3.2 *Model Specification: Empirical Model*

Modeling-induced endogenous technological change is complex because of the nonlinear characteristics and path dependency (Grubb et al. 2000). Therefore, a time-series econometric approach appears to be appropriate for this analysis. A time-series approach and properties presented by Liu and Shumway (2009), who recall the work of Thirtle et al. (2002), have been used. Therefore, the following arguments of the analysis are:

- The variables are not stable time series and co-integrated in the first order.
- There is co-integration among the variables.
- The positive and negative relationships among the variables following the hypothesis established above.
- There is a transmission effect from policies, R&D, and knowledge accumulation to the technology change and market adoption.
- The causalities are unidirectional and between variables.

Introducing the endogenous part into the model has been done in different ways. Most of the models include the endogenous term as a knowledge accumulation function. Also, other models, such as Schmidt et al. (2010), add lags in the explanatory variables.

The price of electricity is a variable that is considered in this analysis. The inclusion is important since market price plays an import role in technology adoption and diffusion. The variable price has been used by many scholars, especially in empirical analysis, like Johnstone et al. (2010), in the econometrical model.

The time-series modeling consists of the following analysis:

- Unit root test to see the stationality of the variables. The variables, as it will be shown below, are not stationary and first-order integrated.
- Co-integration analysis. Since each variable is not stationary in the first difference, along with the assumption of the long-run relationship among the variables, a co-integration analysis is made.
- Vector error correction model (VECM). The variables appear to be co-integrated and a VECM can be obtained in order to see the effects of these variables in the short and long run. Since policy dummy variables are used, the VECM considers these variables as exogenous variables.
- In addition to these analyses, transmission channel in VECM is used and coefficient test: Wald test is performed to see the causality among variables.

The policy analysis is performed by using dummy variables that represent the main federal and state policies regarding the electricity sectors. This is an ex post policy evaluation, but was not performed a structural test of the models to see if the policies have affected significantly the change in direction of technological change and adoption. Instead, the VECM and inclusion and significance in the model of the dummy variables will show if these polices have been affecting the dependent variables.

3.3 Limitations of the Study

The major limitation associated with the present analysis is associated with the data. Because renewable technology does not have long history, the size of data is constrained to 33 data points which can be considered a small sample size in a time-series analysis. The data availability is another factor associated with different variables. At the same time, the source or restriction of using the information is restricted or does not exist for public use. As a consequence, it is necessary to consider only the most representative government policies to be analyzed. Important policies, such as the National Energy Act of 1878 and Public Utility Regulatory Policies Act of 1978, could not be considered for mathematical econometrical reasons, because these Acts were enacted in 1978 and the data started in 1977 (considering the dynamic analysis and lag of variables).

Table 1 Variables and names

Variable	Name	Name (after taking natural logarithm)
Cumulative of number of patent applications	ACUMPATENTS	ACUM1
Number of patent applications (PCT applications)	PATENTS	PAT1
R&D investment in electrical renewable in million USD (2010 prices and exch. rates)	RDRENEW	RD1
Electricity generation from renewable (1,000 kWh)	RENEWGEN	GEN1
Average price of electricity (¢/kWh)	PRICEELECT	PRICE1
Energy Policy Act 1992	EPA1992	
Energy Policy Act 2005	EPA2005	
The American Recovery and Reinvestment Act 2009	ARRA2009	
Renewable Energy Certificates	REC	
Renewable Portfolio Standard	RPS	

Table 2 Main statistics of the variables

Variable	Mean	Median	Maximum	Minimum	Std. dev.
ACUMPATENTS	868.50	370.70	5,133.00	8.00	1,233.04
PATENTS	155.55	41.50	950.20	6.00	263.98
RDRENEW	510.60	305.96	2,228.14	166.66	483.47
RENEWGEN	668,948.20	915,837.00	1,468,394.00	34,349.00	471,374.60
PRICEELECT	13.41	13.26	16.72	10.79	1.94

3.4 Data and Variables

The definition and nomenclature of the variables used in the model are shown in Table 1:

The main statistics of the variables are shown below in Table 2.

The policies are dummy variables with one after each policy was enacted.

The federal policies considered in this paper are:

- ESA = Energy Security Act 1980
- EPA1992 = Energy Policy Act 1992
- EPA2005 = Energy Policy Act 2005

The state policies are:

- REC = Renewable Energy Certificates
- RPS = Renewable Portfolio Standard

Based on Fig. 2, there is no clear evidence of co-integration; however, a co-integration is conducted and the results were positive as the co-integration analysis shows. In the case of the price, the pattern has a negative relationship.

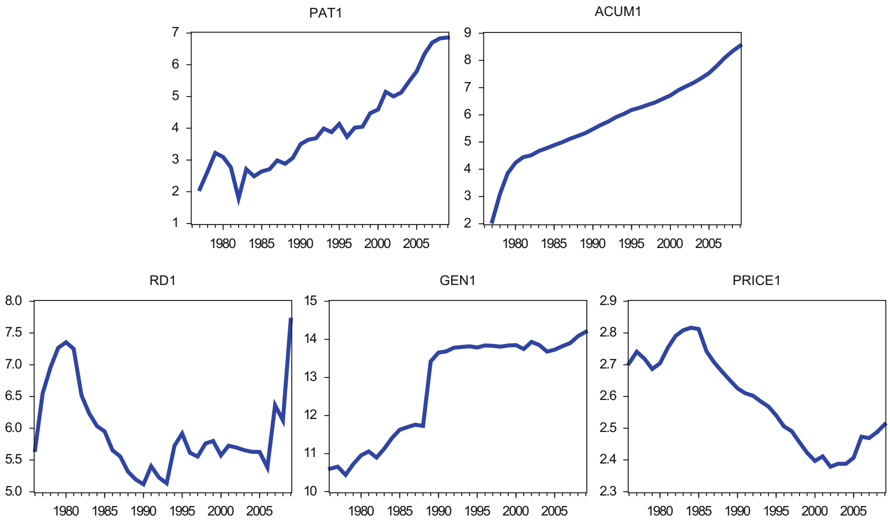

Fig. 2 Trends of variables (natural logarithms)

For the data of the number of patent applications, PCT number of patent applications from the OECD database was used. The PCT were preferred because of the availability of more years. The analysis is for US areas and the data size is considered from 1977 to 2009. The sources of data are OECD, IEA, and EIA.

4 Co-integration Analysis and Results

Applying the Granger causality test, as shown in Table 3, all expected causation direction among the variables were proved, except the relationship between the generation of electricity by renewable and R&D investment. In addition, the causation between price and generation is weak since the results are contradictory using different lags in the analysis.

By applying the augmented Dickey–Fuller test statistic, it is proved that all the variables are not stationary in the initial level and present unit root. At the same time, all the variables are stable and do not present unit root after their first difference. These results suggest a co-integration analysis (Table 4).

The results of the co-integration analysis based on the Trace statistics and Max-Eigen statistic are shown below. Both tests confirm that variables are co-integrated and have two co-integrating equations. Therefore, there is a relationship among the variables in the long run (Tables 5 and 6).

Based on the results, a vector error correction model is obtained. As is shown in the co-integration analysis, two co-integrated equations are considered. The results are shown in Table 7.

Table 3 Summary of causal test (pairwise Granger causality tests)

Variables	Hypothesis	Number of lags	*F* statistics	Prob.
ACUM1–PAT1	ACUM1 does not Granger cause PAT1	4	4.65	0.008
	PAT1 does not Granger cause ACUM1	4	1.35	0.287
RD1–PAT1	RD1 does not Granger cause PAT1	4	3.97	0.016
	PAT1 does not Granger cause RD1	4	2.29	0.096
GEN1–PAT1	GEN1 does not Granger cause PAT1	4	0.58	0.679
	PAT1 does not Granger cause GEN1	4	0.17	0.950
PRICE1–PAT1	PRICE1 does not Granger cause PAT1	4	0.40	0.806
	PAT1 does not Granger cause PRICE1	4	0.87	0.502
GEN1–RD1	GEN1 does not Granger cause RD1	4	0.55	0.698
	RD1 does not Granger cause GEN1	4	2.06	0.121
PRICE1–RD1	PRICE1 does not Granger cause RD1	4	2.78	0.053
	RD1 does not Granger cause PRICE1	4	2.20	0.104
PRICE1–GEN1	PRICE1 does not Granger cause GEN1	4	0.84	0.515
	GEN1 does not Granger cause PRICE1	4	2.65	0.062
PRICE1–GEN1	PRICE1 does not Granger cause GEN1	1	0.15	0.700
	GEN1 does not Granger cause PRICE1	1	6.42	0.016

The three equations indicate that there exist long-run effects. The R&D investment, electricity generated from renewable technologies, and price affect positively the number of patents. Meanwhile, analyzing the first error correction term (knowledge accumulation is not considered), the adjustment effects or feedback effects show that 72.6 % of the adjustment takes place in each period to go back to equilibrium levels. In the second error correction term (considering the knowledge accumulation), the adjustment is 18.8 % in each period. In the short run, the change in the number of patents is affected positively by all the variables including the policies.

In (9), there are long-run effects of the variables. Knowledge accumulation is positive, and the adjustment terms are at 21.7 % and 18.8 % levels. The variation of all the variables has positive effects on the variation of knowledge accumulation, except the variation of the number of patents.

The long-run relationship part in (10) shows that knowledge accumulation and price have not contributed positively to the generation of electricity using renewable technologies. However, R&D investments and number of patents affect positively the use of renewable technologies in the long run. It is important to notice that the adjustment speed to the equilibrium in this equation is 12.5 %, and it is slower than the other equations. Unlike the number of patents and knowledge accumulation, in this case, the policies have multiple results. The federal policy ESA and state RPS programs contribute to generation by using renewable technologies; however, the EPA1992, EPA2005, and REC show negative effects.

Using the equations above and the statistical significance and Walt coefficient significance, the following relation flow has been built:

All variables are not related to energy price. In addition, the relationship from R&D to generation is weak and only statistically significant at 10 %. However,

Table 4 Stationary test results: unit root summary

Variable[a]	Levels	Model	Augmented Dickey–Fuller test statistic		Durbin–Watson stat	Result
			t-Statistic	Prob[b]		
PAT1	Level	Trend and intercept	−1.853	0.655	2.075	Patents is not stationary, has unit root
	First difference	Trend and intercept	−6.929	0.000	2.063	Patents is stationary, no unit root
ACUM1	Level	Trend and intercept	−2.445	0.351	1.872	ACUMPATENTS is not stationary, has unit root
	First difference	Trend and intercept	−7.879	0.000	2.116	ACUMPATENTS is stationary, no unit root
RD1	Level	Only intercept	−2.136	0.233	1.743	RDRENEW is not stationary, has unit root
	First difference	Trend and intercept	−4.675	0.004	1.833	RDRENEW is stationary, no unit root
GEN1	Level	Trend and intercept	−1.262	0.880	1.857	RENEWGEN is not stationary, has unit root
	First difference	Trend and intercept	5.358	0.001	1.981	RENEWGEN is stationary, no unit root
PRICE1	Level	No intercept, no trend	−0.940	0.302	1.865	PRICEELECT is not stationary, has unit root
	First difference	Only intercept	−3.438	0.017	1.863	PRICEELECT is stationary, no unit root

[a]Natural logarithms of variable
[b]Null hypothesis rejected at 5 % significance

Table 5 Summary of co-integration test: unrestricted co-integration rank test (Trace)

Hypothesized number of co-integrated equations	Eigenvalue	Trace statistic	Critical value (0.05)	Prob.
None*	0.821	116.670	69.819	0.000
At most 1*	0.734	63.344	47.856	0.001
At most 2	0.360	22.330	29.797	0.281
At most 3	0.216	8.511	15.495	0.413
At most 4	0.031	0.975	3.842	0.324

* Significant at 5 % level
Trace test indicates 2 co-integrating equations at the 0.05 level
Rejection of the hypothesis at the 0.05 level

Table 6 Summary of co-integration test: unrestricted co-integration rank test (maximum eigenvalue)

Hypothesized number of co-integrated equations	Eigenvalue	Max-Eigen statistic	Critical value (0.05)	Prob.
None*	0.821	53.345	33.877	0.000
At most 1*	0.734	41.014	27.584	0.001
At most 2	0.360	13.820	21.132	0.380
At most 3	0.216	7.537	14.265	0.428
At most 4	0.031	0.975	3.842	0.324

* Significant at 5 % level
Max-Eigenvalue test indicates 2 co-integrating equations at the 0.05 level
Rejection of the hypothesis at the 0.05 level

technology accumulation and technology change do not have any relationship with the levels of generation (market). Therefore, technology diffusion appears to be disconnected from the entire system process and is only directly connected to the policies. These results can be explained because some policies are imposed directly to the market. The connection between federal and state policies and technology change is proven but federal policies does not affected yet to the process of knowledge accumulation. The results are shown in Fig. 3.

As Liu and Shumway (2009) say, the reason for some conflicting results could be explained by the data limitations. Furthermore, the gap between technology change and policies can be explained by the higher renewable costs, since external costs are taken into account (Tsoutsos and Stamboulis 2005). Another reason for no connection with the market is that the effects of energy prices on energy supply technologies are fast (Popp 1998), and the diffusion of new technology is not instantaneous and follows a learning process (Loschel 2002).

Another explanation of the lack of successful market penetration is explained by Nordhaus (2002) mentioning that in the market economies, the private sector determines the allocation of inventive activities. However, as Bielecki (2002) suggests, the possible effects of the improving competitiveness of renewable energy technologies may be seen after 2020.

Table 7 Vector error correction estimates (VEC)

Model 1					Model 2					Model 3				
Δ(PAT1) = β1*(PAT1(−1) + 0.124*RD1(−1) + 0.237*GEN1(−1) + 5.216*PRICE1(−1) − 21.220) + β2*(ACUM1(−1) − 0.133*RD1(−1) + 0.238*GEN1(−1) + 5.901*PRICE1(−1) − 23.415) + β3*Δ(PAT1(−1)) + β4*Δ(ACUM1(−1)) + β5*Δ(RD1(−1)) + β6*Δ(GEN1(−1)) + β7*Δ(PRICE1(−1)) + β8 + β9*ESA + β10*EPA1992 + β11*EPA2005 + β12*REC + β13*RPS					Δ(ACUM1) = β14*(PAT1(−1) + 0.124*RD1(−1) + 0.237*GEN1(−1) + 5.216*PRICE1(−1) − 21.220) + β15*(ACUM1(−1) − 0.133*RD1(−1) + 0.238*GEN1(−1) + 5.901*PRICE1(−1) − 23.415) + β16*Δ(PAT1(−1)) + β17*Δ(ACUM1(−1)) + β18*Δ(RD1(−1)) + β19*Δ(GEN1(−1)) + β20*Δ(PRICE1(−1)) + β21 + β22*ESA + β23*EPA1992 + β24*EPA2005 + β25*REC + β26*RPS					Δ(GEN1) = β27*(GEN1(−1) + 23.393*PAT1(−1) − 23.858*ACUM1(−1) + 7.239*RD1(−1) − 5.424*PRICE1(−1) + 7.647) + β28*Δ(GEN1(−1)) + β29*Δ(GEN1(−2)) + β30*Δ(PAT1(−1)) + β31*Δ(PAT1(−2)) + β32*Δ(ACUM1(−1)) + β33*Δ(ACUM1(−2)) + β34*Δ(RD1(−1)) + β35*Δ(RD1(−2)) + β36*Δ(PRICE1(−1)) + β37*Δ(PRICE1(−2)) + β38 + β39*ESA + β40*EPA 1992 + β41*EPA2005 + β42*REC + β43*RPS				
	Coefficient	Std. Error	*t*-Statistic	Prob.		Coefficient	Std. Error	*t*-Statistic	Prob.		Coefficient	Std. Error	*t*-Statistic	Prob.
β1	−0.727	0.404	−1.801	0.089	β14	−0.218	0.047	−4.638	0.000	β27	−0.125	0.057	−2.179	0.048
β2	0.378	0.486	0.778	0.447	β15	0.188	0.057	3.335	0.004	β28	−0.392	0.232	−1.690	0.115
β3	−0.429	0.151	−2.847	0.011	β16	−0.014	0.018	−0.808	0.430	β29	−0.460	0.239	−1.920	0.077
β4	3.404	1.095	3.109	0.006	β17	1.483	0.127	11.65	0.000	β30	0.548	0.768	0.714	0.488
β5	0.025	0.176	0.140	0.890	β18	0.024	0.020	1.156	0.263	β31	0.092	0.273	0.335	0.743
β6	0.255	0.135	1.885	0.076	β19	0.018	0.016	1.116	0.279	β32	11.900	7.871	1.511	0.155
β7	0.843	1.749	0.482	0.636	β20	0.289	0.203	1.419	0.173	β33	−0.421	3.384	−0.124	0.903
β8	−2.208	0.803	−2.749	0.013	β21	−0.453	0.093	−4.848	0.000	β34	0.833	0.468	1.780	0.099
β9	0.490	0.541	0.906	0.377	β22	0.268	0.063	4.266	0.000	β35	0.789	0.451	1.749	0.104
β10	0.183	0.126	1.447	0.165	β23	0.027	0.015	1.863	0.079	β36	4.664	4.336	1.076	0.302
β11	0.517	0.203	2.548	0.020	β24	0.074	0.023	3.130	0.006	β37	3.158	4.067	0.777	0.451
β12	1.105	0.521	2.122	0.0479	β25	0.037	0.061	0.607	0.552	β38	−4.102	2.485	−1.650	0.123
β13	0.284	0.155	1.833	0.083	β26	0.066	0.018	3.689	0.002	β39	3.520	2.003	1.758	0.102
										β40	−0.690	0.258	−2.671	0.019
										β41	−0.142	0.330	−0.429	0.675
										β42	−0.839	0.881	−0.952	0.359
										β43	0.3321	0.286	1.161	0.267
R-squared = 0.819; DW = 2.622					*R*-squared = 0.981; DW = 2.622					*R*-squared = 0.519; DW = 2.075				

The results for the long and short run are shown below:

Equation (8)

$$\begin{aligned}\Delta(\mathrm{PAT1}) = & -0.726 * [\mathrm{PAT1}(-1) + 0.124 * \mathrm{RD1}(-1) + 0.236 * \mathrm{GEN1}(-1) + 5.215 * \mathrm{PRICE1}(-1) - 21.220] \\ & + 0.377 * [\mathrm{ACUM1}(-1) - 0.132 * \mathrm{RD1}(-1) + 0.23 * \mathrm{GEN1}(-1) + 5.900 * \mathrm{PRICE1}(-1) - 23.415] \\ & - 0.428 * \Delta(\mathrm{PAT1}(-1)) + 3.403 * \Delta(\mathrm{ACUM1}(-1)) + 0.024 * \Delta(\mathrm{RD1}(-1)) + 0.254 * \Delta(\mathrm{GEN1}(-1)) \\ & + 0.843 * \Delta(\mathrm{PRICE1}(-1)) - 2.208 + 0.490 * \mathrm{ESA} + 0.182 * \mathrm{EPA1992} + 0.516 * \mathrm{EPA2005} + 1.104 * \mathrm{REC} \\ & + 0.283 * \mathrm{RPS}\end{aligned}$$

Equation (9)

$$\begin{aligned}\Delta(\mathrm{ACUM1}) = &-0.217 * [\mathrm{PAT1}(-1) + 0.124 * \mathrm{RD1}(-1) + 0.236 * \mathrm{GEN1}(-1) + 5.215 * \mathrm{PRICE1}(-1) - 21.220] \\ &+ 0.188 * [\mathrm{ACUM1}(-1) - 0.132 * \mathrm{RD1}(-1) + 0.237 * \mathrm{GEN1}(-1) + 5.900 * \mathrm{PRICE1}(-1) - 23.415] \\ &- 0.014 * \Delta(\mathrm{PAT1}(-1)) + 1.482 * \Delta(\mathrm{ACUM1}(-1)) + 0.023 * \Delta(\mathrm{RD1}(-1)) + 0.017 * \Delta(\mathrm{GEN1}(-1)) \\ &+ 0.288 * \Delta(\mathrm{PRICE1}(-1)) - 0.452 + 0.268 * \mathrm{ESA} + 0.027 * \mathrm{EPA1992} + 0.073 * \mathrm{EPA2005} \\ &+ 0.036 * \mathrm{REC} + 0.066 * \mathrm{RPS}\end{aligned}$$

Equation (10)

$$\begin{aligned}\Delta(\mathrm{GEN1}) = &-0.125 * [\mathrm{GEN1}(-1) + 23.392 * \mathrm{PAT1}(-1) - 23.857 * \mathrm{ACUM1}(-1) + 7.239 * \mathrm{RD1}(-1) \\ &- 5.424130477 * \mathrm{PRICE1}(-1) + 7.64] - 0.391 * \Delta(\mathrm{GEN1}(-1)) - 0.459 * \Delta(\mathrm{GEN1}(-2)) \\ &+ 0.548 * \Delta(\mathrm{PAT1}(-1)) + 0.091 * \Delta(\mathrm{PAT1}(-2)) + 11.895 * \Delta(\mathrm{ACUM1}(-1)) - 0.420 * \Delta(\mathrm{ACUM1}(-2)) \\ &+ 0.832 * \Delta(\mathrm{RD1}(-1)) + 0.789 * \Delta(\mathrm{RD1}(-2)) + 4.66 * \Delta(\mathrm{PRICE1}(-1)) + 3.157713962 * \Delta(\mathrm{PRICE1}(-2)) \\ &- 4.101 + 3.519 * \mathrm{ESA} - 0.690 * \mathrm{EPA1992} - 0.141 * \mathrm{EPA2005} - 0.838 * \mathrm{REC} + 0.332 * \mathrm{RPS}\end{aligned}$$

*The negative values in parenthesis are lags of the respective variable

Δ denotes the variation of the variable

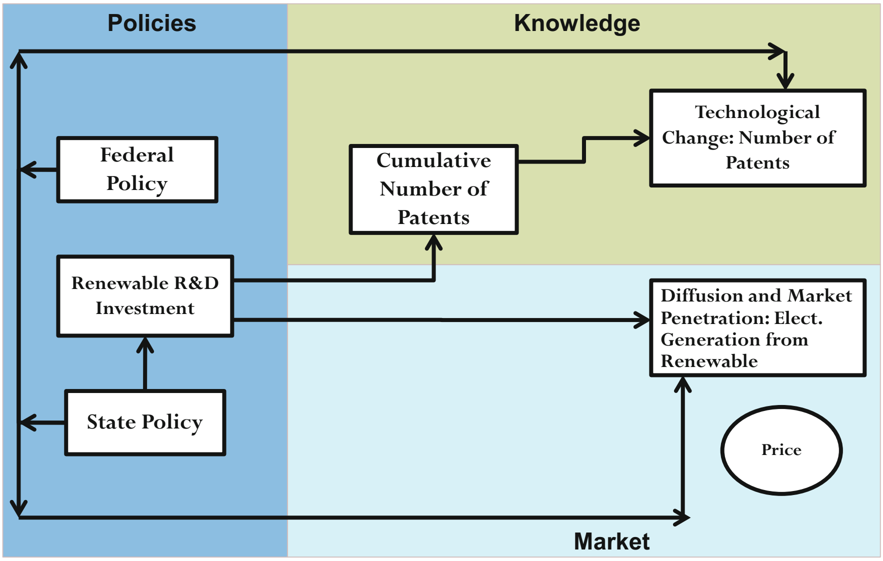

Fig. 3 Relationships in the dynamic process of technological change

5 Conclusions and Recommendations

Following an induced endogenous technological change model, a time-series analysis has been done. After the statistical analysis, it was found that the variables are stable in their first differences and co-integrated. Then three vector error correction models were obtained.

Because it is necessary to reduce energy security risk, the elimination of natural gas and coal in the electricity sector is important. The US government needs to promote new energy alternatives including incentives to switch the production of electricity from carbon plants to carbon-free technologies (Wirth et al. 2003). Diversification of technologies, such as renewable energy technologies, represents the government strategy; however, as the statistical analysis shows, renewable energy technologies are not yet competitive and not able to replace conventional energy sources.

The lack of significance and connection of the market variables to technological change and accumulation show that renewable energy technologies are not massively used in the electricity market in the USA. Despite the long-run relationship among variables showing the association of the patterns of variables, the short-run effects show problems that renewable energy technologies have entering the electricity market. There are many reasons for having this result which include high energy cost from renewable sources, dynamic of the diffusion phase and learning process, and decisions of the market sector for allocating investments.

The existence of a long-run relationship and the market disconnection are indicators (according to the statistical analysis) that the role of the US government is essential to promote technological innovation, especially related to commercialization. The government role is important to solve the problem of renewable energy technologies as well as the improvement of energy security. In the long and short run, policies should address oil substitutes, including electricity, when the market does not ensure the national security (Deutch et al. 2006).

Federal policies affect technological change and diffusion of technology through the market. However, they do not affect knowledge accumulation. This is congruent with what Johnstone et al. (2010) mention that environmental policies positively affect the improvement of renewable energy technologies. State policies have been affecting knowledge accumulation, technological change, and technology diffusion. To ensure more effective policies and to improve energy security, federal policies need to focus on integrating technological change. The knowledge stock needs to be used and be promoted by the federal and state policies simultaneously, connecting to knowledge accumulation and market incentives.

An important aspect in energy security is to apply the right policy and choose the optimal mechanism to promote renewable energy technologies. In this context, R&D investment needs to receive special attention, since R&D expenditures directly influence knowledge accumulation and technology diffusion. Therefore, state policies and R&D investments appear to be more crucial to improve renewable technologies.

As Tsoutsos and Stamboulis (2005) suggest, focusing on specific policies should be limited to niches and then integrated with the diffusion of renewable energy technologies and policies. Therefore, in order to eliminate the gap between technology and market, it is important to have specific policies about the market. The dissociation between the market and technological change does not depend only on policies, but other technological barriers – as indicated by Tsoutsos and Stamboulis (2005).

References

Adelaja A, Hailu YG, McKeown CH (2010) Effects of renewable energy policies on wind industry development in the US. J Nat Policy Res 2(3):245–262

Bielecki J (2002) Energy security: is the wolf at the door? Q Rev Econ Finance 42:235–250

Bosetti V, Carraro C, Galeotti M (2006) The dynamics of carbon and energy intensity in a model of endogenous technical change. Energ J 27:93–107

CRS—Congressional Research Service (2007) Energy Independence and Security Act of 2007: a summary of major provisions. Congressional Research Service, Washington, DC

Deutch JM, Schlesinger JR, Victor DG (2006) National Security Consequences of US oil dependency: report of an Independent Task Force No. 58. The Council on Foreign Relations, Inc., New York, NY

Gillingham K, Newell RG, Pizer WA (2007) Modeling endogenous technological change for climate policy analysis. Discussion paper. Available at http://www.rff.org/rff/documents/rff-dp-07-14.pdf. Accessed 18 Sept 2012

Goulder LH, Mathai K (2000) Optimal CO_2 abatement in the presence of induced technological change. J Environ Econ Manage 39:1–38

Grubb M, Koehler J, Anderson D (2000) Induced technical change: evidence and implications for energy-environmental modeling and policy. Available at http://ideas.repec.org/p/cam/camdae/0031.html. Accessed 18 Sept 2012
Johnstone N, Hascic I, Popp D (2010) Renewable energy policies and technological innovation: evidence based on patent counts. Environ Resour Econ 45:133–155
Kerr S, Newell RG (2003) Policy-induced technology adoption: evidence from the US lead phasedown. J Ind Econ LI(3):317–343
Liu Y, Shumway R (2009) Induced innovation in US agriculture: time-series, direct econometric, and nonparametric tests. Am J Agric Econ 91(1):224–236
Loschel A (2002) Technological change in economic models of environmental policy: a survey. Ecol Econ 43:105–126
McFarland JR, Reilly JM, Herzog HJ (2004) Representing energy technologies in top-down economic models using bottom-up information. Energy Econ 26:685–707
Mignone BK (2007) The national security dividend of global carbon mitigation. Energy Policy 35:5403–5410
Nordhaus WD (2002) Chapter 9: Modeling induced innovation in climate change policy. In: Grubler A, Nakicenovic N, Nordhaus WD (eds) Modeling induced innovation in climate change policy. Re-source for the Future Press, Washington, DC
Pizer WA, Popp D (2007) Endogenizing technological change: matching empirical evidence to modeling needs. Available at http://ideas.repec.org/p/nbr/nberwo/13053.html. Accessed 18 Sept 2012
Popp D (1998) Induced innovation and energy prices. Available at http://www2.ku.edu/~kuwpaper/Archive/papers/Pre1999/wp1998_6.pdf. Accessed 18 Sept 2012
Schmidt SN, Hansen ES, Tops J, Jensen HN, Jespersen ST (2010) Innovation of energy technologies: the role of taxes. Available at http://ec.europa.eu/taxation_customs/resources/documents/common/publications/studies/taxation_energy_innov.pdf. Accessed 18 Sept 2012
Schumpeter J (1942) Capitalism, socialism and democracy. Harper, New York
Solow RM (1956) A contribution to the theory of economic growth. Q J Econ 70(1):65–94
Spector H (2009) A sustainable U.S. energy plan. Nat Resour Res 18(4):285–333
The White House (2002) The national security strategy of the United States of America. The White House, Washington, DC
Thirtle CG, Schimmelpfennig DE, Townsend RF (2002) Induced innovation in United States agriculture, 1880–1990: time series tests and an error correction model. Am J Agric Econ 84(3):598–614
Tsoutsos TD, Stamboulis YA (2005) The sustainable diffusion of renewable energy technologies as an example of an innovation-focused policy. Technovation 25:753–761
Weyant JP, Olavson T (1999) Issues in modeling induced technological change in energy, environment, and climate change. Environ Model Assess 4(2 & 3):67–85
Wirth TE, Gray CB, Podesta FD (2003) The future of energy policy. Foreign Aff 82(4):132–155

Edwin Garces is a PhD student at the Department of Engineering and Technology Management at Portland State University. His interests are in the intersection of technology and economics for energy.

Tugrul Daim is an Associate Professor at the Department of Engineering and Technology Management at Portland State University. His research interests are in management of energy technologies.