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Abstract

Our society's reliance on fossil fuels has many negative results, including compromised national security and foreign relations as well as environmental damage. Many see technology as the key to an improved energy future, and in particular the development of new, cleaner renewable energy sources. The question then remains how to stimulate such technological innovation. In this study, I use U.S. patent data from 1970 to 2001, along with historic energy prices and federal spending data to see the affect energy price and R&D spending have on innovation in the non-hydro renewable energy industries – solar, wind, geothermal, oceanic, and fuel cell. Using a simple regression, I found a very strong, positive relationship between both R&D spending and energy price on innovation in the non-hydro renewable energy industries. This suggests that a policy intended to stimulate renewable energy innovation could do so either through increased federal R&D spending, or by increasing energy prices through taxation or other means.

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Abstract Our society’s reliance on fossil fuels has many negative results, including compromised national security and foreign relations as well as environmental damage. Many see technology as the key to an improved energy future, and in particular the development of new, cleaner renewable energy sources. The question then remains how to stimulate such technological innovation. In this study, I use U.S. patent data from 1970 to 2001, along with historic energy prices and federal spending data to see the affect energy price and R&D spending have on innovation in the non-hydro renewable energy industries – solar, wind, geothermal, oceanic, and fuel cell. Using a simple regression, I found a very strong, positive relationship between both R&D spending and energy price on innovation in the non-hydro renewable energy industries. This suggests that a policy intended to stimulate renewable energy innovation could do so either through increased federal R&D spending, or by increasing energy prices through taxation or other means.

I. Introduction[+]

Overview

Whether motivated by concern for the environment or national security, our nation's energy dependence on fossil fuels has become a common topic of discussion and debate. Environmental concern over the impact of a fossil fuel-driven society has existed for years, but this issue has often taken a back seat to other national and international concerns - until just recently. President Bush confirmed the recent surge in attention given to the energy industry during the 2006 State of the Union address when he described the need for cleaner energy as a national priority, citing our reliance on imported oil from "unstable parts of the world" [1] as the motivation. Given that clean energy has become a widely accepted and publicized national priority, what is to be done about it? According to the President the solution lies in advanced technology; many economists and environmentalists agree[2].

Environmental issues of national and international concern, such as greenhouse gases and subsequent global warming, require long-term solutions. As a result, many environmentalists and economists alike have begun to encourage the use of public policy to induce technological innovation in the energy industry, believing technology to be a good long term means of addressing this dependence.[3]

However, there is strong evidence that the US economy both publicly and privately under-invests in energy R&D, particularly in relation to other technologically

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[+] I would like to thank my thesis advisor, William Shobe, for all his help and advice. His class in Environmental Economics motivated me to pursue this topic, and his knowledge and interest in the subject matter were invaluable.

[1] State of the Union address, January 31, 2006

[2] Margolis and Kammen, 2000; Jaffe, Newell and Stavins, 2000.

[3] Margolis and Kammen, 2000.

intensive industries. Publicly, there has been a 74% reduction in the U.S. Government's spending on energy technology R&D between 1980 and 1996[4]. This lack of federal support coupled with the high risk nature and "spill over" effect of R&D[5] has led to private under-investment in energy technology as well.[6]

Assuming that a cleaner source of energy is a commonly desired good, that technological development is an effective means of achieving it and that there is a current deficit in energy R&D, the remaining public policy issue is how to promote innovation in the clean energy industry. In many economic models related to environmental policy, technology is treated as exogenous, something that is independent of the other factors in the economy, such as economic growth, energy prices, or government spending.[7] However, it is possible to improve on these models by assuming that research and innovation are endogenous, producing better information on which to make policy decisions.

Using U.S. patent data as a quantitative measure of innovation, this study finds that there exists a strong, positive relationship between the level of innovation in the non-hydro renewable energy sector and both energy prices and government spending on renewable technologies. For the purposes of this study, non-hydro renewable energy technologies include those utilizing wind, solar, geothermal, oceanic and fuel cell energy sources. Using a basic econometric model, this study concludes that policies directed at either increasing the price of energy or stimulating federal spending on renewable energy

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[4] Margolis and Kammen, 2000.

[5] The "spill over" effect refers a situation where someone's profit or welfare arises as a byproduct of some other person's or firm's activity. In regards to R&D, the spillover effect relates to the difficulty with which a firm captures all of the benefits of R&D investment.

[6] Margolis and Kammen, 1999.

[7] Popp, 2003.

R&D are likely to result in future increases in innovation within non-hydro renewable technologies.

This paper is divided into 8 sections. First the origins of this study are discussed through a brief summary of the relevant background literature and research. Second, the data is described. Third, the initial observations and trends in the data are reviewed and their relevancy to the econometric model is discussed. The fourth section is an explanation of the model used in this study, followed by a description of the results. Next, the limitations of the model are described, including suggestions for related future work. Finally, the conclusions of this study are discussed, including a final section regarding the policy implications of this study.

Technologies of Interest

The focus of this study is non-hydro renewable technologies which are those utilizing solar (both photovoltaic and thermal), wind, geothermal, oceanic and fuel cell technologies. Certainly, these five technologies are not the only ones relevant to the proliferation of clean energy, but non-hydro renewable technologies are an excellent subject for this study for several reasons. First, one of the most important motivations for developing clean energy is to reduce or eliminate many of the negative environmental impacts of fossil fuel-based energy production. In this area, non-hydro renewables have significant potential.

Fossil fuel-powered energy production negatively affects the environment in two ways, through damage caused by the extraction of the fuel, and damage from the conversion of the fuel into energy. Physical damage to the environment caused by oil spills and mining along with the accumulation of pollutants like carbon dioxide, carbon monoxide, sulfur dioxide, nitrogen oxides and mercury are all the result of fossil fuel-powered energy production. Similarly, I have chosen not to include hydro-electric energy technologies in this study because while it is renewable, it faces many significant environmental impacts such as disrupting natural river flows, river and riverside habitats, fish migration patterns, as well as affecting water quality. Non-hydro renewable energy production however, does not generally suffer from these disadvantages. This is not to say that the production of energy through non-hydro renewable technologies has no negative impact on the environment, but the magnitude of damage is considerably smaller.

Another important characteristic of non-hydro renewable fuels is their abundance and permanence. At no time in the foreseeable future will radiation from the sun or movement of the wind and tides stop or run out, and while variations in natural resource endowments across countries and regions can limit the usefulness of each respective fuel source, they are more ubiquitous and reliable in the long-term than fossil fuel deposits.

This study does not include energy consumption technologies designed to increase energy efficiency. While these conservation technologies certainly have their merits and are often a much cheaper way of reducing fossil fuel usage in the short and medium-term, supply technologies such as non-hydro renewables have the potential to completely change how energy is produced and from where it is obtained.

Finally, non-hydro renewable technologies serve as an appropriate case study for questions regarding the relationship between energy and technology as their utility and success is almost entirely dependent on the level of technology. Looking at the supply side of the energy industry, there are two types of technological innovation. The first is the improvement of established technologies and the second is the creation and development of new energy supply technologies such as the non-hydro renewables addressed in this paper. As discussed below, these two types of energy production technologies (those utilizing established technologies such as coal or petroleum fired power plants, and those using the relatively new technologies of non-hydro renewables) face very different cost functions, with the distinction being driven mainly by the cost of fuels. Energy suppliers using well-established methods and technologies such coal, petroleum, natural gas or wood powered plants face the following production cost function (i):

$$\text{(i)} \qquad Cost^t = Pk^t * K^t + Pl^t * L^t + Pf^t * F^t$$

where Pk^t, Pl^t and Pf^t are the price per unit of capital, labor and fuel in energy sector t; the traditional, fossil fuel powered energy producers. K^t, L^t and F^t are the amounts of capital, labor and fuel used in production. On the other hand, suppliers of energy using non-hydro renewable technologies face the following production cost function (ii) in energy sector n; the non-hydro renewable energy producers:

$$\text{(ii)} \qquad Cost^n = Pk^n * K^n + Pl^n * L^n$$

The difference between the two cost functions is that non-hydro renewable-type energy producers face zero fuel costs. It is also important to note that there are often additional costs related to pollution for producing energy from fossil fuels, such as abatement technologies and pollution taxes. For simplicity, I have included these costs into Pk^t and K^t from cost function (i).

The majority of energy consumed in the US (86% in 2003) comes from fossil fuels including 23% from coal, 23% from natural gas and 40% from petroleum.[8] Energy suppliers using these fuels, and especially petroleum, face the high and often volatile costs of these fuels. Both natural gas and coal are more abundant domestically and less expensive than petroleum, but face their own challenges such as the increasing cost of burning coal in reaction to its high level of pollution. In contrast, the energy input for the non-hydro renewable energy suppliers, i.e. sunlight, wind etc. are available without cost to users. The cost of producing usable energy from these sources is therefore seen only in the process of converting these "free" energy sources into a usable form, through labor and capital. As a result, the level of technology is of significant interest because the capital cost and efficiency of the technologies utilized by non-hydro renewable energy producers constitutes a large proportion of its costs, and in turn determines the economic viability of the energy source.

II. Background Literature

While its application in modeling has become popular in recent years, endogenous technological development is not a new concept. John Hicks was the first to propose the induced innovation hypothesis which he defined as:

> "a change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind – directed to economizing the use of a factor which has become relatively expensive."[9]

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[8] Energy Information Administration; Renewable Energy Annual 2003

[9] Hicks, John R, 1932.

Hicks himself did not apply his theory to any empirical research, but it has been used extensively since then by other economists regarding nearly all topics related to research and development.

Several papers were influential in the development of this study, all of which address the topic of induced innovation and energy policy. Much of the research and model construction that had been done in the past treated technology as an exogenous variable, and the attempts to address technology as endogenous have largely been theoretical. Jaffe, Newell and Stavins wrote, "there has been some tendency to treat technology as a 'black box'."[10] This tendency began to change however as patent data became increasingly available though electronic databases beginning in the early 80's. With this new form of quantitative data on innovation, empirical work on induced innovation became much more common.

In his paper *Induced Innovation and Energy Prices* (2002) David Popp studied the relationship between energy prices and patent levels in energy conserving technologies. Using patents representing a broad spectrum of technologies ranging from coal gasification to insulated windows, Popp found a strong, positive relationship between energy prices and innovation. This positive relationship between technology and energy prices meant that taxes and regulations increasing the price of pollution intensive energy production and consumption would not only push behavior away from such activities, but reduce the future cost of pollution abatement though technological development.

In addition to energy prices, a significant body of literature addressing energy R&D also discusses the effects of federal spending on innovation. Margolis and

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[10] Jaffe, Newell and Stavins, 2000.

Kammen[11] found a high correlation between patent levels and funds for R&D (both private and public) over the past two decades. They also found that although the U.S. is a consistent leader in worldwide R&D spending, that a relatively small portion of that spending goes to the energy sector, resulting in under investment in the energy industry when compared with other technologically intensive industries.

A study by Marshall Goldberg also found a strong, positive relationship between federal subsidies and technological growth.[12] In addition, Goldberg found that strong R&D spending had a clear and positive impact on an industry's success, using data from nuclear, wind, and solar technologies as support. While conceding that many other factors are important, Goldberg concluded that the gap in R&D spending between the nuclear and the wind and solar industries was one of main reasons why nuclear energy is so much more prevalent today than either wind or solar energy. The data support Goldberg's conclusion – between 1943 and 1999, $151 billion (in 1999 dollars) has been spent on R&D for the nuclear, wind and solar industries, but the nuclear industry has received over 90% of that spending – $145.4 billion. Solar technologies on the other hand have received only $4.4 billion and wind even less with $1.3 billion. Some of the discrepancy in these numbers is a result of timing, given that solar energy wasn't really considered a viable source of electricity until the early 70's, while the first electricity-producing nuclear reactor was online by 1951. However, the spending bias towards nuclear energy is still substantial, and Goldberg believes this helped lead to the gap in production between these industries. According to the Energy Information

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[11] Margolis and Kammen, 1999; Margolis and Kammen, 2000.
[12] Goldberg, 2000.

Adminstration (EIA), in 2003 8% of the energy consumed in the U.S. came from nuclear electric power, while only .06% came from solar and .12% came from wind.

Given the conclusions made in the literature discussed above, it seems reasonable that using data on federal spending as well as energy prices is an effective way to address induced innovation within the non-hydro renewable energy sector.

III. Data

U.S. Patents

Many environmental policy-related studies and subsequent models treat the level of technology and innovation as exogenous. This has largely been due to the lack of quantitative data on innovation, making empirical research and econometric modeling difficult. Recently however, the emergence of electronically searchable patent databases has allowed for a reliable quantitative measure of innovation. The patent database used to collect the data for this study includes all US patents issued by the US Patent and Trademark office.

Patent data is useful for measuring innovation for several reasons. Patents can provide a standard and consistent measure of innovation over time, and modern patent data provides sufficiently large data sets for statistically reliable research. However, while the use of patent data has done a great deal to help test and develop the economic theory related to induced innovation, it is not without its limitations. Most importantly, objectively measuring the relative significance of a given patent can be difficult. This study avoids this issue by treating all patents as having an equivalent impact on the overall level of technology. This is a strong assumption as, in reality, each patent contributes uniquely to the technological advancement of a given industry. Other methods of studying innovation exist, such as following historical case studies, but in an effort to create reliable quantitative results, patents are the best option for this study.

The data for this study includes U.S. patents specific to the five non-hydro renewable energy technologies between 1970 and 2001, consisting of solar, wind, geothermal, oceanic and fuel cell technologies. Patent data is currently searchable through 2005, but only those patents with application dates before January 1st 2002 are included. Energy prices during the 2002-2005 period were highly volatile and it would have been informative to include them in this study, but due to the nature of the patenting process recent data is not reliable. After a patent application has been received, it is common for several years to pass before the patent is issued, and because patents are not included in the searchable database until they have been issued, using patent data for recent years could give misleading results.

To collect patent data I used the Examiner Automated Search Tool (EAST) available at the U.S. Patent and Trademark Office's electronic public search facilities in Alexandria, Virginia. Through the EAST program I was able to cross-reference patents related to each of the 5 specific industries of interest and specific years between 1970 and 2001 by searching patent classes/subclasses and application dates simultaneously.

Each U.S. patent is categorized under specific classes and subclasses. For example, patent no. 4,576,006 which is titled: "Geothermal hot water transportation and utilization system", is listed under class no. 60: "Power Plants" and subclass 641.4: "Utilizing natural heat / With deep well turbopump". However, the patent classification system can be difficult to use as many patents can be listed under multiple classes and subclasses. The patent just described for example, while listed under only one class, is listed under three subclasses. Fortunately, the EAST program eliminates the risk of double counting patents listed under multiple classifications, by only listing each patent once even if it is listed under several of the classes/subclasses in my search criteria.[13]

To conduct the patent searches, the US Patent and Trademark office's EAST program was used because it is possible to search for original U.S. patent classifications as opposed to simply searching for current U.S. classifications, as offered by most other search tools. The original U.S. classifications are very specific and are intended to direct the patent to a reviewer who specializes in the related field. On the other hand, current U.S. classifications are sometimes assigned simply for cross-referencing a patent, and therefore don't necessarily relate as directly to the intended function of a patent. For a list of patent frequencies by year and by industry see Appendix B.

Energy Prices

I use energy data from the Energy Information Administration's (EIA) report on Consumer Price Estimates for Energy by Source from 1970 to 2001. The report provides consumption-weighted average prices in nominal dollars per million BTU from four end use sectors (residential, commercial, industrial, and transportation). All energy price data has been adjusted for inflation and is expressed in 1999 dollars.

This study includes energy prices from a wide range of sources: petroleum, nuclear, natural gas, coal, retail electricity, and a measure of aggregate energy that includes all of the previously stated sources as well as wood and waste fuels. All energy price values are consumption-weighted average prices. The price per million BTU of petroleum includes energy from distillate fuel oils, liquid petroleum gas, jet fuel, motor

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[13] A complete list of the patent classes and subclasses used in this study can be found in Appendix A.

gasoline, and residual fuel oil as well as some other miscellaneous petroleum products such as kerosene and lubricants. The value of retail electricity prices are those paid by the final customers, as reported by the electric utility providers. For complete energy price data, see Appendix C.

Federal Subsidies

Federal subsidy data is available for wind and solar technology R&D from the first recorded subsidy in 1975 through 1999. Subsidy values are given for both direct program subsidies as well as off-budget subsidies. Data for the direct program subsides was compiled from budgetary data by the Department of Energy (DOE) as well as the Energy Research and Development Administration, and represents direct, government expenditures. Off-budget subsidies are an indirect means for the government to financially stimulate R&D through policies such as tax credits. Data for the off-budget subsidies was compiled from a much more diverse pool of sources including tax data from U.S. budgetary documents, DOE information and EIA publications as well as less formal sources such personal communications by solar and wind energy representatives.[14]

Although this study does not include federal subsidy data for oceanic, geothermal and fuel cell technologies, it is reasonable to assume that spending on these technologies is closely correlated with spending on wind and solar R&D. The exception to this assumption, however, seems to be the case of federal spending on fuel cell research. This

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[14] For a more detailed discussion of the federal subsidy data see Goldberg, 2000.

will be discussed further in the next section.[15] For a complete list of federal subsidy data see Appendix D.

IV. Initial Findings

Innovation and Energy Price

It appears that between 1970 and 2001 there was a positive relationship between energy price and renewable patent applications as seen in Figure 1 below.

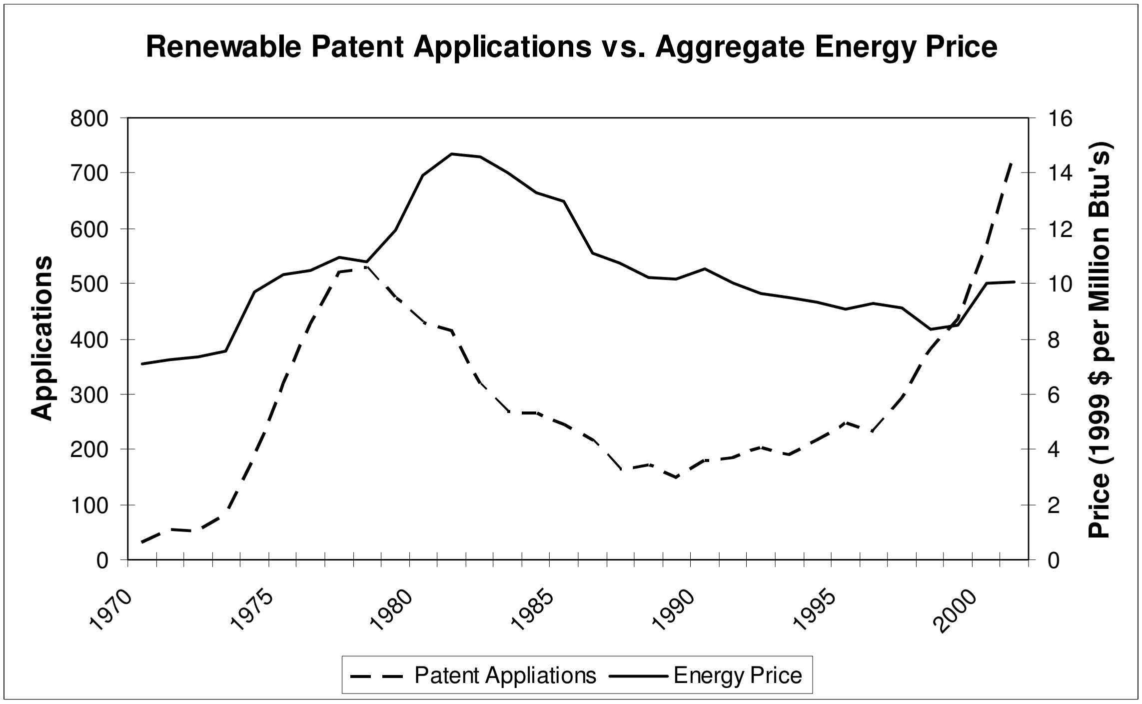

Figure 1: Renewable Patents and Energy Price
Note: Aggregate energy price is a consumption weighted energy price for primary energy (fossil fuels, nuclear, wood and waste) and retail electricity.

However, this initial result indicates that there is a lag of several years for energy prices, as if fluctuations in patent levels are causing future changes in energy prices. This result is counter intuitive to the theory of induced innovation. When considering the

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[15] For a complete list of the federal subsidy data used in this study, see Appendix D.

relationship between energy prices and patent applications we would expect the level of innovation to react to be a function of economic factors such as energy prices, and not the other way around as implied by Figure 1.

The apparent trend in the data discussed above suggests that other forces affecting renewable patents are confounding our measurement of the effect of energy prices on patents. As discussed below, one such omitted influence is impact of federal spending on innovative activity.

Innovation and Federal Subsidies

There are two central forces effecting the incentives for research and development: 1) private forces (such as market energy prices) and 2) public policy, such as state and/or federal incentives in the form of tax breaks, quotas, or subsidies. One would expect, as with energy prices, a positive relationship between federal subsidies for renewable energy technology and renewable energy patents. This expectation is supported by the data, represented here in Figure 2.

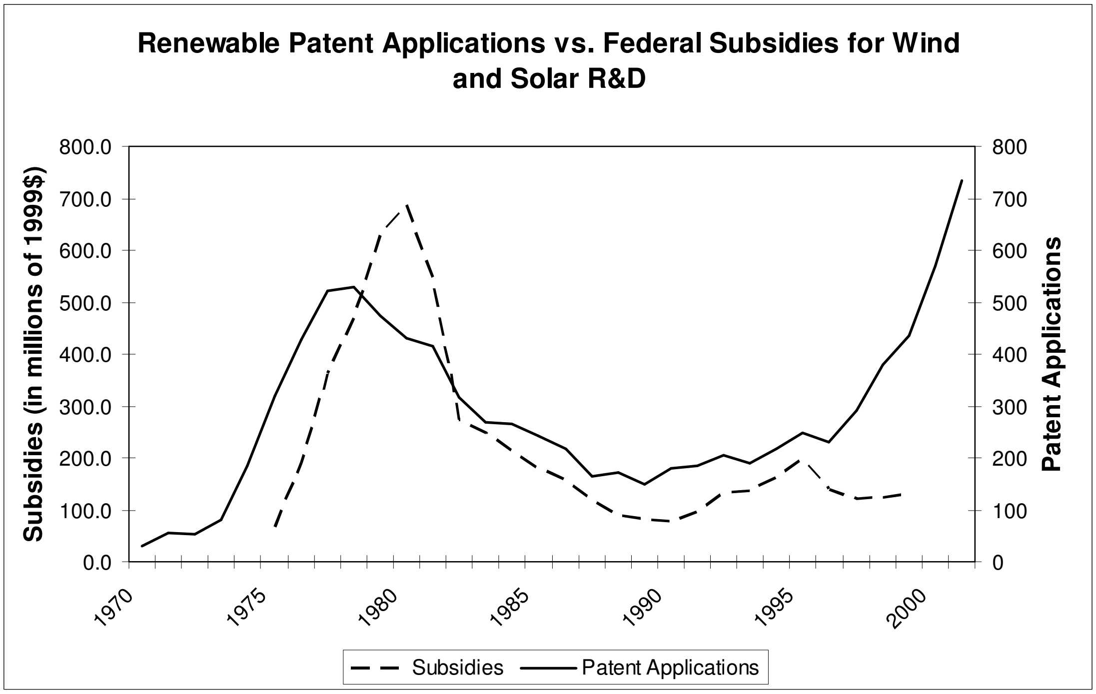

Figure 2: Renewable Patents and Federal Subsidies

From the point where federal spending on wind and solar research began in 1975 and continuing through 1996, the federal spending and patent curves follow each other closely, indicating a strong, positive relationship. However, there is a clear divergence between the trends in federal spending and renewable patent applications beginning in 1996 and continuing through the end of the subsidy data in 1999 (a similar divergence can be seen with renewable patents and energy price in Figure 1). During this period, neither federal spending nor energy prices increase dramatically, but renewable patent applications appear to skyrocket.

The Fuel Cell Phenomenon

The apparent break in an otherwise consistent relationship between federal spending or energy prices and renewable patent applications can be explained by a closer examination of the patent data, and in particular, fuel cell patents. The data shows that fluctuations in patent applications are fairly similar for all of the five renewable energy types except one – fuel cells. The volume of patent applications classified as solar, wind, geothermal and oceanic technologies was relatively low in 1970, increased substantially through the mid 70’s, and dropped off around 1980 remaining low until the early 90’s where they increase again by varying degrees through 2001. Fuel cell patents on the other hand follow a distinct trend line, increasing slowly and steadily from 1970 through 1996 at which point they increase exponentially, leaping from 89 applications in 1996 to 226 in 1998, and continuing to climb all the way to 495 applications in 2001. These trends are illustrated in Figure 3 below.

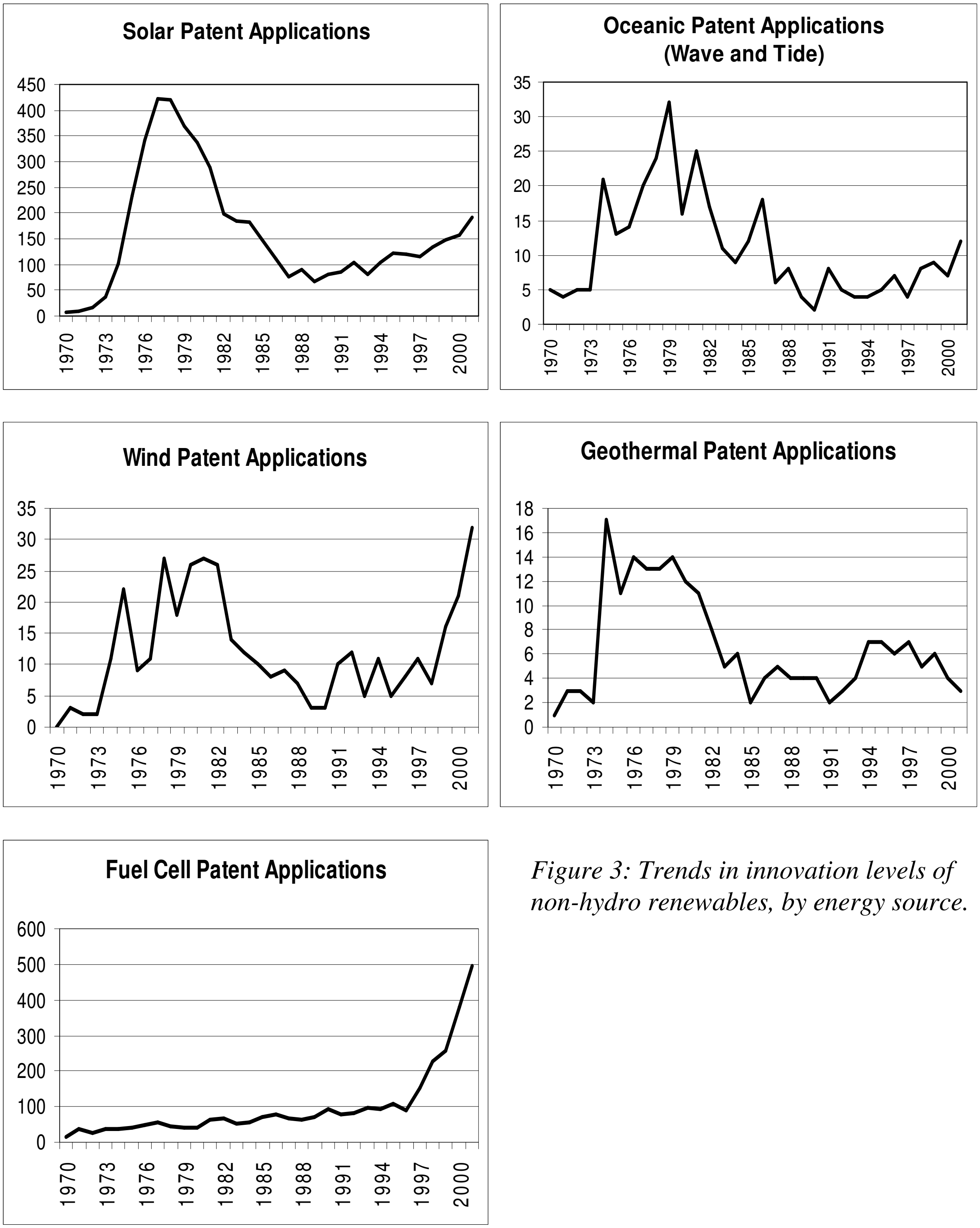

Figure 3: Trends in innovation levels of non-hydro renewables, by energy source.

The distinct trend in fuel cell patent applications may largely be explained by an equally unusual trend in federal spending on fuel cell research. Budgetary documents by the DOE from 1995-2000 showed a surprising and important shift in spending. In 1995 and 1996, federal appropriations to support fuel cell research were consistently low at 4 million dollars annually. In 1997 however, appropriations for fuel cell research by the U.S. government jumped to 49 million dollars while federal research spending in other sectors of the energy industry realized no such dramatic increase. For example, spending on natural gas R&D increased by only 17% and in that same year, and spending on wind and solar R&D actually declined.[16] The limited fuel cell spending data available makes it difficult to explain why the patent applications for fuel cell technologies appear to fluctuate so minimally from 1970 to 1996. However, the jump in federal spending after 1996 does appear to help account for the previously unexplained increase in patent applications between 1997 and 2000. Furthermore, the 'fuel-cell phenomenon' further supports the hypothesis that there exists a positive relationship between federal spending and innovation. Due to the unusual trends in the fuel cell patent data and the lack of sufficient historical data on federal fuel cell R&D spending, I chose to exclude the patent applications related to fuel cell technologies from the final model, though this will be discussed in more detail in the next section.

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[16] EIA estimated for congressional request.
Sources: U.S. Department of Energy, *U.S. Department of Energy Fiscal Year 1999 Budget Request*, DOE/CR-0050 (Washington, DC, February 1998); and *U.S. Department of Energy Fiscal Year 2000 Budget Request*, DOE/CR-0059 (Washington, DC, May 21, 1999).

V. Model

I constructed a simple econometric model using federal spending and energy prices as covariates. An initial version of the model has no delay on the patent application date, implying that movements in energy prices and federal spending would be reflected in the level of innovation within the same year. The model is described here in equation (1):

$$\text{Rpat}_t = C + \beta_1 P_{i,t} + \beta_2 FS_t + \varepsilon \quad (1)$$

Where Rpat is the number of non-hydro renewable patents applied for in year t. C is a constant representing the level of Rpat when all covariates equal zero. β_1 is the coefficient for $P_{i,t}$, where P represents the price of energy in 1999 dollars from source i in year t, and β_2 is the coefficient for FS_t, which is the value of federal subsidies in millions of 1999 dollars for wind and solar R&D in year t.

While the regression results for model (1) above were significant at the 95% confidence level for several energy sources, the coefficient for β_1 was negative for all i.[17] This result is counterintuitive as we would expect the price of energy and the level of public spending to have a positive relationship with the number of renewable patents.

The negative coefficients for β_1 are likely being caused by the zero time lag assumption, which is an unreasonable given the nature of R&D and the patent application process. In order for the R&D market to react immediately to economic incentives, researches would have to first realize and react to the economic stimulus, design and

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[17] See "Results" below.

develop a new technology and then complete the patent application process all within a matter of months – an unrealistic expectation.

To address this model's limitations, I re-estimated the regression above with delays on patent applications ranging from 1-5 years. Based on what would be predicted theoretically and a comparison of the R-squared values for each lag tested, the 2 year lag was chosen as the most reliable. This suggests that the largest response of patent activity to federal funding and energy prices comes two years after an economic stimulus by either economic factor. The revised model reflects the proposed 2 year delay:

$$\text{(2)} \qquad \text{Rpat}_{t+2} = C + \beta_1 P_{i,t} + \beta_2 FS_t + \varepsilon$$

Where Rpat_{t+2} is the number of patents applied for in year t + 2, and all other variables are the same as in the original model. In addition, for the reasons previously discussed regarding the distinct quality of historical fuel cell patent volumes, the model was estimated once more after removing the patent applications related to fuel cell technology (FCpat_{t+2}) resulting in the final model:

$$\text{(3)} \qquad \text{Rpat}_{t+2} - \text{FCpat}_{t+2} = C + \beta_1 P_{i,t} + \beta_2 FS_t + \varepsilon$$

Regression of the data under this new model supports this study's hypothesis: there is a strong, positive relationship between energy prices, federal R&D spending, and innovation in renewable energy technologies.

VI. Results

Table 1 gives the regression results from model (2) and Table 2 gives the regression results from model (3).

Table 1. Regression results from model (2): using all data, including fuel cell patents.

Regression: $Rpat_{t+2} = C + \beta_1 P_{i,t} + \beta_2 FS_t + \varepsilon$

Variable	Coefficient	t-value	F(2,22)	Adjusted R^2	Root MSE
All Energy	17.98006 (6.544561)	2.75*	62.84	0.8375	49.249
Subsidy	.5067489 (.0717204)	7.07*			
Petrol	10.848 (6.139524)	1.77	51.78	0.8089	53.411
Subsidy	.5165903 (.0873134)	5.92*			
Nat. Gas	35.30833 (7.158019)	4.93*	104.79	0.8964	39.33
Subsidy	.5586428 (.0478039)	11.69*			
Coal	2.682823 (21.0322)	0.13	44.02	0.7819	57.054
Subsidy	.6181308 (.0838604)	7.37*			
Nuclear	92.46883 (58.46872)	1.58	50.23	0.8040	54.083
Subsidy	.6133298 (.0635134)	9.66*			
Retail	5.799528 (3.563103)	1.63	50.60	0.8052	53.921
Subsidy	.5753462 (.0698278)	8.24*			

The values in parenthesis are the standard errors of each coefficient.
** = Significant at 95% confidence*

Table 2: Regression results from model (3): excluding fuel cell patent data.

Regression: $Rpat_{t+2} - FCpat_{t+2} = C + \beta_1 P_{i,t} + \beta_2 FS_t + \varepsilon$

Variable	Coefficient	t-value	F(2,22)	Adjusted R^2	Root MSE
All Energy	26.47424 (5.08372)	5.21*	133.76	0.9171	38.256
Subsidy	.5185554 (.0557113)	9.31*			
Petrol	18.18275 (5.30539)	3.43*	88.45	0.8793	46.154
Subsidy	.5110355 (.0754507)	6.77*			
Nat. Gas	41.34144 (5.527095)	7.48*	218.71	0.9478	30.369
Subsidy	.6148653 (.036912)	16.66*			
Coal	39.03541 (19.35919)	2.02	65.82	0.8438	52.516
Subsidy	.5974935 (.0771897)	7.74*			
Nuclear	167.3001 (50.46484)	3.32*	86.22	0.8766	46.68
Subsidy	.6716795 (.0548189)	12.25*			
Retail	11.73159 (2.830605)	4.14*	104.46	0.8961	42.836
Subsidy	.5924296 (.0554727)	10.68*			

It can be seen by comparing the regression results from Tables 1 and 2 that by excluding the data on fuel cell patents model (3) produces the most statistically accurate results, using both R-squared values and t-statistics as the measure of accuracy. In fact, only the coefficients for energy sources 'all energy' and 'natural gas' were significant with 95% confidence in regression (2), whereas all energy sources but coal had significant coefficients with 95% confidence in regression (3).

VII. Model Limitations and Future Work

The simplified model used in this study ignores several important factors that may limit the reliability of its findings. First, as mentioned in section III above, using the frequency of patents to estimate the level of innovation assumes that all patents contribute equally to the level of innovation and technological "knowledge". Several papers[18] describe how, while the number of patents alone can be a good indicator of innovation, the value and importance of that innovation, both in an economic and technological sense, is measured more accurately when patents are weighted by their subsequent citations.

As part of a patent application, inventors are required to cite all pre-existing patents included in the "prior art" of their technology. This means that inventors must give credit to all patents and inventors whose work was instrumental in the development of their own technologies. The result of this practice is that those patents which are the most "valuable" in terms of the advancement of their respective industry, receive the most citations from future patents. Should this study be repeated or developed further in the future, re-estimating the model using citation-weighted patents frequencies could improve the accuracy of the results, and give a greater understanding of how the input variables affect the significance and value of the induced innovation.

A second limitation of the model used in this paper is that the overall level of patented technology is ignored. The total number of patent applications in the US is

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[18] See, for example, Trajtenberg 1990; Hall, Jaffee and Trajtenberg 2005.

influenced by a wide variety of economic and social factors including population demographics, USPTO policies and GDP. Many of these same factors are likely to impact the frequency of patents in the specific technologies studied in this paper. To help control for the impact of these factors, it may be informative to re-estimate the model from this study using the ratio of renewable technology patents to total patents, rather than using a simple count of non-hydro renewable patents as the dependent variable.

VIII. Conclusions

The regression results from model (3) described above indicate a strong, positive relationship between energy prices and federal spending on innovation in the non-hydro renewable technologies. The coefficient values predict that in order to increase the number of non-hydro renewable patents issued by 10 per year would require either a \$19.3 million dollar increase of government spending or an increase in average aggregate energy prices of \$0.38 per million Btu's (in \$1999).

The regression results for each specific energy source may also prove helpful in determining effective policy decisions. Both with and without fuel cell patent applications, the regressions using natural gas prices were by far the most statistically reliable. The regression with natural gas estimates that nearly 95% of the variation of annual non-hydro renewable energy patent applications can be explained by the price of energy from natural gas and federal spending on wind and solar R&D with a two year lag. In addition, the regression on the price of energy from natural gas suggests an even greater impact of energy price on innovation than in the aggregate energy model. In the model using natural gas as the energy price input, an increase of 10 non-hydro renewable energy patents per year would require an increase of only a $0.24 per million Btu's (in $1999).

IX. Policy Implications:

If a goal of policy makers is to increase the use of non-hydro renewable energy by maintaining a high level of technological development in the clean energy industries of the non-hydro renewables, then the last 30 years reflect a failure of this goal. It is clear from this study as well as many others that energy R&D is not exogenous, and that it is strongly influenced by the fluctuation of economic factors. With evidence that both energy price and federal R&D spending positively affect the level of innovation in non-hydro renewable technologies, it would seem logical that policies intended to control these two elements should attempt to move them counter-cyclically, in an effort to maintain a consistent and high level of R&D. The actual movements of these two economic stimuli, however, have in actuality been anything but counter-cyclical and have largely fluctuated together as can been seen in Figure 5.

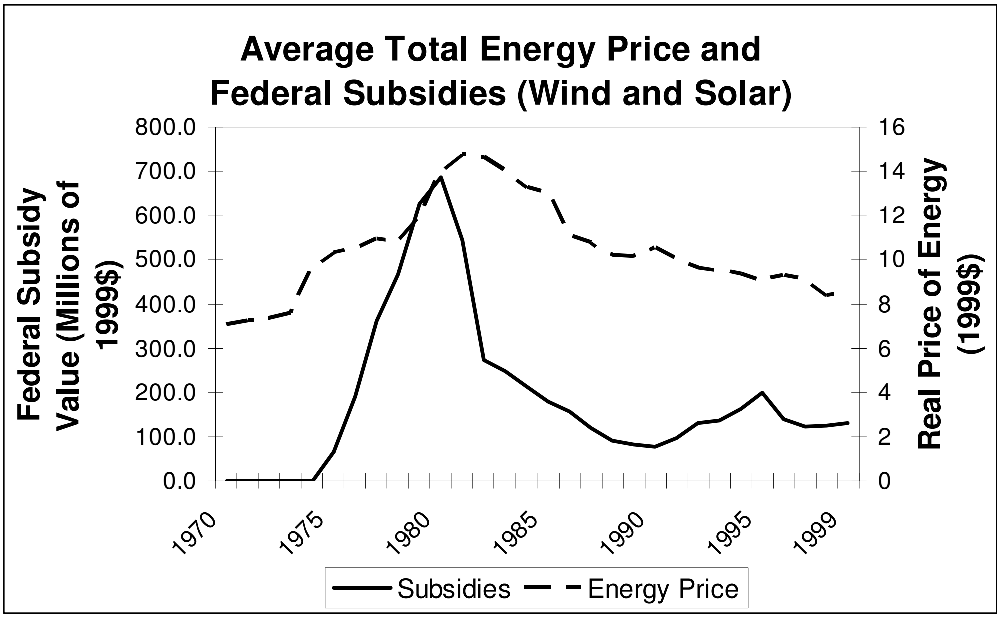

Figure 5: co-cyclical movements of energy price and subsidies

It is understandable how correlated movements of energy prices and federal subsidies could have occurred, as shocks in fuel prices like petroleum may motivate public pressure for subsidies, at least in the short-term. However, efforts to promote the development of renewable energy technologies should be approached with long term goals as opposed to simply reacting to shocks and fluctuations in fuel prices. In order to accomplish a goal of sustainable, consistent renewable energy R&D, policy makers should focus on using federal spending to offset energy price fluctuations: increasing subsidies to renewable energy R&D when energy and fuel prices are low and reducing spending when prices are high. Such a policy structure would allow the government to save money on R&D spending when innovation is sufficiently stimulated by energy prices, and in the case of low prices, use federal dollars to make up for this lack in private market stimulus.

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Appendix A: Patent Classifications

Solar Energy:

Class/Subclass	*Classification*
60/641.8-641.15	Power Plants/Utilizing natural heat/Solar
62/235.1	Refrigeration/Utilizing solar energy
126/561-568	Stoves and Furnaces/Solar heat collector for pond or pool
126/569-713	Stoves and Furnaces/Solar heat collector
126/714	Process of heating by using solar heat
126/903	Stoves and Furnaces/Cross-Reference Art/Solar collector cleaning device
126/904	Stoves and Furnaces/Cross-Reference Art/Arrangements for sealing solar collector
126/905	Stoves and Furnaces/Cross-Reference Art/Preventing condensing of moisture in solar collector
126/906	Stoves and Furnaces/Cross-Reference Art/Connecting plural solar collectors in a circuit
126/910	Stoves and Furnaces/Cross-Reference Art/Heat storage liquid
250/203.4	Radiant Energy/Photocells: circuits and apparatus/Photocell controls its own optical system/Following a target/Luminous Target/Sun
136/206	Batteries: Thermoelectric and Photoelectric/Thermoelectric/Electric power generator/Solar energy type
136/243	Batteries: Thermoelectric and Photoelectric/Photoelectric
136/244-251	Batteries: Thermoelectric and Photoelectric/Panel or Array
136/252-265	Batteries: Thermoelectric and Photoelectric/Photoelectric/Cells
29/890.033	Metal Working/Method of manufacture/Catalytic device making/Solar energy device making

Wind Energy:

290/44	Prime-Mover Dynamo Plants/Electric control/Fluid-current motors/Wind
290/55	Prime-Mover Dynamo Plants/Fluid-current motors/Wind
416/132B	Fluid Reaction Surfaces (i.e. Impellers)/Articulated resiliently mounted or self-shifting impeller or working member/Sectional, staged or non-rigid working member/windmills
416/196A	Fluid Reaction Surfaces (i.e., Impellers)/ Lashing between working members or external bracing/Connecting adjacent work surfaces/Non-turbo machine (windmills)
416/197A	Fluid Reaction Surfaces (i.e., Impellers)/ Cupped reaction surface normal to rotation plane/Air and water motors (natural fluid currents)

Wave and Tide Energy:

290/53	Prime-Mover Dynamo Plants/Tide and Move Motors
290/42	Prime-Mover Dynamo Plants/Electric Control/Tide and Wave Motors
60/495-507	Power Plants/Motor having a buoyant working member
416/6	Fluid Reaction Surfaces/Driven by pulsating or diverse working fluid
417/330	Pumps/Including disengageable rotary or frangible drive connection serially formed pumping chambers (e.g. endless) motor driven/tide or wave motor.
405/76	Hydraulic and Earth Engineering/Fluid control, treatment or containment/Wave or tide

Geothermal Energy:

60/641.2-641.5	Power Plants/Utilizing Natural Heat/Geothermal
60/641.7	Power Plants/Utilizing Natural Heat/Ocean Thermal Energy Conversion

Hydrogen and Fuel Cell Energy:

429/12-46	Chemistry: Electrical Current Producing Apparatus, Product, and Process/Fuel cell, subcombination thereof or method of operating

Source: Popp, David, Induced Innovation, Energy Prices, and the Environment.

Appendix B: Patent Applications

Renewable Patent Applications

Year	Solar	Wind	Oceanic (Wave and Tide)	Geothermal	Fuel Cell	Total
1970	8	0	5	1	16	30
1971	10	3	4	3	36	56
1972	16	2	5	3	27	53
1973	36	2	5	2	37	82
1974	101	11	21	17	36	186
1975	232	22	13	11	41	319
1976	342	9	14	14	49	428
1977	422	11	20	13	55	521
1978	420	27	24	13	44	528
1979	369	18	32	14	41	474
1980	336	26	16	12	41	431
1981	289	27	25	11	63	415
1982	198	26	17	8	68	317
1983	185	14	11	5	53	268
1984	183	12	9	6	55	265
1985	148	10	12	2	72	244
1986	110	8	18	4	77	217
1987	77	9	6	5	68	165
1988	91	7	8	4	63	173
1989	67	3	4	4	71	149
1990	80	3	2	4	92	181
1991	86	10	8	2	80	186
1992	103	12	5	3	81	204
1993	80	5	4	4	98	191
1994	103	11	4	7	92	217
1995	123	5	5	7	108	248
1996	121	8	7	6	89	231
1997	115	11	4	7	154	291
1998	134	7	8	5	226	380
1999	147	16	9	6	257	435
2000	158	21	7	4	380	570
2001	191	32	12	3	495	733

Appendix C: Energy Prices in 1999 Dollars per Million Btu's

Year	Coal	Natural Gas	Petroleum	Nuclear	Wood and Waste	Retail Electricity	Total Energy
1970	1.63	2.53	7.39	0.77	5.54	21.38	7.08
1971	1.73	2.59	7.36	0.74	5.39	21.80	7.24
1972	1.79	2.71	7.09	0.72	5.30	22.08	7.33
1973	1.80	2.74	7.39	0.71	5.22	21.99	7.58
1974	2.97	3.01	10.34	0.68	5.07	25.07	9.70
1975	3.19	3.65	10.37	0.74	4.64	26.66	10.31
1976	3.05	4.27	10.16	0.73	4.48	26.73	10.45
1977	3.05	4.84	10.25	0.74	4.34	27.79	10.94
1978	3.25	4.98	9.81	0.77	4.11	27.90	10.81
1979	3.12	5.30	12.00	0.78	4.31	27.03	11.96
1980	2.95	5.78	14.96	0.87	4.57	28.20	13.93
1981	3.01	6.29	15.91	0.88	4.64	29.58	14.72
1982	2.99	7.30	14.50	0.93	4.39	31.35	14.61
1983	2.84	7.90	13.00	0.97	4.06	31.15	14.03
1984	2.74	7.62	12.31	1.07	4.01	29.66	13.28
1985	2.62	7.14	11.81	1.10	3.75	29.50	12.96
1986	2.46	6.19	8.71	1.06	3.19	28.96	11.10
1987	2.24	5.53	8.86	1.04	3.04	27.48	10.76
1988	2.11	5.32	8.32	1.03	2.93	26.31	10.22
1989	1.99	5.13	8.64	0.94	1.89	25.50	10.14
1990	1.90	4.87	9.52	0.85	1.66	24.64	10.52
1991	1.81	4.57	8.81	0.77	1.69	24.28	10.03
1992	1.72	4.55	8.40	0.70	1.56	23.82	9.65
1993	1.64	4.73	8.08	0.65	1.45	23.50	9.51
1994	1.56	4.59	7.94	0.63	1.55	22.87	9.33
1995	1.50	4.08	7.97	0.59	1.55	22.19	9.05
1996	1.41	4.51	8.51	0.54	1.34	21.42	9.29
1997	1.37	4.70	8.16	0.53	1.18	20.92	9.13
1998	1.32	4.22	6.79	0.51	1.34	20.26	8.36
1999	1.27	4.16	7.33	0.48	1.38	19.37	8.50
2000	1.20	5.44	9.59	0.45	1.55	19.39	9.99
2001	1.21	6.45	8.76	0.41	1.53	20.19	10.06

Source: Nominal price data from the Energy Information Administration and CPI data from the Bureau of Labor Statistics.

Appendix D: Federal Subsidies for Renewable Energy in millions of 1999 dollars.

	Direct Program Budget Subsidies[1]			Off-Budget Subsidies[2]			Total Subsidy (Direct and Off-Budget)		
Year	Solar[3]	Wind	Subtotal	Solar	Wind	Subtotal	Solar	Wind	Total
1970	-	-	-	-	-	-	-	-	-
1971	-	-	-	-	-	-	-	-	-
1972	-	-	-	-	-	-	-	-	-
1973	-	-	-	-	-	-	-	-	-
1974	-	-	-	-	-	-	-	-	-
1975	50.3	15.6	65.9	-	-	-	50.3	15.6	65.9
1976	141.0	49.2	190.2	-	-	-	141.0	49.2	190.2
1977	306.8	55.3	362.1	-	-	-	306.8	55.3	362.1
1978	383.6	84.0	467.6	-	-	-	383.6	84.0	467.6
1979	501.0	125.8	626.8	-	-	-	501.0	125.8	626.8
1980	567.5	117.5	685.0	-	-	-	567.5	117.5	685.0
1981	447.9	95.9	543.8	-	-	-	447.9	95.9	543.8
1982	216.3	57.3	273.6	-	-	-	216.3	57.3	273.6
1983	172.3	50.3	222.6	-	24.5	24.5	172.3	74.8	247.1
1984	143.7	40.3	184.0	3.5	25.5	29.0	147.2	65.8	213.0
1985	131.7	42.2	173.9	3.8	1.8	5.6	135.5	44.0	179.5
1986	109.4	39.9	149.3	3.9	2.7	6.6	113.3	42.6	155.9
1987	91.3	23.4	114.7	3.8	0.0	3.8	95.1	23.4	118.5
1988	75.4	12.6	88.0	3.6	0.0	3.6	79.0	12.6	91.6
1989	66.6	11.6	78.2	3.5	0.0	3.5	70.1	11.6	81.7
1990	63.0	11.6	74.6	3.4	0.0	3.4	66.4	11.6	78.0
1991	80.1	13.5	93.6	3.2	0.0	3.2	83.3	13.5	96.8
1992	104.3	24.9	129.2	3.1	0.0	3.1	107.4	24.9	132.3
1993	105.9	27.5	133.4	3.1	0.0	3.1	109.0	27.5	136.5
1994	124.4	34.1	158.5	3.0	0.0	3.0	127.4	34.1	161.5
1995	135.1	53.5	188.6	2.9	6.5	9.4	138.0	60.0	198.0
1996	95.5	34.5	130.0	2.8	6.8	9.6	98.3	41.3	139.6
1997	85.6	30.2	115.8	2.8	3.6	6.4	88.4	33.8	122.2
1998	85.0	33.7	118.7	2.8	3.5	6.3	87.8	37.2	125.0
1999	89.2	34.8	124.0	2.8	3.6	6.4	92.0	38.4	130.4
2000	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2001	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Source: *Supporting Tables*; Federal Energy Subsidies: Not all technologies are created equal. Goldberg, Marshall, Renewable Energy Policy Project. 2000.