

Article

The Price of Wind: An Empirical Analysis of the Relationship between Wind Energy and Electricity Price across the Residential, Commercial, and Industrial Sectors

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Abstract: This paper quantifies the long-term impact of wind energy development on electricity prices across the residential, commercial, and industrial sectors in the United States. Our data set is made up of state level panel data from 2000 through 2018. This time period covers the vast majority of total wind energy capacity installed in the history of the USA. Our econometric model accounts for the primary factors that influence electricity prices, incorporating both fixed effects and general method of moments in order to more precisely isolate the effect of wind energy. The empirical results conclude that wind energy is positively and significantly related to electricity prices across all sectors, as indicated by the higher average electricity prices in states with higher percentages of wind energy. The price increase is largest in the industrial sector, followed by commercial, then residential. Wind turbine technology has become significantly more efficient, but the technical gains have been offset by the increased indirect costs of incorporating wind energy into the grid. Transmission and balancing costs have increased the final price to consumers. Our results highlight the need to view wind energy development from a more holistic perspective that accounts for structural and systemic costs. This will ensure the continued growth of wind energy. These results provide relevant insight to help wind energy developers, policy makers, and utility companies build a more sustainable energy future.

Keywords: wind; energy; economics; electricity; price; residential; commercial; industrial



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1. Introduction

Wind energy development has expanded rapidly this century [1–3]. The total installed capacity has increased from 18 GW in the year 2000, to 733 GW in the year 2021 [4]. This growth has followed the international green energy transition to slow CO₂ emissions and combat climate change. In the US wind energy has benefitted from government incentives, the Federal Production Tax Credit (PTC), and state level energy regulatory policies called Renewable Portfolio Standards (RPS). These factors, along with the increasing efficiency of wind turbines, have led to an increase of wind energy production in the US from less than 1% of total energy production in 2000, to over 8% in 2020 [5].

1.1. Background

CO₂ mitigation is a significant driver of wind energy development [6]. Transitioning energy productions from fossil fuels toward green electricity sources is a major method of CO₂ reduction. Legislators in many nations have devoted support to new sources of energy in an attempt to mitigate the negative impact of greenhouse gases and CO₂ [7]. Despite these advances in green energy, coal is still the leading source of energy in many developed nations [8,9]. Traditional fossil fuel generating electricity plants are the number one source of greenhouse gases (GHG) in a significant number of developed countries [10] and can account for up to 40% of CO₂ emissions [11]. Wind farm development has been growing steadily each year this century [1,2]. Before the new millennium, wind energy in the US was virtually insignificant as a large-scale energy source. In 2000, total wind

power generation was only 5.6 TWh, and currently in the year 2020, the figure has reached 272.7 TWh [12]. These statistics represent less than 0.2% and over 8% of the total electricity production in the US. This represents an increase of 4875% in under 20 years, as seen in Figure 1, which displays the wind energy totals from our analysis period.

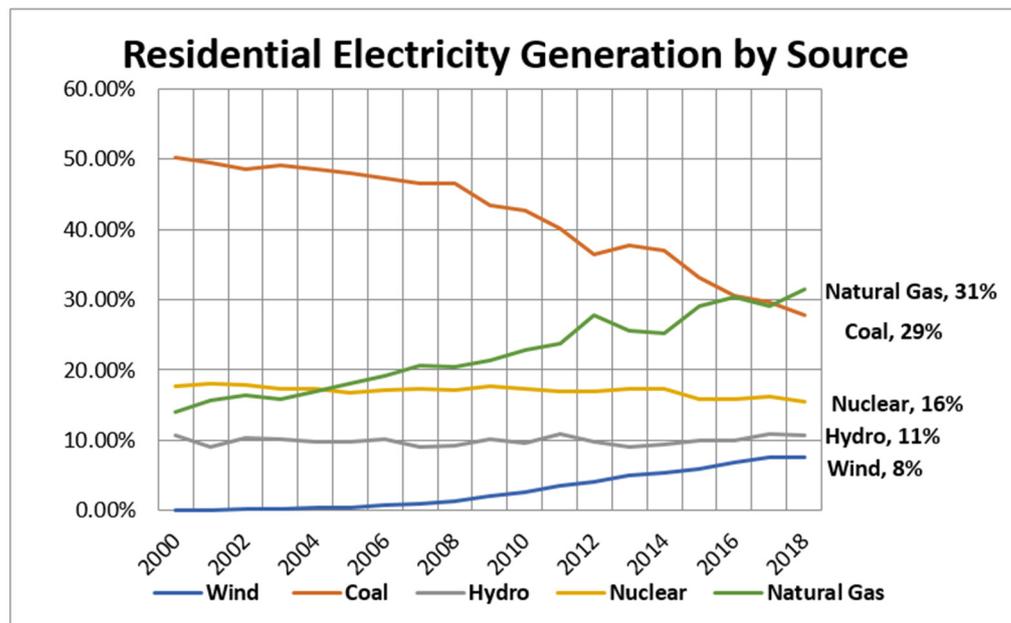


Figure 1. Electricity production by source. Source: US Energy Information Administration [12].

1.1.1. Increasing Economic Efficiency

The Levelized Cost of Energy (LCOE) for wind power has steadily decreased over the past decade [13], see Equation (1). In 2000 the LCOE for wind energy was significantly higher than competing energy sources, but now the difference is negligible. This has helped wind energy become more competitive with fossil fuels from an economic perspective. LCOE has a significant impact on final electricity price to consumers.

Equation (1) Equation for the levelized cost of energy:

$$LCOE = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^n \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \tag{1}$$

- I_t : Investment expenditures in year t
 - M_t : Operational expenditures in year t
 - E_t : Electricity generated in year t
 - r : Discount rate
 - n : Expected lifetime of a wind turbine
- Source: [14].

As wind energy has expanded, turbine technology has advanced as well. The rising height of wind turbines has led to increased economic efficiency and decreased levelized cost of energy. This is because the wind resource supply improves significantly with higher hub heights [15]. Over recent decades, wind turbine size has been essential to wind power cost reduction [16].

1.1.2. Transmission and Volatility

At the same time that wind turbines have become more efficient based upon technological gains, there have also been significant factors working against the cost effectiveness of wind energy. Electricity transmission costs have increased drastically over the past

decade [17]. Wind farms are now being built in less optimal locations, and transmission distance has increased.

Intermittency is an inherent characteristic for the production of wind power [3,18–20]. This is because the speed of the wind is not always strong enough to create wind energy [21]. Intermittency leads to increased levels of volatility in the energy supply [22–25]. In times of high wind power production, the total energy supply in the system increases, which leads to lower short term spot prices [26,27]. Electricity production depends on wind speed, which is a variable that fluctuates significantly [28]. Balancing the supply and demand is an increasing challenge [29]. Baseline energy production facilities have to be constantly ramped up and down, which increases costs for the system as a whole. Many renewable energy facilities have fixed price contracts and are granted priority access to the grid.

1.1.3. Economic Implications

The price of electricity impacts nearly all facets of a nation's economy, from gross domestic product, all the way down to an individual household's standard of living [30,31]. Energy is an essential element in the production of nearly all goods and services, therefore energy prices have a ripple effect to the general level of prices for the country as a whole. Access to dependable and efficient sources of electricity drives economic output [32]. In the context of a rapidly growing global population, and the need to provide clean energy to minimize carbon emissions, policy makers must find pragmatic solutions to provide efficient sources of electricity for their citizens.

1.1.4. Energy Sectors

In 2019, the average national price of electricity in the US was 10.5 cents per kWh [12]. The price differs by type of consumer. The average price for 2019 was 13 cents per kWh for residential, 10.7 cents for commercial, and 6.8 cents for industrial. The difference in rates is based on the consumption characteristics of each sector [33]. The analysis finds that electricity price volatility increases while short-term electricity prices decrease with higher wind energy levels [27].

Residential electricity prices in the US vary significantly from state to state—from a high of 32.47 cents per kWh in Hawaii to a low of 9.59 cents per kWh in Louisiana in the year 2018 [12]. States are given a large amount of freedom to determine their energy development and regulatory structure [34]. Individual states have various attributes that contribute to determine retail electricity rates [35]. These reasons support our decision to analyze electricity price from a state level perspective.

Industrial energy consumers are able to purchase large amounts of energy and benefit from economies of scale [36]. This is one reason that their per unit energy costs are lower than the other two sectors in our analysis. In order to maintain manufacturing processes, factories require large amounts of stable energy supply. The increased volatility of energy prices because of wind energy could potentially affect industrial consumers in the form of higher prices.

Large commercial buildings can benefit from economies of scale that individual households cannot. This can help to explain why the average per unit cost of electricity is lower for commercial customers than residential. Commercial buildings could respond to increased pricing volatility by installing small scale renewable energy of their own and storing it in batteries for use during peak pricing periods [37]. Smart energy management systems are also a way that commercial buildings can adjust to fluctuations in electricity pricing. Smart energy management systems include motion sensor lights, automated thermostats, responsive HVAC systems, and other energy saving systems.

1.1.5. Electricity Market

Supply constantly has to be balanced with demand creating constant equilibrium price fluctuations. Wind energy increases the energy supply and enters the market at a near zero rate of marginal cost. It is subsidized at a much higher rate per MWh than fossil

fuel energy sources [38–40]. Wind energy is also given priority access in order to meet renewable energy requirements [41]. An increase in supply from a heavily subsidized energy source drives down prices during those times but increases the costs for fossil fuel plants that have to scale production up and down. The intermittent nature of wind turbines creates market volatility and short-term price decreases. The production cost of electricity varies minute to minute [42]. This is a result of a number of factors. Electrical rates can vary depending on the timing of energy consumption [43]. The price depends on the time of day and season, based upon peak demand and weather conditions. Afternoon and evenings are peak pricing periods because of peak daily usage trends. Summer is the most expensive season because of weather conditions [42]. The energy production levels of turbines are entirely dependent on wind conditions, which is influenced by seasonal weather conditions.

The structure of the electricity market is affected by multiple government regulations [44]. Government policy can influence the energy mix and the price of energy. The policies help to determine levels of renewable energy development within the state. The importance of government policy for energy development has been growing in recent years [45]. In the US the majority of renewable energy policies are made at the state level [34,46].

Electricity prices are impacted by regulations [44], and Renewable Portfolio Standards (RPS) policies are one of the most significant forms of electricity regulation implemented by state governments. These policies include a mix of taxes, subsidies for renewable energy, quotas, carbon penalties for coal plants, surcharges, feed-in tariffs, and other mechanisms. These standards consist of quotas and percentage requirements for renewable energy. For example, the RPS policy for Texas was created in 1999, and requires that 5880 MW be produced from renewables by 2015, and 10,000 MW by 2025 [47]. The RPS for California is a percentage model. It was established in 2002, and sets renewable energy requirements of 44% by 2024, 52% by 2027, and 60% by 2030 [47]. These regulations increase the share of renewable energy, but also increase the market inefficiency. The RPS variable controls for these factors. Surcharges and feed-in tariffs promote the expansion of renewable energy [48], and the costs of this expansion are passed onto consumers in their energy bills [44].

Another factor is market regulation. Regulations play a significant part in the state level energy market. In the US, the two designations are regulated and deregulated. Each state has either a regulated or deregulated electricity market. Deregulated markets are more open to competition than regulated markets but also lose some of the economies of scale associated with traditional vertically integrated state electricity markets [49].

1.1.6. Price Factors

There are a number of factors that work together to determine the price of electricity. Electricity travels through a complex network of generation, transmission, to distribution for the final customer [50]. According to the US Energy Information Administration, a few of the primary factors that explain the price of electricity are fuel costs, weather, and regulations [33]. Factors such as population, and energy policy can influence electricity use [51]. The cost of electricity generation is significantly affected by the source of energy. Coal, wind, hydro, and natural gas all have differing costs of energy generation based on the inherent characteristics of their source of energy supply. In the case of renewables, the primary production cost lies in the initial manufacturing and construction of the facilities to harness the energy sources [52]. Weather has a significant impact on the price of electricity [33]. Extreme temperatures can increase demand for electricity based for heating and cooling, and the increased demand can drive up prices.

The electricity generation process also determines the price of electricity. Fuel costs are a major factor in our model. For example, producing renewable energy can sometimes be more expensive up front than generating electric energy through traditional fossil fuels [30]. The type of energy source is also connected indirectly to the transmission costs.

Fossil fuel sources such as coal and natural gas are portable and can be moved to the production facilities, while renewables such as wind, solar, and hydro are constrained to the location where the energy resource is available to be harvested. In the case of wind this can translated into increased transmission costs. Power cables that transmit electricity over long distances factor into the cost of electricity [53].

The demand for electricity is affected by customers, level of income, and weather. Population determines the electricity customer base. This drives demand in a large part when partnered with income levels determined by the GDP. Higher population and income create a higher demand for electricity. Fluctuations in weather can influence demand. Higher temperatures lead to higher demand. Summer is the peak season for electricity consumption [33].

The supply side is determined by key factors such as energy source, and amount of renewable energy [54]. Fossil fuel costs fluctuate year to year, and the raw materials used to build renewable energy also experience price changes. The production of electricity from renewables involves high fixed costs and low marginal costs [52]. Wind energy has a near zero rate of marginal costs, but it is currently economically unfeasible to store large amounts of excess electricity.

Billions of dollars in federal subsidies go to the energy market annually. In 2017, the total tax-related support for the energy sector was \$ 17.8 billion [55]. Fossil fuels made up to 77.7% of total energy production, and received USD 4.6 billion (25.8%) of tax breaks. Renewable energy contributed 12.8% of energy production and received USD 11.6 billion (65.2%) [55]. The total amount of tax incentives going to renewables is much higher than fossil fuels, and the margin increases significantly on a per unit basis. The primary method of government support to the energy sector is targeted tax incentives [56]. Billions of dollars in tax breaks annually go to the energy market through these programs. Government funding and state level energy policy are the two of most significant factors in the US electricity market.

1.2. Existing Literature

Our research sets out to determine the impact of wind energy on electricity price by sector. The papers that have researched wind energy and electricity price have produced mixed results. Some of these papers have found that wind energy decreases prices [22,24,51,57], while others have come to the opposite conclusion [3,58,59]. These differing results are because the papers have addressed different aspects of the topic such as spot prices, day-ahead pricing, short term impact, and wholesale prices.

Multiple studies have reported a decrease in electricity as a result of increased wind energy levels. In a study of wholesale electricity prices in Germany, wind energy is found to reduce the price level but increase volatility [22]. A paper published in 2019 reported a decrease in the wholesale electricity price by 11 AUD/ MWh for each additional GW of dispatched wind capacity [51]. Research from the state of Texas that studied spot prices showed that wind energy decreases prices but increases the spot-price variance [24]. The results of research from 2019 discovered a statistically significant price decrease from wind energy generation on real-time hourly spot prices. This impact ranged from a decrease of 0.14 to 0.34 USD per mega-watt hour, for each additional 100 mega-watt hours of wind capacity [57].

In an analysis of global wind power, Timilsina, et al. [3], reported that the costs of wind energy are higher than electricity produced from fossil fuels. In another study out of Germany, researchers found that the policies promoting wind energy and other renewable energy sources increased the price of electricity significantly [58]. Germany has some of the highest levels of per capita wind energy production in the world, which is one reason why so many wind energy papers study Germany. A third paper on electricity prices in Germany reported a near doubling of consumer energy prices over a 15-year period which was partially attributed to the rapid deployment of wind farms in the country [60]. A

common theme among the research on wind energy and price is that wind energy increases price fluctuations.

Wind energy is a relatively new form of large-scale electricity. Because of this, there are gaps in the body of literature on the economic effects of wind energy [25]. To our knowledge our research is the first to address the question of long-term wind energy pricing impact by sector. Our research is also unique because of the length of the time period studied, and the state level data set gives a larger sample size by which to extrapolate more precise results. This analysis studies the effect of wind energy on average price per unit of electricity instead of LCOE in order to quantify the effect on end users. Much of the existing literature deals with wind energy issues that do not directly affect end consumers, such as energy trading markets. Most studies focus on the national level, but more studies are needed at the prefecture level [61]. Spot prices and wholesale prices do not always explain the final price to end users. Our original research provides significant new findings based on econometric analysis of current data.

1.3. Purpose

The purpose of this paper is to empirically measure the long-term impact of wind energy on the price of electricity for end users in the residential, commercial, and industrial sectors. Other researchers have proposed that the advancement of wind energy has had an impact on the price of electricity [62]. Given the mixed results of previous studies, more research is needed on this topic. Our paper approaches the issue differently in regard to the long-term pricing impact, state level focus, and sectoral breakdown. Our research goal is to determine whether this impact has been different across consumer categories.

The life span of a wind turbine is approximately 20 years [63]. Before the year 2000 there was virtually no significant large scale nationwide infrastructure of wind energy to study. We are now reaching the end of the life cycle of the original turbines and have achieved enough saturation, so that there is a sufficient time period available with adequate market saturation to fully analyze the pricing effect of wind energy.

The response to COVID-19 has accelerated the transition from fossil fuels to renewable energy sources [64]. This means that wind energy will be taking on an even greater role in global energy production. As the penetration of wind energy increases, we have to understand how this is impacting the financial sustainability of our energy production. Our research quantifies the impact over the past two decades. This approach facilitates a clear and intuitive presentation of the results in a way that is relevant to policy makers, businesses, industries, voters, and residents of communities who are affected by the price of electricity from wind farms. Policy makers must develop an energy strategy that minimizes environmental negative externalities while providing financially sustainable electricity to consumers.

Wind energy increases energy supply at a volatile rate, that leads to decreased spot prices [24]. This short-term pricing decrease may not hold true for longer periods of time. Our research adds a comprehensive perspective to the pricing discussion by measuring the impact of wind over the three primary energy sectors, and the total price across all sectors.

Based on the review of the scientific literature and economic principals we have constructed the following hypothesis:

Hypothesis 1. *We expect to find a positive relationship between wind energy and electricity price across all three sectors.*

Hypothesis 2. *We expect that the impact will be highest in the residential sector.*

The remainder of this paper will proceed as follows: Section 2, Materials and Methods; Section 3, Results; Section 4, Discussion; Section 5, Conclusion.

2. Materials and Methods

The complex structure of electricity markets necessitates comprehensive modeling techniques to help quantify market dynamics [65]. Our model incorporates the elements of the electricity market and variables that impact electricity price, as discussed in the previous section. This enables us to develop a comprehensive framework by which to quantify the impact of wind energy. The electricity market is not a perfectly competitive market. The basic laws of supply and demand are the foundation for determining price, but government intervention has to be accounted for. The model assumes that electricity price is a product of wind energy, fuel prices, socio-economic factors, energy subsidies, weather, government policy and regulations. This model structure is supported by statistics from the US Energy Information Administration and previous research [12]. The supply and demand curves are the primary components to determine electricity equilibrium price [54], but electricity prices are also significantly impacted by state and federal level government factors. The structure of our model accounts for the basic market forces of supply and demand, and government intervention.

The dependent variable for the model is the average price of electricity for each state. This statistic represents the average price of electricity per kilowatt-hour measured in cents, as reported by the US Department of Energy, Energy Information Agency. This price includes taxes and surcharges. The prices are broken down into four categories in order to more precisely define the impact of wind energy (*ResPrice*, *ComPrice*, *IndPrice*, *TotPrice*). The sectors are residential, commercial, industrial and total. Each sector is the average price to end users in that category and the total is the average price of electricity across all sectors.

The level of wind energy development (*Wind*) in the state is the primary independent variable in our research. This is measured in the percentage of total electricity in the state that comes from wind energy. Each state is significantly different based on size, population, and total energy consumption so the percentage statistic is a more precise measurement for wind energy development.

We include the number of electricity customers by sector (*ResCus*, *ComCus*, *IndCus*, *TotCus*) within the state to help determine the demand for electricity. For each regression we match the price of electricity in each sector with the equivalent number of customers within that sector for each state in our data set. For example, the price of electricity for the industrial sector would be matched with the number of industrial electricity customers within each state. The price of electricity fluctuates according to changes in demand [66].

Our model incorporates Gross Domestic Product (*GDP*) as a measure of economic activity for each state. *GDP* is commonly used by researchers when developing models that quantify questions involving renewable energy. Level of income is a key measure when determining demand. *GDP* can serve to measure monetary resources needed to purchase electricity. Economic activity impacts electricity prices [67]. Higher revenues should create higher demand. Disposable income is a significant factor to determine electricity consumption [68]. Demographics and *GDP* both impact electricity pricing [35].

Three variables are included to help measure government impact on the price of electricity. The first variable is Renewable Energy Portfolio Standards (*RPS*) policies. This variable controls for a number of state level effects such as energy taxes, state level subsidies, energy tariffs, and quotas. Many of these characteristics of *RPS* policies result in price changes for the end user [44]. A second policy variable that we include in this section is deregulation (*DeReg*). Market regulation helps to measure the utility market structure within each state. Each state has either a regulated or deregulated electricity market. Both *RPS* and *DeReg* are recorded as dummy variables in our data analysis. The third variable in this section accounts for government energy subsidies. The largest kind of government subsidies are tax credits (*TaxCred*). This variable controls for distortions in the price of electricity caused by government injection of outside monetary stimulus into the energy market.

To account for the impact of fluctuating fuel costs in the price of electricity, we use the cost of coal and natural gas (*Coal*, *NatGas*). These price changes are reflected in the

production costs of suppliers. The largest portion of the cost of electricity is due to the generation activities [69]. Natural gas and coal are the top two energy sources for electricity in the USA. Weather also plays a significant role in energy consumption. Our model controls for weather conditions by including a variable for temperature (*Temp*).

This theoretical overview enabled us to create a conceptual framework by which to construct our econometric model.

2.1. Empirical Methodology and Data

The goal of our research is to determine the long-term impact of wind energy development on the price of electricity across the residential, commercial and industrial price sectors. To measure this effect, we employ both fixed effects and system generalized method of moments models in our analysis. Our model assumes that the price of electricity in a state is a function of wind energy development, fuel prices, energy policy, government regulation, weather, and socio-economic factors. This section explains the econometric methods used to measure the impact of these variables on the electricity price. We utilize a large set of panel data. This allows our model to control for unobserved state and year heterogeneity [70]. These variables potentially have non-linear relationships based on the literature regarding hedonic regression models. To meet the linear assumptions of the model, variables were transformed to logarithmic form, except for binary variables and percentages, similar to models used in energy studies [71–73]. We estimate our model using a larger sample size than previous studies, which improves the accuracy of estimates and produces more reliable standard errors [46].

2.1.1. Fixed Effects Model

We chose to implement a fixed effects regression model for our initial set of regressions for a number of reasons. The ordinary least squares (OLS) model can produce inconsistent and biased parameters because of the omission of time-invariant covariates. Additionally, an OLS model that does not control for state-level time-invariant characteristics will produce biased standard errors if the errors are heteroskedastic in the group. In the case that omitted time-invariant variables are correlated with the policy variables, the fixed effects model will produce an unbiased estimate of the parameters and control for unobserved unit heterogeneity [46]. We conducted a Hausman test that rejected the random effects model, meaning that a fixed effect specification is more appropriate for our data set. A random effects model will not be consistently estimated if the effects are correlated with the independent variables [67]. By utilizing state and year fixed effects we control for differences between states and exogenous technological progress, producing accurate coefficient estimates [46]. The large section of the panel data helps us to control for any possible unobserved state and year heterogeneity. State-specific panel data allows us to control for unobserved characteristics that would not otherwise be modeled, and also track state level trends over time [46].

The equation below is estimated to determine the impacts of wind energy and other variables on electricity price.

$$\log Y_{i,t} = \alpha_i + \beta_2 W_{i,t} + \gamma \log S_{i,t} + \delta_1 \log F_{i,t} + \delta_2 P_{i,t} + \delta_3 \log T_{i,t} + \varepsilon_{it} \quad (2)$$

The dependent variable $Y_{i,t}$ is the price of electricity in state i in period t . The notations i and t represent states and years, respectively, where $i = 1, \dots, 49$, $t = 2000, \dots, 2018$. α_i parameters denote state effects that are included in the model measure any potential state-specific factors that could influence prices beyond the explanatory variables included. $Y_{i,t}$ stands for electricity price by sector (residential, commercial, industrial, and total). $W_{i,t}$ is the independent variable for wind energy, measured as the percentage of electricity being produced by wind energy in the state. $S_{i,t}$ represents socio-economic control variables. $R_{i,t}$ are the dummy variables for state regulation and government energy policy. $F_{i,t}$ stands for price of fuel, both coal and natural gas. $T_{i,t}$ is the log form of average temperature in the

state. β, γ, δ , are the parameters and vectors of parameters to be estimated in the equation. ε_{it} is the error term.

2.1.2. General Method of Moments Model

In this study, the second phase of empirical analysis was estimated using the system Generalized Method of Moments (GMM) estimator developed by Arellano and Bover and Blundell and Bond [74,75]. Our GMM model also assumes that the price of electricity in a state is a function of wind energy development, energy prices, energy policy, government regulation, weather, and socio-economic factors. These variables potentially have a non-linear relationship, so we created a log-linearized form of the empirical model.

We utilized a system GMM model for a number of reasons. Ordinary Least Squares (OLS) regressions produce biased and inconsistent estimates within dynamic panel data because of the omission of unobserved time invariant state effects [76]. The OLS levels coefficient estimate of the lagged dependent variable tends to be generally biased in an upward direction because the lagged dependent variable is correlated positively to the permanent effects of the dynamic panel regressions [77]. The system GMM estimator removes the bias of this method [78]. The GMM estimator deals with the problems of fixed effects and endogeneity of regressors, and removes dynamic panel bias from the model [79]. The problem of endogeneity of regressors is eliminated by instrumenting the lagged dependent variable and endogenous factors by incorporating variables that are not correlated with the fixed effects.

In dynamic panel model estimations, endogeneity issues often arise because time lagged variable, is correlated with error term. Arellano and Bond [74,80] created the system GMM estimator that produces internal instrument variables to eliminate endogeneity issues. GMM is an ideal method to study local governments [81]. The method is optimal when using lagged dependent variables [82,83] such as the dependent electricity price variables used in our research. GMM creates a statistical structure to deal with endogeneity by transforming the data internally [84]. GMM produces parameter estimates that are consistent in a model where the regressors are not entirely exogenous, controls for heteroscedasticity [85] and autocorrelation [86]. The system GMM estimator also creates consistent and efficient parameter estimates in the regression outputs when the regressors are not completely exogenous [78]. This means that they are correlated with current and past realizations of the error, where heteroscedasticity and autocorrelation exist [86]. Estimations using the system GMM estimator have increased levels of efficiency because they incorporate extra instruments through an additional assumption, where the first differences of instruments are not correlated with the fixed effects [86].

For the GMM model we specify a dynamic panel model using a lagged dependent variable. Consider the following equation:

$$\log Y_{i,t} = \alpha + \beta \log Y_{i,t-1} + \gamma W_{i,t} + \delta_1 \log S_{i,t} + \delta_2 \log F_{i,t} + \delta_3 \log T_{i,t} + u_i + e_{i,t} \quad (3)$$

where i , indicates the state ($i = 1, \dots, N$) and t represents the time period ($t = 1, \dots, T_i$).

The equation is the same as the initial equation for the fixed effects model but modified to fit the GMM model. $Y_{i,t}$ is the electricity price by sector. $Y_{i,t-1}$ represents the lagged dependent variable. $W_{i,t}$ represents the independent variable measuring wind energy, the percentage of electricity being produced by wind energy in the state. $S_{i,t}$ is the category with socio-economic control variables. $R_{i,t}$ are the dummy variables for state regulation and government energy policy. $F_{i,t}$ stands for price of coal and natural gas. $T_{i,t}$ is the log form of average temperature in the state. β, γ, δ , are the parameters and vectors of parameters to be estimated in the equation, u_i is unobserved time-invariant individual effects, and $e_{i,t}$ is the error term.

2.2. Data

Our model incorporates state level panel data from 49 states over the years 2000–2018. Hawaii is omitted because of lack of temperature data. We selected this time period for

multiple reasons. The 19-year date range encompasses the vast majority of total wind energy development in the history of the United States [87]. The drastic increase in wind energy in the United States began around the year 2000 [88]. The level of wind energy development in the US was relatively insignificant before the year 2000, so it is difficult to define any significant relationship between electricity price and wind energy before this time period. 2018 was the most current complete year available for some of our variables. We collected data from reputable agencies such as the National Conference of State Legislatures, US Department of Energy the US Department of Commerce, the U.S. Energy Information Administration, and others.

Electricity price is also a product of location. The prices of electricity are different based on state. For example, in 2019 the average price per kWh was 28.2 cents in Hawaii, but only 7.7 cents in Louisiana [12]. These statistics support our decision to use state level data in our analysis, as displayed in Table 1. Each state has a different energy consumer profile. Individual states have unique energy consumer profiles. Climate, regulations, transmission costs, number of consumers, GDP levels, and other factors are significantly different based on location.

Table 1. Data descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
ResPrice	950	1.07	0.12	0.84	1.59
ComPrice	950	1.00	0.12	0.75	1.56
IndPrice	950	0.86	0.15	0.60	1.51
TotPrice	950	0.99	0.13	0.74	1.55
Wind	950	0.03	0.06	0.00	0.37
ResCus	950	6.20	0.43	5.35	7.13
ComCus	950	5.36	0.40	4.58	6.26
IndCus	950	3.90	0.51	2.27	5.23
TotCus	950	6.26	0.42	5.44	7.19
GDP	950	11.28	0.45	10.37	12.45
RPS	950	0.47	0.50	0.00	1.00
DeReg	950	0.30	0.46	0.00	1.00
TaxCred	950	10.12	0.26	9.67	10.41
Temp	931	1.71	0.07	1.39	1.87
NatGas	950	1.03	0.07	0.89	1.14
Coal	950	1.54	0.12	1.33	1.67

2.3. Dependent Variables, Electricity Price

Residential Price—ResPrice, Commercial Price—ComPrice, Industrial Price—IndPrice, and Total Price—TotPrice

These variables represent the average electricity price for end users by state. All units are measured in cents per kWh, log form. Total price combines the residential, commercial, industrial, and transportation sectors to display an average total price for electricity in the state. The data comes from the US Energy Information Administration [12].

2.4. Independent Variables

Wind Energy—Wind

Wind energy is our primary independent variable. It is measured by the percentage of electricity for the state that is supplied by wind energy. For example, in 2018, 16% of the energy for the state of Texas was provided by wind energy. The wind energy data set was provided by the US Energy Information Administration [12].

2.5. Socio-Economic

2.5.1. Residential Electricity Customers—ResCus, Industrial Customers—IndCus, Commercial Customers—ComCus, Total Customers—TotCus

These variables measure the number of electricity customers by sector within each state. There are four categories for this variable to match with the four variables for

electricity price by sector. The variables serve to help determine electricity demand. This data was sourced from the US Energy Information Administration [12].

2.5.2. Gross Domestic Product—GDP

The GDP variable represents total Gross Domestic Product of the state in the given year, in log form. This data set was gathered from the Bureau of Economic Analysis in the US Department of Commerce [89].

2.6. Fuel Prices

2.6.1. Coal Price—Coal

Our model incorporates the two leading sources of energy generation in the US, natural gas and coal [15]. The coal price is measured in dollars per short ton. Data was collected from the US Energy Information Administration [12].

2.6.2. Natural Gas Price—NatGas

The natural gas price is measure in dollars per thousand cubic feet. Both variables are converted into log for our econometric models. Data was sourced from the US EIA [12].

2.7. Regulation and Policy

2.7.1. Renewable Portfolio Standards—RPS

RPS is a binary variable in the form of 1 if the state has implemented an RPS policy, and 0 if there is not an RPS policy in place during that year. The statistics are gathered from the US Department of Energy, in the Database of State Incentives for Renewables and Efficiency [90].

2.7.2. Market Regulation—DeReg

In the econometric model deregulation is measured as a binary variable where 1 stands for a deregulated state electricity market and 0 for a regulated state electricity market. The data set was sourced from the energy management firm Eisenbach Consulting (Tyler, TX, USA) [91].

2.7.3. Government Subsidies—TaxCred

Our third variable in this category is government energy subsidies in the form of tax credits. Tax credits are the largest source of government subsidies to the energy industry. This statistic is measured in millions of dollars, log form. Data was used from the US Energy Information Administration [12].

2.8. Weather

Temperature—Temp

To determine the effect of weather on electricity prices we use the average annual temperature by state. Numbers are measured in Fahrenheit. Data was gathered from the National Centers for Environmental Information, National Oceanic and Atmospheric Administration [92].

3. Results

3.1. Wind Energy

Percentage of wind energy displayed positive coefficients in all eight regression outputs, see Tables 2 and 3 for all variable results. These results were statistically significant in six of the eight results. The fixed effects model produced positive and significant wind energy results in four of four outputs, and the GMM models produced positive coefficients in four of four, and significant in two of four. Although directionality was the same across all sectors (residential, commercial, industrial and total), wind energy produced the highest level of pricing increase in the industrial sector. According to the regression outputs, higher

percentages of wind generated electricity lead to higher prices of electricity within the state.

Table 2. Fixed effects model. Electricity price dependent variable.

Variable	Residential	Industrial	Commercial	Total
Wind	0.064 ** (0.027)	0.126 *** (0.044)	0.090 *** (0.032)	0.057 * (0.031)
Customers	−0.050 (0.082)	−0.064 *** (0.014)	−0.197 *** (0.059)	−0.105 (0.094)
GDP	0.031 (0.040)	−0.066 (0.051)	−0.021 (0.040)	0.010 (0.045)
RPS	0.011 *** (0.004)	−0.002 (0.006)	0.004 (0.005)	0.007 (0.004)
DeReg	0.032 *** (0.012)	0.021 (0.019)	0.009 (0.014)	0.021 (0.013)
TaxCred	−0.006 (0.015)	0.005 (0.024)	−0.018 (0.018)	0.000 (0.017)
NatGas	−0.075 *** (0.018)	0.173 *** (0.029)	0.039 * (0.021)	0.006 (0.020)
CoalPrice	0.224 *** (0.036)	0.186 *** (0.057)	0.224 (0.044)	0.209 *** (0.040)
Temp	0.266 *** (0.092)	−0.183 (0.147)	0.170 (0.108)	0.150 (0.103)
_cons	0.353 (0.438)	1.640 *** (0.619)	1.786 *** (−0.478)	0.935 * (0.496)

Notes: Standard errors in parenthesis. *, **, and ***, denote significance at the levels of 10%, 5%, and 1% respectively.

Table 3. General method of moments model. Electricity price dependent variable.

Variable	Residential	Industrial	Commercial	Total
L1.	0.861 *** (0.028)	0.814 *** (0.027)	0.883 *** (0.024)	0.866 *** (0.024)
Wind	0.016 (0.028)	0.078 * (0.044)	0.066 ** (0.031)	0.034 (0.031)
Customers	−0.085 ** (0.042)	0.013 (0.011)	0.0382 ** (0.019)	−0.068 (0.047)
GDP	0.053 (0.039)	−0.029 (0.020)	−0.043 ** (0.018)	0.038 (0.043)
RPS	0.015 ** (0.004)	0.010 (0.007)	0.007 (0.005)	0.014 *** (0.005)
DeReg	0.010 (0.007)	0.016 (0.012)	0.028 *** (0.011)	0.009 (0.008)
TaxCred	−0.008 (0.009)	−0.017 (0.014)	−0.017* (0.010)	−0.005 (0.009)
NatGas	0.090 *** (0.012)	0.212 *** (0.019)	0.123 *** (0.013)	0.126 *** (0.013)
Coal	0.009 (0.021)	−0.022 (0.034)	0.004 (0.024)	−0.024 (0.022)
Temp	0.001 ** (0.000)	0.000 (0.001)	0.000 (0.001)	0.001 * (0.000)
_cons	−0.021	0.427 * (0.224)	0.406 * (0.160)	0.038 (0.218)

Notes: Standard errors in parenthesis. *, **, and ***, denote significance at the levels of 10%, 5%, and 1%, respectively.

3.2. Socio-Economic

The number of customers for each sector produced mixed coefficients and varying levels of significance across both models. The same is true for GDP. Our empirical regression

results do not demonstrate clear directionality for either of these variables in relation to electricity price across sectors.

3.3. Policy and Regulation

The RPS policy variable was positive in seven of eight results, and statistically significant in three of those seven. Complete energy market states display higher levels of electricity prices. The coefficients for this variable were positive in eight of eight, and statistically significant in two of eight. Government energy subsidies in the form of tax credits produced mixed coefficients and were only significant in one of eight outputs. These results do not display a strong relationship between government subsidies and the price of electricity.

3.4. Fuel Prices and Weather

Natural gas prices had a positive relationship with electricity prices in seven of eight outputs and were statistically significant in six of these seven. All of the natural gas coefficients in the GMM model were positive and significant over the 1% level, demonstrating a high level of effect on electricity prices across all sectors. The price of coal was positive in six of eight results. The p -values were statistically significant in three of the four fixed effects outputs, but insignificant in all of the GMM outputs.

The variable for average temperature was positive across seven of eight regression outputs and statistically significant in three of those seven. This implies that higher temperatures are increasing demand and driving up electricity prices.

4. Discussion

The econometric analysis in our research finds a statistically significant positive relationship between wind energy percentage and the price of electricity for end users across all three sectors, and for the total of price electricity. In both the fixed effects model and GMM, all regression outputs return positive coefficients for electricity price in relation to wind energy. The positive impact is demonstrated across residential, commercial, and industrial sectors in the form of electricity price increases. The levelized cost of wind energy has been decreasing as turbine technology has improved [13], but this does not account for all of the costs involved in the end price to consumer. Structural and systemic indirect costs have risen faster and offset cost decreases from technical gains in turbine technology.

While all of the sectors experience price increases, the industrial sector was impacted the most by the development of wind energy in our empirical results. The characteristics of manufacturing help to explain this phenomenon. Industrial manufacturing plants often operate 24 h a day. Industrial production requires uninterrupted power [93]. It is also true that some industrial facilities can alternate between fuel sources in order to utilize less expensive energy sources based on current market trends, such as switching between electricity from the grid and using power from onsite natural gas generators. However, this ability to change between fuel sources has decreased significantly over the past two decades. From 1994 to 2014 the amount of production that could switch between fuel sources dropped from 24% to 10% [94], see Figure 2. This means that the industrial sector has become less able to adapt and change between energy sources and is now more dependent on the fluctuating electricity market. This is one potential explanation for the more volatile wind energy supply raising prices more for the industrial sector.

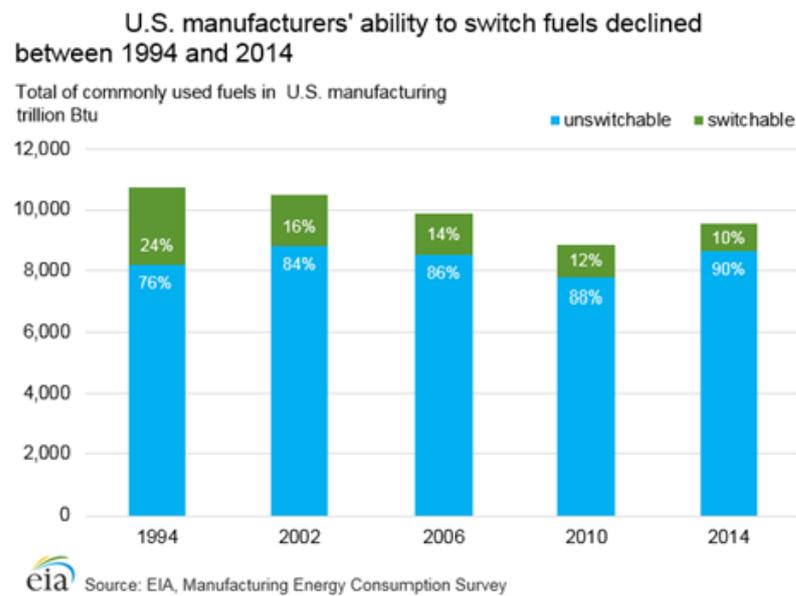


Figure 2. Manufacturing fuel source flexibility. Source: US Department of Energy, Energy Information Administration [94].

The gains in technical efficiency of the turbines have been offset by the indirect costs associated with incorporating high percentages of wind energy into the electricity grid. The primary indirect costs associated with wind energy include, volatility, supply balancing, premature closure of existing power plants, and transmission [95,96]. The most significant limitation of wind energy is not in the technology, but in the resource itself. Wind turbines do not produce energy 24/7. This causes gaps in production. The intermittency complicates the electricity market by creating volatility. The energy sources that produce more stable levels of power, such as hydro, nuclear, coal and natural gas, are called upon to balance supply levels to meet demand. The continual state of flux creates the need to ramp supply up and down. Wind energy is given priority access to the grid [64]. Fossil fuel plants must power up and power down based on fluctuation of supply and demand. This increases operating inefficiencies that pass on additional costs to consumers in the form of higher average electricity prices in the long-term.

Electricity transmission costs are a significant reason for the price increase associated with higher levels of wind energy within a state. Over the past two decades, transmission costs have increased by over 400% [17]. Annual spending on electricity transmission systems has increased from USD 9.1 billion in 2000 to USD 40.0 billion in 2019, see Figure 3. The majority of this has gone to new investment. Redesigning our energy systems to incorporate larger shares of renewables and phasing out fossil fuels has come at a significant financial cost. Wind farms are often built in remote locations, away from the population centers that they supply energy to [97]. This necessitates the construction of vast lengths of transmission cables. The positive aspect is that once the wind farms are operational and connected to the grid, their marginal cost of electricity production is much lower than other sources of energy.

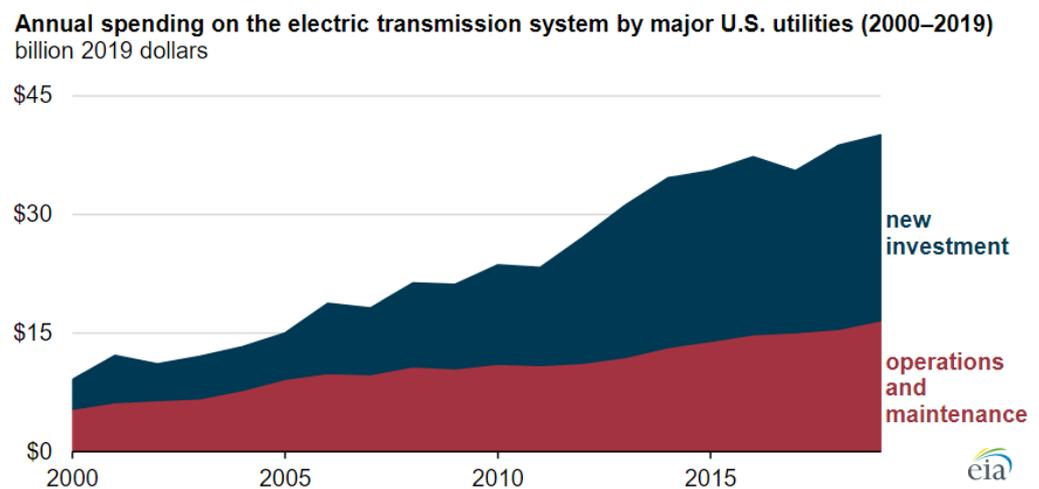


Figure 3. Electricity transmission cost. Source: US Department of Energy, Energy Information Administration [17].

In order to meet renewable energy quotas and percentage targets, power companies often take existing power plants offline to make way for new renewable sources [35]. Prematurely closing these electricity facilities means that utility companies do not fully recuperate the investment costs associated with each plant. This loss of revenue streams raises prices to end consumers. Decommissioning existing plants that were already connected to the grid and replacing them with wind farms that are farther from population centers increases the transmission costs associated with long distance cables.

The quantitative analysis did not find a definitive connection between our socio-economic variables and the price of electricity over our nineteen-year time period. The variables representing GDP and number of customers produced mixed coefficients and differing levels of significance across all sectors in both the fixed effects and GMM models. We cannot ascertain any clear relationship based on these results.

Our variables representing government policy and electricity market regulation displayed a significant relationship for both RPS policy and market regulation, but the tax subsidy variable reported unclear results. The results for the RPS variable indicate that states that have implemented RPS policies have higher electricity prices. This result does not mean that RPS policies should be eliminated, however they should be redesigned to ensure a minimization of cost increases in order to provide economically efficient energy to customers. States with deregulated energy markets have higher electricity prices in all sectors in both models. Government subsidies have an insignificant effect on the price of electricity in our models. This means that the injections of government capital have not had the desired impact of decreased electricity prices for consumers. The capital could have possibly ended up going toward increased profits for utility companies instead of decreasing electricity bills. Further research would be valuable to determine where exactly this money ends up and how to better design government energy subsidies.

Higher prices of both natural gas and coal lead to higher electricity costs for end users. These two fossil fuels are the leading sources of electricity generation in the nation. This is an intuitive result that supports the Energy Information Administration's report that fuel costs play a significant role in determining the final price of electricity. Temperature displays a strong positive relationship with electricity price, meaning that higher temperatures lead to increased energy demand and higher equilibrium prices. This result is supported by the fact that average energy prices are highest in the summer months [33].

Electric power grid stability is maintained by the balance of generation and demand [98]. In order to increase the global share of wind energy, innovative solutions must be adapted to overcome energy storage and grid balancing issues. Problems involving load leveling and peak shaving, emergency response, and voltage regulation, can limit the integration of wind energy into existing energy networks [99]. Wind energy requires

effective and safe Energy Management Systems (EMSs) to utilize energy storage [98]. Grid-level Large-scale Electrical Energy Storage (GLEES) is an essential method of balancing the supply and demand of electricity production, distribution, and consumption [99]. This grid scale energy storage technology is increasingly being deployed all over the world [98]. Energy storage can help facilitate renewable energy integration [100], but the full elimination of balancing issues requires massive storage capacities [101].

Another solution for surplus wind turbine electricity storage is the Power to Gas (P2G) processes [102]. P2G is a chemical energy storage technology, that can convert surplus renewable electricity into storable methane via electrolysis and subsequent methanation [103,104]. This technique can play a significant role in the future of wind energy storage because it addresses electrical grid stability in systems with a high share of renewable energy [102]. P2G is a promising technology that can enable cross-sector integration [105].

Vehicle to Grid technology (V2G) is a potential partner with wind energy to alleviate some of the problems associated with grid integration and indirect costs. These plug-in electric vehicles can be connected to the power grid with a bidirectional connection, so vehicles can charge and discharge electricity [106]. V2G's can perform quick-response, high-value electric services in order to balance grid load fluctuations [106,107]. This vehicle-to-grid system can help to improve grid efficiency, reliability, voltage control, congestion management, and provide storage for excess electricity [108]. Integrating V2G into the existing power grid on a large scale, will require a number of actions including an aggregative infrastructure to meet industry standards, and more high-powered home charging capabilities [109]. As the technology advances in the near future, this partnership can become more prevalent.

Suggestions for Further Research

During the course of our analysis of wind energy research, we discovered gaps in the body of existing research. There is minimal analysis of wind energy impact on utility prices at the state level in the United States that accounts for differences between sectors. Our research helps to fill this gap, but more analysis of similar questions would also be beneficial. Future researchers could look at this problem from a slightly different geographic perspective. Our research utilizes state level panel data. Additional papers could perform quantitative analysis with data measuring the differing impacts on rural, urban, and suburban residents. Electricity price would remain the independent variable, while adjusting energy source data and control variables to account for the different characteristics of rural, urban, and suburban locals. Our research area is also limited to the US, so we would welcome other researchers to test these questions in other nations.

Electricity can cross state borders in the form of energy imports and exports. Future studies should also research the topic from a grid level perspective. Electricity travels through a complex network of electricity substations, power lines, and distribution transformers before it reaches final consumers. The United States power system is made up of three main interconnections managed by the North American Electricity Reliability Commission, the Western, Eastern, and ERCOT (Austin, TX, USA) [110]. Within these interconnections, there are regional transmission organizations, and balancing authorities. Individual states are not completely isolated in terms of electricity production and consumption. Individual state governments decide how much wind energy to develop, tax rates, and other regulations. Our research analyzes the question of wind energy and electricity price at the state level in order to produce research that can be used by policy makers to reduce costs and expand wind energy development, but grid level analysis could better account for flows of electricity between states. Solar energy development and local energy also effect the price of electricity. RPS policies accelerate the development of both wind and solar energy. These policies include energy tax policy and mandates for wind and solar production percentages. We included this variable in our model as a proxy to account for a taxes, regulation, and overall renewable development, but we do not include specific solar and local tax variables. Our paper focuses on the impact of wind energy, but

we encourage other researchers to compare the pricing effect of wind energy versus solar energy, and to quantify the extent that taxes impact the price of electricity produced by wind turbines.

Our research provides valuable insight to citizens, policy makers, and wind developers. Government policy makers must strive to balance environmental conservation with the rising standards of living for their citizens. Economic justice concerns for those living at or near the poverty line can be dealt with by providing clean and affordable electricity to households. Efficient electricity generation will also benefit the national economy as a whole because increases in the price of electricity have a negative effect on economic development [30]. Policy makers should understand the importance of sustainable electricity supply as a means to achieve sustainable economic growth [32]. The findings of this research have importance to the United States and nations around the world seeking to develop a clean and efficient electricity supply.

5. Conclusions

We set out to quantitatively measure the price of wind, by empirically testing the long-term relationship between wind energy development and electricity price in the residential, commercial, and industrial sectors. Our first step was to conduct a review of research involving renewable energy and electricity costs. After studying relevant articles, we were able to understand the structure of the electricity market and the variables that impact electricity price. By determining these factors, we could then collect the appropriate panel data from reputable agencies. Next, we established an econometric model as a structure by which to analyze the research topic. We employed both fixed effects and GMM models. Using two empirical methods improves the robustness of the results. The results of our research indicate that wind energy indirectly passes on additional costs to consumers in the form of higher electricity costs.

The protocols instituted in response to COVID-19 have made significant changes to our electricity market structure. According to the World Economic Forum, these changes have drastically accelerated the transition from fossil fuels to renewable energy [64]. During the global economic shutdowns, energy demand decreased significantly. This decreased demand put financial strain on energy producers. Renewable energy sources are often given priority access to the grid, so the decrease in demand was absorbed by traditional power plants, and not the renewable energy producers. Given the growing importance of wind energy, sustainable and cost-effective solutions need to be implemented to combat cost increases indirectly caused by wind energy development.

There is no debate that wind turbines are improving in economic efficiency. Policy makers and industry experts must push for more cost-effective methods to provide electricity to end users at sustainable prices. Price calculations based solely on LCOE and short-term spot prices are not sufficient to base long term energy policy. This paper fills a gap in the literature by addressing the long-run pricing impact of wind energy on residential, commercial, and industrial consumers. The potential limitations of our research center around the complexity of the electricity market and the difficulty in perfectly quantifying all the contributing factors, such as competing energy sources, and state level energy imports.

In conclusion, our empirical results show increased electricity prices in states with higher percentages of wind energy. Our analysis demonstrates the need to assess wind energy development from a holistic view of the entire electricity market. Structural and systematic costs associated with increased levels of wind energy must be accounted for. Energy planning should include electricity balancing costs, infrastructure modifications, and transmission costs in order to more accurately assess the long-term pricing impact of wind energy on end users. Wind energy is increasing in economic efficiency, but these technological gains have been offset by price increases in transmission and balancing costs associated with volatility of supply. Governments must improve energy production and distribution with the objective of enhancing access to affordable electricity among citizens

in order to improve their standard of living [31]. As indirect costs are reduced, wind energy can play an even greater role in our sustainable energy future.

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