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Edmond Baranès – Julien Jacqmin – Jean-Christophe Poudou

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Non-renewable and intermittent renewable energy sources: friends *and* foes?*

Edmond Baranes †, Julien Jacqmin ‡and Jean-Christophe Poudou§

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Abstract

This paper studies the links between non-renewable and intermittent renewable energy sources in the production of electricity. We argue that the relationship between the price of natural gas and investments in solar and wind capacity is represented by a bell-shaped curve, as opposed to being linear. Hence, for relatively low natural gas prices, the two modes of production are substitutes. After a price threshold is reached, the two are complementary. A theoretical model explains this as the trade-off resulting from two forces: the input price differential of these two modes of production and the risks related to the unpredictable nature of renewable energy. Using U.S. state-level data from 1998 to 2012, we find that this relationship is robust to various empirical specifications.

Keywords: Renewable energy production, natural gas, factor complementarity, electricity production

JEL: D22, D24, Q41, Q42

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†edmond.baranes@univ-montp1.fr LAMETA and Labex Entreprendre, University of Montpellier 1, UFR Economie, Site de Richter, Avenue Raymond Dugrand, CS 79606, 34960 Montpellier, Cedex 2, France, Tel: +33(0)434432477

‡julien.jacqmin@univ-montp1.fr

§jean-christophe.poudou@univ-montp1.fr

1 Introduction

As the world struggles to address climate change, renewable energy is becoming an increasingly important electricity source. However, non-renewable sources of energy are still important. As the world moves forward with investments in renewable energy, such as wind and solar power, it is important to consider the interrelationship between renewable energy and non-renewable energy sources such as natural gas.

This relationship is complex; it is simultaneously adversarial and cooperative depending on a number of factors. Natural gas is a direct competitor to renewable energy in both the contract and spot bulk power markets. At the same time, the operational flexibility of gas-fired generation makes it a promising resource to offset natural fluctuations in sunlight and wind.

Natural gas and intermittent renewables are mostly seen as substitutes, both in the economic literature and the policy arena. Indeed, considering their intrinsic technical substitutability within power generation, it is quite natural to assume that an increase in the price of natural gas will increase incentives to invest in renewable energy generation. However, the unpredictable intermittency and the comparative advantage in terms of the input price of renewable energy undoubtably provide some scope for complementarities. This is particularly true for natural gas, due to its high degree of flexibility in electricity production. Natural gas generators can almost instantaneously supply the market when needed.

Other studies have analyzed the complex nexus between natural gas and intermittent renewable energy. However, the economic literature on the interplay between natural gas and renewable energy is relatively new. The literature can roughly be divided into three categories: papers that explore the relationship using a theoretical model, studies that provide a policy perspective, and papers that empirically analyze the determinants of investments in renewable energy.

The theoretical literature has largely overlooked the complementary relationship between renewable energy and natural gas. Most theoretical analysis explains how choices (in terms of capacity or inputs) between conventional and intermittent generation technologies are made. Some studies provide a social point of view, such as the partial equilibrium analysis in Ambec and Crampes (2012) or the general equilibrium framework in Schwerin (2013). Other studies look for strategic market-based explanations, such as Bouckaert and De Borger (2013) and Aflaki and Netessine (2012). All these studies consider thermal-based primary energy sources and intermittent ones to be substitutes, in that a rise in fuel prices eventually leads to increased investment in renewable energy.

However, some nuances to this basic property have been identified in the literature. For example, Bouckaert and De Borger (2013) show that from a strategic point of view, capacity choices between conventional dispatchable and intermittent generation technologies (in a duopolistic setting) may be strategic complements when intermittent generation conditions are unfavorable. But they remain net substitutes at the equilibrium, considering capacity cost effects. Using an electricity peak-load pricing model, Chao (2011) concludes that "the wind generation capacity generally substitutes the investment in combined cycle GT capacity but complements the investment in gas turbine units." In the same vein, Garcia et al. (2012) analyze optimal versus equilibrium mix of renewable and non-renewable technologies and state that "renewable capacity should be seen as a substitute to baseload technologies and complementary to peak generation technologies." Recently, Ambec and Crampes (2014) find that, in the optimal energy mix, capacities installed for intermettent sources can be lowered when environmental damages (or carbon taxes) go over a certain level. This can be interpreted as a complementary relationship between intermettent sources and fossil fuels when are considered the impact of different public policies that aim to decarbonate electricity production.

These conclusions have also been acknowledged in the policy literature. For instance, Lee et al. (2012) argues that a complementary relationship between natural gas and renewable energy sources can be established. Technical, environmental, political and economic considerations explain this claim. From an economic point of view, both energy sources have different risk profiles, so they may be complementary portfolio options. They argue that natural gas price volatility would be balanced by stable (near zero) generating costs of renewable energy investments and, on the flipside, natural gas plants' low up-front costs counterbalance inherent risks due to the intermittency of renewable generation plants.

This complementary relationship is also studied in the empirical literature on the determinants of investment in and production of renewable energies (see Delmas and Montes-Santo (2011), Fabrizio (2013) and Hitaj (2013), among others).[1] These papers

[1] There is also a substantial literature that estimates the energy cross-price elasticities based on applied production theory. See Stern (2010) for a survey. Our analysis does not consider substitutability

mainly focus on the impact of various policy tools (such as feed-in tariffs or renewable portfolio standards). In some of these studies, the price of natural gas or other fossil fuels is used as a control variable. Using European data, Marques et al. (2010) find a *positive* relationship between the share of contribution of renewables to the energy supply and the natural gas price, i.e. substitutability. Using U.S. data, Shrimali and Kniefel (2011) find a significant *negative* relationship between the share of nonrenewable (wind, solar, biomass and geothermal) capacity and the total net generation, i.e. complementarity: "The flexible natural gas based plants are used for overcoming the intermittency issues inherent in renewable power generation — in particular wind, the dominant renewable source." Shrimali and Kniefel (2011, p.4737).

We first develop a model, which shows that the relationship between the production of electricity using natural gas and renewable intermittent energy is more complex than originally thought. Using a simple theoretical framework, we analyze the basic trade-off that an energy producer faces when he plans to build supplementary intermittent capacity in renewable energy and knowing that the spot natural gas market can be used to supply the market in the event of production shortfalls.

We find that renewable sources and natural gas can sometimes be complementary, while at other times be substitutable input factors. More precisely, we find that for relatively low prices of natural gas, they are substitutes, as the absence of an input cost for renewable production is less valued. On the other hand, for relatively high natural gas prices, they are complementary, as the flexibility of a fossil fuel energy source can circumvent the intermittency of renewable energy sources (as they cannot be stocked and are not perfectly predictable).

We then examine these predictions using U.S. state-level data from 1998 to 2012, collected from the U.S. Energy Information Administration. Using capacity investments in intermittent renewable energy as the dependant variable, we use a panel tobit model to study its determinants. We focus mainly on renewable energy investment's relationship with the observed price of natural gas, using various socioeconomic, electricity market, policy and tax factors as control variables. In contrast with the literature, we allow for a more general relationship than a linear one between our two main variables of concern.

Our analysis has implications for policymakers. It suggests a need for more compre-

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or complementarity as a technological relationship between inputs or as a strategic link between supply decisions, but rather through an indirect price effect of a flexible input onto an investment decision. In some sense, we consider gross substitutability or complementarity.

hensive policies in the energy sector. It also highlights how various policies influencing the natural gas market (e.g, the rise of political tensions or the signing of free trade agreements with major natural gas exporters, the authorization to search and exploit new gas resources using new technologies, or the introduction of a tax on natural gas) could impact the renewable energy sector. Based on our conclusions, the relationship between these two energy sources is more complex than originally thought and depends in large part on the prevailing market conditions, and more specifically the price of natural gas.

Section 2 presents a simple theoretical model of generation mix under production uncertainty. In Section 3, we study the empirical link between the gas and the renewable markets in the context of electricity production. We conclude in Section 4. Proofs of results are found in the Appendix.

2 Theoretical Model

We model the basic tradeoff an energy producer faces when he (or she) plans to invest in renewable capacities, knowing that natural gas can be used to supply the market in instances of excess demand, such as during peak periods or a production failure.

In the model, we aim to reconcile the two contrasting views of the relationship between natural gas and renewables. While natural gas and renewable power are usually viewed as competitors, these two energy sources may be also seen as complements that fit well together in the electric system. The underlying trade-off can be seen through the contrasting effects the natural gas price may produce on the investment level of capacity in renewable. In the following, we consider that natural gas and renewable energy can be substitutable energy sources when the natural gas price positively affects capacity in renewable energy. In contrast, they can be considered as complementary when an increase in the natural gas price reduces capacity in renewables. Similar types of trade-offs have already been analyzed in more general microeconomic settings (see for instance Blair (1974) and Abel and Eberly (1994)).

The main features of our framework are twofold: First, instead of affecting input prices, uncertainty affects the maximal level of output achievable using a given technology (in this case, renewable capacity). Second, at the margin, the more secure and flexible source of supply (here, natural gas) is always more expensive than the risky or unsecured technology (here, the renewable one). Hence, the energy producer will balance the benefit of producing electricity at a zero marginal cost with the risk of having to use the spot market to produce electricity from natural gas.

Let $k \geq 0$ be the renewable capacity investment in electricity from the intermittent sources (in terms of capital cost).[2] We assume that this investment is normalized to represent an additional capacity that generates $f(k)$ kWh, where $f(k)$ is a twice differentiable, positive, increasing and concave production function, so that $f(0) = 0$. We denote $\phi = f^{-1}$ such that $\phi(y)$ depicts the necessary renewable capacity to generate y kWh. This assumption implies that investment opportunities exhibit non-increasing returns in terms of generation. We denote the intermittence factor by $x \in \{0, 1\}$, such that $\text{Prob}(x = 1) = \pi$ (windy, sunny) and $\text{Prob}(x = 0) = 1 - \pi$ (cloudy, gloomy, lull). Therefore, the available electricity from renewable source is $xf(k)$.

The natural gas price (i.e. on spot markets) is assumed to be certain, or equal to its common knowledge expected value, and is denoted by w, while q_x denotes the short-term supply of natural gas (which is adjustable). At the time of delivery, the energy demanded (which is, for simplicity, deterministic and exogenous) is given by $Q > 0$, and the output price of electricity is $p > w$.

Let $U : \mathbb{R}_+ \to \mathbb{R}, x \mapsto U(x)$ be the firm owner's von Neumann–Morgenstern utility function. U is twice differentiable, strictly increasing and strictly concave. We then denote $r(\Pi) = -U''(\Pi)/U'(\Pi) > 0$, the Arrow-Pratt measure of absolute risk aversion for a profit Π.

For a competitive producer, the problem is to choose ex-ante q_0, q_1 and k such that its expected profit $\Pi = \pi U(pQ - wq_1 - k) + (1 - \pi) U(pQ - wq_0 - k)$ is maximized. That is:

$$\max_{k, q_0 \geq Q, q_1 \geq \max\{0, Q - f(k)\}} \pi U(pQ - wq_1 - k) + (1 - \pi) U(pQ - wq_0 - k).$$

Let us consider the state-contingent decision q_x^* that the producer could take if the state of nature x occurs. As derived in the Appendix, due to the cost of q_x^* in each state of nature and the covered market condition, we have that $q_0^* = Q$ and $q_1^* = \max\{0, Q - f(k)\}$. Thus, the competitive producer's problem can be reduced to the

[2] We assume that (an infinite amount of) gas turbines have been already installed and that these costs are sunk.

choice of k ex-ante such that:

$$\max_k \ \pi U\left(pQ - w\left(\max\{0, Q - f(k)\}\right) - k\right) + (1-\pi)\, U\left((p-w)\, Q - k\right).$$

Now our aim is to understand the features of the solution of this problem and to study how the optimal renewable capacity investment k varies with respect to the natural gas price w. We focus on the case where the renewable capacity is less than the realized demand, namely when $k^* < \phi(Q)$,[3] the first-order condition for an interior solution becomes:

$$\pi\left(f'(k^*)w - 1\right) U'(B) = (1-\pi)\, U'(A) \tag{1}$$

where $A = (p-w)\,Q - k^*$ and $B = A + wf(k^*)$. This condition has the following interpretation. Whenever it is optimal for the producer to invest in renewable capacities, he balances the marginal expected net reward of having this capacity available to produce electricity at a zero unit cost when demand occurs (i.e. $\pi(f'(k)w - 1)$) and the marginal expected cost of having to buy extra natural gas on the spot market (which depends on his attitude towards risk, $U'(.)$).

At this stage, our main objective is to assess when k^* is an increasing or a decreasing function of w. In other words, can renewable intermittent energy and natural gas be substitutable or complementary input factors? In the following, we argue that this is intrinsically related to the intermittent nature of renewable energy and the supply risk it creates.

First, we state a result that gives sufficient conditions for intermittent energy and natural gas to be substitutes.

Result 1. *Renewable energy and natural gas are substitutes if at least one of the following three conditions are met: (i) there is no intermittency (ii) the producer is risk-neutral or (iii) the natural gas price is very low.*

Proof. See appendix □

Conditions reported in Result 1 can be viewed as limiting cases under which re-

[3] When the renewable capacity investment is sufficient to cover the realized demand, the optimal investment will be $k^* = \phi(Q)$, and all the energy demand is served through the costless renewable capacity.

newable energy and natural gas are substitutes in the the energy mix. Here, k^* is a decreasing function of the natural gas price w. First, when intermittency is not an issue[4] then there is no risk to supply due to cloudy, overcast or non-windy weather (i.e. $\pi = 1$). In this context, the producer faces a trade-off between the monetary cost of investing in new renewable capacities and the benefit obtained with certainty from not having to purchase this energy from the gas spot market. This opportunity return is becoming more important when the gas price increases, so is the marginal investment in renewables. Energy factors are then substitutes. Second, if the producer is risk-neutral, the same trade-off is again at play, except that the opportunity return is taken in expectation, proportionally reduced by the probability of sunshine or wind. Finally, if the natural gas price is very low (say below a given threshold), the previous opportunity return is nil, so is the investment in renewable capacities. Thus a slight increase of the natural gas price above this threshold makes the investment in renewables profitable, which implies subtitutability between both factors.

The contrepart of Result 1 is that whenever the producer is risk-averse, intermittence is an issue or natural gas prices are not very low, complementarity between renewable energy and natural gas is a possibility. Our second result gives sufficient conditions for intermittent energy and natural gas to be complements in the energy mix.

Result 2. *Renewable energy and natural gas are complements if the following necessary condition is met:*

$$\left(\frac{\pi}{1-\pi}\right)\frac{f'(k^*)}{f(k^*)}\frac{U'(B)}{U'(A)} \leq \frac{Q}{f(k^*)}r(A) - \left(\frac{Q}{f(k^*)} - 1\right)r(B). \tag{2}$$

Proof. See appendix □

Result 2 illustrates that depending on the strength of risk aversion, the degree of intermittency and the level of natural gas price, renewable capacity investments can be decreasing as the natural gas price is increasing. In this setting, the marginal cost related to a lack of wind or sunlight increases faster than the marginal benefit of having access to a free input.

We can further interpret the inequality condition in Eq. (2). The left-side of the inequality is the product of three elements that can be viewed as the *degree of flexibility* the energy producer faces. Indeed it is respectively composed of the probability rate

[4]For example, there could be technological advances that make it possible to store wind or solar energy of the electricity it produces.

of sunlight or wind $(\pi/(1-\pi))$, the marginal rate of decrease in renewable production due to the investment k when the natural gas price rises $(f'(k)/f(k))$ and the marginal rate of substitution between profits in both state of nature (that is in case of lack of renewable energy source, the rise in profits needed to compensate the monetary loss when sun shines or wind blows due to a lower renewable capacity investment). Hence when the solar or wind capacity investment diminishes, the left hand side of Eq. (2) describes the ability with which the competitive energy supplier can balance profit losses in case of sunshine or wind by gains in the contrary case. Moreover, one can see that the marginal rate of substitution between profits decreases as natural gas prices rise, since B decreases less than A when w increases. As a result, the degree of flexibility becomes lower as the gas price rises.

Second, the right-side of the inequality can be viewed as the *degree of risk aversion* the energy producer exhibits, as it involves the difference of Arrow-Pratt coefficients of absolute risk aversion for both state of nature weighted by a corresponding risk exposure ratio.

Then, one can now argue that whenever the degree of flexibility is *weaker* than the degree of risk aversion, the energy producer will have an incentive to lower renewable capacity investments when natural gas input prices rise. In that case, renewable and fossil energy cources can be viewed as complementary. Then, in some circumstances it is more likely that the degree of risk aversion overcomes the degree of flexibility of the producer for high gas prices. Moreover one can expect that above a price threshold, an increase in the price of natural gas will lead to a decrease in investments in renewable capacities. In our general framework, it is not possible to provide conditions about this price threshold without considering a given class of von-Neumann-Morgenstern utility function.

In the following, we give one example for which Result 2 occurs. From the discussion above, let us consider a constant absolute risk aversion utility function, where $U(z) = -\exp(-\theta z)$ and $\theta \geq 0$, where $\theta > 0$ is the risk aversion parameter and the linear production function is $f(k) = ak$, where $a > 0$. We can see that

$$k(w) = \left\{ \begin{array}{c} 0 \\ \min\{Q, \hat{k}(w)\} \end{array} \right. \quad \text{if} \quad \begin{array}{c} w < \frac{1}{a\pi} \\ w \geq \frac{1}{a\pi} > 1 \end{array}$$

where

$$\hat{k}(w) = \frac{1}{w\theta a} \ln\left(\frac{\pi(wa-1)}{1-\pi}\right).$$

Differentiating $\hat{k}(w)$ with respect to w gives

$$\hat{k}'(w) = \frac{1}{w}\left[\frac{1}{\theta(wa-1)} - \hat{k}(w)\right].$$

We see that there is a unique $\bar{w} : \hat{k}'(\bar{w}) = 0$ when $\hat{k}(\bar{w}) = \frac{1}{\theta(\bar{w}a-1)}$ (it is a transcendental equation). Hence, $\hat{k}(w)$ is increasing if $w < \bar{w}$ and is decreasing otherwise, as depicted in Figure 1.[5]

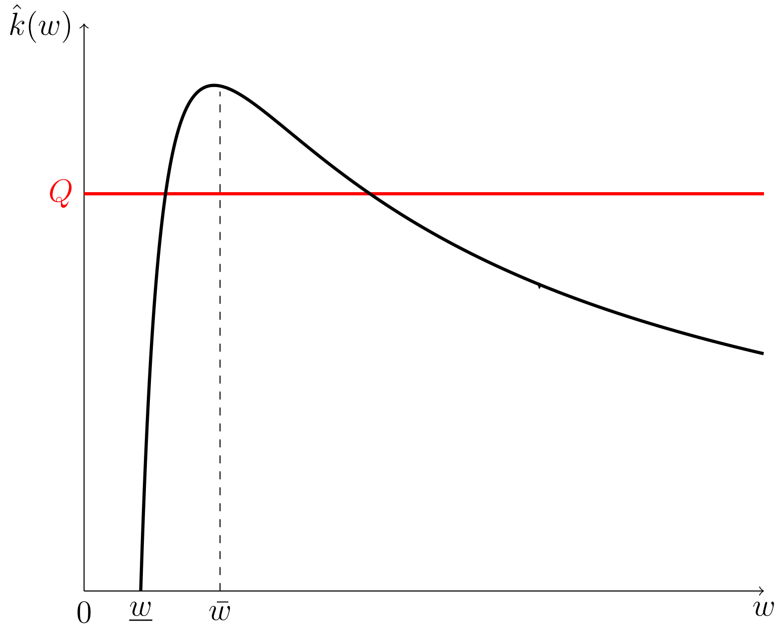

Figure 1

Renewable capacity investment (k) as a function of the price of natural gas (w)

The black line denotes capacity. The red line denotes the electricity demand.

In this example, the two energy sources can be seen as substitutes when the natural gas price is sufficiently low, and complements otherwise. This result is a testable prediction; the following section presents data and an empirical model to see if the model's results hold in the real world.

[5]A similar shape has been obtained for a DARA utility function, $U(z) = \ln(1 + \theta z)$, where $\theta > 0$.

3 Empirical Model

We now study the empirical link between non-renewable and renewable electricity markets. More precisely, we focus on the relationship between investments in intermittent renewable methods of producing electricity and the input price of a non-renewable technology (in our case, natural gas).

Figure 2 is a scatterplot showing the relationship between the natural gas price and renewable capacity investments for 49 U.S. states between 1998-2012, as well as a quadratic fit (only considering strictly positive renewable capacity investments). The graphic suggests that a non-linear relationship is more plausible than a linear one. This observation is consistent with our theoretical model, which suggests that a bell-shaped curve would provide a better fit for the link between the price of natural gas and renewable capacity investments. It confirms the idea stated in Results 1 and 2 that, for relatively high natural gas prices, these two energy sources can be complementary. In what follows, we show that this suggestive evidence is robust to various empirical approaches.

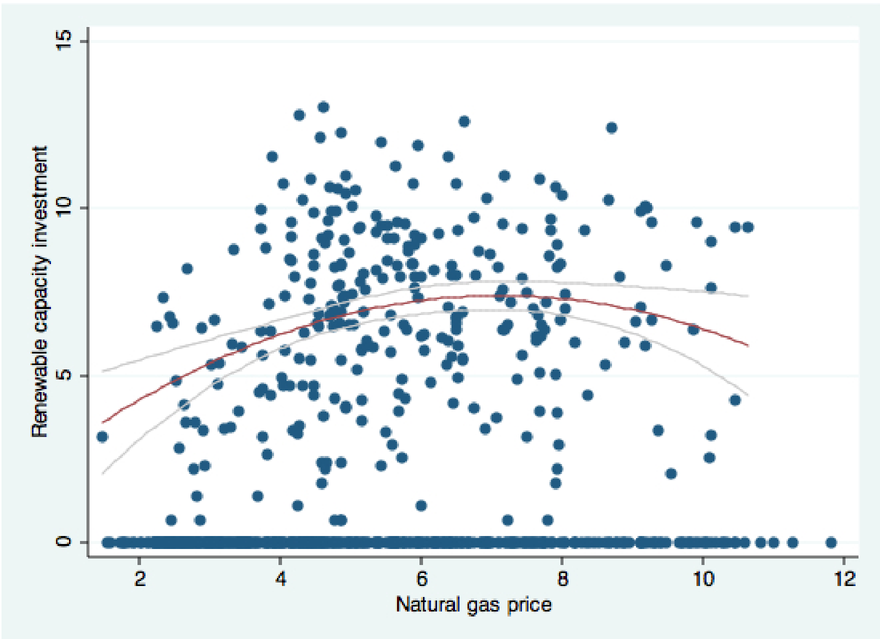

Figure 2
Scatterplot of (log of) renewable capacity investments and average natural gas price for all U.S. states between 1998 and 2012 and a quadratic fit (with conficence intervals of 95%)

3.1 Methodology

To test the main result of our theoretical framework, we use U.S. state-level data from 1998 to 2012.[6] One major concern with our data is the high number of censored observations, as investments in additional capacity are bounded to be weakly positive. Out of our 732 observations,[7] 445 observations have a renewable capacity investment equal to zero, i.e. there were no investment in renewable capacities during these years/states.

Empirical methods such as random and fixed effects panel models result in biased and inconsistent estimates, as they are not able to account for the possible qualitative difference between corner and strictly positive observations. To accommodate for these non-negative dependent variables, we use a censored tobit model for panel data with random effects. Hence, our zero-valued observations are assumed to be true zeros (i.e. the effective outcome that is observed which is characterized as a corner solution) and there is no rounding to zero of investment below a positive value.[8]

Let the vector X_{it} represent all our explanatory variables, including the natural gas price variables, in a state $i = 1, ..., N$ in time $t = 1, ..., T$. We can define the latent, unobservable, renewable capacity investment y^*_{it} as:

$$y^*_{it} = \alpha_i + X_{it}\beta + \epsilon_{it}$$

where the error terms ϵ_{it} are i.i.d. $\mathcal{N}(0, \sigma_e^2)$ and the random effects α_i are i.i.d $\mathcal{N}(0, \sigma_a^2)$. We estimate a censored panel tobit model where this latent variable determines the value of the observed variable y_{it}, which can be defined as:

$$y_{it} = \begin{cases} y^*_{it} & \text{if} \quad y^*_{it} > 0 \\ 0 & \text{if} \quad y^*_{it} \leq 0 \end{cases}$$

[6]Our database can be downloaded from our website.

[7]From our original sample of 735 observations, we exclude three observations that are missing the price of natural gas. Despite this, we analyze our data as a balanced panel.

[8]In our robustness analysis, we depart three times from this approach. First, we transform our dependent variable into a dummy variable, which describes whether or not new investments have occurred. To analyze this case, we use a probit model. Second, there are no statistics that allow the fixed effects to be conditioned out of the likelihood (Stata (2009)). Hence, it is not possible to compute conditional fixed effects. Despite being biased and inconsistent, we compute unconditional fixed effect estimators. Third, we use compute conventional fixed effect estimators. In each cases, we show that our main results hold. Another complementary approach would be to estimate a self-selection model. Unfortunately, it is unclear which variable plays a role in the decision to invest and not in the decision of how much to invest in renewable capacities.

Since it is impossible to compute fixed effects with this approach, we control for unobserved heterogeneity using a random heterogeneity-specific component for each state. This assumption implies that state- specific effects are uncorrelated with our independent variables. The problem of endogeneity will be further discussed in our robustness analysis.

Due to the absence of closed-form solutions, the log likelihood is computed using a numerical approximation (Gaussian quadrature). Following a change in the number of quadrature points, estimates tend to be unchanged. This can be explained by our sample size and large within-group observations. Hence, our results seem to be reliable. In order to estimate the variance-covariance matrix of our estimator, we apply the bootstrap procedure for the standard errors with 200 repetitions. Further robustness checks are derived at the end of this section.

3.2 Data

3.2.1 Dependent Variables

Our analysis focuses on capacity investments, as opposed to accumulated investments, market share or generation because it highlights better the outcome of our economic decision. Using this dependent variable allows us to more clearly analyze the outcome of the investment decision, net of previous years. It is also a more ideal variable than electricity generation because capacity investments are not influenced by unpredictable year-to-year weather conditions; as with its zero marginal cost, renewable energies are the first in the merit order of electricity generation. Finally, in line with our theoretical model, we focus on aggregate investments in two renewable energy sources: solar and wind. They are both non-flexible intermittent and renewable sources of production. Compared with electricity produced from hydropower, biofuel or biomass, they do not create large negative environmental externalities through their capacity installments, the production of electricity or the supply of inputs. We use state-level data as states are a coherent entity with respect to the energy policies implemented.

Our data comes from U.S. Energy Information Administration (2014). It has the double advantage of having state-level data on both renewable capacity investments and natural gas prices. The information is obtained from the EIA-860 form. To consider both the increasing number of units producing electricity and the increase in productivity observed over time, we multiply the number of generators installed by their nameplate capacity (i.e. maximum output of a generator expressed in megawatts). As zeros and positive values are analyzed separately, We take its log of the positive values as the original data is heavily right-skewed and has a non-normal kurtosis.

3.2.2 Independent Variables

Our focus is on the price of natural gas, which is the unit price of the main input in the production of non-renewable electricity. Other independent variables act as controls and are classified into three categories (socioeconomic, electricity market and policy/tax factors). This is a stark contrast with Marques et al. (2010) or Shrimali and Kniefel (2011), which mainly focused on the impact of tax and policy tools on renewable energies using, among other things, prices as control variables. We will also consider a more general specification than them.

We now provide detailed descriptions of our independent variables.

1. Price of natural gas

   Our *natural gas price* data is from EIA (2013). It is the average price paid (in nominal dollars per million Btu) by the electric power sector for natural gas for each state and year combination. It includes the cost of natural gas as well as insurance, freight and taxes. As for our dependent variable, we use yearly data as it is more appropriate to understand investment behaviors which occur in the long run.

   To study the relationship between the input price of natural gas and investment in renewable energy, we consider both a linear and a quadratic term. As there might be lags between the price observed (or estimations of it) at the time an investment is decided upon and the time when the capacity investment is available, we include up to four-year lags. The economic explanation for using lags comes from the red tap or construction timing and delays related with the investments. Due to multicollinearity between these price variables, we focus on our most representative results, which use a one-year lag.[9]

[9]Due to the quadratic terms and the lags, up to 10 gas price variables were simultaneously considered. Our results hold further using no lag or two-years lag but standard errors are impacted, leading to lower significance levels.

2. Electricity market factors

   The first three factors (*state size*, *wind availability* and *sun availability*) are all measures of the feasibility of installing wind and solar farms. These are the only variables that are held constant across all years in our data.

   One would expect states of larger size to host more investments. *Wind availability* is the wind generation potential for each state at an 80 meter height, with capacity factors of at least 30% measured in TWh/year, as provided by National Renewable Energy Laboratory (2011). *Sun availability* is the solar radiation for flat-plate collectors facing south at a fixed tilt (kWh/m^2/day), as measured in the largest city of each state (National Renewable Energy Laboratory (2010)). We expect these variables to positively influence our dependent variable.

   Growth in electricity sales is the growth in the amount of electricity sold for each state compared with the previous year. It is a measure of the incremental demand for electricity. *Electricity price* is the average price of electricity sold by state producers of electricity. Since the price of electricity is a good proxy for the per-unit returns derived from installed capacities, the coefficient of this variable is expected to be positive.

   Production % renew. energy and *production % nuclear energy* represent, respectively, the market share of electricity produced using intermittent and renewable sources and using nuclear sources. Data for both variables is from the U.S. Energy Information Administration (2014) database. Due to agglomeration effects in the production of renewable energy, the production share of renewable energy is expected to be positive. This variable also shows how the accumulated stock of renewable energy investment influences new investments. Conversely, nuclear energy's share of production is expected to be negative, as it is complicated to easily switch from one source of production to renewable energy.

   Experience with ISO/RTO is the cumulative number of years (including fractions of years) that a state has been active in a Regional Transmission Organization (RTO)/Independent System Operator (ISO). These institutions facilitate the transmission of electricity between states. Computed from Federal Energy Regulatory Commission (2014), this variable is a proxy for the quality of a state's electricity grid and how easy it is to switch from one source of electricity production to another. Due to the intermittent nature of renewable energy, more experience in such an organization is expected to lead to more investments in renewable energy capacity.

3. Socioeconomic factors

   The first two socioeconomic factors, *population* and *GDP per capita*, are obtained from U.S. Census Bureau (2014) and U.S. Bureau of Economic Analysis (2014), respectively. *Population* is the number of inhabitants (in million) and *GDP per capita* is the nominal GDP per capita (in thousand \$). Both coefficients are expected to be positive. The first because it is a proxy for the total demand for renewable energy, and the second because emission reductions, which tend to result from increased reliance on renewable energy, are a normal good.

   Using electoral data, the other two socioeconomic variables are proxies for the tastes of residents. *Democrat governor* is a dummy variable, which takes the value 1 when the state governor is a Democrat. *LofCV indicator* is an index based on the scorecard produced by League of Conservative Voters (2014), which lists the "greenness" of state representatives' at the federal congress on environmental issues using voting data. It is a categorical/ordinal variable between 0 and 3, where the most environmental friendly states are awarded a 3 and the least environmentally friendly are awarded a 0. Both these variables are expected to be positively correlated with investment in renewable energy capacity.

4. Policy and tax factors

   To facilitate the interpretation of our main results, we use two aggregate variables based on information derived from the Database on State Incentives for Renewables and Efficiency DSIRE (2014). *Policy* is the number of regulatory and policy tools (among public benefit funds, renewable portfolio standard, net metering system, interconnected standard, required green power option and feed-in tariff) in place to promote investments in renewable energy in each year for each state. *Tax* is the number of financial incentives available (from personal, corporate, sales and property tax measures). We expect that these two categorical variables have a positive impact on additional investments.

The summary statistics of our dependent and independent variables can be found in Table A1 of the Appendix.

3.3 Main results

The main results of our paper are provided in Table 1. Each of the five regressions looks at the determinants of renewable capacity investments. The first column displays our base model which only includes dependent variables related with the electricity market. The linear and quadratic term related with *natural gas price* are both significant at a 1% threshhold. The first is positive and the second is negative. This supports our theoretical result that the relationship between *natural gas price* and *renewable capacity investments* is non-linear. Hence, we have an inverted-U-shaped relationship between the two variables. In line with our model, this means that for relatively low prices, a marginal increase in price tends to increase investments in renewable energy. Above this price threshhold, the reverse holds and they are complements, as a marginal increase in prices tends to decrease investments in renewables.

In regression (1), the coefficient estimates for the electricity market factors are in line with what we have predicted in the previous subsection. *Wind availability* and *sun availability* are both positive, but only the former is significant.[10] Larger states host more investments but this is not significant. States facing an increasing demand for electricity tend to invest less in renewable energies. One explanation can be that investments in technologies with more flexibility are preferred as they are a safer way to secure the supply of the electricity demanded. An increase in *electricity price* means a higher return for each capacity unit invested. This coefficient is positive and significative. Previous investments in renewable energies call for more investments but this coefficient is not significative. On the contrary, when nuclear energies have a prominent place in the production of electricity, less investments are taking place. This is due to the lack of flexibility of nuclear energies, which coupled with renewable energies, can lead to a problem in term of security of electricity supply. Having an *experience with ISO/RTO* helps improving the quality of the grid, and subsequently the switch from one source of energy to another, this has a positive and significant impact on renewable capacity investments.

Regression (2) introduces other important covariates related with the socioeconomic context. This does not change our previous results. We observe that a higher *GDP per capita* leads to more important investments. One explanation is that wealthier states become more concerned about the quality of the environment. One way to improve it

[10] This can be explained by the marginal importance of solar energy compared to wind energy, as it accounts for about 4% of our renewable capacity investments.

Table 1

Renewable capacity investments as a continuous variable (log of): Panel data Tobit model

	(1)	(2)	(3)	(4)	(5)
Natural gas price	1.822***	1.283**	1.254**	1.984**	-0.043
	(0.525)	(0.576)	(0.575)	(0.804)	(0.237)
Natural gas price (squared)	-0.153***	-0.118***	-0.109**	-0.160***	
	(0.043)	(0.044)	(0.044)	(0.06)	
Wind availability	0.112**	0.116*	0.095*	0.104**	0.108**
	(0.056)	(0.063)	(0.051)	(0.052)	(0.053)
Sun availability	1.368	1.333	0.516	-0.966	-1.014
	(2.552)	(2.311)	(1.892)	(1.969)	(2.018)
State size	0.002	0.001	0.002	0.002	0.001
	(0.019)	(0.019)	(0.016)	(0.015)	(0.015)
Growth in electricity sales	-10.319**	-13.068***	-12.459***	1.685	2.767
	(5.225)	(5.045)	(4.808)	(6.29)	(6.127)
Electricity price	1.218***	0.798***	0.374	0.03	0.046
	(0.228)	(0.25)	(0.246)	(0.253)	(0.26)
Production % renew. energy	16.003	8.421	4.129	-7.993	-7.493
	(12.933)	(14.01)	(13.312)	(10.795)	(10.674)
Production % nuclear energy	-12.384**	-12.173*	-10.409**	-7.68	-8.288*
	(5.918)	(6.254)	(5.289)	(4.694)	(4.82)
Experience with ISO/RTO	0.502***	0.446***	0.364***	0.18*	0.158
	(.0113)	(0.123)	(0.105)	(0.101)	(0.105)
GDP per capita		0.16**	0.093	-0.042	-0.041
		(0.079)	(0.06)	(0.067)	(0.068)
Population		0.16	0.157	0.214	0.220
		(0.274)	(0.201)	(0.15)	(0.15)
Democrat governor		-0.03	-0.086	0.114	0.073
		(0.673)	(0.653)	(0.619)	(0.624)
LofCV indicator		0.344	- 0.022	0.183	0.159
		(0.279)	(0.29)	(0.277)	(0.279)
Policy			0.741**	0.192	0.178
			(0.306)	(0.302)	(0.292)
Tax			1.117***	0.445	0.423
			(0.316)	(0.313)	(0.319)
Constant	-23.408**	-25.569***	-17.881**	-9.788	-5.152
	(9.286)	(8.569)	(7.165)	(9.173)	(8.96)
Year fixed effects	No	No	No	Yes	Yes
Log likelihood	-996.347	-990.239	-975.114	-932.710	-937.517

Robust standard errors in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Sample: 732 observations - 49 states - period 1998-2012 (including 445 left-censored observations) is to invest in renewable energies. *Population*, *democrat governor* and *LofCV indicator* have all an impact on our dependant variable which is not significant.

Regression (3) also includes our *policy* and tax factors. They are both positive and significant. Our previous results remain for the most unchanged.[11] Their sign remains unchanged but *electricity price* and *GDP per capita* are not significant anymore. This is due to their high degree of correlation with *policy*, repectively 0.52 and 0.58. The change in sign of *LofCV indicators* can also be explained by its correlation with *policy*.

Regression (4) includes in addition year effects. By using a dummy for each years, we are able to capture unobserved time-invariant effects. This can reduce potential concerns about time-varying macroeconomic effects which have an impact on investments and are not included in our model. It also captures some of the effects created by technological changes in the renewable sector which have made capacities less costly and/or more productive, information which is, unfortunately, not available to include in our model. Due to this reason, this is our preferred regression. This is confirmed by the likelihood ratio test. By considering these year effects, we have that our main results remain. *Natural gas price* and *Natural gas price (squared)* are respectively positive and negative at the 5% and 1% level. With their respective values, the maximum of the inverted-U curve is at around 6.2$ per million Btu, while the average is 5.3.[12] Note that this also impacts some of our coefficients. This is due to the whithin variance of the variables which is now captured by these yearly dummies.

Compared with specification (4), specification (5) only allows a linear relationship between *natural gas price* and *additional renewable capacity*. This linear term has a negative sign, meaning that an increase in price leads to less investments. However, this is not significant, i.e. we cannot claim that these two intermittent sources of energy are complementary. Hence, our data is better estimated using both a linear and a quadratic term.[13]

In conclusion, these results tend to confirm our theoretical prediction. While, for relatively low natural gas price, renewable energy and natural gas are substitutable inputs, they are complementary for high natural gas prices. This is in line with Results

[11] Note that considering individually the policies composing these aggregate indicators does not impact our results. Results are available upon request.

[12] Remark that this is very close to the maximum of the quadratic fit of our data pictured in Figure 2 which does not consider any control variables.

[13] Adding a further cubic and quartic term does not impact this conclusion. Results are available upon request.

1 and 2 from our theoretical model. Our theoretical explanation is that for high prices of natural gas, the cost associated with the unpredictable intermittency of renewable energy cannot outweigh the cost savings from using a freely available input.

3.4 Robustness analysis

We examine the robustness of our results using alternative specifications, the regressions of which are shown in Table 2. Regression (4) is our benchmark case. We use different dependent and independent variables as well as alternative estimation procedures. Finally we discuss the issue of endogeneity. Our robustness analysis confirms, and further strengthens, our main results. Due to the various approaches used, it is complicated to compare the parameter estimates of our control variables but they tend to be similar accross specifications.[14] Eventual changes can be explained by the use of fixed effects, of other estimators or of other dependent variables. Hence, in this analysis, we will focus on our main variables of concern.

First, in our main results, we consider a random component for each state, to account for state-specific conditions potentially impacting the dependent variable. With tobit panel data, it is not possible to consider state fixed effects. However, it is possible to compute unconditional state fixed effects, although these estimates are biased and inconsistent. Results are shown in regression (6). We see that the parameter estimate for *natural gas price* is positive and for *natural gas price (squared)* is negative. Both are significant at the 1% level. This is in line with our main result.

In regression (7) and (8), we examine the robustness of our results with respect to different independent variables. First, using the same data, we redefine *renewable capacity investment* as a dummy variable, where 1 denotes that an investment was made. Due to this change, we use a different estimation strategy. We examine it using a panel probit model with random effects. We see from regression (6), where marginal effects at the means are computed, that the estimates for the linear and squared terms of *price of natural gas* have the expected signs and are both significant at, respectively, a 10% and 5% level. Even though the levels of the estimates differ from the ones before, they tend to give a maximum of the inverted-U relationship at a similar price level.

Next, in regression (8), we look at the determinants of changes in electricity produc-

[14] Remark that the price threshhold, defined as the maximum of the quadratic relationship between *natural gas price* and *renewable capacity investment* is always close to 6 $ per million Btu.

Table 2
Robustness analysis

Dependent variable Renewable Energy (log of)	(6) Capacity Tobit	(7) Capacity Probit	(8) Production Tobit	(9) Capacity Tobit	(10) Capacity FE
Natural gas price	1.750***	0.508*	2.103*		1.245***
	(0.667)	(0.276)	(1.114)		(0.353)
Natural gas price (squared)	-0.148***	-0.045**	-0.155**		-0.111***
	(0.05)	(0.02)	(0.079)		(0.027)
Average petroleum price				0.162**	
				(0.078)	
Wind availability		0.014***	0.159*	0.111**	
		(0.004)	(0.091)	(0.051)	
Sun availability		-0.038	0.267	-1.143	
		(0.146)	(3.28)	(1.956)	
State size		0.001**	0.006	0.001	
		(0.0003)	(0.028)	(0.014)	
Growth in electricity sales	3.194	-2.105	-17.89**	2.964	2.624
	(5.721)	(2.058)	(8.63)	(6.112)	(3.01)
Electricity price	0.321	-0.110***	0.557	0.076	-0.066
	(0.253)	(0.04)	(0.412)	(0.27)	(0.198)
Production % renew. energy	-13.489*	58.089***	0.301	-7.622	24.02**
	(7.22)	(13.202)	(19.441)	(10.702)	(11.782)
Production % nuclear energy	-2.942	-0.578	-12.715	-8.864*	0.987
	(9.331)	(0.357)	(9.828)	(4.699)	(11.782)
Experience with ISO/RTO	0.156*	0.002	0.522**	0.217**	0.146*
	(0.086)	(0.024)	(0.237)	(0.103)	(0.075)
GDP per capita	-0.111	0.015	0.101	-0.055	-0.028
	(0.069)	(0.009)	(0.125)	(0.069)	(0.059)
Population	-0.440	0.041***	0.137	0.273*	0.606
	(0.379)	(0.012)	(0.384)	(0.144)	(0.408)
Democrat governor	-0.040	0.061	2.13**	0.119	0.112
	(0.415)	(0.129)	(1.052)	(0.629)	(0.347)
LofCV indicator	0.082	0.202***	0.463	0.094	0.025
	(0.289)	(0.078)	(0.632)	(0.276)	(0.183)
Policy	-0.043	0.131**	0.729	0.181	0.265
	(0.217)	(0.059)	(0.604)	(0.277)	(0.231)
Tax	0.254	0.079	1.348**	0.381	0.312
	(0.307)	(0.055)	(0.671)	(0.33)	(0.231)
Constant	302.629	-3.264***	-24.667	-5.289	-6.215
	(256.085)	(1.109)	(13.363)	(8.66)	(3.321)
Year fixed effects	Yes	Yes	No	Yes	Yes
State fixed effects	Yes	No	No	No	Yes
Log likelihood	-838.527	-275.069	-1298.47	-933.901	/

Robust standard errors in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Sample: 732 observations - 49 states - period 1998-2012

(6) and (9) Renewable capacity investment as a dependent variable (445 left-censored observations)

(7) Renewable capacity investment dummy as a dependent variable

(8) Renewable energy production (408 left-censored observations)

(10) Renewable capacity investment ($log(a + y)$ with $a = 0.3$ as a dependent variable

tion from renewable sources instead of renewable capacity investments, also using data from U.S. Energy Information Administration (2014). Again, we find similar results as before. Note however that standard errors are negatively impacted whenever we consider year fixed effects in the regression, as conjectural factors are more important when we consider production rather than investment as a dependent variable.

In regression (9), compared with our benchmark case, we use the price of a different mode of production. we use the average petroleum price (EIA (2013)) instead of the price of natural gas. Looking at cases with both a linear and a quadratic term and with only a linear term, we find that the specification with the best fit and the most significant result is the one with a lag of one year and only a linear term. We see that an increase in the average petroleum price leads to a increase in investments. This means that renewable energies and petroleum are substitutes. In light with Lee et al. (2012), this can be explained by the lack of flexibility of petroleum in circumventing the intermittence problem created by renewable energy sources.

In regression (10), we abstract from the problem created by the high degree of censorship in our data by estimating a panel data with fixed-effects. As zero and positive outcomes are not treated separately anymore, we have added a constant ($a = 0.3$) before taking the log of our renewable capacity investment dependent variables. This method, often used in the trade literature interested in the determinants of foreign direct investments, prevent us from omitting zero outcomes from our sample. We use Huber/White estimators to estimate the variance-covariance matrix. We find that, again, our two main variables of concern have their expected signs. *Price of natural gas* is positive and *price of natural gas (squared)* is negative. Both are significant at the 1% threshhold. Further, we have also excluded from our sample states without any positive observation for our dependent variables, i.e. without renewable capacity investments. Our main results hold.[15]

One final important issue to discuss is endogeneity. In our context, the main potential source of endogeneity is reverse causality. As argued by Wiser and Bolinger (2007), renewable energies can impact the natural gas market, as it shifts its demand. On the one hand, renewable energy investments could reduce the overall demand for natural gas, leading to downward pressure on prices. On the other hand, the unpredictable intermittency of renewable energy could cause spikes in natural gas demand when there is no wind nor sunlight. These temporary shifts can lead to increased price dispersion.

[15] Results are available upon request.

Hence, the overall impact on the price of natural gas is indeterminate.

There are several factors that can explain why endogeneity does not undermine our main results. First, the scope for reverse causality is limited by the fact that we look at marginal rather than accumulated investments in renewable capacities. The impact on the natural gas price is much more limited due to the relatively small level of annual investments compared with accumulated investments. Second, our main specification considers a one-year lag between the price of natural gas and renewable capacity investments. It is unlikely that price expectations in the gas market are impacted by investments that will produce electricity in a year, especially considering the important cost of natural gas storage. Finally, the fact that we look at long-run investment behavior (in opposition to short-run production behavior) and that we use yearly data undermines the scope for reverse causality. In our sample, on average, only one percent of the electricity production comes from renewable sources.

However, there is the possibility of an omitted variable bias created by a third variable not included in our model, which influences both the natural gas price and renewable capacity investments. It is unclear in which direction this could bias our estimators. In our context, this could be due to unobserved policies (such as a decision to phase out nuclear power) or demand/supply shocks (such as a technical problem that makes it impossible to use a dam or a nuclear power plant). Note however that some of these unobserved factors are captured by our year fixed effects.

4 Conclusion

This paper provides new theoretical and empirical insights into the relationship between renewable methods of producing electricity (focusing on wind and solar power), and non-renewable methods. We study the degree of substitutability and complementarity between these two sources of energy. This relationship is not linear. Due to the unpredictable intermittency from these renewable natural resources, natural gas can be complementary, as it can effectively supply the market on demand. Using U.S. state-level data, we find that an increase in the price of natural gas can lead to a decrease in investment in renewable energy capacity.

Our theoretical model provides an explanation for the bell-shaped relationship between the price of natural gas and renewable capacity investments. It highlights the trade-off between the relative input price advantage of renewable energy and the uncertainty related to the unpredictable intermittency of these energy sources, which must be replaced in the blink of an eye when there are shortfalls. We argue that this second force increases proportionally more with the price of natural gas, giving scope for complementarities.

Our results suggest that a comprehensive approach to energy supply is appropriate. Investments in renewable and non-renewable energy should be considered in tandem due to the interrelationship between these two electricity sources. It is essential that the renewable energy sector does not ignore the natural gas market. Direct policies (such as taxes or subsidies) or indirect policies that affect the natural gas market can impact the renewable energy sector significantly. New free trade agreements or tense political relationships with major natural gas exporting countries, as well as policies towards natural gas exploration and exploitation can have an effect on investments in the renewable sector.

Precisely defining the price threshold at which natural gas becomes a complement instead of a substitute is outside the scope of this paper. This could be particularly interesting with a more comprehensive database. Another issue concerns the high quantity of data censoring. Another, complementary, estimation strategy would be to consider it with a self-selection approach a la Heckman. However, in the U.S. context, it is unclear which variable plays a role in the selection step and not in the intensity step. One way to avoid this indentification problem would be to use the methodology developed by Raymond et al. (2010). We hope that our work will lead to further research on these issues.

Another interesting question concerns how the relationship between natural gas and renewable energy will evolve over time. Is there scope for a higher degree of complementarity between these two sources of electricity? Further investments in the electricity grid and technological advances will most likely improve the interconnectivity between the various types of electricity, both at the state and national level. However, this might be offset by the evolution of technologies related to the storage of electricity/renewable power or the imperfectly predictable nature of renewable energy sources. It will be interesting to further analyze how these two forces will evolve.

References

Abel, A. B. and J. C. Eberly (1994). Unified Model of Investment Under Uncertainty. *The American Economic Review*, 84(5), 1369–1384.

Aflaki, S. and S. Netessine (2012). Strategic Investment in Renewable Energy Sources. *INSEAD working paper*, 2012/59/TOM, 34.

Ambec, S. and C. Crampes (2012). Electricity Production with Intermittent Sources of Energy. *Resource and Energy Economics*, 34(3), 319–336.

—— (2014). Environmental Policy with Intermittent Sources of Energy. *Procedings of the Conference "Energy and Climate Economics"*, page 27.

Amir, R. (2005). Supermodularity and complementarity in economics: an elementary survey. *Southern Economic Journal*, 71(3), 636–660.

Blair, R. D. (1974). Estimation of the Elasticity of Substitution when Input Prices are Random. *Southern Economic Journal*, (1), 141–144.

Bouckaert, J. and B. De Borger (2013). Intermittent Electricity Generation and Investment in Capacity. *Research paper / University of Antwerp*, page 33.

Chao, H. (2011). Efficient Pricing and Investment in Electricity Markets with Intermittent Resources. *Energy Policy*, 39(7), 3945–3953.

Delmas, M. A. and M. Montes-Santo (2011). U.S. State Policies for renewable Energy: Context and Effectiveness. *Energy Policy*, 39(2273-2288).

DSIRE (2014). Database of State Incentives for Renewables and Efficiency. `http://www.dsireusa.org/`.

EIA (2013). State Energy Price and Expenditure Estimates State Energy Price and Expenditure Estimates 1970 Through 2011. Technical report, U.S. Energy Information Administration.

Fabrizio, K. R. (2013). The Effect of Regulatory Uncertainty on Investment: Evidence from Renewable Energy Generation. *Journal of Law, economcs and Organization*, 29(4), 765–798.

Federal Energy Regulatory Commission (2014). Regional Transmission Organizations (RTO)/Independent System Operators (ISO). `http://www.ferc.gov/industries/electric/indus-act/rto.asp`.

Garcia, A., J. M. Alzate, and J. Barrera (2012). Regulatory Design and Incentives for Renewable Energy. *Journal of Regulatory Economics*, 41(3), 315–336.

Hitaj, C. (2013). Wind power development in the United States. *Journal of Environmental Economics and Management*, 65(3), 394–410.

League of Conservative Voters (2014). National Environmental Scorecard. `http://scorecard.lcv.org/`.

Lee, A., O. Zinaman, J. Logan, M. Bazilian, D. Arent, and R. L. Newmark (2012). Interactions, Complementarities and Tensions at the Nexus of Natural Gas and Renewable Energy. *The Electricity Journal*, 25(10), 38–48.

Marques, A. C., J. A. Fuinhas, and J. R. P. Manso (2010). Motivations driving renewable energy in European countries: A panel data approach. *Energy Policy*, 38, 6977–6885.

National Renewable Energy Laboratory (2010). Solar radiation data manual for flat-plate and concentrating collectors. `http://rredc.nrel.gov/solar/pubs/redbook/`.

—— (2011). Estimates of windy land area and wind energy potential. `http://apps2.eere.energy.gov/wind/windexchange/pdfs/windmaps/windpotential.pdf`.

Raymond, W., O. Mohnen, and S. van der Loeff (2010). Persistence of innovation in Dutch manufacturing: Is it spurious? *The Review of Economics and Statistics*, 92(3), 495–504.

Schwerin, H. (2013). Capacity Planning with Supply Uncertainty of Clean Technology. In *12th journées Louis-André Gérard-Varet*.

Shrimali, G. and J. Kniefel (2011). Are government policies effective in promoting deployment of renewable electricity resources? *Energy Policy*, 39, 4726–4741.

Stata (2009). *Stata Longitudinal-Data/Panel-Data Reference Manual: Release 11*. Stata press.

Stern, D. I. (2010). Interfuel substitution: A meta-analysis. *Journal of Economic Surveys*, 26(2), 307–331.

U.S. Bureau of Economic Analysis (2014). U.S. Economic Accounts. `http://www.bea.gov/`.

U.S. Census Bureau (2014). Population Estimates. `http://www.census.gov/popest/states/NST-ann-est.html`.

U.S. Energy Information Administration (2014). Electricity data. `http://www.eia.gov/electricity/data.cfm#summary`.

Wiser, R. and M. Bolinger (2007). Can deployment of renewable energy put downward pressure on natural gas prices? *Energy Policy*, 35(1), 295–306.

Appendix

Contingent decisions. Ex post, if $x = 1$ then profit will be $\Pi_1 = pQ - wq_1 - k$ with $q_1 \geq 0$ because the renewable capacity investments k are used to serve the demand. If $f(k) \geq Q$, that is $k \geq \phi(Q)$, $q_1^* = \arg\max_{q_1} \Pi_1 = 0$. If $k < \phi(Q)$, then $q_1 \geq Q - f(k)$ because capacity k is too limited to meet overall demand Q. We have that $q_1^* = Q - f(k)$. As a result, $q_1^* = \max\{Q - f(k), 0\}$. If $x = 0$, then profit will be $\Pi_0 = pQ - wq_0 - k$, with $q_0^* \geq Q$ such that $q_0^* = \arg\max_{q_0 \geq Q} \Pi_0 = Q$. ■

Proof of Result 1. Using standard results from the comparative statics theory (see for instance Amir (2005)), we know that $k^*(w)$ will be increasing (or respectively decreasing) on a given domain, if the expected profit Π exhibits an increasing differences (respectively decreasing differences) with respect to (k, w) in that domain. As Π is assumed to be twice differentiable, increasing differences occurs when $\frac{\partial^2 \Pi}{\partial k \partial w} > 0$ and decreasing differences occurs when $\frac{\partial^2 \Pi}{\partial k \partial w} < 0$. Here we have:

$$\text{(A.1)} \qquad \frac{\partial^2 \Pi}{\partial k \partial w} = \pi f'(k)U'(B) + (1-\pi)QU''(A) - \pi(f'(k)w - 1)(Q - f(k))U''(B)$$

Point i is proven as follows. If the renewable energy is not intermittent (when $\pi = 1$), from Eq. (A.1) we have that $\frac{\partial^2 \Pi}{\partial k \partial w} = f'(k)U'(B) - (f'(k)w - 1)(Q - f(k))U''(B) > 0$ whenever $f'(k)w - 1 > 0$. As shown in (1), this is true at the optimum.
If the producer is risk-neutral (i.e. U' is constant), from Eq. (A.1) we have $\frac{\partial^2 \Pi}{\partial k \partial w} = \pi f'(k)U'(B) > 0$. On this basis, renewable energy and natural gas are substitutes in the producer's electricity mix. This proves Point *(ii)*.

Finally, when $k^* = 0$, to take into account the corner condition, Eq. (1) can be rewritten as:

$$[\pi f'(0)w - 1]\, U'\left((p-w)\, Q\right)) \leq 0$$

From this, one can define $\underline{w} = 1/\left(f'(0)\pi\right)$ so that for $w \in [0, \underline{w}]$, renewable capacity investment is equal to zero. The natural gas is too cheap to make the investment into renewable capacities valuable. Hence in a right neighborhood of $\underline{w}$, then $k^* > 0$, so by continuity k^* is necessary locally increasing. This proves point *(iii)*. ■

Proof of Result 2. From Eq. (A.1) and using Eq. (1), we can rewrite $\frac{\partial^2 \Pi}{\partial k \partial w}$ and show when it is non positive, that is when Π exhibits decreasing differences (evaluated at the optimum). Rigourously, concavity of Π in k is nedeed at this stage, to allow such a substitution. Fortunately, this is the case due to the concavity of U and f. Then we have:

$$\begin{aligned} \frac{\partial^2 \Pi}{\partial k \partial w} &= U'(A)\left[\pi f'(k^*)\frac{U'(B)}{U'(A)} + (1-\pi)\left\{(Q - f(k^*))r(B) - Qr(A)\right\}\right] \geq 0 \\ &\Rightarrow \left(\frac{\pi}{1-\pi}\right)\frac{f'(k^*)}{f(k^*)}\frac{U'(B)}{U'(A)} \leq \frac{Q}{f(k^*)}r(A) - \left(\frac{Q}{f(k^*)} - 1\right)r(B). \end{aligned}$$

. ■

Summary statistics

Table 3
Summary statistics

Variable	Mean	Standard Deviation	Min	Max
Additional renewable capacity (log)	2.648	3.709	0	13.045
Natural gas price	5.312	22.133	1.48	11.81
Wind availability	11.915	22.133	0	94.918
Sun availability	4.222	0.558	2.4	5.7
State size	200.031	250.912	4.002	1717.854
Growth in electricity sales	0.013	0.035	−0.215	0.187
Electricity price	8.195	2.72	3.89	18.06
Production % renew. energy	0.011	0.028	0	0.248
Production % nuclear energy	0.177	0.182	0	0.808
Experience with ISO/RTO	3.796	4.492	0	14
GDP per capita	40.161	9.486	21.524	72.454
Population	6.016	6.52	0.491	38.041
Democrat governor	0.443	0.497	0	1
LofCV indicator	1.802	1.313	0	4
Policy	1.822	1.632	0	6
Tax	1.199	1.200	0	4