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

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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 relevant. While moving forward with investments in wind and solar power projects, it is important to consider the relationship between renewable energy and non-renewable energy sources such as natural gas. 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 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 renewables do not produce.

Other have analyzed the complex relationship between natural gas and intermittent renewable energy. However, the economic literature on the interplay between natural gas and renewable energy is relatively new. The theoretical literature has largely focused on the technological assumption that fossil fuels and renewables can substitute one for another. Most theoretical analysis explain 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 (2014) and Aflaki and Netessine (2017). 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 the substitutability between renewables and fossil fuels have been identified in the literature. For example, Bouckaert and De Borger (2014) 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 (2015) have studied the optimal energy mix when renewables are used and find that capacities installed for the purpose of balancing intermittent sources can be lowered when environmental damages (or carbon taxes) go over a certain level. This can be interpreted as a complementary relationship between intermittent sources and fossil fuels when the impacts of different public policies that aim to decarbonate electricity production are considered.

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, the energy sources have different risk profiles, so they may be complementary portfolio options. Lee *et al.* argue that natural gas price volatility would be balanced by stable (near zero) generating costs of renewable energy investments and, on the flip-side, 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), Hitaj (2013) and Polzin et al. (2015) , among others).[1] These papers mainly focus on the impact of various policy tools (such as feed-in tariffs or renewable portfolio standards) using aggregate data. 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 renewable (wind, solar, biomass and geothermal) capacity and the total net generation, i.e. complementarity. Using their own words, "The flexible natural gas based plants are used for overcoming the

[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.

intermittency issues inherent in renewable power generation — in particular wind, the dominant renewable source." Shrimali and Kniefel (2011, p.4737).

The aim of our analysis is to consider, both from an empirical and theoretical point of view, the extent of *gross substitutabilities or complementarities* between intermittent renewables sources and natural gas. For this purpose, we rather study the indirect price effect of a flexible input onto an investment decision than the technological relationship between inputs or the strategic link between supply decisions. We follow this approach because renewable energies are must-run technologies. Hence, the strategic decision happens at the investment rather than at the production stage.

In a first step, using U.S. state-level data from 1998 to 2015, collected from the U.S. Energy Information Administration, we look at the empirical link between the renewable energy and the natural gas market. We use a panel Tobit model to study the determinants of capacity investments in intermittent renewable energy. We focus mainly on renewable energy investment's relationship with the price of natural gas, using various socioeconomic, electricity market, policy and tax factors as control variables. Hence, we follow a macro approach in the sense that we use aggregate yearly data at the state level. In contrast with the literature, we allow for a non-monotonic relationship between our two main variables of concern. As confirmed by various empirical specifications, we find that this relationship is best represented by an inverted U-shape.

In a second step we develop a model that reproduces and explains what is at stake behind this empirical fact. Using a simple theoretical framework, 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).

Our analysis has some implications for policymakers. It suggests a need for more comprehensive policies in the energy sector. Our paper highlights how various policy changes could have a wide impact, as the markets composing the energy sector are intertwined in a more complex manner than originally thought. For example, the Trump administration has recently decided to ease drilling rights and investments in new pipeline projects to boost the U.S. production capacities (Goldberg (2017)). Other examples like increasing political tensions between Russia, the world's biggest exporter of natural gas, and European countries or the signing of bilateral free trade agreements between importing and exporting nations will not only have an influence on the natural gas market. These changes will also have an impact on investments in renewable energies, depending on the prevailing market conditions and, more specifically, the price of natural gas. Hence, caution is needed when anticipating the consequences of these changes.

2 Empirical evidence

We first study the empirical link between non-renewable and renewable electricity markets. More precisely, we focus on the relationship between investments in renewable energy sources and the input price of a non-renewable technology, in our case, natural gas. Figure 1 shows the relationship between the natural gas price and renewable capacity investments for 49 U.S. states between 1998-2015, as well as a quadratic fit (only considering strictly positive investments). The graphic suggests that a non-linear relationship is more plausible than a linear one. In what follows, we show that this suggestive evidence is robust to various empirical approaches.

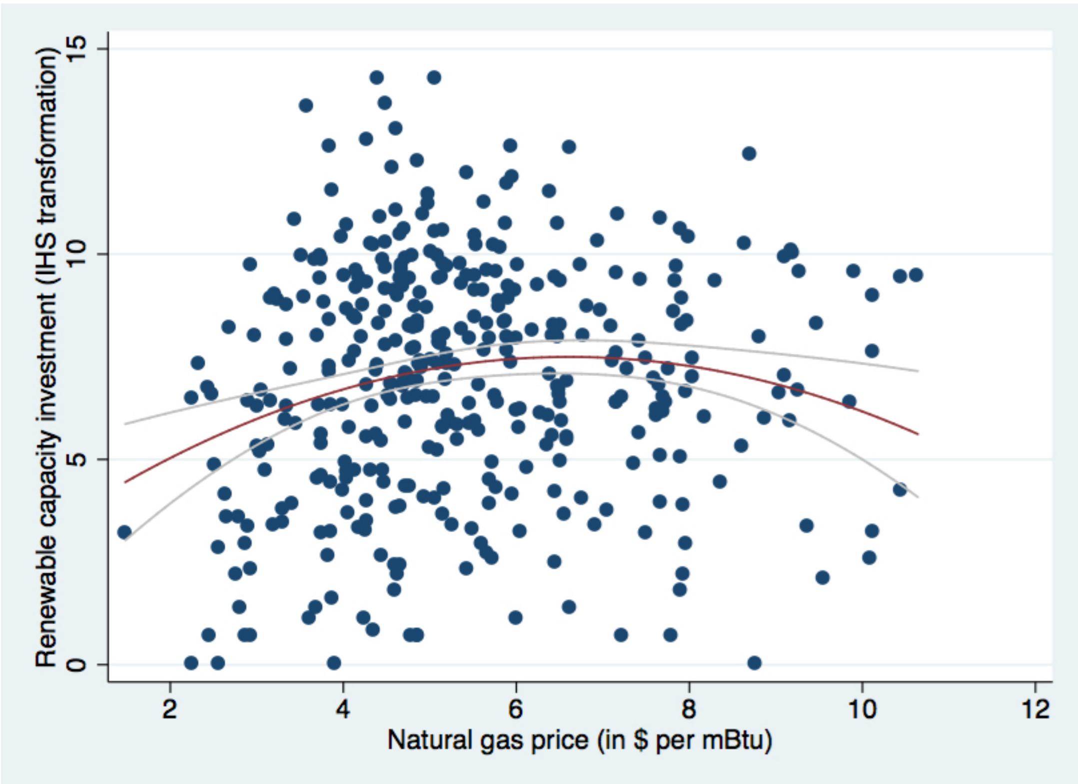

Figure 1
Scatterplot of renewable capacity investments (inverse hyperbolic sine transformation) and average natural gas price for all U.S. states between 1998 and 2015 and a quadratic fit (with confidence intervals of 95%)

2.1 Data

2.1.1 Dependent variables

Our analysis focuses on capacity investments, as opposed to accumulated investments, market share or generation to better highlight the outcome of our investment decision, net of previous years and independently from unpredictable weather conditions. Finally, in line with our theoretical model, we focus on investments in two sources: solar and wind. They are both non-flexible intermittent and renewable sources of production that don't create negative externalities through their capacity installments, the production of electricity or the supply of inputs. We use state-level data rather than data at the level of power pools. The main reason is that power pools are a rather new phenomena and are not present in many states. Hence, state-level data allows us to consider a bigger and more representative set of observations. More control variables are also available at the state level which is a coherent entity with respect to the energy policies implemented.

Our data comes from U.S. Energy Information Administration (2017) where state-level data on both renewable capacity investments and natural gas prices is available (via 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 our dependent variable is heavily right-skewed and has a non-normal kurtosis, we apply the inverted hyperbolic sine transformation to deal with this problem, as in Rodriguez et al. (2015).[2]

2.1.2 Independent variables

Our explanatory variable is 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 under three categories: socioeconomic, electricity market and policy/tax factors. This is a stark contrast with Marques et al. (2010), Shrimali and Kniefel (2011) and others who use an aggregate approach like us, but focused mainly on the impact of tax and policy tools using, among other things, prices as control variables. We will also consider a more general specification than them by allowing non-linearities.

[2] Our results hold if, as done in our robustness analysis and advised in Cameron and Trivedi (2010), we add a small constant before taking the log of our dependent variable.

1. Price of natural gas

   As we need to restrict the analysis to publicly available data, we do not have access to the estimated future prices of natural gas as used in the business plans assessing these renewable energy projects. Instead we use data from EIA (2016). *Natural gas price* 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. We consider both a linear and a quadratic term. As there might be time lags between the time the investment is decided and the production facility is operational, we include up to four-year lags. The economic explanation comes from the red tapes, construction timing and delays related to the investments. Due to multicollinearity between these price variables, we focus on the specification assuming a one-year lag.[3] Hence, by considering prices lagged by one year, we assume that investors use, at the time of the investment decision, the current natural gas price as an estimation of its expected future price.[4]

2. Electricity market factors

   The first three factors (*state size*, *wind potential* and *sun potential*) all measure the feasibility of installing wind and solar farms. These are variables that are held constant across years. One would expect larger states to host more investments. *Wind potential* 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 potential* 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)).

   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.

[3] Our results hold further using no lag or two lags but standard errors are sometimes impacted, leading to lower significance levels.

[4] Note that, as our results hold in the case where we use contemporaneous data, this means that the investor's price expectations are fulfilled, at least at the time it is possible to reap the fruits of the investment decided in $t-1$.

Production % renew. energy, *production % nuclear energy* and *production % natural gas* represent, respectively, the market share of electricity produced using intermittent and renewable sources, nuclear sources and natural gas. Data for these variables comes from the U.S. Energy Information Administration (2017) database. Due to agglomeration effects in the production of renewable energies, the sign of *Production % renew. energy* is expected to be positive. However, this could be counteracted by an increasing difficulty in integrating this intermittent energy source in the policy mix. 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. Conversely, *production % natural gas* is expected to have a positive sign as it technically complements renewable energy sources providing services in smoothing the intermittency of renewable energy availability. However this does not necessarily suggest greater overall natural gas generation. This allow us to control for the increasing importance of the natural gas, due to the shale gas boom, in the energy input mix.

Experience with ISO/RTO is the cumulative number of years that a state (or a part of it) has been active in a Regional Transmission Organization/Independent System Operator. These institutions facilitate the transmission of electricity between states. Computed from Federal Energy Regulatory Commission (2017), 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 intermittency, more experience in such an organization is expected to lead to more investments.[5]

3. Socioeconomic factors

The first two socioeconomic factors, *population* and *GDP per capita*, are obtained from U.S. Census Bureau (2017) and U.S. Bureau of Economic Analysis (2017), 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 are a normal good.[6]

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

[5] The quality of our results is independent from the way we measure the role of the ISO/RTO (using a dummy variable or including a square term instead).

[6] Of course these are also proxies for the overall energy demand.

state governor is a Democrat. *LofCV indicator* is an index based on the scorecard produced by League of Conservative Voters (2017), 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 4, where the most environmental friendly states are awarded a 4 and the least environmentally friendly are awarded a 0. Both these variables are expected to have a positive sign.

4. Policy and tax factors

   As it is not the core focus of our paper, we use two aggregate variables based on DSIRE (2017). *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 renewable 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 sign. Note that our results remain unchanged if we use a less parsimonious approach where separate dummies for each policies separately.

The summary statistics of our variables can be found in Table 3 and 4 of the Appendix.

2.2 Methodology

From our 877 observations, 494 observations have an investment equal to zero, i.e. there were no capacity investment during these years/states.[7]

Linear panel data models result in biased and inconsistent estimates, as they are not able to account for the 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 zeros are seen as actual outcomes and are generated by the same mechanisms as our positive outcomes. It was used previously by Delmas and Montes-Santo (2011), Hitaj (2013) or Rodriguez et al. (2015) in the literature on the determinants of renewable investments. Other approaches to treat these zeros are derived and discussed later on in the paper.

[7]From our original sample, we exclude five observations that are missing the price of natural gas or recent data on nuclear energy production. Despite this, we analyze our data as a balanced panel.

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. $\mathcal{N}(0, \sigma^2_e)$ and the random effects α_i are i.i.d $\mathcal{N}(0, \sigma^2_a)$. 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:

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

Due to the incidental parameter problem raised by Neyman and Scott (1948), we control for unobserved heterogeneity using a random heterogeneity-specific component for each state, instead of the fixed effects model. 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.

2.3 Main results

Our main empirical results are provided in Table 1. Each of the three regressions looks at the determinants of renewable capacity investments. The first column displays our base model without year fixed-effects. The linear and quadratic term related with *natural gas price* are significant respectively at the 1% and 5% threshold. The first is positive and the second is negative. This supports our suggestive evidence that the relationship between *natural gas price* and *renewable capacity investments* is non-linear. Precisely, we have an inverted U-shaped relationship between the two variables. This means that for relatively low prices, a marginal increase in price tends to increase investments in renewable energy. Above this price threshold, 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 discussed in the previous subsection. *Wind potential* and *sun potential* are both positive, but only the former is significant. 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 significant. Previous investments in renewable energies call for more investments but this coefficient is not significant. On the contrary, when nuclear energies have a prominent place in the production of electricity, less investments are taking place. This relationship is significant and is due to the lack of flexibility of nuclear energies. Depending more on natural gas has a positive but not significant impact on investments. Having *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 investments. For the socioeconomic covariates, we observe that a higher *GDP per capita* leads to more investments but this is not significant. *Population*, *Democrat governor* and *LofCV indicator* have all an impact on our dependent variable which is not significant. *Policy* and tax factors are both positive and significant.

Regression (2) includes in addition years 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. For example, it can capture the influence of the U.S. shale gas boom on renewables and some of the effects created by technological changes in the sector. 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 hold. *Natural gas price* and *natural gas price (squared)* are respectively positive and negative at the 5% level. With their respective values, the maximum of the inverted U-curve is at around 5.87$ per million Btu, while the mean value is 5.186$.[8] Note that this also impacts the size of some of our coefficients. This is due to the within variance of the variables which is now captured by these time dummies.

[8]Remark that this is very close to the maximum of the quadratic fit of our data pictured in Figure 1 which does not consider any control variables.

Table 1

Renewable capacity investments as a continuous variable : Panel data Tobit model

	(1)	(2)	(3)
Natural gas price	2.099***	2.302**	-0.137
	(0.611)	(0.098)	(0.255)
Natural gas price (squared)	-0.174**	-0.196**	
	(0.049)	(0.076)	
Wind potential	0.112*	0.117**	0.122**
	(0.06)	(0.059)	(0.061)
Sun potential	1.024	-0.322	-293
	(2.09)	(1.943)	(1.99)
State size	0.004	0.004	0.003
	(0.017)	(0.015)	(0.015)
Growth in electricity sales	-16.9***	-4.38	-2.624
	(6.01)	(7.48)	(7.297)
Electricity price	0.219	-0.137	-0.125
	(0.314)	(0.326)	(0.325)
Production % renew. Energy	-15.226**	-21.397**	-21.931**
	(7.5)	(8.85)	(8.94)
Production % nuclear energy	-15.23	-21.4	-21.931
	(7.502)	(8.851)	(8.939)
Production % natural gas	4.618	1.69	1.86
	(4.954)	(4.255)	(4.479)
Experience with ISO/RTO	0.353***	0.202	0.187
	(0.114)	(0.127)	(0.129)
GDP per capita	0.034	-0.044	-0.034
	(0.046)	(0.059)	(0.059)
Population	0.182	0.231	0.228
	(0.217)	(0.164)	(0.167)
Democrat governor	-0.246	-0.17	-0.185
	(0.701)	(0.673)	(0.682)
LofCV indicator	0.531	0.79*	0.782*
	(0.37)	(0.405)	(0.408)
Policy	1.02***	0.271	0.268
	(0.332)	(0.324)	(0.31)
Tax	1.193***	0.451	0.407
	(0.422)	(0.419)	(0.427)
Constant	-22.456***	-13.803*	-9.038
	(8.067)	(8.396)	(8.213)
Year fixed effects	No	Yes	Yes
Log likelihood	-1374.88	-1327.1411	-1332.205

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

Sample: 877 observations - 49 states - period 1998-2015 (including 494 left-censored observations)

Compared with specification (2), specification (3) only allows a linear relationship between *natural gas price* and *additional renewable capacity*. This linear term has a negative sign, though close to zero, meaning that an increase in price leads to less investments. However, this is not significant, i.e. we cannot claim that these two sources of energy are complementary. Hence, our data is better estimated using both a linear and a quadratic term.[9]

Overall our results all go in the same direction. While, for relatively low natural gas price, renewable energy and natural gas are substitutable inputs, they are complementary for high natural gas prices.

2.4 Robustness analysis

We examine the robustness of our results using alternative specifications, the regressions of which are shown in Table 2. Regression (2) 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. Note however that, due to the various approaches used, it is complicated to compare directly the parameter estimates of our control variables, although they tend to be similar across specifications.[10] Eventual changes can be explained by the use of state/year 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 conditional fixed effects because there are no statistic that allow the fixed effects to be conditioned out of the likelihood (Stata (2009)). However, it is possible to compute unconditional state fixed effects, although these estimates are biased and inconsistent. In addition time-invariant variables drop out. Results are shown in regression (4). We see that this does not influence our parameter estimates and that both are significant at the 1% level.

In regression (5) and (6), we examine the robustness of our results with respect

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

[10]Remark that the price threshold, 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	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Renewable Energy	Capacity Tobit	Capacity Probit	Product. Tobit	Capacity Tobit	Capacity FE	Capacity Spline	Cap. Tob. Wind
Natural gas price	2.13***	0.57**	2.28**		1.28***		2.29**
	(0.78)	(0.24)	(1.02)		(0.47)		(1.14)
Natural gas price (squared)	-0.18***	-0.05***	-0.17**		-0.12***		-0.19**
	(0.06)	(0.02)	(0.08)		(0.04)		(0.09)
Average petroleum price				0.16**			
				(0.08)			
Natural gas price spline 1						0.46**	
						(0.22)	
Natural gas price spline 2						-1.34***	
						(0.48)	
Wind potential		0.02***	0.18*	0.12**		0.11*	0.12**
		(0.004)	(0.11)	(0.06)		(0.06)	(0.05)
Sun potential		0.23**	0.66	-0.42		1.06	-1.34
		(0.12)	(3.65)	(1.94)		(2.12)	(1.93)
State size		0.001***	0.006	0.003		0.004	0.005
		(0.00)	(0.03)	(0.02)		(0.02)	(0.01)
Growth in electricity sales	-2.23	-1.46	-13.45	-2.1	-1.02	-17.01***	-6.81
	(6.87)	(1.86)	(8.82)	(7.35)	(3.58)	(5.96)	8.76
Electricity price	0.16	-0.11***	0.84**	-0.11	-0.15	0.25	-0.05
	(0.27)	(0.04)	(0.4)	(0.33)	(0.2)	(0.31)	0.37
Production % renew. energy	-21.11***	0.91	-9.46	-24.22***	3.72	-15.34**	-3.61
	(6.47)	(1.71)	(12.93)	(9.13)	(5.82)	(7.51)	(9.38)
Production % nuclear energy	0.35	-1.11***	-1.05	-7.2	4.02	-7.08	-12.36**
	(8.77)	(0.42)	(10.06)	(4.65)	(5.78)	(5.74)	(5.38)
Production % natural gas	10.39***	-0.86**	9.75	1.2	0.84	4.91	-8.31**
	(3.63)	(0.37)	(7.9)	(4.29)	(2.64)	(5.02)	(3.93)
Experience with ISO/RTO	0.2**	0.02	0.44**	0.22*	0.16*	0.35***	0.34
	(0.09)	(0.02)	(0.2)	(0.13)	(0.08)	(0.11)	(0.15)
GDP per capita	-0.08	0.02**	0.01	-0.04	-0.01	0.04	0.03
	(0.05)	(0.01)	(0.07)	(0.06)	(0.05)	(0.05)	(0.07)
Population	0.21	0.06***	0.05	0.28*	0.85**	0.18	0.21
	(0.38)	(0.01)	(0.42)	(0.16)	(0.36)	(0.22)	(0.16)
Democrat governor	-0.25	-0.02	1.5	-0.18	-0.09	-0.25	0.13
	(0.45)	(0.11)	(1.05)	(0.71)	(0.37)	(0.71)	(0.77)
LofCV indicator	0.66**	0.37***	0.71	0.71	0.3	0.51	0.54
	(0.32)	(0.07)	(0.64)	(0.4)	(0.23)	(0.37)	(0.39)
Policy	0.08	0.1**	0.91	0.29	0.31	1.04***	0.33
	(0.25)	(0.05)	(0.59)	(0.31)	(0.21)	(0.33)	(0.34)
Tax	0.25	0.1**	1.29	0.41	0.31	1.13***	0.75
	(0.34)	(0.05)	(0.72)	(0.42)	(0.27)	(0.43)	(0.35)
Constant	-24.57	-4.59	-28.59	-9.39	-8.61**	-19.61**	-10.91
	(2267.38)	(0.87)	(14.43)	(7.81)	(3.41)	(8.23)	(8.71)
Year fixed effects	Yes	Yes	No	Yes	Yes	No	Yes
State fixed effects	Yes	No	No	No	Yes	No	No
Log likelihood	-1231.07	-279.57	-1680.13	-980.63	/	-1376.81	-1139.42

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

Sample: 877 observations - 49 states - period 1998-2015

(4), (7) and(9) Renewable capacity investment as a dependent variable (494 left-censored observations)

(5) Renewable capacity investment dummy as a dependent variable

(6) Renewable energy production (433 left-censored observations)

(8) Renewable capacity investment ($log(a + y)$ with $a = 0.3$ as a dependent variable and heteroskedasticity-consistent standard errors.

(10) Wind capacity investment (566 left-censored observations)

to different dependent 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: a panel Probit model with random effects. We see from regression (5), 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. 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 (6), we look at the determinants of changes in electricity production from renewable sources instead of renewable capacity investments, also using data from U.S. Energy Information Administration (2017). 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 because renewable energy has a low variable cost.

In regression (7), we use the average petroleum price (EIA (2016)) 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 an increase in investments. This means that renewable and petroleum energy sources are substitutes. FollowingLee et al. (2012), this can be explained by the lack of flexibility of petroleum in circumventing the intermittency problem created by renewable energy sources.

In regression (8), we treat differently the problem created by the high number of zero observations by performing a least square dummy variable regression. Before this, we have added a constant ($a = 0.3$) before taking the log of all our dependent variables. It is independent from the constant chosen, although if the constant is too large it decreases within sample variation. Again, in this case, time-invariant variables drop out and our main findings remain valid. Further, we have also excluded from our sample states without any positive observation for our dependent variables. Our main results hold.[11] Hence our conclusions are both observed from inter- and/or intra-regional variations in our observations.

In regression (9), we use a semi-parametric model using a spline approach. We split the *natural gas price* range into different intervals, at knots, and make a linear regression between these knots. Assuming different numbers of knots, we retain the

[11] Results are available upon request.

specification with two intervals, as suggested by Akaike Information criterion. On the one hand, we find that, for the 50% smallest price observations, the best linear approximation has a positive sign. On the other hand, we find that, for the 50% largest price observations, the best linear approximation has a negative sign. Both are significant at the 10% and 1% thresholds. Applying this piecewise linear model confirms that the relationship between our two variables of concern is non-linear.

In regression (10), we focus only on renewable investments in the wind sector. We obtain similar results with a positive sign for the linear term and a negative sign for the quadratic term. They are both significant in the case of investments in wind energy while they are not significant for investments in solar energy, with and without a quadratic term.[12] The main reason for this difference is that the development of solar energy is quite limited in our sample, around 4% of all investments in renewable capacities. In addition, only 149 of our 877 observations have a strictly positive value. Another potential interpretation is related to the characteristics of these primary energy sources. Wind tends to blow at night, during off-peak hours, while sun shines during daytime at peak hours. In some sense this is related to capacity constraint which is more likely to be binding during the day for solar energy than for wind energy. As a result solar energy has a higher shadow cost than wind.

One final important issue to discuss is endogeneity. 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. In addition, in our sample, on average, only one percent of the electricity production comes from renewable sources. Second, our main specification considers a one-year lag between the price of natural gas and renewable capacity investments. It is unlikely that prices 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 dispatch behavior) and that we use yearly data undermines the scope for reverse causality. 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. 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

[12]Results available upon request.

problem that makes it impossible to use a dam or a nuclear power plant). Note however that many of these unobserved factors are captured by our year/state fixed effects.

3 A theoretical explanation

This section provides a model developed to shed some light on our empirical findings (see Tables 1 & 2) that investment in renewables and natural gas electricity generation are positively related for a high variable cost of natural gas. In this model, we aim to reconcile the two contrasting views of the relationship between natural gas and renewable energy sources that can be rival as well as complementary technologies.

We model the basic tradeoff a state-level representative energy company (hereafter referred as the firm) faces when it 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. One may think that our stylized energy firm is an investor-owned utility or a fully private firm that aims to optimize its energy portfolio by considering investment in renewable capacities.

The underlying trade-off can be seen through the contrasting effects the natural gas price may produce on the investment of capacity in renewable. To that purpose, we say that natural gas and renewable energy are substitutable energy sources when the natural gas price positively affects capacity in renewable energy. In contrast, they are 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 incorporating uncertainty with respect to input prices or investment factors (see for instance Blair (1974) and Abel and Eberly (1994)).

The main features of our framework are twofold: First, uncertainty affects the maximal level of output achievable using a given technology (in this case, renewable power production). 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).

Let $k \geq 0$ be the renewable capacity investment in electricity from the intermittent sources (in terms of capital cost).[13] We assume that this investment is norma-

[13] We assume that (a very large amount of) gas turbines have been already installed and that

lized to represent an additional capacity that generates $f(k)$ kWh, where $f(k)$ is a twice differentiable, positive, increasing and concave (but not necessarily strictly) 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 intermittency factor by $x \in [0, 1]$, such that $\text{Prob}(x = \xi) = \pi(\xi)$ where $\pi(x)$ is a continuous density function. In case of windy or sunny weather, i.e favorable conditions, the intermittency factor is close to one but it can be zero for cloudy, gloomy or lull weather conditions. The function $\pi(x)$ describes the expected weather conditions based on meteorological inference. 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[14], and is denoted by w, while $q(x)$ denotes the short-term supply of power from natural gas-fired power plants (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 market or social value of this electricity delivered is assumed to be given by $V(Q) = v$.

For a representative state-level firm[15], the problem is to choose $q(x)$ *ex-post* and k *ex-ante* such that its expected valuation of the operating profit from the intermittent activity for the firm, denoted $\Pi = \int_0^1 \pi(x)U(v - wq(x) - k)\,dx$ is maximized, where U is a twice differentiable function, strictly increasing and strictly concave.[16]

Due to intermittency, the renewable source of energy is not always available, then the short-term supply of natural gas $q(x)$ is necessarily not lower than $Q - xf(k)$,

these costs are sunk. This assumption allows us to better disentangle the problems arising from the emergence of intermittent renewable energy sources.

[14]It might be argued that the short run risk associated with weather conditions may be overwhelmed by the long term risk associated with the natural gas price. We do not ignore that a trend of the literature suggests a relationship between the uncertainty in natural gas prices and the return to renewable investments, mainly for hedging purposes (e.g. Berry (2005), Bolinger et al. (2006) or Graves and Litvinova (2009)). However in order to concentrate on the effects of natural gas price anticipated levels and to avoid an increasing level of complexity in the model, we voluntarily do not consider volatility as an explanatory factor for renewable investments.

[15]Other interpretations are also possible. For instance it might be that the firm is a fringe competitor that has committed to deliver Q units. The fringe competitor is non-strategic, takes the natural gas price as given, considers investing in intermittently available capacity. Then the natural gas price could then be interpreted as the spot price if intermittent energy sources are not available. However considering strategic markets with multiple firms, such as some that specialize entirely in renewable power, while others have only fossil-fueled power plants have been studied by Bouckaert and De Borger (2014) and do not support complementarities.

[16]This utility function represents the difference of evaluation in profit for all states of nature. For instance it can mimic the increasing cost of a black-out that could arises in case of an energy shortage.

whenever it is nonnegative. Considering that the natural gas has a higher supply cost in each state of nature x and considering the covered market condition, the supply of natural gas obeys to $q\,(x) = \max\{0, Q - xf(k)\}$. Thus, the firm's problem can be reduced to the *ex-ante* choice of k that maximizes:

$$\max_{k} \int_0^1 \pi(x)U\left(v - w\max\{0, Q - xf(k)\} - k\right)dx.$$

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, that is when demand is sufficiently high, namely when $k^* < \phi(Q)$.[17] The first-order condition for an interior solution becomes:

(1)
$$\int_0^1 \pi(x)\left(wxf'(k^*) - 1\right)U'\left(A_x\right)dx = 0$$

where $A_x = v - wQ + wxf(k^*) - k^*$. Denoting that $\mathbb{E}\left(U'\right) = \int_0^1 \pi(x)U'\left(A_x\right)dx > 0$ and $\mathbb{E}\left(xU'\right) = \int_0^1 x\pi(x)U'\left(A_x\right)dx$, one can rewrite (1) in a more interpretable way

(2)
$$wf'(k^*)\mathbb{E}\left(xU'\right) = \mathbb{E}\left(U'\right)$$

This condition has the following interpretation. Whenever it is optimal for the firm to invest in additional renewable capacities, it balances the expected marginal utility of the opportunity net reward for *not* having to buy costly natural gas on the spot market (i.e. $wf'(k^*)\mathbb{E}\left(xU'\right)$) and the expected marginal utility of one monetary unit spent in capacity (i.e. $\mathbb{E}\left(U'\right)$). Hence whenever it is strictly positive[18], k^* solves the equation $f'(k^*) = \mathbb{E}\left(U'\right)/(w\mathbb{E}\left(xU'\right))$.

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 partial supply risk it creates.

[17]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. This is the situation that may arise for solar energy sources that are more likely to meet the demand during the day then wind sources. This is consistent with the empirical result we find in page 16.

[18]As a result $k^* = 0$ is optimal if $w < \underline{w} = 1/[f'(0)\mathbb{E}\left(x\right)]$.

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

$$\frac{f'(k^*)}{f(k^*)} \leq \frac{\partial}{\partial w}\left(\frac{\mathbb{E}\left(xU'\right)}{\mathbb{E}\left(U'\right)}\right). \tag{3}$$

If it is not, they are substitutes.

The Result illustrates that depending on the strength of aversion to intermittency, the degree of intermittency and the level of natural gas price, renewable capacity investments can be decreasing as the natural gas price is increasing. This occurs when 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. (3). The left-side of the inequality can be viewed as the *degree of flexibility* the energy firm faces. Indeed it is the marginal rate of decrease in renewable production due to the investment k when the natural gas price rises ($f'(k)/f(k)$). Hence when the solar or wind capacity investment diminishes, the left hand side of Eq. (3) describes the ability with which the firm can balance profit losses in case of sunshine or wind by gains in the contrary case. The right-side of the inequality can be viewed as the *degree of intermittency aversion* the firm exhibits. Indeed it represents the variation with respect to the natural gas price of the expected marginal rate of substitution between profits in all states of nature (i.e. $\mathbb{E}\left(xU'\right)/\mathbb{E}\left(U'\right)$). That is, the rise in profits needed to compensate the monetary loss due to a lower renewable capacity investment when sun shines or wind blows.

One can now argue that whenever the degree of flexibility is *weaker* than the degree of intermittency 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 sources can be viewed as complementary.

The condition represented in Eq. (3) of our Result may be easily seen *not* to hold when intermittency is not an issue.[19]. In this context, the firm 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 natural gas price increases, so is the marginal investment in renewables. Indeed, when there is no

[19]For example, there could be technological advances that make it possible to store wind or solar energy of the electricity it produces. Indeed in this case $\pi\left(x\right)$ becomes a degenerated distribution such that $\pi\left(1\right) = 1$ and $\pi\left(x\right) = 0$ for $x \neq 1$.

more uncertainty about the state of nature in the short-term, the expected marginal rate of substitution between profits vanishes to 1 and necessarily an increase in the natural gas price will not change it, the degree of intermittency aversion equals zero. Energy factors are then substitutes as in the standard version of the firm's choice of inputs.

Moreover this substitutability setup also arises in two others contexts. First, it holds when the firm exhibits a constant substitution between profits in all states of nature, that is it has a purely monetary-based decision criteria as $\mathbb{E}\left(xU'\right) = \mathbb{E}\left(x\right)$. Second, energy factors are also substitutes when the natural gas price is very low. Indeed, we have seen above that if $w < \underline{w} = 1/[f'(0)\mathbb{E}\left(x\right)]$ then $k^* = 0$. As a result, for values of the natural gas price in the right neighborhood the threshold $\underline{w}$, we have $f'(k^*)/f(k^*) \to \infty$ and condition (3) does not hold. On the contrary, the complementarity condition (3) holds possibly when intermittency impacts strongly the generation activity, when the firm holder evaluates differently profits earned in different states of nature and when natural gas prices are high.

In our general framework, it is not possible to provide conditions about this price threshold without considering a given class of the function U. We give one example for which the inequality given in our Result holds. Let us consider a constant relative risk aversion utility function, with $U\left(z\right) = z^{\theta}$ where $\theta \in [0,1]$ is the relative risk aversion parameter and the linear production function is $f\left(k\right) = ak$, where $a > 0$. Moreover we assume a uniform distribution for x, i.e. equiprobable intermittency, so that $\pi(x) = 1, \forall x \in [0,1]$. When $\theta = 1/2$, we can see that

$$k(w) = \begin{cases} 0 & \text{if} \quad w < \frac{2}{a} \text{ or } w > \frac{v}{Q} \\ \min\{Q, \hat{k}(w)\} & \qquad \text{otherwise} \end{cases}$$

where

$$\hat{k}(w) = 3\,\frac{(wa-2)\,(v-wQ)}{3+(wa-3)wa}.$$

On can see that there is a unique maximum for $\hat{k}(w)$ that is $\bar{w} = \frac{2av-3Q+\sqrt{\Delta}}{(av-Q)a}$ with $\Delta = (va)^2 - 3avQ + 3Q^2$. Hence, $\hat{k}(w)$ is increasing if $w < \bar{w}$ and is decreasing otherwise, as depicted in Figure 2.

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 reminiscent of the ones we had in the previous empirical section and notably when figure 2 is compared with figure 1.

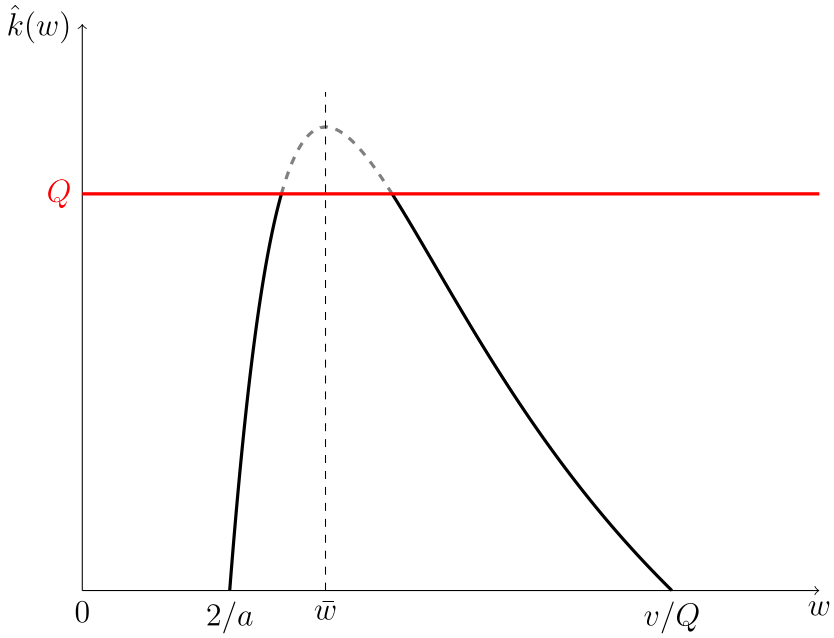

Figure 2
Renewable capacity investment (k) as a function of the price of natural gas (w)
The black line denotes capacity. The red line denotes the electricity demand.

4 Conclusion and policy implications

This paper provides new insights into the relationship between renewable methods of producing electricity (focusing on wind and solar power), and dispatchable non-renewable methods. We study the degree of substitutability and complementarity between these two sources of energy. This relationship is not linear. Using aggregate investment data, we find that, for relatively high prices only, an increase in the price of natural gas can lead to a decrease in renewable investments. The reverse holds for relatively low prices. Our theoretical explanation unveils a potential story behind this non-monotonic relationship. It highlights the trade-off between the relative degree of flexibility of renewable energy with respect to natural gas and the degree of intermittency aversion a representative state company exhibits when the renewable energy source must be replaced in the blink of an eye when there are shortfalls. We argue that this second force increases proportionally with the price of natural gas, giving scope for complementarities.

Our results suggest that a comprehensive approach to energy supply is more 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.

Some issues remain open. A first methodological issue is the high quantity of zero observations in our dependent variable. Another, complementary, estimation strategy would be to consider it with a self-selection approach a la Heckman. However, it is unclear which variable plays a role in the selection step and not in the intensity step.[20] Another related question concerns how the relationship between natural gas and renewable energy will evolve. What will be the impact of technological advances in the electricity grid impact? How will the ability to store electricity of renewable energy sources influence this? We leave these questions for future investigations.

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[20]Looking at developing countries, Pfeiffer and Mulder (2013) use the quality of institutions to identify this problem.

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Appendix

Summary statistics

Table 3
Summary statistics (1)

Variable	Units	Mean	Standard Deviation	Min	Max
Renewable capacity investment *(inverse hyperbolic sine transf.)*	Megawatts	3.329	4.24	0	14.962
Natural gas price	USD/MBtu	5.186	2.027	1.48	11.81
Wind potential*	TWh/year	11.915	22.133	0	94.918
Sun potential*	kWh/m^2 /day	4.222	0.558	2.4	5.7
State size*	Km^2	200.031	250.912	4.002	1717.854
Growth in electricity sales	%	0.011	0.034	−0.215	0.187
Electricity price	cents/Kwh	8.547	2.815	3.89	18.06
Production % renew. energy	%	0.019	0.042	0	0.315
Production % nuclear energy	%	0.177	0.182	0	0.808
Production % natural gas	%	0.203	0.221	0	0.989
Experience with ISO/RTO	Years	3.795	5.405	0	17
GDP per capita	K USD	43.283	11.229	21.788	87.523
Population	Millions	6.096	6.628	0.491	38.994
Democrat governor	Dummy	0.431	0.495	0	1
LofCV indicator	Index variable	1.748	1.329	0	4
Policy	Number of	2.053	1.708	0	6
Tax	Number of	1.351	1.238	0	4

Variables marked with (*) are time invariant

Table 4
Summary statistics (2): Correlation matrix

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
(1) Renewable capacity investment	1.000																
(2) Natural gas price	0.118	1.000															
(3) Wind potential	0.312	−0.038	1.000														
(4) Sun potential	0.05	0.031	0.182	1.000													
(5) State size	0.141	−0.159	0.238	−0.241	1.000												
(6) Growth in electricity sales	−0.106	−0.279	0.071	0.083	0.045	1.000											
(7) Electricity price	0.189	0.224	−0.19	−0.225	0.101	−0.222	1.000										
(8) Production % renew. Energy	0.48	0.014	0.307	0.015	0.069	−0.026	0.055	1.000									
(9) Production % nuclear energy	−0.127	0.062	−0.197	−0.072	−0.289	−0.064	0.297	−0.224	1.000								
(10) Production % natural gas	0.079	−0.003	−0.086	0.071	0.227	−0.07	0.541	−0.08	−0.186	1.000							
(11) Experience with ISO/RTO	0.411	0.243	0.086	−0.217	−0.138	−0.172	0.521	0.378	0.084	0.096	1.000						
(12) GDP per capita	0.389	0.234	−0.023	−0.268	0.202	−0.108	0.605	0.356	0.01	0.274	0.482	1.000					
(13) Population	0.301	0.026	0.035	0.13	0.101	−0.041	0.228	−0.02	0.158	0.218	0.148	0.122	1.000				
(14) Democrat governor	0.044	0.131	−0.094	−0.151	−0.125	−0.056	0.044	0.041	0.05	−0.12	0.65	0.106	−0.019	1.000			
(15) LofCV indicator	0.076	0.2	−0.317	−0.244	−0.324	−0.114	0.48	−0.104	0.251	0.226	0.289	0.204	0.118	0.207	1.000		
(16) Policy	0.433	0.217	−0.078	−0.185	−0.135	−0.185	0.531	0.287	0.125	0.179	0.607	0.553	0.161	0.213	0.448	1.000	
(17) Tax	0.377	0.143	0.121	0.136	−0.061	−0.075	0.347	0.232	0.093	0.125	0.328	0.306	0.146	0.026	0.165	0.378	1.000

Proof of Result. 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:

$$\frac{\partial^2 \Pi}{\partial k \partial w} = \int_0^1 U'(A_x)\,\pi(x)\left[x f'(k) + (w x f'(k) - 1)(Q - x f(k))\, r(A_x)\right] dx$$

Defining $r(\Pi) = -U''(\Pi)/U'(\Pi) > 0$, the Arrow-Pratt measure of aversion to intermittency, one can rewrite as:

$$\frac{\partial^2 \Pi}{\partial k \partial w} = f'(k)\left\{\mathbb{E}(xU') + f(k) w B\right\} - f(k) C$$

where expressions B and C write:

$$\begin{aligned} B &= \int_0^1 x\pi(x)\left(\frac{Q}{f(k)} - x\right) U'(A_x)\, r(A_x)\, dx > 0, \\ C &= \int_0^1 \pi(x)\left(\frac{Q}{f(k)} - x\right) U'(A_x)\, r(A_x)\, dx > 0. \end{aligned}$$

Hence one can see that $\frac{\partial^2 \Pi}{\partial k \partial w} \leq 0$ if $\frac{f'(k)}{f(k)}\mathbb{E}(xU') + f'(k) w B \leq C$. Then Π exhibits decreasing differences evaluated at the (interior) optimum if

$$\frac{f'(k^*)}{f(k^*)}\frac{\mathbb{E}(xU')}{\mathbb{E}(U')} \leq \frac{C}{\mathbb{E}(U')} - \frac{B}{\mathbb{E}(xU')}.$$

Rigourously, concavity of Π in k is needed at this stage, to allow the substitution of the first order condition (2). Fortunately, this is the case due to the concavity of U and f.

Moreover, it is not too difficult to verify that:

$$\frac{C}{\mathbb{E}\left(U'\right)}-\frac{B}{\mathbb{E}\left(xU'\right)}=\frac{\partial}{\partial w}\left(\frac{\mathbb{E}\left(xU'\right)}{\mathbb{E}\left(U'\right)}\right)\frac{\mathbb{E}\left(xU'\right)}{\mathbb{E}\left(U'\right)}.$$

As a result:

$$\frac{f'(k^*)}{f(k^*)}\leq\frac{\partial}{\partial w}\left(\frac{\mathbb{E}\left(xU'\right)}{\mathbb{E}\left(U'\right)}\right).$$

If this condition is true, the Π exhibits decreasing differences (evaluated at the interior optimum) so $k^*(w)$ is increasing in w. If the reserve condition is true then $k^*(w)$ is decreasing. ■