

Renewable and non-renewable intermittent energy sources: friends and foes?

*Preliminary draft - Comments are welcome**

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Abstract

This paper studies the links between renewable and non-renewable intermittent energy sources in the production of electricity. More precisely, we argue that the relationship between the natural gas price and capacity investments in solar and wind power energy is far from univocal. We find that this relationship is not linear but is better represented by a bell-shaped curve. Hence, for relatively low gas price, the two modes of production are substitutable. 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 the intermittence of renewable energies. 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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1 Introduction

What is the interplay between natural gas and renewable energy in electric generation? The penetration of intermittent renewable generation is a key issue in the transition to a cleaner environment and the climate change mitigation. It is clear that the use of intermittent energy, such as wind and solar power, and its relationship with natural gas depends on the way the power generation system is functioning. This relationship is complex, it is simultaneously adversarial and cooperative to varying degrees according to a number of contingencies. Natural gas is a direct competitor to renewable energy in both contract and spot bulk power markets. At the same time, the operational flexibility of gas-fired generation makes it a promising resource for balancing the natural fluctuations in sunlight and wind, so long as a market exists to induce the gas generator to provide balancing and other grid support services. However, 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, in a first step, to consider that an increase of the price of natural gas will increase incentives to invest in renewable generation plants. Yet, this relationship does not seem that univocal. The unpredictable intermittency and the comparative advantage in term of input price of renewable modes of production give undoubtedly scope for complementarities. This is particularly true for natural gas due to its high degree of flexibility in the electricity production, as generators can almost instantaneously generate electricity to supply the market in case of need.

We first develop a model that shows a more complex than originally thought relationship between the production of electricity using natural gas and renewable intermittent energies. Using a simple theoretical framework, we analyze the basic tradeoff 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 case of production failure or during peak periods. Then, sometimes renewable and natural gas are complementary sometimes they are substitutable input factors. More precisely, we find that for relatively low input price of natural gas, they are substitutes, as the absence of input cost for renewable production is less valued. On the other hand, for relatively large price of gas, they are complementary, as in this case the flexibility of this fossil 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 the capacity investments in intermittent renewable energies as dependant variable, we use a panel tobit model to study its determinants. We focus mainly on its relationship with the observed price of natural gas, using various socioeconomic, electricity market, policy and tax factors as control variables.

Policy implications could be derived from our analysis. It calls for a more comprehensive approach for policies in the energy sector. It also highlights how various policies influencing the gas market (the rise of political tension or the signature of a free trade agreement with a major gas exporter, the authorization to search and exploit new gas resources using new technologies, the introduction of a tax on gas, etc.) could impact the renewable sector. Based on our conclusions, the relationship between these two factors of production is more complicated than originally thought and depends in large part on the initial market conditions prevailing in the gas market, and more specifically the price of gas.

Other studies have studied the complex nexus between natural gas and intermittent renewable energy. However, the economic literature on the interplay between natural gas and renewable energy is still recent and appears not so much developed. For clarity, we can distinguish three blocks of papers: papers that explore the relationship using a theoretical model, those who offer a policy perspective and finally papers that empirically analyze the main determinants of the investment in renewable energies.

From a *theoretical point of view* this complementary relationship has been poorly identified in the literature. Most theoretical analysis explain how choices (in terms of capacity or inputs) between conventional and intermittent generation technologies are made. On one hand, a social point of view is adopted, as in Ambec and Crampes (2012) in a partial equilibrium analysis or Schwerin (2013) in a general equilibrium framework, and on the other hand, some papers look for strategic market-based explanations as in Bouckaert and De Borger (2013) or Aflaki and Netessine (2012). In all these analysis, optimal choices of thermal-based primary energy and intermittent one are found to be substitutable inputs in the sense that a raise of fuel prices increase investment in the renewable energy, at the end. However, some nuance 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 comple-

ments 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, p. 3951) 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.*’.

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 but also economic considerations explain this claim. From a strict economic point of view, both energy sources have different risk profiles so that they may offer complementary portfolio options. They argue that natural gas price volatility would be balanced by stable (near zero) generating costs of renewable energy investments and, at the opposite, natural gas plants low upfront costs counterbalance inherent risks due to intermittency of renewable generation plants.

This complementary relationship was also *studied empirically* in the literature studying the determinants of investment/production of renewable energies (see among others Delmas and Montes-Santo (2011), Fabrizio (2013) or Hitaj (2013)).¹ These papers mainly focus on the impact of various policy tools (like feed-in tariffs or renewable portfolio standards). In some of these studies, the price of natural gas or other fossil fuels is used 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. Based on U.S. data also, Shrimali and Kniefel (2011) find a significant *negative* relationship between the share of nonrenewable (wind, solar, biomass and geothermal) capacities to 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).

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

¹There is also a substantial literature which estimates the energy cross price elasticities based on applied production theory. See Stern (2010) for a survey.

market in the context of electricity production. We conclude in Section 4.

2 Theoretical Model

We model the basic tradeoff an energy producer faces when he (she) plans to build supplementary intermittent capacity in renewable energy, knowing that the spot gas market can be used to supply the market in case of production failure or during peak periods. Similar type of tradeoffs have already been analyzed in more general microeconomic settings (see for instance in Blair (1974) or Abel and Eberly (1994)). Basically from a general point of view, the main features of our framework are twofold: First, instead of bearing on input prices uncertainty does concern the maximal level of output achievable using a given technology (i.e. 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 and the cost created by the risk of having to use the spot market to produce electricity with gas.

Let $k \geq 0$ be the additional investment into intermittent capacities to be installed (in terms of capital cost).² We assume that this investment is normalized as to represent an additional capacity that generates $f(k)$ kWh where $f(k)$ is a positive increasing 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 by $x \in \{0, 1\}$ the intermittence factor such as $\text{Prob}(x = 1) = \pi$ (windy, sunny) and $\text{Prob}(x = 0) = 1 - \pi$ (cloudy, gloomy, lull). Therefore, the available electricity is $xf(k)$.

The gas input (spot) price is assumed certain (or equal to its expectation) and is denoted by w while q_x denotes the gas short term supply (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 is $p > w$.

Let $U : \mathbb{R}_+ \rightarrow \mathbb{R}, x \mapsto U(x)$ be the firm's owner von Neumann–Morgenstern utility function, U is strictly increasing, strictly concave.

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

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 what is the state contingent decision q_x^* that the producer could take if the state of nature x occurs. Clearly, as fully 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 is to choose ex ante k such that

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

Then we have to consider two alternative cases, whenever the renewable capacity would be chosen to be sufficient to cover the realized demand or nor. In the former case, i.e. if $k \geq \phi(Q)$, then the first order condition is such that:

$$-\{\pi U'(pQ - k) + (1 - \pi) U'((p - w)Q - k)\} < 0$$

The optimal investment will be $k^* = \phi(Q)$.

The second case to consider is the renewable capacity cannot cover the realized demand i.e. if $k < \phi(Q)$. Then the first order condition for an interior solution becomes the following:

$$(1) \quad \pi (f'(k)w - 1) U'((p - w)Q + wf(k) - k) - (1 - \pi) U'((p - w)Q - k) = 0$$

This condition has a clear interpretation. Whenever it is optimal for the producer to invest in an additional renewable capacity, 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 gas on the spot market (which depends on his attitude towards risk $U'(\cdot)$).

Let us now examine some basic characteristics of this interior solution. From (1) we see that when $w = 0$ then the first order condition becomes $-U'(pQ - k) < 0$. In this

case, we have that $k^* = 0$. Then for $k = 0$, Eq. (1) can be rewritten as:

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

From this, one can define $\underline{w} = 1/(f'(0)\pi)$ so that for $w \in [0, \underline{w}]$, additional investment in renewable capacity is equal to zero.

When $w > \underline{w}$, let $k(w)$ be the solution of Eq. (1) if $k(w) < Q$. Rewriting (1) yields

$$(2) \quad f'(k)w = 1 + \frac{1 - \pi}{\pi} \frac{U'(A)}{U'(B)}$$

Differentiating Eq. (1) with respect to w leads to

$$\begin{aligned} & (k'(w) f''(k)w + f'(k)) U'(B) + \left[k'(w) (f'(k)w - 1)^2 - (f'(k)w - 1)(Q - f(k)) \right] U''(B) \\ &= -\frac{1 - \pi}{\pi} (k'(w) + Q) U''(A) \end{aligned}$$

where $A = (p - w)Q - k$ and $B = A + wf(k)$. Hence, this static comparative can be simplified as follows

$$(3) \quad k'(w) = -\frac{\pi f'(k)U'(B) + (1 - \pi)QU''(A) - \pi(f'(k)w - 1)(Q - f(k))U''(B)}{\pi f''(k)wU'(A) + \pi(f'(k)w - 1)^2 U''(B) + (1 - \pi)U''(A)}$$

The denominator is negative (as the objective is concave) but the numerator has not a constant sign. Our main point is to assess if and when it could be the case that $k'(w) < 0$, i.e. can renewable intermittent energy and natural gas be complementary input factor. We argue that this complementarity is intrinsically related to two forces: the intermittence nature of renewable energy we consider and the supply risk this creates. Indeed if the producer were risk neutral (i.e. U' is constant), from Eq. (1) it can easily be derived that $k(w) = (f')^{-1}(1/(\pi w))$ which is clearly an increasing function³ of w : on that basis renewable energy and natural gas are substitutes in the producer's electricity mix.

If renewable energies were not intermittent anymore⁴, then there is no risk to be failing due to a cloudy, gloomy or lull situation. This is the case when $\pi = 1$ and again

³This can be seen putting $U'' = 0$ in Eq. (3). that is $k'(w) = -\frac{f'(k)}{f''(k)w} > 0$.

⁴For example, as a consequence of technological advances that make it possible to stock wind or solar energy or the electricity it produces.

the renewable energy and natural gas are substitutes since

$$k'(w) = -\frac{f'(k)U'(A) - (f'(k)w - 1)(Q - f(k))U''(A)}{f''(k)wU'(A) + (f'(k)w - 1)^2 U''(A)} > 0$$

Moreover, one can check that for $w \rightarrow \underline{w}$ then $k'(\underline{w}) > 0$. Indeed, we have proved above that $k^*(\underline{w}) = 0$ so that the numerator of $k'(w)$ becomes $\pi f'(0)U'(A) > 0$. Hence, in all these cases, the marginal benefit of using free inputs to produce electricity is always larger than the marginal cost of not having these free inputs due to their unpredictable intermittent nature. We sum up these first results.

Result 1. *The renewable energy and natural gas are substitutable inputs in the electricity mix if at least one of the following three situation arises : (i) the producer is risk neutral; (ii) there is no intermittency or (iii) the natural gas price is very low (w is in a right neighborhood of \underline{w}).*

Hence, whenever the producer is risk averse, intermittence is an issue or natural gas price are not very low, complementarity between renewable energy and natural gas factor can be considered.

From Eq. (3), one can see that the sign of $k'(w)$ is given by the sign of the numerator. Using Eq. (2), this numerator rewrites:

$$U'(A) \left[\pi f'(k) \frac{U'(B)}{U'(A)} + (1 - \pi) \{(Q - f(k))r(B) - Qr(A)\} \right]$$

where $r(\Pi) = -\frac{U''(\Pi)}{U'(\Pi)} > 0$ is the Arrow-Pratt measure of absolute risk-aversion for a profit Π . Remark that the first term between brackets is always positive, hence only the sign of the second term can be negative depending on whether $r(A)/r(B)$ is sufficiently high (at the optimum), that is

$$(4) \quad \frac{r(A)}{r(B)} > \frac{Q - f(k)}{Q}$$

In particular, this condition is always verified if the utility function is DARA as $\frac{r(A)}{r(B)} > 1 \geq \frac{Q - f(k)}{Q}$. Unfortunately, this is not a sufficient condition for $k'(w)$ to be negative.

We therefore have the following result.

Result 2. *Under the condition described by Eq. (4), the renewable energy and natural gas may be complementary inputs in the electricity mix.*

Result 2 illustrates that depending on the strength of risk aversion, the weight of intermittency and the level of the natural gas price, additional investment in renewable capacity can be decreasing as the natural gas price is increasing. In this setting, the marginal cost related to the unavailability of wind or sun increases faster than the marginal benefit of having access to a free input. After a price threshold, an increase in the price of gas will lead to a decrease in investments into renewable capacities. However, in our general framework it is not possible to give clear cut conditions for such a result, without considering a given class of VNM utility function.

In the following we give two standard examples for which Result 2 occurs.

Example 1. Let us consider a CARA utility function where $U(z) = -\exp(-\theta z)$ and $\theta \geq 0$ where $\theta > 0$ is the risk aversion parameter and the linear production $f(k) = ak$ where $a > 0$. We can see that

$$k(w) = \begin{cases} 0 & \text{if } w < \frac{1}{a\pi} \\ \min\{Q, \hat{k}(w)\} & \text{if } w \geq \frac{1}{a\pi} > 1 \end{cases}$$

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 (resp. decreasing) if $w < \bar{w}$ (resp. $w > \bar{w}$), as depicted in Figure 1.

Example 2. Let us consider a DARA utility function such that $U(z) = \ln(1 + \theta z)$ where $\theta > 0$ is a parameter that increases the risk aversion measure and a linear production function $f(k) = ak$ where $a > 0$. We now have that

$$\hat{k}(w) = \frac{(\pi wa - 1)(1 + \theta(p - w)Q)}{\theta(wa - 1)}$$

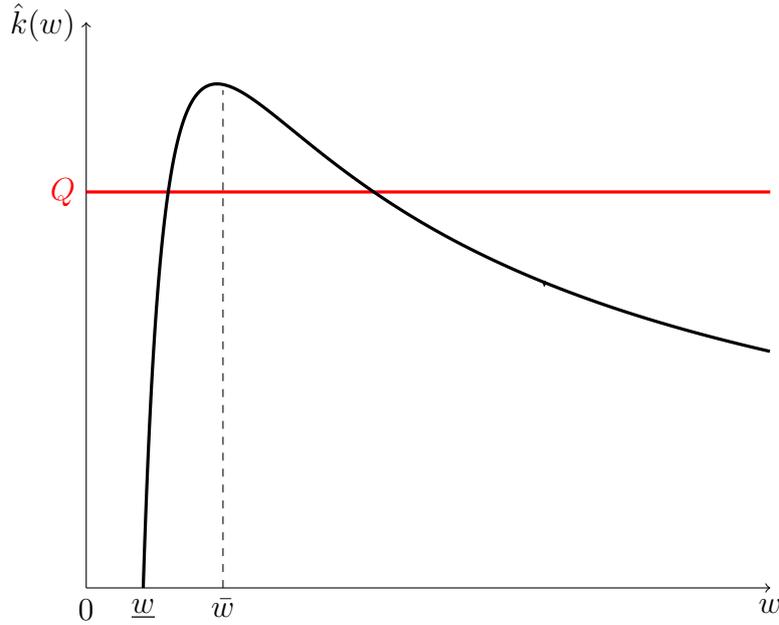


Figure 1

Additional renewable capacities as a function of the price of natural gas (Examples 1 and 2)

Black line: capacity , red line: demand

Similarly to Example 1, the threshold value for the natural gas price equals

$$\bar{w} = \frac{1}{a} \left[1 + \sqrt{\frac{(1 - \pi) (\theta Q (ap - 1) + a)}{\pi \theta Q}} \right]$$

Again $\hat{k}(w)$ is increasing (resp. decreasing) if $w < \bar{w}$ (resp. $w > \bar{w}$).

3 Empirical Model

We now study the empirical link between the non-renewable and renewable market in the context of electricity production. We focus more precisely on the relationship between additional investments in intermittent/renewable capacities of producing electricity and the input price of the non-renewable technology. Here, we will mainly consider the price of gas. Figure 2 represents the scatterplot of these observations for 49 U.S. states between 1998-2012, as well as a quadratic fit (only considering strictly positive additional renewable capacities). From this graphic, a non-linear relationship seems more plausible than a linear one. This observation tend to support our theoretical insight according

to which a bell-shaped curve gives a better fit for the link between the price of gas and investment in renewable energies. In the following, we show that these suggestive evidences are robust to various empirical analysis.

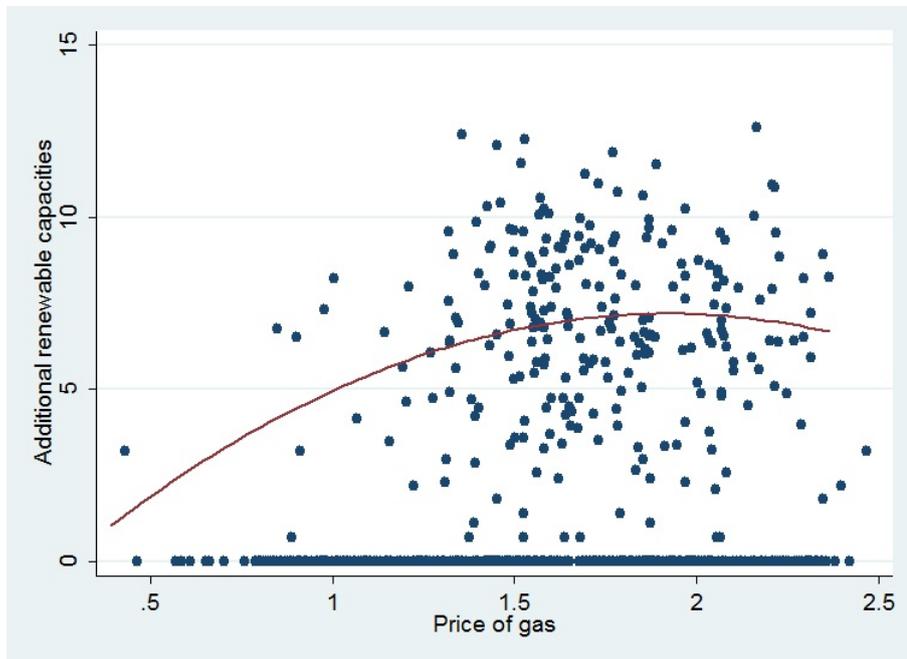


Figure 2

Scatterplot of Additional Renewable Capacities (in log of MW) and Average Natural Gas Price (in log of USD/MMBtu) for all U.S. states between 1998 and 2012, with a quadratic fit

3.1 Methodology

To test the main result of our theoretical framework, we use a U.S. state-level data from 1998 to 2012. One major concern of our data is the high number of censored observations, as investments in new capacities are bounded to be weakly positive. Out of our 732 observations⁵, 445 of them are equal to zero. 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 nonnegative dependent variables, we

⁵Due to three missing price of gas observations, we had to drop them. Despite this, we analyze our data as a balanced panel.

apply a censored tobit model for panel data with random effects.⁶

Let the vector X_{it} represent all our explanatory variables, including the gas price variables, in a state $i = 1, \dots, N$ in time $t = 1, \dots, T$. We can define the latent, unobservable, additional investment in capacities y_{it}^* as:

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

Where the error terms ϵ_{it} are i.i.d. $\mathcal{N}(0, \sigma_\epsilon^2)$ 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:

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

Due to the impossibility to compute fixed effects with this approach, our unobserved heterogeneity is controlled for using a random heterogeneity specific component for each state. This assumption implies that state specific effects are uncorrelated with our independent variables.

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. Further robustness checks are derived in the end of this section.

3.2 Data

3.2.1 Dependent Variables

As analyzed previously in the literature, we focus on marginal capacity investments, in opposition to accumulated investments, market share or generation. Using this dependent variable allows us to analyze more clearly the outcome of the strategic investment

⁶In our robustness analysis, we depart twice from this approach. First, we transform our dependent variable into a dummy outcome which describes whether or not additional investments have occurred. To analyze this case, we use a probit model. Second, there is no sufficient statistics to 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. In both cases, we show that our main results hold.

decision, net of anterior years. We focus on capacity investments rather than on the generation of electricity, as this outcome variable is not influenced by the unpredictable year-to-year weather conditions. Finally, following our theoretical model, we focus on the aggregate of two renewable sources: solar and wind energies. They have in common to be 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 collected this data from the U.S. Energy Information Administration (2014). It has the double advantage of having state level data on both renewable capacities and the price of gas. The information was obtained from EIA-860 form. To consider both the increasing number of units producing electricity and the increase in productivity observed throughout the years, we multiplied the number of generators installed by its nameplate capacity (i.e. maximum rated output of a generator which is expressed in megawatts).

3.2.2 Independent Variables

In relationship with our theoretical framework, our focus is on the price of gas, which is the unit price of the main input in the production of electricity. Other dependent variables are classified under three categories (socioeconomic, electricity market and policy/tax factors) play the role of control variables. This is a stark contrast with the literature which has mainly concentrated its attention on the impact of tax and policy tools on investments in renewable energies, using, among other things, price variables as control variables. Even though governments cannot directly influence this price, which is the result of market forces, several political decisions can have an important, indirect, impact on the price of gas at the equilibrium: signing of a trade agreement or tense diplomatic relationship with a gas trade partner, tax on gas, discovery of new important natural resources, introduction of legislation allowing the use of new extraction techniques, etc.

1. Price of gas

Our *price of gas* data has been collected from EIA (2013). It is (the log of) the average price paid (in nominal dollars per million Btu) by the electric power sector for natural gas (including supplemental gaseous fuel) for each states and years observed. It includes the cost of natural gas as well as insurance, freight and tax

expenses. In order to study the relationship between the input price of natural gas and the investments in renewable energies, 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 the investment was decided and the installations could start functioning, we include up to four-year lags. These lags can be explained by red tapes or by construction timing and delays. Due to multicollinearity between these price variables, we focus on our most representative results where a lag of one year is observed.⁷ Our results carry on further but standard errors are impacted, leading to lower significance levels.

Even though this was not the main focus of their work, previous studies have found diverging results while analyzing this relationship. Some (see a.o. Marques et al. (2010)), have found a positive relationship, meaning that these two modes of productions are substitutable. Others like Marques and Fuinhas (2011) or Shrimali and Kniefel (2011) have observed a negative link which means that the two are complements. We show that, below (resp. above) a threshold price, they tend to be substitutes (resp. complements). Hence, we expect the linear coefficient to be positive and the quadratic one to be negative, i.e. an inverted-U curve.

2. Socioeconomic factors

The first two socioeconomic factors, *population* and *GDP per capita*, were respectively obtained from the U.S. Census Bureau (2014) and the U.S. Bureau of Economic Analysis (2014). *Population* is the (log of) number of inhabitants and *GDP per capita* is the (log of) per capita gross domestic product in nominal value. Both coefficients are expected to be positive. The first because it is a proxy for the total demand for renewable energies. The second because emission reductions, engendered by renewable energies, are a normal good.

Using electoral data, the other two socioeconomic variables are proxies for the taste of inhabitants. *Democratic governor* is a dummy variable which takes the value 1 when the state governor is from the democratic party. *League indicator* is an index based on the scorecard produced by the League of Conservative Voters (2014) which lists the greenness of the votes in the house and senate on environmental issues. It is a categorical/ordinal variable between 0 and 3 where the last category holds for the most environmental friendly states and 0 for the least. Both these variables should have a positive impact on investments on renewable capacities.

⁷Due to the quadratic terms and the lags, up to ten gas price variables were simultaneously considered.

3. 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 panel farms. These are the only variables which are fixed over the years in our data. We take the logs of each of them. Larger states are expected to host more additional capacities. *Wind availability* is the wind generation potential for each state at 80 meters with capacity factors of at least 30% measured in GWh/year, as provided by the National Renewable Energy Laboratory (2011). *Sun availability* is the solar radiation for flat-plate collectors facing south at a fixed tilt (kWh/m²/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 and is a measure of the incremental demand for electricity. *Price of electricity* is the (log) of the price of electricity sold by state producers of electricity. Being a good proxy of the returns derived from the capacity investment, the coefficient of this variable is expected to be positive. *Production share renewable energies* and *production share nuclear energy* stand, respectively, for the market share of electricity produced using intermittent and renewable sources and using nuclear sources. Due to agglomeration effects in the production of renewable energies, the former is expected to be positive. On the other hand, the latter is expected to be negative, as a higher share of the electricity produced with nuclear energy makes it less interesting for renewable investments, as it is complicated to easily switch from one source of production to the other. All these informations were obtained from the U.S. Energy Information Administration (2014) database.

Experience with ISO/RTO is the cumulative number of years of experience that, or at least a share of, a state has been active in a Regional Transmission organization/Independent System Operator. These institutions aim at easing the transmission of electricity over interstate areas. Computed from the Federal Energy Regulatory Commission (2014), this variable is a proxy of the grid quality and how easy it is possible to switch from one to the other source of electricity production to the other. Due to the intermittent nature of our renewable energies, more experience in such an organization is expected to lead to more investments in capacities.

4. Policy and tax factors

While these factors are the ones of concern in the literature studying the determi-

nants of investments in renewable energies, they play the role of control variables in our setting. To facilitate the readability 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). On the one hand, *policy* is the number of regulatory and policy tools (from public benefit funds, renewable portfolio standard, netmetering system, interconnected standard, required green power option and feed in tariff) implemented to promote investments in renewable in each year for each of the states. On the other hand, *tax* is the number of financial incentives available (from personal, corporate, sales and property tax cuts). We expect that these two categorical variables should 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 exposed in Table 1. Each of the three regressions looks at the determinants of additional renewable capacities. They differ on two dimensions: whether or not the square of price of gas and yearly dummies are considered. Regression (1) has none of the two. Regression (2) estimates the parameter of the square of *price of gas* whiteout year effects. Regression (3) considers both the square of *price of gas* and yearly fixed effects in its specification. In order to present these results, we proceed in two steps. First, we focus the estimated parameters for the *price of gas* parameters. Then, we analyze the estimates for our control variables.

In regression (1), where only a linear term is used for *price of gas*, we obtain a negative coefficient sign which has no significant impact on our dependent variable. Hence, based on this result, we cannot conclude that gas and renewable energies are complements or substitutes in our dataset. In the next two regressions, we have that the linear and quadratic estimates for *price of gas* are significant and have rather similar levels. In regression (2), the former is significant at a 1% level and the latter at a 5% level. In regression (3), considering year dummies, significance levels drop respectively to 5% and 10%. Hence, year effects slightly negatively influence the strength of this result. These results give support for the idea that the relationship between the *price of gas* and *additional renewable capacities* is non-linear. The linear coefficient estimates is positive

Table 1
Additional renewable capacities as continuous variable
(Tobit model)

Variables	(1)	(2)	(3)
Price of gas	−0.558 (0.604)	7.963** (3.317)	8.747** (4.457)
Price of gas (squared)		−2.650*** (1.012)	−2.490* (1.375)
Population	1.003 (0.623)	0.965 (0.612)	1.388** (0.573)
GDP per capita	7.192*** (2.189)	6.188*** (2.208)	2.427 (2.614)
Democratic governor	−0.164 (0.437)	−0.074 (0.438)	0.080 (0.419)
League indicator	0.016 (0.261)	0.109 (0.262)	0.349 (0.273)
State size	1.313* (0.760)	1.392* (0.750)	0.657 (0.730)
Wind availability	0.857*** (0.222)	0.827*** (0.218)	0.981*** (0.204)
Sun availability	5.978 (4.244)	5.336 (4.178)	1.927 (3.946)
Growth in electricity sales	−10.335* (5.402)	−12.732** (5.439)	0.927 (5.974)
Price of electricity	4.410** (2.002)	4.200** (1.993)	1.150 (1.812)
Production share renewable energies	−0.099 (7.702)	0.338 (7.652)	−10.659 (7.381)
Production share nuclear energy	−7.086** (3.406)	−6.894** (3.361)	−5.452* (3.097)
Experience with ISO/RTO	0.333*** (0.078)	0.335*** (0.078)	0.173** (0.080)
Policy	0.656*** (0.214)	0.607*** (0.213)	0.178 (0.210)
Tax	0.929*** (0.271)	0.900*** (0.277)	0.382 (0.267)
Constant	−86.013*** (13.271)	−87.483*** (13.116)	−66.600*** (14.651)
Year effects	no	no	yes
Log likelihood	−963.208	−959.671	−924.030
Pseudo R^2	0.408	0.409	0.421

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

(Log of) additional renewable capacities as a dependent variable (445 left censored observations)

Standard errors are in parenthesis

significant at 10% ** , significant at 5% and * significant at 1%*

while the quadratic one is negative. Hence, we have an inverted-U relationship between the two variables. This means that, for relatively low gas prices, a marginal increase in price tends to increase the capacity investments in the renewable energy production. In this case, they can be seen as substitutes. After this price threshold, the reverse holds and they are complements, as a marginal increase in gas prices tends to decrease investments in the renewable mode of producing electricity. The price threshold is defined by the maximum of our inverted-U curve. In regression (2), it is at 1.5 and at 1.75 in regression (3), slightly to the left and to the right of the mean of *price of gas*. Note that according to the likelihood ratio test performed, the last specification, with year effects, is the most preferred one.

The coefficient estimates for socioeconomic control variables tend to be similar for our three specifications and to be as expected. We see that more populated states have higher levels of investment in new capacities. Although this is only significant in the case with year fixed effects. The coefficient estimates for *GDP per capita* are also positive but tend to become insignificant as soon as year fixed effects are considered. Both our taste proxies (*democratic governor* and *league indicator*) have no significant impact on additional renewable capacities.

Wind availability is the first parameter related with the electricity market. We see that all three estimates are positive and significant at a 1% threshold. This is in contrast with the estimates for *sun availability* which are positive but not significant. This can be explained by the fact that investments in solar energy tend to be very small compared to the ones in wind energy in our sample. In regression (1) and (2), we have that a higher *growth in electricity sales* leads to lower investments in renewable capacities. One explanation for this results is that states with high increase in demand for electricity prefer to invest in non-intermittent modes of production to supply the market and ensure that it is fully covered. However, this effect becomes insignificant in regression (3) as, due to the relatively high within variation in this parameter gets absorbed by the year dummies. As it increases the benefits of investments in renewable capacities, the sign of *price of electricity* is, in line with our expectations, positive. Although, the effect becomes insignificant with year dummies. While *production share renewable energies* is not significant in any of our cases, *production share nuclear energy* is always significant and has, as expected from our discussion in the previous subsection, a negative sign. Finally, we see that the experience accumulated with an ISO and a RTO is important in explaining the rise in renewable capacities.

Both our policy and tax factors have a positive impact on our dependent variable. How-

ever, this impact becomes insignificant as soon as yearly effects are considered.

In conclusion, these results tend to confirm our theoretical prediction. While, for relatively low prices of gas, renewable energies and gas are substitutable inputs, they are complementary for large prices of gas. Our theoretical explanation is that for larger price of gas, the cost related with the unpredictable intermittency of renewable energies cannot compensate its main economic benefit of using a freely available input.

3.4 Robustness analysis

We have used other specifications to test the robustness of these results, the regressions of which are exposed in Table 2. We proceed in three steps. First, we consider several other model specifications, keeping the same endogenous variable as before. Second, we assume different endogenous variables than *additional renewable capacities* as a continuous variable. Finally, we discuss the issue of endogeneity. These robustness analysis tend to confirm, and further strenghten, our main results. As there are few changes in the parameter estimates of our control variables, we focus on our variables of concern.⁸

Many other model specifications have been assumed, keeping our original dependent variable. We only focus on the most important. First, in our main results, we have considered for each state a random component to consider how state specificities might impact our independent variable. With tobit panel data, it is not possible to consider state specific fixed effects. However, it is possible to compute unconditional state fixed effect although estimates are biased and inconsistent. Results are shown in regression (4). On the one hand, we see that the parameter estimate for *price of gas* is positive and significant at the 10% level. On the other hand, we have that, for our quadratic term, the estimate is significant at the 5% level and is negative. This is in lign with our main results.

In regression (5), we use another price variable than the one for natural gas. There, we use the average petroleum price (EIA (2013)). Looking at cases with both a linear and a quadratic term and with only 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 a one percent increase in the average petroleum price leads to a 1.6% increase in investment in renewable capacities. Hence, we have that, considering the

⁸Note however, that the strenght of our results are, in some of these robustness checks, impacted when year dummies are part of the specification. Hence, part of these additional results are influenced by yearly changes in the level of our variables.

Table 2
Robustness analysis

Variables	(4)	(5)	(6)	(7)
Price of gas	5.415* (3.163)		2.175* (1.144)	12.844** (5.566)
Price of gas (squared)	-1.983** (0.962)		-0.771** (0.358)	-3.779** (1.705)
Average petroleum price		1.571*** 0.421		
Population	28.854*** (7.062)	1.370** (0.564)	0.219 (0.147)	0.554 (0.962)
GDP per capita	0.167* (2.711)	3.752* (2.122)	1.345* (0.705)	9.029** (3.715)
Democratic governor	-0.043 (0.428)	-0.171 (0.431)	-0.060 (0.170)	2.132*** (0.766)
League indicator	-0.104 (0.268)	-0.085 (0.252)	0.023 (0.104)	0.696 (0.465)
State size		1.152* (0.689)	0.284 (0.194)	2.308* (1.190)
Wind availability		0.842*** (0.2)	0.142*** (0.054)	1.450*** (0.348)
Sun availability		3.205 (3.765)	0.728 (1.024)	6.377 (6.604)
Growth in electricity sales	-9.295* (5.241)	-4.209 (5.381)	-4.485** (2.027)	-19.415** (9.828)
Price of electricity	5.764** (2.296)	3.301* (1.879)	0.421 (0.607)	6.780** (3.27)
Production share renewable energies	-12.382* (7.289)	-0.293 (7.551)	35.622*** (11.588)	-7.832 (13.796)
Production share nuclear energy	-0.975 (5.248)	-6.835** (0.859)	-1.418* (9, 303)	-6.206 (3.077)
Experience with ISO/RTO	0.485*** (0.085)	0.298*** (0.078)	0.078** (0.036)	0.427*** (0.137)
Policy	0.327 (0.215)	0.640*** (0.209)	0.179** (0.085)	0.461 (0.379)
Tax	0.924*** (0.309)	0.828*** (0.271)	0.210** (0.099)	0.977** (0.478)
Constant	-1248.580*** (277.578)	-74.097*** (11.800)	-17.627*** (3.860)	-121.928*** (21.060)
State fixed effect	yes	no	no	no
Log likelihood	-870.638	-956.809	-268.604	-1279.88
Pseudo R^2	0.434	0.408	0.452	0.381

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

Standard errors are in parenthesis

(Log of) additional renewable capacities (445 left censored observations) for regressions (4) and (5), Dummy of additional renewable capacities (0/1) for regression (6) and (log of) additional renewable generations (408 left censored observations) for regression (7)

** significant at 10%, ** significant at 5% and *** significant at 1%*

average input price of electricity, that it is a substitute for renewable energies.

In addition to this, we have also considered various ways to specify *policy* and *tax*. We have used individually each of the items composing it, looked at experience rather than presence of a policy or tax. Our main conclusions are not influenced by these changes. As done in regressions (6) and (7), we have also checked how our results are changing with respect to different independent variables. First, using the same data, we have changed *additional renewable capacities* into a dummy variable where one means that some investments were made. This case was treated as 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 gas* have the expected signs and are both significant (only at the 10% level for the linear term). Note that estimates represent the marginal effects at means. 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.

In regression (7), we look at the determinants of additional electricity production from renewable sources instead of additional capacity investments, also using data from the U.S. Energy Information Administration (2014). We find very similar results, as the linear term for *price of gas* is positive while the quadratic one is negative and the maximum of the quadratic approximation is at 1.7. They are both significant at the 5% level. Hence, this means that our results carry on further to the additional production of renewable energies.

Note as well that similar results prevail if we only consider wind as a renewable mode of production. However, only considering solar energy leads to results which are not significant. This can be explained by its negligible presence in the total production of electricity.

One last important issue to discuss is endogeneity. In our context, the main potential source of endogeneity is reverse causality. As argued by Wisser and Bolinger (2007), investments in renewable energies can impact the gas market as it shifts its demand. On the one hand, it could reduce on the overall demand for natural gas, leading to a downward pressure on prices. On the other hand, due to the unpredictable intermittency of renewable energies, the demand for natural gas can be concentrated in times when there is no wind nor sun. These temporary shifts can lead to a higher price dispersion. Hence, the overall impact on the price of natural gas is indeterminate.

There are several reasons 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 total investments in renewable capacities. The impact on the price of natural gas is much more limited due to the relatively small level of marginal investments compared with the total accumulated investments. Second, our main specification considers a one year lag between *price of gas* and *additional renewable investments*. It is unlikely that the formation of price expectations in the gas market is impacted, one year ahead, by investments that produce electricity only by then, especially knowing the important cost of natural gas storage. Finally, using a two stage approach, we have empirically tested the presence of endogeneity. As lagged *price of gas* variables were correlated with our independent variable of concern but uncorrelated with our dependent variable, we used them as instrumental variables. Performing the Durbin-Wu-Hausman test, we find that the hypothesis according to which *price of gas* suffers from endogeneity is rejected.

4 Conclusion

This paper sheds some new theoretical and empirical lights on the relationship between renewable and non-renewable intermittent modes of producing electricity. We study the degree of substitutability and complementarity between these two sources of energy. Our main finding is that this relationship is not linear. This is at least true for sun/wind power energies which, due to the unpredictable intermittency from these renewable natural resources, can be complementary to natural gas, as it can very effectively supply the market on demand. Using U.S. data at the state level, we find that an increase in the price of natural gas can lead to a decrease in the investments into intermittent renewable capacities.

Our theoretical model gives an explanation behind the bell-shaped relationship between the price of gas and capacity investments in renewable energies. It highlights the trade-off between the relative input price advantage of wind/sun power energies and the uncertainty related to the unpredictable intermittency of these energies which must be compensated in the blink of an eye by natural gas.

These results suggest several policy considerations. Our conclusions support a comprehensive energy supply policy approach. Investments in renewable and non-renewable modes of electricity production should be thought jointly due to the various interconnections between the two. It is of utter importance for the renewable sector to keep

an eye on the gas market. Direct (such as taxes or subsidies) or more indirect policies targeted to the gas market can impact them significantly. New free trade agreements or tense political relationships with major gas exporting countries as well as authorizations to search and exploit natural gas resources can have an ambiguous effect on the investments in the renewable sector. Intermittent renewable and non-renewable energies can be both friends and foes. It depends on the initial price level of gas. Defining more precisely the price threshold separating these two scenarios is outside the scope of this paper. We hope that our work will lead to further empirical research on this issue. This could be particularly interesting to do this with a more comprehensive database.

Another interesting question concerns how this relationship will evolve through time. Is there scope for a higher degree of complementarity between these two modes of producing electricity? Further investments in the electricity grid and technological advances will most likely improve the interconnections between the various production units, state and country wide. However, this might be counterbalanced by the evolution of technologies related with the storage of electricity or the imperfectly predictable nature of renewable energy sources. It will be interesting to further analyze how these two forces will evolve.

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Appendix

Contingent decisions. Ex post, if $x = 1$ then profit will be $\Pi_1 = pQ - wq_1 - k$ with $q_1 \geq 0$ because renewable capacity installed k is used to serve the demand. If $f(k) \geq Q$, that is $k \geq \phi(Q)$, $q_1^* = \arg \max_{q_1} \Pi_1 = 0$. While if $k < \phi(Q)$, then $q_1 \geq Q - f(k)$ because capacity k is too short to serve the 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 $q_0^* = \arg \max_{q_0 \geq Q} \Pi_0 = Q$.

Statistic tables

Table 3
Summary statistics

Variable	Mean	Standard Deviation	Min	Max
Additional renewable capacities (log)	2.648	3.709	0	13.045
Price of gas (log)	1.585	0.421	0.392	2.469
Population (log)	15.136	1.007	13.104	17.454
GDP per capita (log)	3.666	0.230	3.069	4.283
Democratic governor	0.443	0.497	0	1
League indicator	1.802	1.313	0	4
State size (log)	11.731	1.092	8.295	14.357
Wind availability (log)	10.456	3.744	0	15.692
Sun availability (log)	1.431	0.137	0.875	1.740
Growth in electricity sales	0.013	0.035	-0.215	0.187
Price of electricity (log)	2.055	0.307	1.361	2.896
Production share renewable energies	0.011	0.028	0	0.248
Production share nuclear energy	0.177	0.182	0	0.808
Experience with ISO/RTO	3.796	4.492	0	14
Policy	1.822	1.632	0	6
Tax	1.199	1.200	0	4